Open-File Report 15-07

Geologic Map of the Paonia Quadrangle Delta County, Colorado

Author's Notes

COLORADO GEOLOGICAL SURVEY
COLORADO SCHOOL OF MINES

by
David C. Noe

Colorado Geological Survey
Colorado School of Mines
Golden, Colorado
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FOREWORD

The purpose of Colorado Geological Survey's (CGS)Open-File Report 15-07, *Geologic Map of the Paonia Quadrangle, Delta County, Colorado* is to describe the geology, mineral and groundwater resource potential, and geologic hazards of this 7.5-minute quadrangle located east of Delta in western Colorado. CGS staff geologist David Noe completed the field work on this project during the summer of 2013. The geologic map plates and the Author's Notes report were created using field maps, structural measurements, photographs, and field notes generated by the investigator.

This mapping project was funded jointly by the U.S. Geological Survey (USGS) and CGS. USGS funding comes from the STATEMAP component of the National Cooperative Geologic Mapping Program, award number G13AC00213, authorized by the National Geologic Mapping Act of 1997, reauthorized in 2009. CGS matching funding comes from the Colorado Department of Natural Resources Severance Tax Operational Funds, from severance taxes paid on the production of natural gas, oil, coal, and metals in Colorado.

Karen Berry
State Geologist and Director
Colorado Geological Survey

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

LIST OF PLATES

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INTRODUCTION

The Paonia 7.5-minute quadrangle is located in Delta County, Colorado (**Figure 1**). The region is known for its orchards, vineyards, and organic agriculture. **Figure 2** shows the major physiographic features of the area. The North Fork Gunnison River (known locally as the North Fork River) flows across the northwestern corner. The lowest elevation in the quadrangle (5,550 feet) is where the river exits to the west. To the northwest and southeast of the river are numerous gravel- or mud-and-gravel-capped mesas, including Pitkin, Stewart, Lamborn, and Bone Mesas. Minnesota Creek flows across the north-eastern and north central parts of the quadrangle. The town of Paonia (2010 population: 1,497) is located at the confluence of Minnesota Creek and the North Fork River.

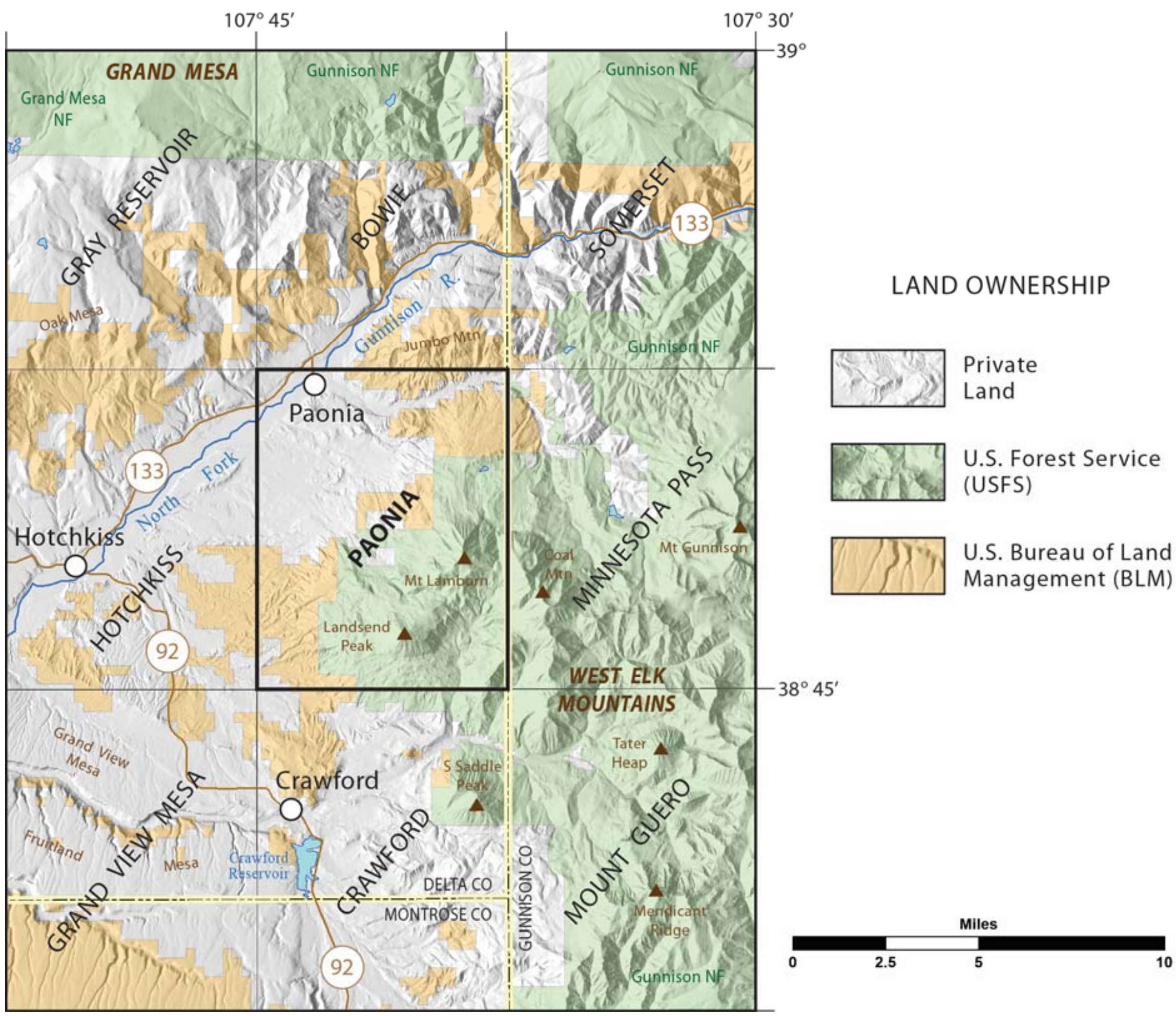

Figure 1. Index map of the Paonia 7.5-minute quadrangle in western Colorado.
Land ownership in the quadrangle consists of private land parcels and federal public lands that are administered by the U. S. Bureau of Land Management (BLM) and U. S. Forest Service (USFS).

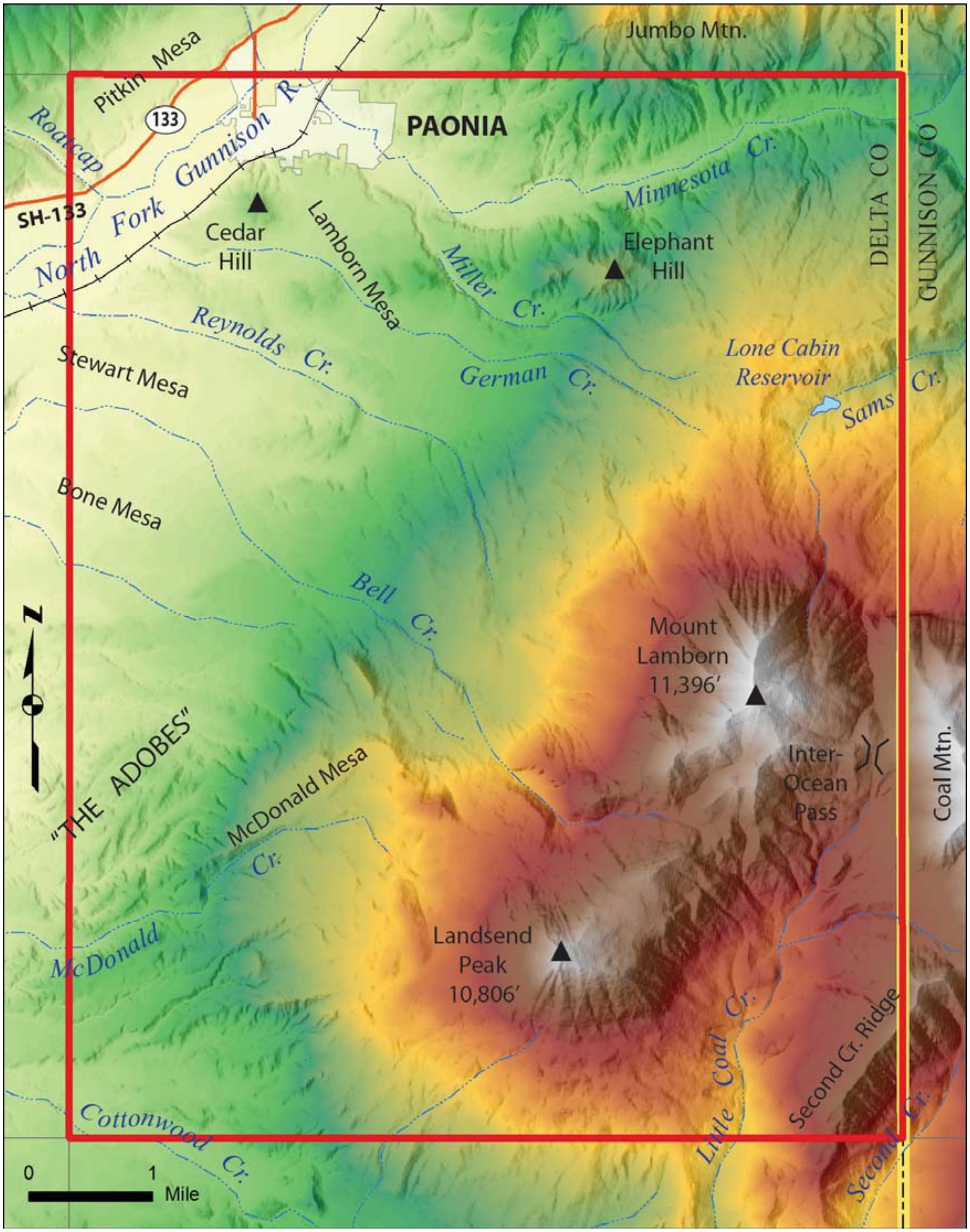

Figure 2. Shaded-relief index map of the Paonia quadrangle, showing major physiographic features. There are five geomorphic areas: (1) The North Fork Gunnison River valley, through which the river flows from northeast to southwest; (2) a succession of low mesas to the northwest and southeast of the valley; (3) the valley of Minnesota Creek in the northeastern part; (4) the high peaks of the westernmost West Elk Mountains in the southeastern part; and (5) the shale badlands and mesas of “the adobe hills," or “the adobes,” in the southwestern part.

A cluster of high peaks and ridges, including Mt. Lamborn (11,398 feet), Landsend Peak (10,806 feet), and Second Creek Ridge, dominates in the southeastern part of the quadrangle. These summits constitute the westernmost part of the West Elk Mountains. In the southeastern part of the quadrangle is an area of gravel-capped mesas, of which McDonald Mesa is the largest and highest, flanked by shale basins and badlands known locally as "the adobe hills," or simply, "the adobes."

PREVIOUS MAPPING STUDIES

Previous geologic mapping in the area was done by the U.S. Geological Survey (USGS) and the Colorado Geological Survey (CGS). The earliest regional geological map of the area was made by Hayden (1877) (scale 1:253,440); a portion of that map is shown on the **Back Cover**. The study area is included in a regional geologic map of the Montrose 1° x 2° sheet (Tweto and others, 1976) (1:250,000) and in intermediate-scale geologic maps by Hail (1972) (1:48,000), Gaskill (1977) (1:48,000), and Ellis and others (1987) (1:100,000). The northern part was mapped as part of a coal investigation by Dunrud (1989) (1:50,000). Junge (1978) mapped the surficial geology of the Paonia 7.5-minute quadrangle as part of a folio of 1:24,000-scale, geologic-hazard maps in the North Fork River valley area.

The Paonia 7.5-minute quadrangle geologic map is a result of an ongoing project by the CGS to map the geology of the Uncompahgre, Gunnison, and North Fork River valleys in western Colorado. Adjacent 1:24,000-scale geologic maps by CGS include the Hotchkiss (Noe and Rodgers, 2014) and Crawford (Noe and Klink, 2015) 7.5-minute quadrangles.

Geologic mapping of the Paonia quadrangle was undertaken by the CGS as part of the STATEMAP program. STATEMAP is a component of the National Cooperative Geologic Mapping Act, administered by the USGS. The purpose of the CGS STATEMAP program is to produce 1:24,000 scale geologic maps that focus on surficial units, bedrock units, and structural features. The maps can be used for land-use planning, geologic-hazard assessment, geotechnical engineering, and for mineral and groundwater resource development. They can also be used to learn about an area's unique geologic history. For the current status of CGS STATEMAP projects, see http://coloradogeologicalsurvey.org/geologic-mapping/.

MAPPING METHODOLOGY

The Paonia quadrangle geologic map is shown on **Plate 1**. The geologic interpretations are based on (1) CGS field investigations conducted from June to August, 2012; (2) other published and unpublished geologic maps and reports; and (3) interpretation of remote-sensing images. The image data include color, 1-m resolution, digital orthophotos taken in 2011 by the National Agricultural Imagery Program (NAIP); a 10-m resolution digital elevation model (DEM); and the Google™ Earth on-screen map viewer.

Bedrock geology and surficial deposits were mapped in the field on the orthophotos. Locations of key data points were recorded with a portable GPS receiver. ***All GIS locations reported herein and in the GIS database are in Universal Transverse Mercator (UTM), North American Datum 1983, Zone 13N projected coordinates, with units in meters.*** Bedrock structure measurements including bedding and fracture orientations were taken using a Brunton compass. Fossil, rock, and soil samples were collected, where possible, for age dating and material description purposes.

Mapping from the orthophotos was digitized into GIS using ESRI ArcMap. The GIS point, linear, and polygonal shapefiles were created by digitizing onto a computer screen. The field mapping was visually matched and digitized onto semi-transparent topographic map, NAIP orthophoto, and shaded DEM images. We used ERDAS IMAGINE 2010 to create the 3-D oblique geologic map shown in **Plate 2**.

DESCRIPTION OF MAP UNITS

This section contains descriptions of surficial and bedrock units from the geologic map. The surficial units are organized by the dominant process of deposition and by age, and are listed from youngest to oldest in terms of latest depositional activity. The bedrock units are organized by increasing age. The geologic time divisions and nomenclature used in this report are shown in **Appendix A**. Sediment-clast sizes are based on the modified Wentworth grain-size scale (Wentworth, 1922; Ingram, 1989). For each description, grain sizes are listed in the order of their relative abundance. Color names are taken from Munsell rock- and soil-color charts (Geological Society of America, 1991; GretagMacbeth, 2000). Stages of calcic soil development are described using the classification system of Machette (1985). Length and distance measurements are given in terms of inches, feet, and miles.

SURFICIAL DEPOSITS

The surficial deposits in the Paonia quadrangle are Quaternary (Holocene and Pleistocene) in age. The deposits shown on the map are generally more than 5 feet thick. Contacts between surficial units may be gradational, and mapped units may locally include deposits of other types. The deposits have not been age dated unless noted. Relative age assignments (early, middle, late) are based primarily on the degree of erosional modification of original surface morphology, height above modern stream levels, and degree of dissection, slope degradation, and soil development.

HUMAN-MADE DEPOSITS

af **Artificial fill (late Holocene)** – Gravel, sand, silt, clay, and rock or concrete debris emplaced to construct dams, embankments, or other human-made structures. Fills may be engineered (built with controlled compaction) or completely uncontrolled. Their compositions and properties are varied. Thickness is typically less than 20 feet.

dr **Disturbed and reclaimed land (late Holocene)** – Disturbed land includes areas such as surface gravel pits or other large excavations, and associated stockpiled or spoil materials. Reclaimed areas are covered with fill or overburden materials that consist of gravel, sand, silt, clay, or rock debris, similar to unit **af**. Thickness of fill, overburden, stockpiled, or spoil materials is typically less than 20 feet.

ALLUVIAL DEPOSITS

Gravel, sand, silt, and clay deposited in major river valleys and tributary drainages, in alluvial fans, and as older alluvial terrace, valley fill, or fan deposits. Erosion of the landscape through time has preserved the older deposits as elevated remnants, forming an *inverted topography*. Topographic inversion occurs when streams abandon their former courses and erode downward through soil or rock (in this case, soft shale) that borders the valley side. As a result, the stream migrates to a new course, and a newer, lower-elevation, stream valley is formed. Remnants of the older, abandoned deposits are preserved and are recognized today as mesa-capping gravel bodies.

We use an informal, numerical nomenclature for the alluvial deposits. The numbers, used as suffixes for the map units, refer to alluvial terrace levels along major and tributary stream valleys. Each level contains deposits that are generally correlative in terms of age and topographic elevation above the modern stream level. The youngest deposits, which floor the modern stream valleys, are designated as level one ("Alluvium one"). Progressively older levels are designated as two, three, etc. Analytical age-dates are rare for these deposits; therefore, we use geomorphic principles (see discussion above, under **Surficial Deposits**) to group different types of alluvial deposits and assign relative ages. Our correlations and groupings are similar to but more detailed than those from previous studies of the region by Hail (1972), Sinnock (1978) and Cole and Sexton (1981). There appears to be a relationship between the ages of alluvial river gravels in western Colorado and Pleistocene glacial moraines, as demonstrated by Sinnock (1978). The interpreted age relationships between our alluvial map units and Rocky Mountain glaciation episodes are shown in **Table 1**.

Table 1. Interpreted glaciation and age correlations of alluvial map units in the Paonia quadrangle

Map Unit Suffix	**Glaciation Episode**	**Marine Oxygen Isotope Stage (MIS)**	**Age Range** (in thousands of years)
1b and 2	Pinedale	MIS 2	11.7-30 ka
3	Late Wisconsin	MIS 4	50-89 ka
4 and 5	Bull Lake	MIS 6	130-190 ka
6	Pre-Bull Lake	MIS 10-12	340-480 ka
7	Pre-Bull Lake	MIS 16-20	620-750 ka
older	Pre-Bull Lake to Late Pliocene?	MIS 22 and older	800-850 ka to >3,250 ka?
Units and ages are regionally comparable to those of Hail (1972), Sinnock (1978), and Cole and Sexton (1981). Age ranges compiled from Porter (1989), Pierce (2003), Madole and others (2005), and Aber (2006).			

Alluvial Deposits of the North Fork Gunnison River

Gravel, sand, silt, and clay deposited by the North Fork Gunnison River. The younger deposits (**Qan$_{1a,b}$**) comprise the modern river flood plain. Several levels of ancestral North Fork deposits (**Qan$_2$** to **Qan$_5$**) are present as alluvial terraces that increase in age with increasing height above the modern river. The modern North Fork River valley is 0.6 to 1.0 miles wide. The older terrace-forming deposits are 0.5 miles wide or less. All of the deposits overlie erosional straths cut into soft Mancos Shale strata. **Table 2** is a summary of the map units that comprise the North Fork alluvial gravel deposits.

Table 2. Summary of North Fork alluvial gravel (Qan-series) map units in the Paonia quadrangle

Map Unit	**Age**	**Terrace Height** (feet)	**Deposit Thickness** (feet)	**Notes**
Qan$_{1a}$	Holocene	0-2	<15?	Modern river; meander-channel and overbank deposits; reworking upper part of unit **Qan$_{1b}$**; low overbank terraces; full thickness of unit not exposed
Qan$_{1b}$	Holocene to late Pleistocene	5-6	>25?	Partially exposed in a number of gravel pits; full thickness of unit not exposed; underlies modern river valley; covered in many places by mud fan (**Qamf**) deposits
Qan$_2$	late Pleistocene	80-90	10-15	Loess- or fan-gravel-covered terraces to the north of the North Fork River; comprises the SE rim of Pitkin Mesa
Qan$_3$	late Pleistocene	140-160	10-15	Loess- or fan-gravel-covered terrace remnants to the north of the North Fork River
Qan$_4$	late middle Pleistocene	?	?	Not positively identified in quadrangle; possibly covered by alluvial fan deposits to the north of the North Fork River
Qan$_5$	late middle Pleistocene	300	10-15	Fan-gravel-covered terrace remnants to the north of the North Fork River
Older North Fork alluvial deposits (**Qan$_6$** to **Qan$_{10}$**) are found to the north and west of the Paonia quadrangle, higher on the flanks of Grand Mesa (for descriptions, see Noe and Rodgers, 2014).				

North Fork alluvial gravel deposits are similar in appearance, composition, and thickness, regardless of age. They consist of well-rounded, discoid to oval cobbles, pebbles, and rare small boulders up to 1.5 feet in length (**Figures 3a and 3b**). The matrix is coarse sand. The gravel clasts are composed mostly of basalt and porphyritic igneous rocks. The proportion is variable. Sources of gravel include the central and northern West Elk Mountains (granodiorite and monzonite porphyries and lesser amounts of hornfels, fine-grained meta-quartzite, and other low-grade metasedimentary rocks), and Grand Mesa (basalt and trace amounts of sandstone, clinker, and chert). Source-area lithologies were interpreted using maps by Gaskill and Godwin (1966), Godwin (1968), Tweto (1977), and Tweto and others (1978).

North Fork terraces may be overlain by age-equivalent to somewhat younger fan gravel (**Qg**-series) deposits, marking paleo confluences with tributary streams. We map North Fork alluvial deposits as dashed lines where they are exposed in hill slopes at the base of a tributary gravel deposit. In other

Figure 3. Alluvial deposits of the North Fork Gunnison River (**Qan**-series).
(a) Alluvium 1a (**Qan$_{1a}$**) in the modern, active floodplain of the North Fork, at Paonia River Park. The sediment consists of slightly bouldery, pebble-cobble gravel, composed of monzonite porphyry with minor hornfels and sandstone, and a sand matrix. [UTMX: 274872, UTMY: 4306147]
(b) Alluvium 2 (**Qan$_2$**), poorly exposed in an alluvial terrace along the edge of Pitkin Mesa. It is similar to the modern deposits in terms of composition and gravel sizes. The lower two-thirds of the hill is Mancos Shale, mostly covered by a thin colluvial deposit. [UTMX: 273809, UTMY: 4306101]

locations, the North Fork terraces may be overlain by eolian silt deposits (loess, unit **Qe**), which are described separately.

Alluvial Deposits Along Tributary Streams

Gravel, sand, silt, and clay deposited by streams that are tributary to the North Fork Gunnison River. The younger deposits (**Qa**) comprise the modern stream flood plain. Two levels of ancestral stream deposits (**Qa$_3$** and **Qa$_4$**) are present as alluvial terraces that increase in age with increasing height above the modern valley of Minnesota Creek, along the southern side of the valley near Dry Gulch.

Qa **Alluvial deposits along tributary stream (Holocene to late Pleistocene)** – Sand, gravel, silt, and clay in and underlying the modern flood plain of tributary streams. The flood plain consists of active, low-sinuosity to meandering channels, poorly sorted sandy to gravelly channel deposits, and finer-grained overbank deposits. The unit may include colluvial deposits along the valley margins. It is sometimes partially overlain by alluvial fan (**Qf**) or mud fan (**Qamf**) deposits. The gravel in **Qa** deposits along Roatcap Creek consists primarily of basalt. Along Minnesota Creek, upper Bell Creek, and the tributary streams in Little Coal Creek basin, the gravel consists primarily of monzonite porphyry. Thickness is poorly known but generally less than 15 feet.

Qa_3 **Alluvium three along tributary stream (late Pleistocene)**

Qa_4 **Alluvium four along tributary stream (late middle Pleistocene)** – These two alluvial deposits are found in terraces to the south of Minnesota Creek, between Cedar Hill and Dry Gulch, where they underlie most of lower Lamborn Mesa. We interpret that they represent ancestral courses of that stream during times of glacial-outwash flows. The deposits are quite similar in clast size, sorting, rounding, and texture to the North Fork (**Qan**-series) alluvial deposits described previously. The main difference is that they are completely devoid of basalt. They are composed largely of porphyritic igneous-rock cobbles and pebbles, with lesser amounts of black hornfels, greenish fine-grained quartzite, brownish sandstone, and chips of pinkish red clinker. The **Qa_3** and **Qa_4** terrace gravels are partially overlain by age-equivalent fan deposits (**Qg**-series) and by younger landslide deposits (**Qls**). Farther up-valley, to the east, these and possibly older alluvial deposits are found on both sides of the Minnesota Creek valley, either as localized remnants or as covered deposits that have been overrun by landslides; those localized occurrences are marked with red-and-black “bull’s eyes” (as generic, **Qg** lag deposits; see next section). The main terrace deposits are 10 to 20 feet thick.

Mixed Debris Flow and Alluvial Gravel and Gravelly Mud Deposits

Gravel, boulders, clay, silt, and sand deposited by former tributary streams that flowed to the ancestral North Fork River. Upland gravel deposits of various ages (**Qg**-series) are scattered throughout the quadrangle. Typically, they form a series of elevated and dissected, gravel-capped mesas having linear to fan-like geometries. From younger to older, the remnant deposits are found at progressively higher elevations. Gravelly mud deposits predominate in the Bone and Stewart Mesa areas. **Table 3** is a summary of the map units that comprise the **Qg**-series gravel deposits.

We interpret the fan-shaped gravel bodies to be debris flow complexes that formed in upland basins and valleys and/or as terminal fans of the tributary streams at river confluences. The linear gravel bodies appear to be alluvial and debris-flow valley-fill deposits of modern or paleo tributary streams. In some cases the original shale valley sides still exist; in other cases the former confining walls are eroded away. The fans deposits range from 0.4 miles to nearly one mile wide. The valley-fill deposits range from 0.1 to 0.6 miles in width. In the case of the older deposits (**Qg_2** to **Qg_7**; and **Qg**), the remnant valleys and basins mark the paths of paleo tributary streams. They were much like the region's modern tributary valleys and basins in terms of distribution and morphology.

Table 3. Summary of debris flow and alluvial gravel (Qg-series) map units in the Paonia quadrangle.

Map Unit	Age	Deposit Thickness (feet)		Notes
		Basalt*	Porphyry*	
Qg_1	Holocene	Not present	5-15?	Scattered deposits in some modern tributary stream valleys and at base of mesa slopes; includes some recent debris flow deposits adjacent to the high peaks; full thickness of unit not exposed
Qg_2	late Pleistocene	5-10	10-15	Valley fill deposits; generally rarely preserved; most extensive deposits are in the Bell Creek-Bone Mesa area
Qg_3	late Pleistocene	5-30	10-30	Basin fan, valley fill, and terminal fan deposits to north and south of North Fork River
Qg_4	late middle Pleistocene	Not present	10-20	Basin fan, valley fill, and terminal fan deposits to south of North Fork River
Qg_5	late middle Pleistocene	>20	10-30	Scattered remnant deposits capping isolated hills and ridges to south of North Fork River; a few larger basin fan deposits in the Bell Creek area
Qg_6	middle Pleistocene	Not present	10-20	Scattered remnant deposits capping isolated hills and ridges to south of North Fork River
Qg_7	middle to early Pleistocene	Not present	10-15	Scattered remnant deposits capping isolated hills and ridges to north of North Fork River; may contain 640-ka Lava Creek B ash in nearby quadrangles
Qg	middle to early Pleistocene	Not present	5-100	Undifferentiated unit consists of scattered deposits at various age levels, capping isolated hills and ridges to south of North Fork River; the oldest and thickest is atop McDonald Mesa and on the high benches that flank the Mt. Lamborn, Landsend Peak, and Second Creek Ridge; includes moraine-like deposit in upper Little Coal Creek
Units and ages are regionally comparable to those of Hail (1972), Sinnock (1978), and Cole and Sexton (1981). * Basalt gravels are found to the north of the modern North Fork River; porphyry gravels are found to the south of the river.				

The terminal, tributary fan deposits may grade onto ancestral North Fork and Minnesota Creek alluvial terraces (**Qan**- and **Qa**-series). Based on such pairings, we map five levels of **Qg**-series map units that are correlatable with the alluvial terraces. In most exposures, the basal fan gravels overlie and thus are somewhat younger than the river gravels. In upland basins, we could map up to seven levels of **Qg** deposits and assign them to numbered map units based on the local geomorphic succession. Where we could not determine a local succession of deposits, and for much older gravels deposits such as the one that caps McDonald Mesa, we assign an un-numbered designation of **Qg**.

The composition and texture characteristics of **Qg**-series deposits in the Paonia quadrangle vary considerably as a function of different sediment sources and depositional processes. Gravel deposits to the north of the North Fork River are composed almost entirely of basalt clasts, sourced from late Miocene basalt flows that cap Grand Mesa. Minor amounts of sandstone, siltstone, clinker, chert, carbonate concretions, and shale and tuff rip-up clasts may be present; they are sourced from Upper Cretaceous to Miocene-aged bedrock units that outcrop in the upper slopes of Grand Mesa. Minor amounts of well-rounded porphyry and hornfels clasts, originally from the West Elk Mountains, may be present; these most likely eroded from older, North Fork River terraces. The basalt-gravel **Qg** deposits are mostly comprised of debris flow facies. They contain sub-angular, very poorly sorted pebbles to very large boulders in a mud to sandy mud matrix. The boulders are commonly up to 5 to 6 feet long. In addition, clast-supported alluvial deposits of basalt gravel, marking episodic stream-flooding events, are present in some locations. These findings generally agree with those from an earlier study in the area by Cole and Sexton (1981), who refer to the debris flow deposits as "pediment deposits." The basalt-gravel deposits range from 5 to 30 feet thick.

Gravel deposits to the south of the North Fork River are composed mainly of monzonite porphyry clasts, derived from Oligocene laccoliths of the West Elk Mountains. Hornfels and fine-grained quartzite clasts may be present in minor amounts, derived from metamorphosed Mancos Shale surrounding the laccoliths. An example of a modern debris flow deposit (**Qg$_1$**) is shown in **Figure 4**. Older, gravel-rich deposits having debris flow and occasionally alluvial facies are found capping Elephant Hill (**Figure 5a**) and other, lower hills around Stewart Mesa to the west; McDonald Mesa (**Figure 5b**); and many small, unnamed mesas and benches in the Cottonwood Creek and Little Coal Creek drainages. In certain areas, the author could assign relative age designations to different levels of gravel and could number the deposits; in other areas this was not possible and the undifferentiated **Qg** designation is used for the mapped deposit. This includes an unusual **Qg** deposit in the eastern upper Little Coal Creek basin that consists of a pair of elongate, dissected moraine or earth flow deposits on the flank of Coal Mountain.

Figure 4. Porphyry-clast gravel deposit (**Qg$_1$**), gravel-rich, modern debris flow facies.
This recent debris flow was deposited on the lower slope of Coal Mountain. It consists of subangular porphyry and minor hornfels clasts. The deposit partially fills a narrow upland basin. This debris flow path doubles as an avalanche path during the winter. [UTMX: 282369, UTMY: 4296383]

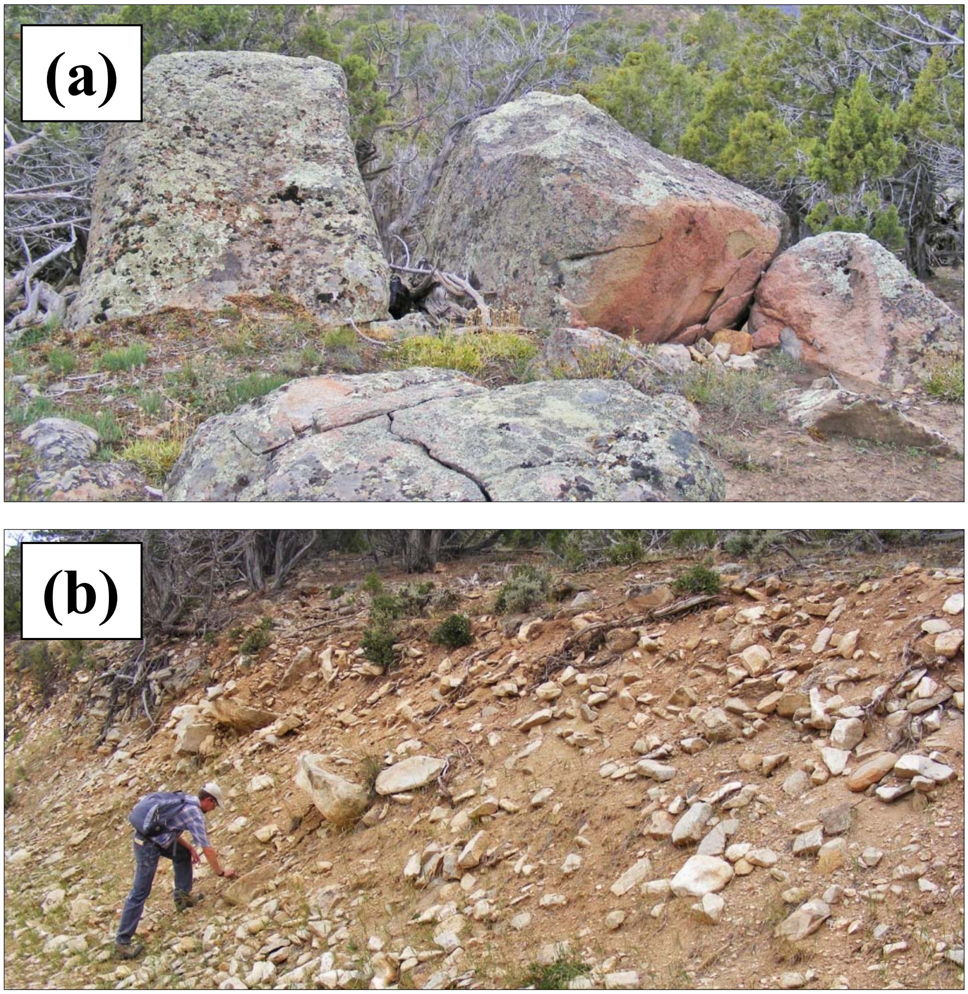

Figure 5. Porphyry-clast gravel deposits (**Qg**), gravel-rich, ancient debris flow and alluvial facies.
(a) Debris flow deposit at the top of Elephant Hill. The deposit contains numerous, large boulders of porphyry, up to 7 feet long, and is generally very poorly sorted. The source area for the gravel is on Mt. Lamborn, more than three miles away. [UTMX: 279222, UTMY: 4303344]
(b) Mixed debris flow and alluvial deposits capping McDonald Mesa, exposed in a road cut along the northeastern side. The deposit contains both matrix- and clast-supported sediments and abundant, clay-rich, fine-grained sediment. This is perhaps the oldest fan and/or valley fill deposit in the Paonia quadrangle. The sediments are deeply weathered, as evidenced by differentially grussified porphyry clasts and scattered pockets of stage 3+ calcic soils. [UTMX: 274501, UTMY: 4296730]

The high benches surrounding the high peaks of the West Elk Mountains are capped by a potentially distinct type of **Qg** deposit. The deposits are quite old (middle to early Pleistocene, or perhaps even late Pliocene in age?), based on their high landscape position. They are typically heavily vegetated. Where exposed, they are gravel rich and have generally wedge-shaped geometries, with upper surfaces that descend gently away from the slope break against the steeper mountains. The proximal portions are up to 100 feet thick, and they appear to thin distally. The sediments are very poorly sorted and contain angular rock clasts of varying sizes. They may contain extraordinarily large blocks of porphyry bedrock

(**Figure 6**), especially on benches that are downhill from highly eroded parts of the mountain faces. There appear to be several levels or ages of the deposits. The author interprets these as being debris avalanche deposits, resulting from episodic, large-scale failures of the adjacent, uphill mountain slopes.

Figure 6. Porphyry-clast gravel deposit (**Qg**), gravel-rich, debris avalanche facies.
This exposure, in a high bench above Reynolds Creek Spring No. 4, is a wedge of unsorted, angular rock fragments and sandy gravel debris. It contains several extremely large blocks of porphyry bedrock that are the size of rooms or small houses. The deposit overlies the upper part of the Mancos Shale, which is exposed in the non-vegetated patch at the far left. [UTMX: 278279, UTMY: 4297787]

Mud-rich **Qg**-series fan deposits occur in the Bone, Stewart, and Lamborn Mesa areas, in the west central northwestern parts of the quadrangle. They range in composition from gravelly mud to muddy gravel. Several ages of fans are present. Their source area consists of a large landslide complex in Mancos Shale on the western sides of Mt. Lamborn and Landsend Peak. The gravel is derived from those two peaks. Those deposits are generally poorly exposed. In contrast to rather well-formed gravel caps elsewhere, the gravelly mud deposits form rounded mesa caps with indistinct edges (**Figure 7**). This morphology may be due to their relatively moderate resistance to erosion (as compared to the more resistant gravel caps). The deposits appear to be comprised of mixed debris and mud flow and alluvial facies, which filled broad valleys and upland basins. The author has assigned numbered **Qg**-series designations to these particular deposits because deposits of different ages are recognized, based on the relative increase in age with increasing height of the deposits above the modern valley floors.

Isolated gravel pod or lag (Holocene to Pleistocene) – Black-and-red "bulls' eyes" mark the locations of small, relict gravel deposits. They occupy the tops of hills and points and appear to be in place. Some of the deposits consist of rounded pebbles and cobbles of North Fork River or Minnesota Creek origin (alluvial outwash deposits). Other deposits consist of sub-angular basalt-, porphyry-, and/or sandstone-clast gravels that represent a wide variety of depositional settings (for example, debris flows in fans or valley fills; alluvial deposits in tributary streams and arroyos; or talus, rock glacier, or debris avalanche deposits). These remnant gravel bodies are too small in extent to map as polygons at the map scale. In the GIS database, these point shapefiles are assigned to the **Qg** series of deposits. Thickness is 5 to 20 feet.

Figure 7. Porphyry-clast gravelly mud deposit (**Qg_4**), gravelly mud flow facies.
This is the down-valley edge of a gravelly mud fan deposit, exposed erosionally in upper Lamborn Mesa to the south of German Creek. The unit is poorly exposed, but it contains more than 50% mud matrix with suspended, subround pebbles of porphyry gravel. Mt. Lamborn is the source of the gravel; a large landslide complex in the Mancos Shale at the base of the peak is the source of the mud. Because of its high mud content, it is difficult to distinguish the deposit from the underlying Mancos Shale (which, at this location, is the Sharon Springs Member – **Kmss**). [UTMX: 275757, UTMY: 4302577]

MUD FLOW AND ALLUVIAL FAN DEPOSITS

Qamf **Alluvial, mud flow, and mud fan deposits (Holocene to late Pleistocene) –** Grayish-pink to grayish-orange, well to occasionally poorly sorted, poorly consolidated, locally gravel-bearing, clayey to sandy silt. The deposits primarily consist of poorly defined silt layers, typically less than an inch to a few inches thick. The muddy sediments are derived primarily from the Mancos Shale. The gravel is derived locally, eroded from older debris flow deposits and landslides. The deposits are formed by channelized to laterally unconstrained mud flows or mud-and-gravel debris flows. Alluvial floods may rework the sediments. There are occasional stringers and lenses of gravel and sand, especially in the basal deposits and in the vicinity of sand and gravel sources. The unit forms valley-head and valley-side alluvial fans and tributary stream valley fills (**Figure 8**). It forms low-gradient mud fans and coalesced fan aprons that cover large areas of the modern North Fork River and Minnesota Creek floodplains. Notably, much of the town of Paonia is built on a large mud fan. The unit is best developed within the "adobe hills" area of the quadrangle, particularly in areas underlain by the Smoky Hill Member of the Mancos Shale. Thickness is 5 to 10 feet in valley-head areas, and may exceed 20 feet along valley reaches and 20 to 40 feet at the heads of terminal mud fans.

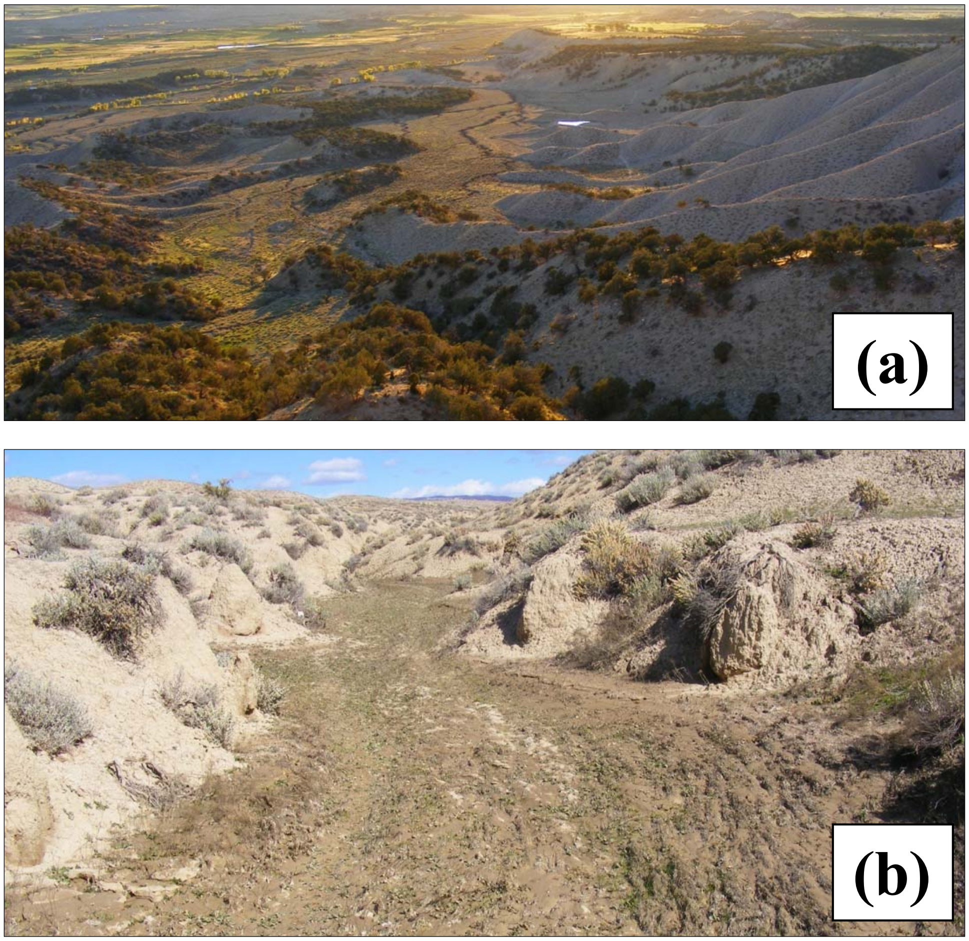

Figure 8. Alluvial, mud flow, and mud fan deposits (**Qamf**).
(a) Looking down-valley into a basin that is tributary to Cottonwood Creek, in the southwestern part of the map area. Mud flow deposits fill the basin, resulting in a flat-topped deposit. The basin is surrounded by Mancos Shale "adobe hills" [UTMX: 275336, UTMY: 4293867]
(b) An arroyo incised into a mud flow deposit in the "adobe hills." The deposit is exposed in the arroyo walls and at the base of the channel. Its top is marked by a flat surface, about five feet above the arroyo floor, which abuts against the flanking shale hills. The basal part of the deposit contains occasional, small, cut-and-fill channels with lags of porphyry gravel. This stream reach had experienced a flash flood only a few days before. [UTMX: 272173, UTMY: 4296744]

Qf **Alluvial fan deposits (Holocene) –** Poorly to moderately sorted gravel, clay, silt, and sand. The fan sediments are deposited by flood, debris, and sheet flow processes. Alluvial fans form at the mouths of stream valleys where the drainage loses confinement. In the Paonia quadrangle they are relatively rare, occurring at the mouth of Roatcap Creek and in upland basins along Bell Creek and Little Coal Creek. They are thickest and are rich in gravel at the apex. The deposits thin and become finer and less gravel-rich distally, where they merge contiguously into mud fan or alluvial floodplain deposits. Thickness is 5 to possibly 20 feet.

Qfo **Older alluvial fan deposits (late Pleistocene) –** Composition and mode of deposition is the same as for **Qf**. We mapped dissected fans several older alluvial fans in upland basins along Bell Creek and Little Coal Creek. The fans are inactive, and are bypassed by the modern streams. Thickness is 5 to 20 feet.

MASS WASTING DEPOSITS

Qls **Landslide deposits (Holocene to middle Pleistocene) –** Unsorted to moderately sorted clay, silt, sand, gravel, boulders, and rock fragments; may contain very large blocks of displaced and weathered shale bedrock. The deposits record the failure of a hill slope and the down-slope movement of debris (**Figure 9**), either within an individual landslide body or a larger landslide complex. The matrix and rock types, compositions, and sizes of fragments present reflect the properties of the local source areas. Landslide debris may contain bodies of relatively undisturbed rock or soil.

Landslides are the most common surficial deposits in the Paonia quadrangle. A broad belt of landslide complexes surround Mt. Lamborn and Landsend Peak. They occupy the middle slopes, flanked uphill by rock glaciers (**Qrg**), block-glide landslides (**Qlsb**), and older gravel deposits (**Qg**), and downhill by mixed debris flow, alluvial gravel, and gravelly mud deposits (**Qg$_1$**

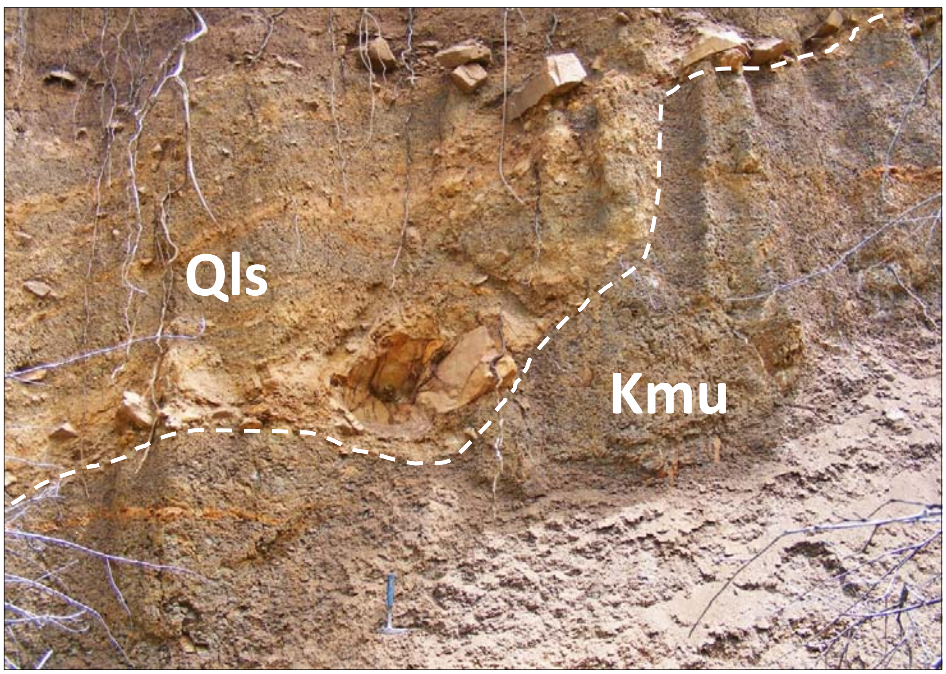

Figure 9. Landslide deposits (**Qls**) exposed in an arroyo to the north of Sams Divide.
The deposit overlies weathered and slightly deformed bedrock of the upper part of the Mancos Shale (**Kmu**). It contains slumped and transported shale bodies, limestone concretions, and fragments and blocks of sandstone. The basal failure surface is undulatory and highly irregular, and is marked by a dashed line. The rock hammer, at bottom center, is 11 inches long. [UTMX: 281555, UTMY: 4302720]

through **Qg_7**). The landslide complexes are 0.5 to 2 miles in width and contain numerous, internal head scarps and amalgamated landslide deposits (**Figure 10**). They are composed largely of failed blocks and earth flows of weathered Mancos Shale, with variable amounts of porphyritic and hornfelsic rock detritus shed from the higher peaks. Each landslide complex probably records a history of numerous periods of activity during late to middle Pleistocene glacial and interglacial stages. In the Reynolds Creek Springs area on the northwestern flank of Mt. Lamborn, and on the southern flank of Landsend Peak, the master head scarps appear to roughly coincide with the transition between metamorphosed Mancos Shale and less stable, unmetamorphosed shale farther away from the laccoliths.

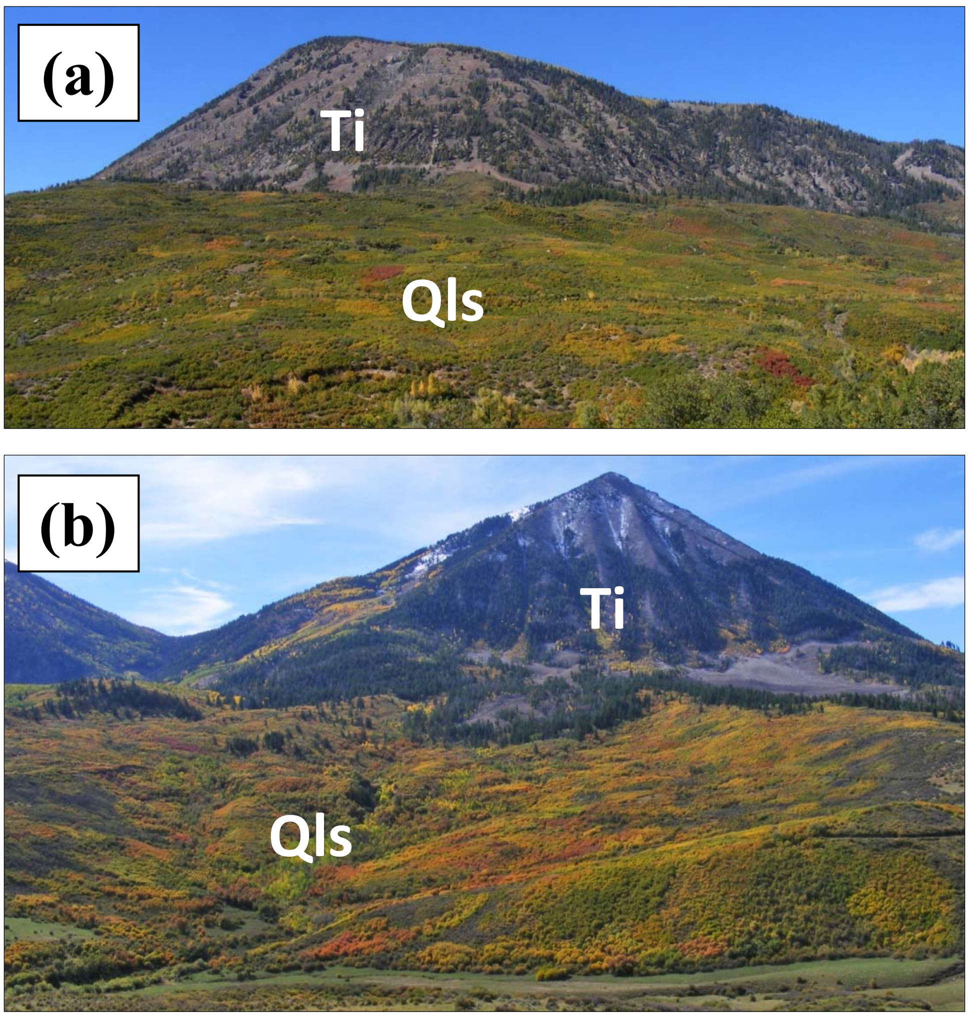

Figure 10. Landslide (**Qls**) complexes on the flanks of the high peaks of the West Elk Mountains.
(a) Southeastern flank of Landsend Peak, above Little Coal Creek. [UTMX: 280688, UTMY: 4291717]
(b) Northern flank of Mt. Lamborn, near Lone Cabin Reservoir. [UTMX: 281454, UTMY: 4301859]
The landslide complexes consist of hummocky ground that is extensively vegetated by Gambel oak and serviceberry bushes. In contrast, the steeper slopes of intrusive igneous rocks (unit **Ti**) that form the peaks are forested with evergreen or aspen trees.

Elsewhere in the quadrangle, individual landslides form in hill slopes composed of clay-rich Mancos Shale. Upland gravels from mesa caps, or sandstone blocks and fragments from rimrock outcrops, may be incorporated into the landslide, either during primary slope failure, or later during erosion and retreat of the head scarp. Some landslides within the quadrangle are clearly active. Others appear to be inactive, although they may be metastable and potentially capable of reactivation. The landslide scarps are mapped as separate features **–** some are fresh, while others are modified by erosion and retain the arcuate shape of the failure surface. Thickness is 5 to possibly greater than 100 feet.

Qlsb **Block-glide landslide of Mesaverde Group rocks (Holocene to Pleistocene) –** A small mesa to the northeast of Sams Divide, near Lone Cabin Reservoir, is unusual in its geomorphology and makeup. The mesa surface slopes gently to the northeast and is marked by a series of arcuate, down-dropping scarps and benches. Fine-grained sediments of Holocene age (unit **Qamf**) have locally filled narrow depressions downhill from the scarps. The main, capping deposit consists of poorly exposed, displaced sandstone, siltstone, and shale. There is no porphyry present. At the southwestern, uphill margin, the sandstone is fine to medium grained and is tan to medium-brown color. It has low-angle trough and hummocky cross-stratification and rippled bedding, and in places is chaotically tilted out of place to form "tombstone blocks" (**Figure 11**). To the northeast within the deposit, the sandstone becomes light-reddish-brown in color, and is interbedded with siltstone and shale in rough, disturbed bands (**Figure 12**). The siltstone and shale are pale- to light-red, purplish-red, or reddish-orange, colors typically associated with coal-burned rock, or clinker. Carbonaceous shale fragments are uncommon, but are locally present. The deposit thickens toward the northeast. It is underlain by Mancos Shale and is flanked by landslides such as described previously for unit **Qls**.

Figure 11. "Tombstone blocks" of sandstone in block-glide landslide deposits (**Qlsb**) near Sams Divide. These are two examples of chaotically tilted blocks, which have random orientations. The sandstone at this location is most likely displaced Rollins Sandstone (**Kir**). [UTMX: 281082, UTMY: 4302357]

Figure 12. Typical exposures of sandstone and siltstone-and-shale in block-glide landslide deposits (**Qlsb**). The sandstone, at left, forms broken small blocks. The siltstone and shale, at right, form small pieces and fragments. Those lithologies are roughly interbedded in bands within the northeastern part of the deposit. The reddish color may indicate burning of former coal beds to form clinker. The rocks at this location are most likely displaced Williams Fork Formation strata. [UTMX: 282336, UTMY: 4303224]

This assemblage of rock types is typically associated with the lower part of the Mesaverde Group (Rollins Sandstone and Bowie Shale Members of Lee, 1912). The nearest, previously mapped Mesaverde outcrop is on Lion Mesa, 1.5 miles to the east (Ellis and others, 1987). Based on field evidence, the author interprets that this deposit is a block-glide landslide, with Mesaverde strata being displaced atop one or more slip planes in the uppermost Mancos Shale. The presumed slip planes, and the slope of the deposit's upper surface, are generally coincident with the regional dip (to the northeast at about 8 degrees). The numerous, internal scarps within the body of the deposit are interpreted to be detachment scarps. The deposit is bounded to the south by a limb of moderately dipping Mancos Shale, and is separated from that structural feature by an inferred or covered fault or a fold axis. Thickness is poorly known; the deposit is about 5 to 30 feet thick in the southwestern part of the mesa, and may be more than 60 feet thick in the northeastern part, in the adjacent Minnesota Pass quadrangle.

△ **Sandstone-block rubble deposits (late Pleistocene) –** Yellow triangles mark a number of distinctive deposits along a ridge line to the north of Lone Cabin Reservoir, in the northeastern part of the quadrangle. The deposits consist of chaotic mixtures (rubble) of sand, clay, and sandstone, siltstone, and shale chips, fragments, and blocks. There is no porphyry present. The sandstone is fine to medium grained, and the fragments and blocks range in size from a few millimeters to more than 10 feet long. The blocks have a variety of orientations, including overturned. Low-angle trough and hummocky cross-stratification are evident, as well as *Ophiomorpha* trace fossils and occasional, broken fragments of oyster shells. The siltstone is pale- to light-red, reddish-orange, or purplish-red, colors typically associated with coal-burned rock, or clinker. The matrix materials include millimeter-sized, carbonaceous shale fragments. The deposits are partially consolidated and contain variable amounts of patchy, calcic soil cementation (Stage 3+).

As noted for the block-glide landslide unit **Qlsb** (above), this assemblage of rock types is typically associated with the Rollins Sandstone and Bowie Shale Members of the Mesaverde Group. The rubble deposits are unusual in their geomorphology and distribution. They occupy the top of the ridge, forming nine individual hills. They are surrounded on all sides by Mancos Shale that dips moderately (32 to 40 degrees) toward the north-northwest. The rubble deposits are asymmetric, in that they extend farther downhill to the south-southeast in all cases, and are inset into the slopes above Sams Creek (**Figure 13**). The rubble bodies are more resistant than the surrounding shale. They appear to be filling local catchments within the shale. The author interprets that these are remnant fill deposits in steep gullies in Mancos Shale that were once at the base of a caprock (now eroded away) of basal Mesaverde strata. Erosional rockfall, slope wash, and landslide debris filled the gullies. Thickness is probably 5 to 50 feet.

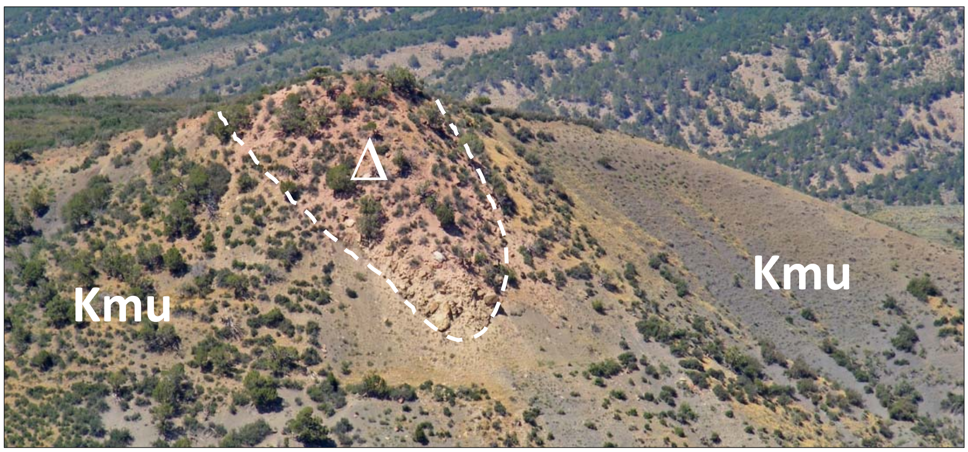

Figure 13. Sandstone-block rubble deposit (△) on ridge top to the north of Sams Creek. This deposit, located just to the east of the Paonia quadrangle, is the best exposed of nine that form the summits of a mile-long ridge. Here outlined by a dashed line, the deposit consists of a body of tan to light-red sandstone, siltstone and shale rubble, or sedimentary breccia, perched asymmetrically upon an isolated hill top. It is surrounded by the gray-colored upper part of the Mancos Shale (**Kmu**). [UTMX: 283481, UTMY: 4301415]

Qt **Talus deposits (Holocene to late Pleistocene) –** Light- to dark-gray, angular blocks and fragments of monzonite porphyry, with a variably distributed matrix of sand-, gravel-, and silt-sized material of the same composition. The rock blocks are commonly up to 6 feet in length, but occasionally blocks of up to 10 feet in length are present. Talus cones and aprons form along the steep sides of laccoliths peaks, sheets, and plugs, as composite aprons or at the mouths of rock chutes. They are primarily deposited by rockfall or snow-avalanche processes. The talus typically overlies and grades laterally into the proximal parts of rock glacier deposits (unit **Qrg**) (**Figure 14**). Thickness is poorly known, but may range from 5 to 100 feet.

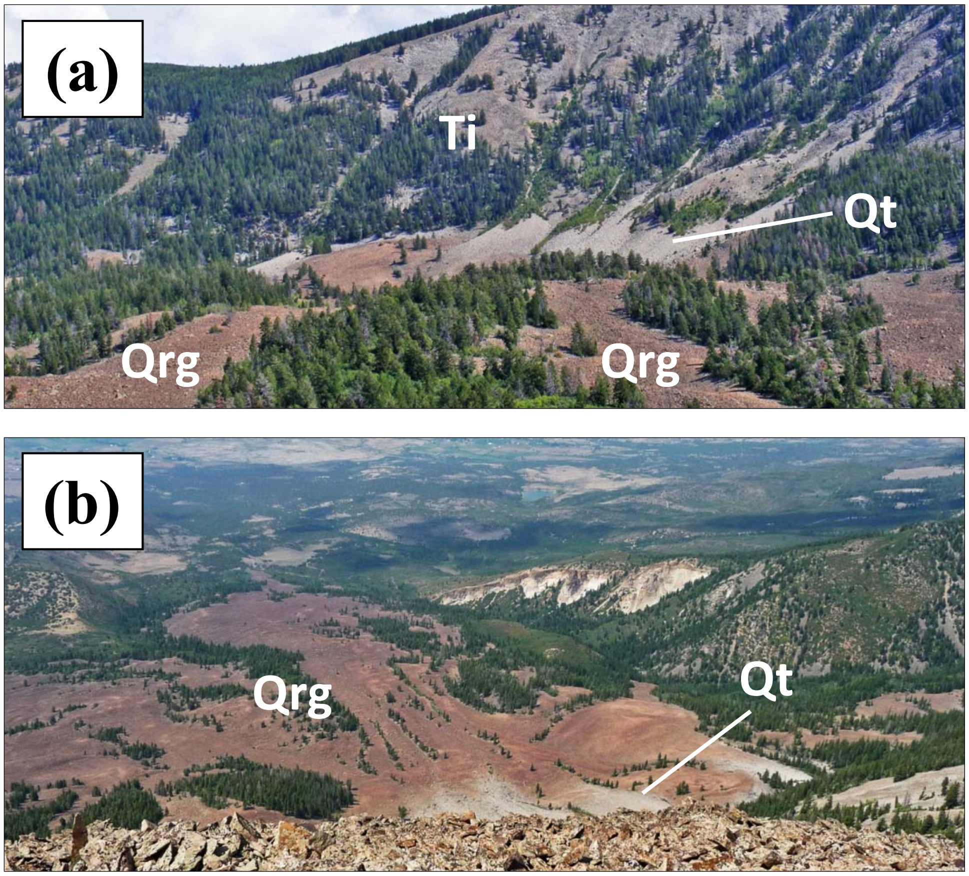

Figure 14. Talus (**Qt**) and rock glacier (**Qrg**) deposits on the northwestern side of Landsend Peak.
(a) Looking uphill, to southeast, toward the source area. [UTMX: 276913, UTMY: 4296428]
(b) Looking downhill, to northwest, from the summit of the peak. [UTMX: 278465, UTMY: 4294675]
The talus forms light-gray talus cones at the base of rockfall chutes, and are sourced from the intrusive igneous rocks (unit **Ti**) that make up the peak. It overlies and grades down-slope into the rock glacier deposits, which have oxidized to orange in color. The rock glacier deposits display flow banding, which is accented by patterns of trees that grow on its surface.

Qrg **Rock glacier deposits (Holocene to late Pleistocene) –** Medium-orange to orange-brown, angular blocks of monzonite porphyry, forming undulating surfaces with visible flow bands. The rock blocks are commonly up to 6 feet in length. They have been roughly size-sorted by freeze-thaw processes and movements of interstitial ice. Finer matrix materials are typically not present at the surface, but may occur deeper within the deposits. The rock glaciers form at the base of talus cones, and are basically talus material that has been remobilized. The contact between the talus and rock glacier deposits is marked by changes in color and sorting (**Figure 14**, above). The toes of the rock glacier deposits are typically well formed, with steep, rounded, terminal slopes. It is unknown whether there is still interstitial ice remaining within the rock glaciers, or whether parts of them are actively moving. In the Paonia quadrangle, rock glaciers occur at relatively low altitudes (7,200 to 9,400 feet in most cases). Most of the rock glaciers are

0.2 to 0.5 miles long from proximal source to terminal snout. In certain cases, they may exceed a mile in length. The longest descends from the northwestern flank of Landsend Peak to the Mays Spring area in Bell Creek basin, a fall of 1,700 feet in elevation over a total distance of 1.6 miles (**Figures 14** and **15**). The substrate over which the rock glaciers have flowed consists of monzonite porphyry, Mancos Shale, or older landslide deposits. In many locations, they appear to spill over pre-existing landslide head scarps. Where the substrate is clay-rich, the rock glaciers appear to have formed minor terminal and medial moraines consisting of compressed mud. Those mud moraines appear to be up to 10 feet high and a few tens of feet wide. Thickness of this unit is poorly known, but may range from 5 to 50 feet.

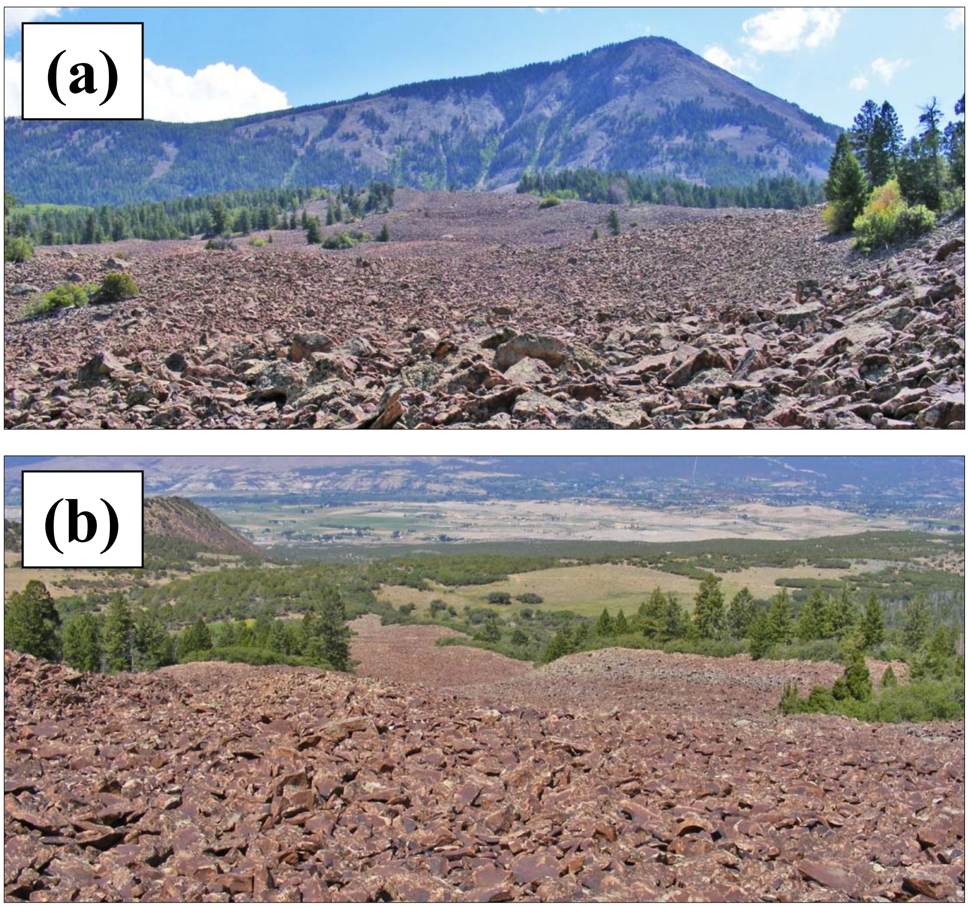

Figure 15. Details of surface of rock glacier deposits (**Qrg**), from rock glacier shown in Figure 12.
(a) Looking uphill, from the middle of the deposit. [UTMX: 277189, UTMY: 4296744]
(b) Looking downhill, from the same spot. The hummocky topography was produced by flowage of ice and rock blocks. Iron and manganese oxides coat the rock block surfaces.

Qc **Colluvial deposits (Holocene to late Pleistocene) –** Sediments locally transported by water and gravity, found generally at the base and lower part of slopes. Deposits consist of locally derived clay, silt, sand, and boulders. Veneers (a few feet thick) of colluvium commonly cover mesa slopes throughout the quadrangle, but were too thin to map in most cases. The author mapped a prominent colluvial deposit along the southern slope of McDonald Mesa. There, colluvial material has raveled onto and accumulated upon a landslide head-scarp face, sourced locally by a mesa-capping gravel deposit (**Qg**). Thickness is not known, probably 5 to 15 feet.

The author mapped several colluvial flatirons in “the adobe hills” area in the southwestern part of the quadrangle, which are shown on the map as thin, dashed, black lines. These are the remnants of colluvial deposits on the sides and ridges of shale-cored hills. The line represents a boundary between gravelly slope material (which is typically too thin to map as a colluvial deposit) and in-place shale bedrock.

EOLIAN DEPOSITS

Qe **Loess or clay-chip dune deposits (Holocene to late Pleistocene) –** Pale-red silt or sandy silt, or olive-gray to pale-yellowish-brown chips of shale, deposited primarily as windblown material. The deposits appear massive or have weakly developed bedding or relict soil-zone development. Loess deposits are found capping alluvial-gravel terrace deposits (**Qan$_2$** and **Qan$_3$**) on mesas to the north and south of the North Fork River. Older loess deposits may be present overlying older gravel deposits (**Qg**-series) in the Lamborn and Bone Mesa areas, and on McDonald Mesa; those deposits were not mapped as **Qe**, however, as there are few exposures and we could not define any mappable boundaries.

The loess deposits record the accumulation of windblown silt and sand. They are similar in appearance to mud fan and valley fill deposits (**Qamf**). The deposits are distinguished on the basis of color (reddish for loess, versus light gray to yellowish brown), depositional geometry (sheet-like for loess, versus linear or fan-shaped), and age (mainly late Pleistocene for loess, versus mainly Holocene). Weak, calcic soils (Bt-Bk, Stage I and II) are developed near the top of the loess deposits. In some cases there are internal soil horizons that are either poorly developed or partially preserved. Exposures are poor. The loess deposits are occupied by small farms and used extensively for agriculture. Thickness is 5 to 20 feet.

Shale-chip dune deposits occur along the western edge of a gravel-capped mesa (“Cemetery Mesa,” near the mouth of German Creek) (**Figure 16**), and just to the south, on a shale-capped bluff between German and Reynolds Creeks. The deposits are elongate along the mesa edge, and are wedge-shaped in cross section, with the thickest part along the mesa edge. This relationship reflects that the clay chips are sourced from shale exposures in the hillsides just to the west and downhill from the deposits, and transported short distances by eastward-blowing winds. Thickness is up to 10 feet.

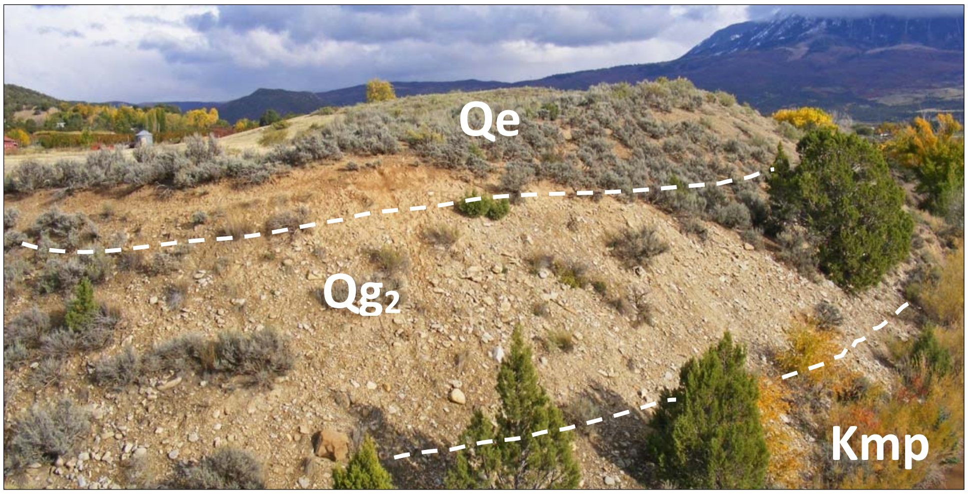

Figure 16. Eolian shale-chip dune deposit (**Qe**) exposed at the western edge of "Cemetery Mesa." The deposit forms an elongate, topographically high dune along the edge of the hill. It overlies older, late Pleistocene fan gravel deposits (**Qg$_2$**). The clay chips are locally sourced from the hill slope below, from the Prairie Canyon Member of the Mancos Shale (**Kmp**). [UTMX: 273458, UTMY: 4304084]

BEDROCK UNITS

The bedrock in the Paonia quadrangle consists of Tertiary-age igneous rocks, which form the high peaks, and Cretaceous-age sedimentary rocks, primarily Mancos Shale, which underlie the lowlands and the middle slopes of the peaks. Contacts between the bedrock units are commonly covered by surficial deposits and vegetation. The mapped formation contacts are approximate.

TERTIARY IGNEOUS ROCKS

Ti **Monzonite porphyry (Oligocene)** — Light to medium gray when fresh, medium orange to light reddish-brown to whitish when weathered, medium-grained, monzonite porphyry. The rock is densely dotted with light gray to whitish and brown to black phenocrysts (**Figure 17**). The light-colored phenocrysts are plagioclase feldspar as equant to subequant, euhedral to irregular, broken or partially digested crystals, up to 3 mm in length. The dark-colored phenocrysts are primarily hornblende as elongate crystals up to 3 mm in length that are commonly cracked or broken, which in some samples have been partially altered to ferrous oxide compounds. There are some opaque minerals, possibly magnetite, and possibly occasional pyroxene and biotite. Quartz is exceedingly rare, and occurs as solitary, very fine grains that have a rounded form and partially digested margins. The matrix typically makes up about 50-60% of the rock and consists of a mixture of mircrocrystalline alkali feldspar and small fragments of plagioclase (based on feldspar staining of thin sections). Quartz was not recognized as a matrix component. The overall feldspar-quartz composition of the rock from several laccoliths and intrusive sheets is estimated to be 50-55% plagioclase and 45-50% alkali feldspar, with only a trace of quartz, which identifies the rock as a monzonite.

Figure 17. Monzonite porphyry (**Ti**) in a hand sample from Mt. Lamborn, above Bell Creek basin. The rock contains abundant phenocrysts of whitish plagioclase and black hornblende, in a matrix of microcrystalline alkali feldspar. [UTMX: 278306, UTMY: 4297989]

The rock forms intrusive laccoliths, sheets, sills, and dikes. The three main mountain peaks within the quadrangle, Mt. Lamborn, Landsend Peak, and Second Creek Ridge are well-formed, steep-sided laccoliths with exposed magma-body relief of 1,200 to 3,000 feet (**Figure 18**). The three main laccoliths appear to have smaller (or possibly buried), satellite laccoliths and other sheets, sills, or dikes on their flanks. These intrusive bodies closely resemble the main laccoliths in terms of their rock composition and fabric. The field mapping of boundaries between the various intrusive bodies and the surrounding or draping Mancos Shale was problematic due to heavy vegetation cover.

The laccoliths are draped in places by moderately dipping sedimentary rocks (primarily Mancos Shale) that were upturned and metamorphosed to hornfels during the emplacement of the magma bodies. The best-exposed contact between unit **Ti** and the Mancos Shale may be viewed along Bell Creek, near the southwestern tip of the Mt. Lamborn laccolith (**Figure 17**). There, the creek has incised through a draping cap of hornfels (metamorphosed upper part of the Mancos Shale, unit **Kmu**) wall rock, exposing the crystallized magma body below. The contact is wavy, much like the billows of a cloud. The body of the intrusion consists of monzonite porphyry with large-scale flow banding. There is a 20-foot-thick zone of banded, iron-rich porphyry along the contact. Banded porphyry of this type was recognized in several places at the outer edges of the laccoliths, and those occurrences are shown on the geologic map. Two other notable exposures of unit **Ti** occur along the western flank of Second Creek Ridge (**Figure 18b**), and along the western flank of Mt. Lamborn (a feature that is well known to local residents as “the Lamb”) (**Figure 20**). At both of those locations, large-scale erosion and episodic rock avalanches have exposed cores of whitish monzonite porphyry in the hillsides.

Figure 18. The three main monzonite porphyry (**Ti**) laccoliths in the Paonia quadrangle.
(a) Mt. Lamborn and Landsend Peak, seen from Elephant Hill. [UTMX: 279224, UTMY: 4303344]
(b) Second Creek Ridge, seen from the Little Coal Creek basin. [UTMX: 280246, UTMY: 4295788] The laccoliths have steep side-slopes. Erosion has removed much of the Mancos Shale that once draped the igneous intrusions. The exposed intrusive rocks have been only minimally eroded, and so the shapes of today's peaks closely mimic the shapes of the original intrusive bodies.

The rocks appear to be somewhat altered and bleached, possibly by hydrothermal processes. Hornblende is largely dissolved from those rocks, and the feldspars appear to have partially dissolved crystal boundaries.

Intrusive sheets, sills, and dikes occur in some locations surrounding the main laccoliths, notably in the Bell Creek and Little Coal Creek drainage basins (**Figure 21**). They are composed of monzonite porphyry that is similar in appearance to the rock from the laccolith. The sills and sheets were intruded into the Mancos Shale along bedding planes. The encasing shale has been locally metamorphosed to hornfels. The strata in these localities are sometimes moderately dipping, perhaps indicating the presence of a deeper, buried igneous body.

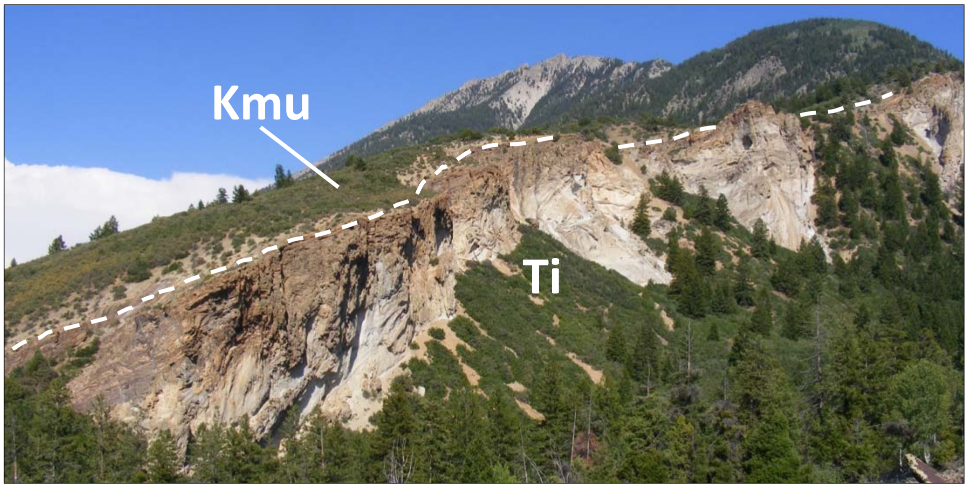

Figure 19. Exposure of monzonite porphyry laccolith body (**Ti**) draped by Mancos Shale, along Bell Creek. The outcrop consists of a core of white-gray-tan monzonite porphyry with broad, looping flow bands; a zone of reddish-brown, iron-rich porphyry that parallels the contact; and metamorphosed Mancos Shale (**Kmu**) that drapes and overlies the porphyry. The contact that marks the outer wall of the laccolith is shown by a dashed line. Influenced by the stately appearance of numerous rock buttresses along the cliff face, this exposure is locally known as "the Hall of Presidents." [UTMX: 277606, UTMY: 4296815]

Figure 20. "The Lamb," an exposure of monzonite porphyry (**Ti**) on the western flank of Mt. Lamborn. Erosion and episodic failures of the rock slope, through rock avalanche and debris flow processes, has produced a raw scar of exposed, whitish-gray monzonite porphyry. Faint flow bands, from when the intruded material was molten, can be seen in the rock face. This view is from the upper gravel benches that flank the peak. Seen from the afar in North Fork valley area, this exposure is said to resemble a white lamb, a white llama, or a white buffalo. [UTMX: 278998, UTMY: 4298428]

The Tertiary igneous rocks in the quadrangle have not been age dated. However, recent age analyses by Garcia (2011) for nearby laccoliths in the West Elk Mountains, using $^{40}Ar/^{39}Ar$ biotite and apatite fission track methods, yielded ages of 33.8 to 29.68 Ma, or middle to late Oligocene.

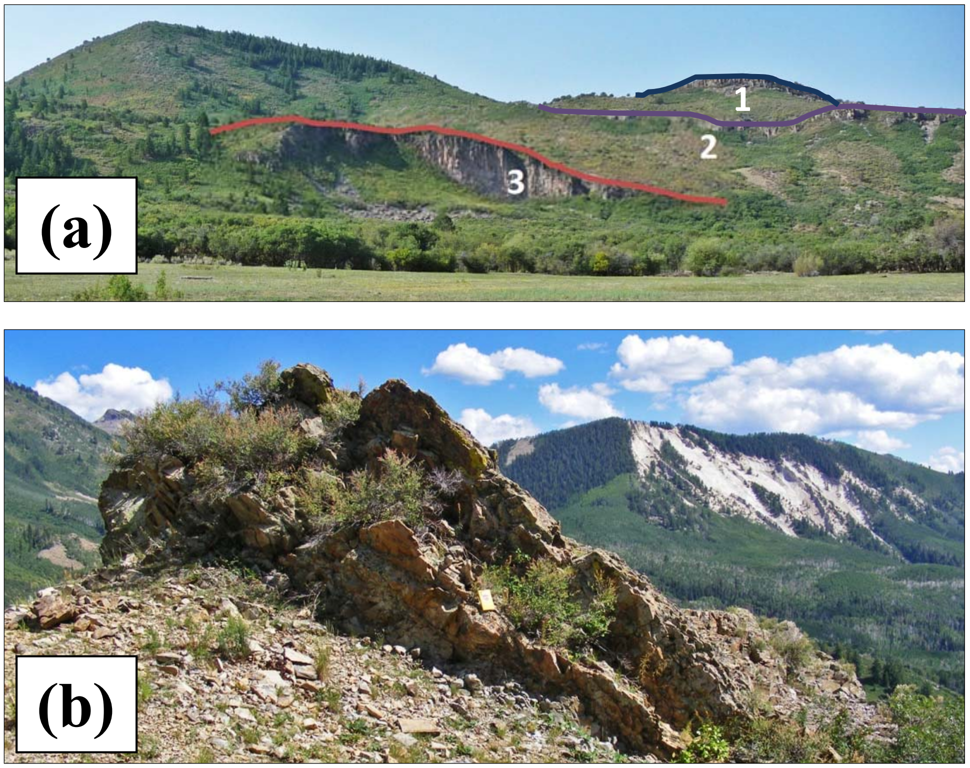

Figure 21. Shale-encased, intrusive sheets, sills, and dikes of monzonite porphyry (**Ti**).
(a) Cliff-forming, nested intrusive bodies in Bell Creek basin, separated by slope-forming Mancos Shale. Bodies 1 and 2 are lenticular sills intruded into moderately dipping shale that has been metamorphosed to hornfels. Body 3 has a flat top and steep flanks, and appears to be at the core of a fold. It is contiguous with exposures in the dense brush below, at the core of the fold. It may be the top of another folded sheet, or the tip of a buried laccolith. [UTMX: 276931, UTMY: 4297736]
(b) A steeply angled dike of monzonite porphyry in Little Coal Creek basin, dipping at 78° S. The dike cuts across gently dipping (5° S) Mancos Shale hornfels. This particular dike contains siliceous fracture fills, which is unusual for intrusions in the Paonia quadrangle [UTMX: 281638, UTMY: 4296238]

CRETACEOUS SEDIMENTARY ROCKS

A thick interval of Upper Cretaceous sedimentary rocks is exposed in the Paonia quadrangle. Most of the map area lies within the outcrop belt of the Mancos Shale. Approximately the uppermost four-fifths of that 4,000-foot thick shale occur within the quadrangle. The oldest strata, in the Montezuma Valley Member of the Mancos Shale, crop out in the southwestern corner of the map. The youngest Mancos Shale strata crop out in the northeastern corner on the middle slopes of Jumbo Mountain, and in the upper-elevation areas of the Little Coal Creek drainage basin in the east-central part of the map. A possible partial outcrop of the overlying Rollins Sandstone of the Iles Formation, Mesaverde Group, occurs in the Little Coal Creek basin.

The intrusive igneous laccoliths, sheets, and sills, described previously for unit **Ti**, are draped or intruded into steeply dipping sedimentary rocks (primarily Mancos Shale) that were upturned and metamorphosed to hornfels during the emplacement of the magma bodies. An example is shown in **Figure 22**. The hornfels metamorphism occurs in shale rocks that are in proximity to the igneous rocks. The major laccoliths are surrounded by a hornfels zone that is up to half a mile wide. Hornfels metamorphism also occurs in shale rocks where igneous sheets and sills have intruded into the shale along bedding planes. Original bedding textures (such as ripple laminations and bioturbation) and invertebrate-fossil imprints are typically preserved in the hornfels.

A generalized stratigraphic column of the mapped bedrock units and sub-units is shown in **Figure 23**. Thickness ranges of the bedrock units are derived from nearby oil-and-gas well logs, particularly the Dyco Morrell #1 (API #05029060560000, located in sec 12, T 13S, R 92W). CGS STATEMAP geologic mapping includes the collection and cataloging of fossils. We collected marine invertebrate fossils of Late Cretaceous age from several locations in the quadrangle. The fossils are potentially useful as paleo-environmental or biostratigraphic-age indicators. **Appendix B** contains a listing of Cretaceous fossils found in and near to the quadrangle by CGS and previous authors.

Figure 22. Moderately dipping metamorphosed shale, or hornfels, to the north of Inter-Ocean Pass. Here, the upper part of the Mancos Shale (**Kmu**) dips at 41° to the north, in a gap between the flanks of the Mt. Lamborn and Coal Mountain laccoliths. The shale was uplifted, tilted, and metamorphosed by the emplacement of igneous magmas that inflated to form the laccoliths. [UTMX: 282422, UTMY: 4298541]

Mesaverde Group (Upper Cretaceous)

Kir **Rollins Sandstone Member of Iles Formation** — Gaskill (1977; Plate 1) mapped several small, isolated bodies of interbedded sandstone, shale, coal, and carbonaceous shale on the western flank of the Coal Mountain laccolith as Mesaverde Formation (unit *Kmv* on his map). Of these, a single outcrop of highly broken and possibly partially metamorphosed sandstone (quartzite) occurs within the Paonia quadrangle. It is located along the eastern border of the map, in the upper Little Coal Creek basin, near the eastern terminus of **Cross Section A-A'**. The author did not visit this outcrop, but examined it from 0.5 miles away using binoculars. It appears to

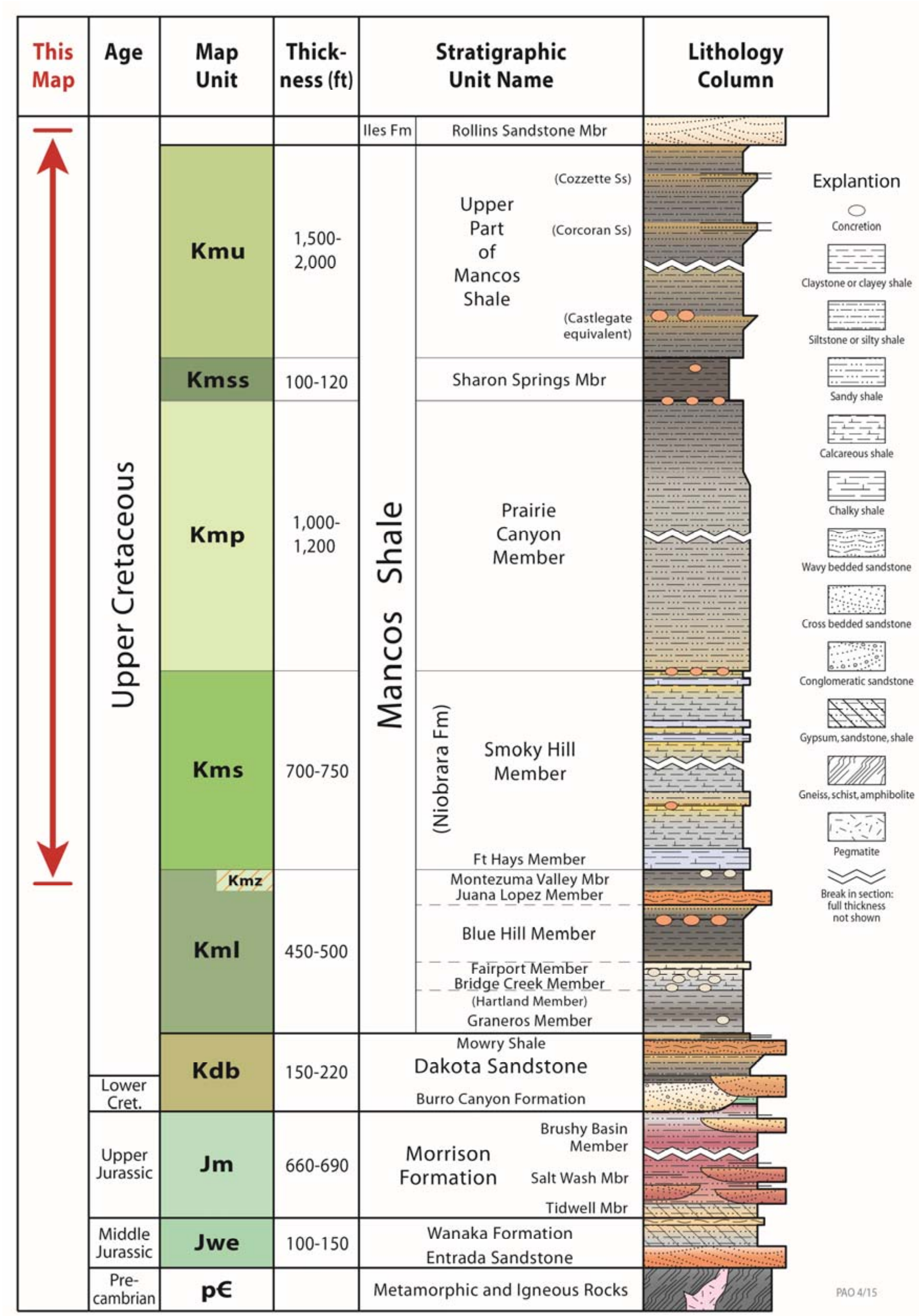

Figure 23. Generalized stratigraphic column of bedrock units for the Paonia quadrangle.
Red arrow, at left, denotes the bedrock units exposed in outcrops and shown on the geologic map.

overlie Mancos Shale black hornfels strata, and it generally dips westward, away from the Coal Mountain laccolith, at an angle of about 30°. Less than 30 feet of the sandstone is preserved in the outcrop. In accordance with Gaskill's descriptions, this basal Mesaverde sandstone would be the Rollins Sandstone Member. The stratigraphic nomenclature for this unit follows that of Collins (1976), although the usage of group vs. formation nomenclature within the Piceance Basin is variable, as reported in Johnson (1989).

Mancos Shale (Upper Cretaceous)

The Mancos Shale is marine in origin (Cross and Purington, 1899; McGookey and others, 1972). It consists of clayey to sandy to calcareous shale with minor limestone, sandstone, and bentonite beds. We recognize five members of the Mancos Shale in outcrops in the Paonia quadrangle, representing the upper four-fifths of the formation. The member units are distinguished on the basis of composition, color, and fossil assemblages. Their contacts are conformable unless indicated. The Mancos Shale is poorly exposed in the central and southeastern parts of the quadrangle, where it occurs at higher altitudes, and is mostly covered by Quaternary deposits and is heavily vegetated. There, we depended on localized exposures for making observations and descriptions. The Mancos Shale is relatively well exposed across "the adobe hills," in the southwestern part of the quadrangle, and also on the flanks of Jumbo Mountain and Elephant Hill, in the north-central part. In those areas, we were able to make more complete observations and descriptions of the bedrock units.

Kmu **Mancos Shale, upper part** — Olive-gray to pale-yellowish-brown, non-calcareous, silty to sandy shale. The unit is present across the northern and northeastern parts of the map area, around the base of the West Elk Mountains laccoliths (where it has been metamorphosed into hornfels), and in the Little Coal Creek basin in the southeastern part. It is almost completely exposed in the southwestern slopes of Jumbo Mountain (**Figure 24**). It is mostly covered in many areas by landslides. A few internal horizons could be distinguished locally. One is a 30-foot-thick, sandy shale zone in the lower part of the unit that contains large concretions up to 10 feet in diameter. The concretions yield abundant, but poorly preserved, bivalves and *Baculite* ammonites. From our mapping of other nearby quadrangles, this zone contains fossils from the *B. aspiriformis* and *B. sp.* (smooth) Taxon Range Zones, making it approximately age equivalent to the Castlegate Sandstone interval. Near the top of the unit are two intervals of thinly interbedded sandstone, siltstone, and sandy shale. The intervals may correspond to the Corcoran and Cozzette Members of the Iles Formation, being offshore-marine equivalents of those members. Overall unit thickness is around 1,500 to 2,000 feet.

Kmss **Sharon Springs Member** — Dark-gray to black, organic-rich, clay shale. In outcrop, it weathers to mottled pale to moderate red to grayish red. This relatively thin unit is locally exposed in several areas across the map, including the vicinity of Wiley Springs (**Figure 25**), McDonald Mesa, Bell Creek, Lamborn Mesa, Pitkin Mesa, and the lowermost slopes of Jumbo Mountain (**Figure 24**). In intervening areas, its outcrop belt is mostly covered by landslides. The town of Paonia is flanked and underlain by Sharon Springs black shale. Fresh exposures are rare and contain abundant healed fractures. The unit contains a number of white to orange bentonite

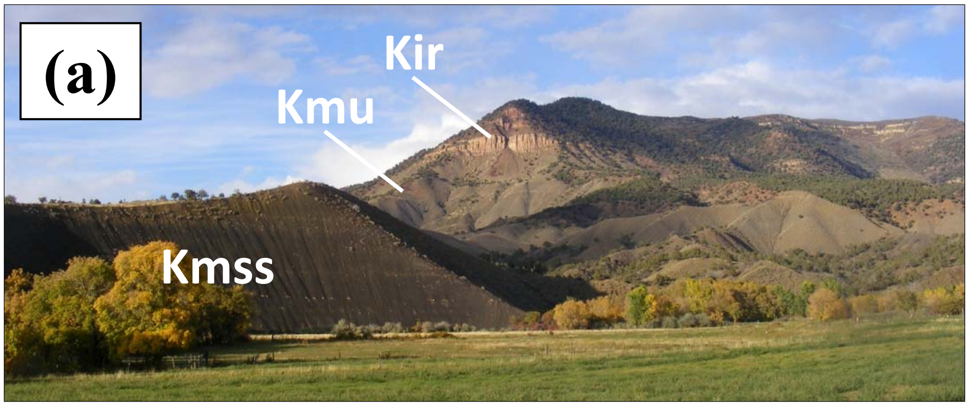

Figure 24. Upper Mancos Shale and lower Mesaverde Group strata.
(a) Upper part of the Mancos Shale (**Kmu**) exposed in the middle slopes of Jumbo Mountain. The outcrops consist of dark to medium olive-gray, non-calcareous shale, broken by occasional zones of sandy shale and concretions or thin-bedded sandstones. In the foreground is an exposure of the underlying Sharon Springs Member (**Kmss**), which consists of black shale with bentonite beds and concretions. The mountain (which is north of the map area) is capped by the lower part of the Mesaverde Group. The Rollins Sandstone Member of the Iles Formation (**Kir**) forms a distinctive cliff at the base of the Mesaverde interval. [UTMX: 278013, UTMY: 4304252]
(b) Relatively fresh, medium-gray shale (**Kmu**) exposed in an irrigation ditch cut to the north of Sams Creek. It consists of indistinctly laminated silty claystone, with occasional ironstone carbonate lenses and seams of orange to white bentonite. [UTMX: 282816, UTMY: 4302439]

beds (0.5 to 6 inches thick) and discontinuous, sometimes lenticular-shaped concretions. The bentonite beds are occasionally locally sheared and folded. In many places, due to patchy exposures, or landslides, or vegetation cover, the top or bottom of the unit could not be positively identified. In such cases, the entire exposure was mapped as the Sharon Springs Member. The unit is 100 to 120 feet thick. In nearby oil-and-gas well logs, it forms a prominent, widespread marker that is used for making subsurface correlations.

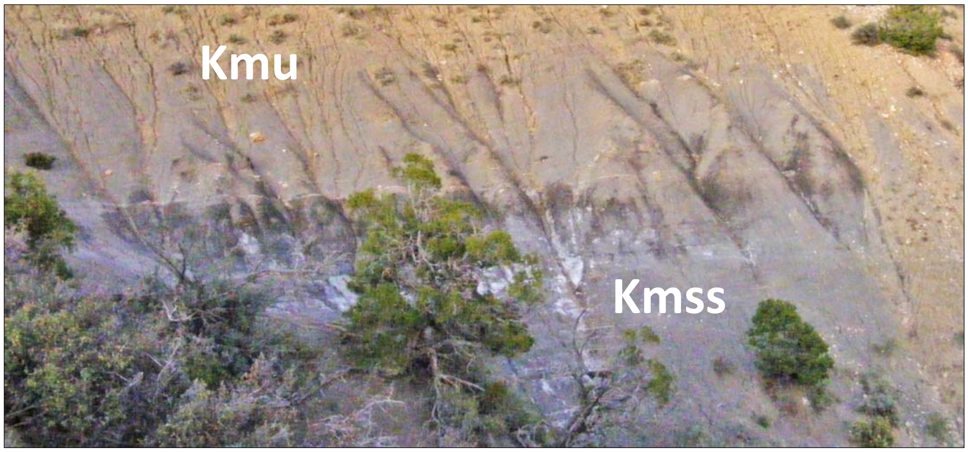

Figure 25. Sharon Springs Member of the Mancos Shale (**Kmss**) exposed near Wiley Springs. The outcrop consists of black, non-calcareous shale, interspersed with thin, whitish bentonite beds and ovoid to lenticular concretions. Here, the Sharon Springs Member appears to form a laterally extensive aquitard. The numerous seeps that make up Wiley Springs occur along the upper contact of the unit where it is overlain by the upper unit of the Mancos Shale (**Kmu**). The contact horizon between units at this outcrop could not be positively identified. [UTMX: 275341, UTMY: 4293864]

Kmp **Prairie Canyon Member** — Light- to medium-gray to pale-yellowish-brown, silty to sandy shale. In outcrop, it weathers grayish orange to grayish yellow. This unit underlies Bone and Stewart Mesas and the upper "adobe hills" in the western part of the map, but is mostly covered by Quaternary deposits. It occasionally contains small, rounded discs of very fine, bioturbated sandstone. The discs appear to be individual sand ripples that weather out of the shale. Overall, the unit is less sandy than in the Grand Junction and Montrose areas (Cole and others, 1997; Noe and others, 2007). Fossils are sparse and consist of thin *Inoceramus* fragments. Both the upper and lower contacts of the Prairie Canyon Member are marked by horizons of medium orange, dolomitic, iron-rich concretions, up to 3 feet in diameter. The lower-contact concretion zone is about 60 feet above the highest limestone bed in the underlying Smoky Hill Member, and can be traced for miles across the "adobe hills" in the Paonia and Hotchkiss quadrangles (**Figure 26**). Thickness is 1,000 to 1,200 feet.

Kms **Smoky Hill and Fort Hays (Niobrara) Members, undivided** — These two members are age-equivalent to the Niobrara Formation of central and eastern Colorado. The Smoky Hill Member makes up most of the unit and consists mainly of dark-gray to light-gray, slightly calcareous to calcareous shale. It weathers to a distinctive, pale yellowish orange or very pale-brown color, known locally as "Mancos blonde." The Smoky Hill Member is distinguished by the presence of thick-shelled *Inoceramus* fragments (including *I. platinus* and *Magadiceramus subquadratus*), often encrusted with *Pseudoperna congesta* oysters. Freshly exposed bedding planes are speckled with small, white, forams and coccoliths. There are occasional limestone beds (peloid-rich mudstone or packstone) up to 1 foot thick. Fracture-filling seams of fibrous gypsum are present throughout the unit. The Smoky Hill Member is often covered by thin residuum. It is

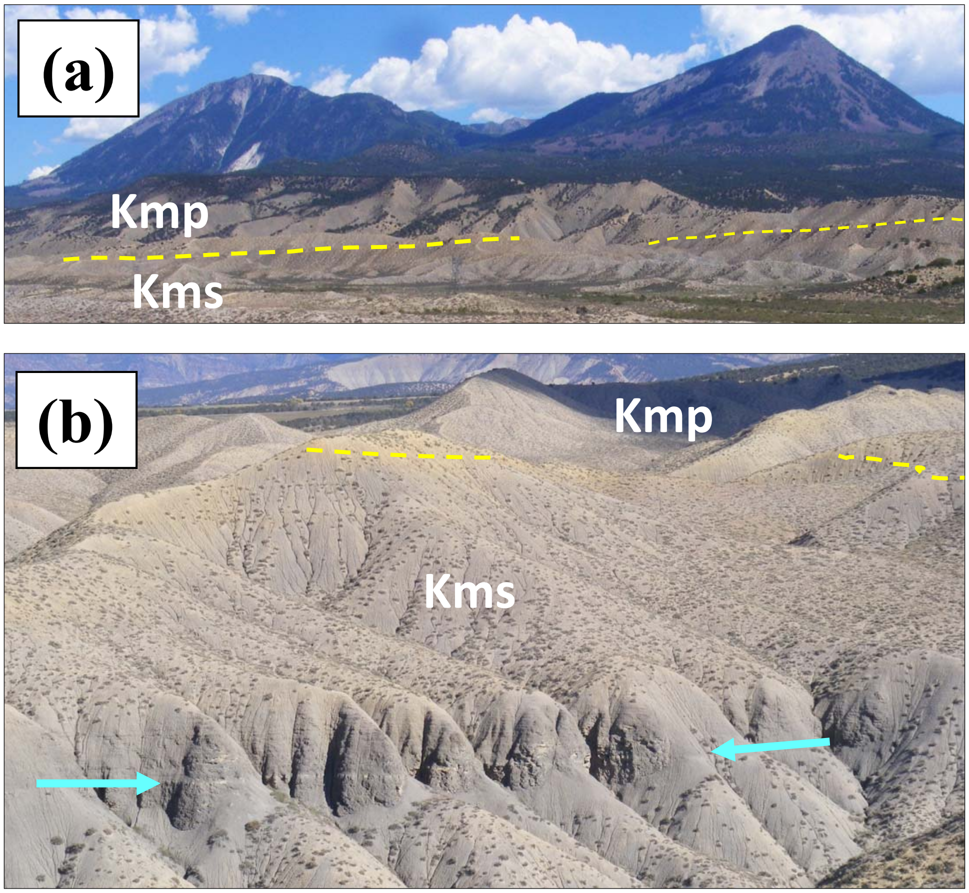

Figure 26. Prairie Canyon (**Kmp**) and Smoky Hill (**Kms**) Members of the Mancos Shale in the "adobe hills." **(a)** Seen from a basin near the Hotchkiss/Paonia quadrangle boundary. [UTMX: 271898, UTMY: 4296259] **(b)** Seen from a nearby ridge above McDonald Creek. [UTMX: 272212, UTMY: 4294987] The contact between the members, which is well exposed across the area along a prominent concretion zone, is marked with a yellow dashed line. Below the contact is calcareous shale of the Smoky Hill Member. The unit contains a zone of thin, cliff-forming, chalky limestone beds (light blue arrows) about 40 feet below the contact. Above the contact is non-calcareous, slightly sandy shale of the Prairie Canyon Member, which forms a steeper, more rugged topography.

moderately well exposed in the "adobe hills" in the southwestern part of the map (**Figure 26**). The much-thinner, underlying Fort Hays Member forms the basal strata of the Niobrara interval, and overlies a regional unconformity (Weimer, 1983). It does not outcrop in the Paonia quadrangle, being covered by the alluvium of Cottonwood Creek. In nearby quadrangles, it consists of thinly interbedded limestone, marl, and shale beds. Thickness of the undivided Smoky Hill and Fort Hays Members is 700 to 750 feet.

Kmz **Montezuma Valley Member** —Medium- to dark-gray, shaly mudstone. This member is poorly exposed in a small area to the southwest of Cottonwood Creek, in the southwestern corner of the map. It consists of brownish-gray, clayey shale that is weathered to a residuum at the ground surface. More extensive outcrops occur in the nearby Hotchkiss (Noe and Rodgers,

2014) and Crawford (Noe and Klink, 2015) quadrangles. This member is included as part of the undivided lower Mancos unit (**Kml**) on the cross sections. The uppermost 50 feet of the unit crop out in the quadrangle.

Older Sedimentary Bedrock Units Shown on Geologic Cross Section

Cross Section A-A' runs southwest from Pitkin Mesa, near the town of Paonia, to the upper Little Coal Creek basin, and includes Cedar Hill ("P Hill," to locals) and Mt. Lamborn. The cross section line is shown on **Plate 1**. The cross section itself is shown on **Plate 2**.

The older sedimentary bedrock units described below are included as subsurface units on the cross section. They do not crop out within the Paonia quadrangle but occur in surface exposures to the south and west. Reported thickness values are from outcrops in the Gunnison River gorge. The Jurassic stratigraphy in this region has undergone a revision since it was mapped by Hansen (1968, 1971). His Wanakah Formation included strata that were later redefined as the Tidwell Member of the Morrison Formation (O'Sullivan 1992a, 1992b). For this report we derive thickness values and general unit descriptions from measured sections by both authors, using O'Sullivan's formation designations.

Kml **Mancos Shale, lower part, undivided (Upper Cretaceous)** — This unit includes several members of the Mancos Shale that have been mapped in detail by CGS in nearby quadrangles (Noe and Rodgers, 2014; Noe and others, 2015). From youngest to oldest, they are the Montezuma Valley, Juana Lopez, Blue Hill, Fairport, Bridge Creek, Hartland, and Graneros Members. The unit contains intervals of calcareous to non-calcareous shale. The intervals vary in organic content; in particular, the Juana Lopez and Blue Hill Members contain organic-rich, black shale. Some of the intervals contain calcarenite beds (Juana Lopez and Fairport) or abundant concretion horizons (Bridge Creek). The thicknesses and general makeup of the individual units are shown in **Figure 23**. The thickness of the undivided unit is 450 to 500 feet.

Kdb **Mowry Shale, Dakota Sandstone, and Burro Canyon Formation, undivided (Upper and Lower Cretaceous)** — The Mowry, Dakota, and Burro Canyon units were described in detail by Noe and others (2015) from outcrops in the nearby Lazear quadrangle. The Mowry Shale consists of clayey to silty shale with thin interbeds of siltstone and very fine-grained sandstone. Bedding thickness is on the scale of millimeters to a few inches. It is a transitional unit between the Dakota Sandstone and Mancos Shale. Its upper contact (which is called the "Dakota Silt" marker by the oil-and-gas industry) is conformable, and its lower contact is unconformable (Currie and others, 2008). The Dakota Sandstone consists of interbedded shale and sandstone. The upper part contains mostly marine shale with thin zones or lenses of very fine to fine grained, rippled to hummocky cross-stratified sandstone. The lower part contains lenticular to tabular bodies of fine to medium grained sandstone, carbonaceous shale, and coal, and is variable in thickness. It is Upper Cretaceous (Cenomanian) in age in west-central Colorado (Merewether and Cobban, 1986). Its lower contact with the Burro Canyon Formation is unconformable. The Burro Canyon Formation contains lenticular bodies of chert-pebble conglomerate, conglomeratic sandstone,

sandstone, and minor shale. The unit is highly variable in thickness. In some places it is absent, and the Dakota Sandstone rests directly upon the Morrison Formation. The thickness of the undivided Mowry-Dakota-Burro Canyon interval varies from 150 to 220 feet.

Jm **Morrison Formation (Upper Jurassic)** — The Morrison Formation unit consists of three members, from youngest to oldest, the Brushy Basin, Salt Wash, and Tidwell Members. The Brushy Basin Member consists of non-calcareous shale with occasional lenses of sandstone (Noe and others, 2015). The Salt Wash Member is similar to the Brushy Basin Member, but it contains more abundant lenticular sandstone bodies. The Tidwell Member contains beds of gypsiferous shale, gypsum, and tabular to lenticular sandstone (O'Sullivan, 1992a, 1992b). The Morrison Formation is 660 to 690 feet thick.

Jwe **Wanakah Formation and Entrada Sandstone of the San Rafael Group, undivided (Middle Jurassic)** — The Wanakah Formation contains relatively laterally continuous beds of shale, gypsum, thinly bedded sandstone, and minor limestone (the Pony Express Limestone Member). The Entrada Sandstone consists of very fine to fine grained sandstone with eolian cross bedding, horizontal planar bedding, and massive fabrics. It is the oldest sedimentary formation in the area. Since 1980, authors have assigned these two formations to the Middle Jurassic (U.S. Geological Survey GEOLEX database; http://ngmdb.usgs.gov/Geolex/NewUnits/unit_11048.html, accessed January, 2012). The Wanakah Formation is 45 to 55 feet thick. The Entrada Sandstone is 50 to 100 feet thick.

pC **Precambrian Rocks (Proterozoic)** — The Precambrian crystalline basement rocks of the Gunnison Uplift include mica schist, quartzitic and migmatitic gneiss, amphibolite, granodiorite, and pegmatite (Hansen, 1968, 1971). The top-of-Precambrian surface is a major nonconformity that spans approximately 1.5 Ga (Kellogg and others, 2004).

STRUCTURAL GEOLOGY

The Paonia quadrangle lies along the boundary between the Colorado Plateau and Southern Rocky Mountains physiographic provinces (Fenneman and Johnson, 1946). The Colorado Plateau is on the western side of the map. Its main structural feature is the Gunnison Uplift, which formed as a result of movement along basement faults during the Late Cretaceous-Eocene Laramide orogeny (Hansen, 1965; Tweto, 1977; Dickinson and others, 1988). This feature is expressed in Mancos Shale outcrops that dip generally north-northeast to northeast, toward the Piceance Basin, at shallow angles of 10° or less.

The Southern Rocky Mountains are represented on the eastern side of the map by the peaks of the West Elk Mountains. There, the structure has been highly influenced by the intrusion, during Oligocene time, of localized, laccolithic igneous plutons and associated sheets, sills, and dikes. Intrusion of the laccoliths into the Mancos Shale resulted in draping of shale strata against the sides of the laccoliths. A zone of metamorphosed shale (hornfels) developed in those draping strata. Regional, post-Miocene erosion has exposed many of these laccoliths and partially eroded the cover of hornfels. In several locations within the quadrangle, the author mapped steeply dipping hornfels in the vicinity of laccoliths and other, smaller igneous bodies. The structure around the laccoliths is largely hidden by poor exposures and abundant vegetation. A number of localized faults and folds are inferred based on discontinuous exposures of Mancos Shale.

A few folds in the northern part of the quadrangle do not appear to be related to the emplacement of the laccoliths. One fold, mapped just to the north of Lone Cabin Reservoir, appears to be an abrupt monocline that runs in a WSW-ENE direction and continues eastward into the adjacent Minnesota Pass quadrangle. It consists of a zone of steeply dipping (24-40° to the NNW) Mancos Shale that is at least ¼ mile wide. Its northern (lower) fold axis is coincident with a small-displacement fault and is mostly covered by block-glide landslide (**Qlsb**) deposits. Its southern (upper) fold axis was not located and is probably covered by landslides (**Qls**). A poorly defined anticline and syncline were mapped near the town of Paonia. They are based on dip-direction reversals in gently dipping Mancos Shale. The syncline axis is covered by surficial deposits. It appears to pass beneath the town and the lowermost reach of Minnesota Creek. The anticline crosses the lower southwestern slope of Jumbo Mountain.

In **Cross Section A-A'** (**Plate 2**), the Mt. Lamborn laccolith is shown having a base that is concordant with the underlying sedimentary strata. While field evidence is lacking, this is based on geometries described for other laccoliths in the West Elk Mountains and in Utah (Gilbert, 1877; Cross, 1894; Hunt and others, 1953). In addition, little is known about the nature of feeder-system conduits beneath the laccoliths in the Paonia quadrangle. In the cross section, an inferred fault is depicted as a possible pathway for the magmas that fed the Mt. Lamborn laccolith. This is merely conjectural, as there is no outcrop exposure of the base of the laccolithic body, or of the underlying sedimentary strata.

Few strike and dip readings were recorded in the quadrangle. This is due in part to greater amounts of precipitation occurring at the middle to high altitudes, resulting in deep weathering of the Mancos Shale and development of thick residual-soil cover. In addition, the shale there is mostly hidden beneath Quaternary gravels, landslides, and colluvium, and vegetation including aspen forests, Gambel oak and serviceberry thickets, grasslands, and agricultural lands. The Mancos Shale is best exposed in the lowland “adobe hills,” where precipitation and vegetative cover are both diminished, and also on the slopes of Jumbo Mountain, to the north of Minnesota Creek.

MINERAL RESOURCES

The Paonia quadrangle contains local sand and gravel resources. The area was explored in the past for clay, and oil and gas. In the following paragraphs, we outline those resources, associations with soil or bedrock units from the geologic map, and current activity.

Construction aggregates. Gravel and sand have been produced from commercial pits along the North Fork River valley. In addition to three active, permitted pits, there are two inactive pits that either have terminated permits or were operated prior to 1981 (Schwochow, 1981; Keller and others, 2002; Guilinger and Keller, 2004). Most of the pits are located within the modern floodplain of the North Fork

River, while one is atop an older gravel terrace (**Qg$_2$**). The mined deposits contain pebble-cobble gravels with rounded and smooth, hard clasts of basalt, porphyritic igneous rock, or hornfels, with a coarse sand matrix. Gravel deposits in the quadrangle become increasingly weathered with age. The weathering produces light to heavy accumulations of calcic soil (Bk to K horizons) and may cause disintegration of some gravel clasts, particularly the basalt. The modern floodplain and younger terraces (**Qan$_1$** to **Qan$_3$**) contain the most likely potential gravel resources.

Clay. The extensive "adobe clay hills" of Delta County once provided raw materials for a thriving brick-manufacturing industry. Many of the region's older buildings were constructed with distinctive, yellow bricks from the North Fork area (Switzer, 2012). Today, industrial brick manufacturing in Colorado is concentrated in the Denver area. However, the many members of the Mancos Shale, varying in color, composition, clay types, and minor occurrence of pure-clay bentonite beds, offer raw materials that could potentially be used for making kiln-fired brick and ceramic ware.

Oil and gas. The quadrangle contains one inactive oil and gas test well, near Cottonwood Creek in the southwestern corner, which was drilled and abandoned in 1949 (Fitzgerald and others, 2014). Historic, potential target formations in the region included the Dakota Sandstone (part of unit **Kdb**) and the Entrada Sandstone (part of unit **Jwe**). There is currently oil-and-gas exploration activity in this part of western Colorado. The focus is the Niobrara-equivalent interval of the Mancos Shale. Horizontal drilling is being used to test calcareous, brittle, fractured strata. In the Paonia quadrangle, unit **Kms** (undivided Fort Hays and Smoky Hill Members) represents the Niobrara interval. The principal targets are chalky, calcareous zones. Unit **Kms** forms surface outcrops across the southwestern part of the map area, in "the adobe hills." The Smoky Hill Member extends into the subsurface and is overlain by 0 to over 1,500 feet of shale strata in the northern part of the quadrangle, and most likely beneath the laccolithic intrusions of the West Elk Mountains (see **Cross Section A-A', Plate 2**). A study of the oil and gas potential of prospective geologic units in the area of the Paonia quadrangle is beyond the scope of this mapping project.

Coal. Although Paonia is known as a coal mining town, there are no coal-bearing outcrops within the Paonia quadrangle. There are active coal mines upriver, in the Bowie-Somerset area along the North Fork River valley. The mines there produce coal from the lower part of the Mesaverde Group. There are no older, historical coal mines within the quadrangle (Carroll and Bauer, 2002).

Geothermal. No developed geothermal resources exist in the Paonia quadrangle. However, there is an actively producing hot water well only a half-mile to the west, on Stewart Mesa in the adjacent Hotchkiss quadrangle. The Colonel Chinn well was drilled during the early 1900's. It has a total depth of 4,499 ft and produces water from a cased interval at a depth of 1,850 ft (Headden, 1909; Barrett and Pearl, 1978), at a temperature of 41° C (106° F) (Cadigan and others, 1976). This and other geothermal resources in the Hotchkiss area are discussed in the above-listed references, and are discussed in greater detail in CGS' geologic map of the Hotchkiss quadrangle (Noe and Rodgers, 2014).

GROUNDWATER RESOURCES

A variety of groundwater resources exist in the Paonia quadrangle. The modern alluvial valleys of the North Fork River and Minnesota Creek contain alluvial aquifers that are charged by annual runoff from snow melt in the nearby mountains and throughflow. Gravel bodies capping the upland mesas flanking the river valley, mostly to the north and less commonly to the south, are separated from upland groundwater sources. At those locations, groundwater is recharged by throughflow from the adjacent, higher mountains, or with surface water that is diverted onto the mesa surfaces by irrigation canals.

There are 60 groundwater wells in the quadrangle, according to GIS data from the Colorado Division of Water Resources. Most of the wells are permitted for domestic or household use. Other permitted uses include irrigation (4), stock (2), commercial (1), and industrial (1). The wells are mostly located along the alluvial valleys and gravel-capped mesas from the previous paragraph. Deeper wells in the quadrangle may produce from sandy or calcareous zones in the lower and middle Mancos Shale. Reported water-well depths range from 2 to 640 feet. A majority of the wells along the North Fork River valley are less than 40 feet deep, while those along Minnesota Creek are in the 40- to 70-foot depth range. The wells on Lamborn and Bone Mesas vary greatly in depth, and include the deepest well in the quadrangle. Pump rates for the 60 wells in the quadrangle vary widely, from 1 to 225 gpm. A large number of the wells, however, produce at pump rates of 15 gpm or less.

Several groundwater springs in the West Elk Mountains have been developed for use as municipal water supplies by the towns of Paonia and Crawford, and for agricultural uses on Lamborn and Bone Creek Mesas. The springs occur on the middle-elevation slopes along the western sides of Mt. Lamborn and Landsend Peak; most of them are named on the topographic base map. Interestingly, the springs vary in their geologic settings. Many of them are within the large landslide complexes (unit **Qls**), and are located in internal landslide-scarp faces, downhill from the master landslide scarps (**Figure 27a**). The springs also occur in other Quaternary units, such as rock glaciers (**Qrg**) and their associated mud moraines, debris-flow valley fills (**Qg$_1$**), and alluvial fans and older alluvial fans (**Qf** and **Qfo**) (**Figure 27b**). At one location, a line of springs developed coincident with the top to the Sharon Springs Member of the Mancos Shale (**Kmss**). This clay-rich member appears to form an aquitard, resulting in perched groundwater flowing through the overlying, more-permeable upper unit of the Mancos Shale (**Kmu**). The source of all of these springs appears to be snowmelt from the nearby mountain peaks. Additionally, there may be some unknown amount of water storage within the fractured Mancos Shale hornfels metamorphic zone that surrounds the intrusive igneous bodies of the laccoliths and subsidiary sheets, sills, and dikes.

GEOLOGIC HAZARDS

We recognize several potential geologic hazards in the Paonia quadrangle. The hazards arise when naturally occurring geologic processes affect public safety or cause economic loss. Human

Figure 27. Examples of groundwater springs in different geologic settings.
(a) The Reynolds Creek Springs, near Roeber Reservoir. The line of springs crosses a hillside, and is indicated by heavy deciduous tree cover in an area that otherwise contains sparse, brushy vegetation. The spring line runs between the arrows. These springs occur beneath a master landslide (**Qls**) head scarp that marks an approximate boundary between hornfels metamorphism of Mancos Shale in the uphill direction and unmetamorphosed shale in the landslide body. [UTMX: 278148, UTMY: 4299554]
(b) The Kauer Spring area, in Bell Creek basin. Here, an unusual wetland has aggraded in the terminal part of an alluvial fan (**Qf**) that spills into the basin. It appears as a steep-fronted, vegetated terrace, seen from downhill of the fan edge (between arrows). Groundwater flowing through the fan discharges at its distal end because the deposit thins and becomes finer grained. [UTMX: 277660, UTMY: 4298007]

activities may greatly increase the rate of process activity and level of hazard. Geologic hazards are detrimental to the financial well-being, and sometimes the safety, of individual property owners and owners of public and private facilities.

Debris flow and **mudflow** hazards occur in hilly areas along confined stream reaches (units **Qa** and **Qamf**) and in alluvial and mud flow fans (**Qf**, **Qg$_1$**, and **Qamf**). These flows are produced by large rainfall events, and are sometimes generated by failures of saturated landslides. Debris flows are dense, heterogeneous mixtures of mud, rock fragments, and plant materials (Varnes, 1978). They can form at any point along a drainage including on the sides of valleys. They may cause deep erosion in some areas and dump thick deposits in other areas (both on the order of several feet). The moving sediment flows may pose significant life-and-limb safety hazards and can cause damage to roads and buildings. Much of the upland terrain has the potential to generate debris flows. In July 2012, debris flows occurred along the western side of Mt. Lamborn during a heavy rain storm (**Figure 28**). One of the flows, which was constrained by a narrow valley, caused significant damage to a municipal spring facility. Mudflows are typically gravel poor. They may occur in stream valleys and basins within the "adobe hills," and in the large, low-gradient mudflow fans that extend onto the North Fork River and Minnesota Creek flood plain. All areas meeting the above descriptions should be considered at risk. Construction of residences, businesses and critical facilities in those areas should be avoided if possible.

Figure 28. Rock and snow avalanche chutes along the western side of Mt. Lamborn.
The snow avalanche chutes are marked by a lack of conifer-tree vegetation (dark green), and are either bare rock or are colonized by low-growing, deciduous vegetation (light green). Debris flows or debris avalanches may also occur in the chutes. In 2012, debris flows ran in the chute to the left, as well as from "the Lamb" to the right. The latter damaged a nearby water facility. [UTMX: 278308, UTMY: 4298339]

Stream flooding hazards and associated high water tables exist within the modern North Fork River flood plain (**Qan$_{1a}$**) and the valleys of tributary streams (**Qa** and **Qamf**). Flooding may be due to annual snowmelt and occasional, large rainfall events. Occupied structures and critical facilities in those areas should be avoided. FEMA Flood Insurance Rate Maps (FIRMs) are available for this particular area of western Colorado, and FEMA Flood Hazard Area mapping is viewable via the Delta County Interactive Mapping Resources web site (http://www.deltacounty.com/382/Delta-County-Interactive-Mapping-Resourc). The North Fork River flood of record was in 1884, with an estimated peak discharge of 50,000 second-feet (Follansbee and Sawyer, 1948). Flooding on the North Fork River is at least partly mitigated by an upstream dam at Paonia Reservoir, on Muddy Creek, which is a major tributary.

Landslides (**Qls**) are common in the quadrangle, particularly as large landslide complexes on the middle-elevation slopes that surround the peaks of the West Elk Mountains. At lower elevations, in the populated areas of the quadrangle, landslides are a potential hazard along shale slopes that are capped by gravel deposits. In these areas, ground water infiltrates through the permeable gravel and perches on the more impermeable shale. The ground water flows laterally to the flank of the mesa where springs and ground seeps occur. Water may also seep into the underlying shale causing further weakening of the bedrock by additional weathering, increased pore pressure, and/or dissolution of gypsum fracture filling. Pore pressure and the accelerated weathering of the shale meet a threshold where steep slopes are unable to support themselves and the earth materials begin to shear and move downward. The landslides range from Pleistocene to Holocene in age. Small, active landslides and areas of active slope creep occur at some locations. Landslides that appear to be inactive should be considered to be metastable. Modifications such as loading or cutting into hill slopes, or increases in groundwater levels and pore pressures could reinitiate existing landslides or create new landslides. Mesa edges ("view lots") and mesa side-slopes are susceptible (**Figure 29**), particularly on mesas where agricultural irrigation adds to the natural groundwater seepage at the mesa edge. Potential landslide areas should be avoided where possible. Where avoidance is not possible, the site should undergo

Figure 29. Active landslides (**Qls**) along the side-slopes of mesas and hills.
(a) Landslide complex along the side of Stewart Mesa, near Coburn. The mesa side consists of over-lapping, active landslide deposits. The top of the mesa is agricultural land that is heavily irrigated. The mesa-capping deposit is a paleo North Fork River gravel deposit (**Qan$_3$**) that has a sandy matrix and high hydraulic conductivity. Several small seeps and springs issue from the hillside. Fresh, overlapping head scarps run along the mesa edge and extend down slope. (This is just to the west of the map area, but similar landslides exist in the Paonia quadrangle.) [UTMX: 271697, UTMY: 4303005]
(b) Active, gravity-driven slope creep affecting the Cedar Hill Cemetery, southwest of Paonia. The eastern part of the cemetery, pictured here, occupies landslide deposits on the lower slopes of Cedar Hill (locally known as "P Hill"). [UTMX: 274239, UTMY: 4304325]

a detailed hazard investigation and mitigation. Mitigation may be expensive, but not nearly as much as the costs of damage and repairs to structures and facilities resulting from new or reinitiated landslide movements.

Rockfall hazards, in the populated areas of the quadrangle, are present along the faces and toes of slopes that are capped with cobbly to bouldery gravel deposits (**Qg**-series units). The size of the falling rock clasts is a function of the grain-size character of the sediment deposit and the exposure of the slope to groundwater seepage and freeze-thaw processes. Large precipitation events may trigger rock falls, as well. The best mitigation is to avoid rockfall-prone slopes and roll-out zones. Rockfall is prevalent around the high peaks of the West Elk Mountains and their subsidiary hills, where intrusive-igneous rocks (monzonite porphyry, unit **Ti**) are exposed. Cones and aprons of talus (**Qt**) form at the base of the steep slopes and rockfall chutes, and are indicative of active rockfall processes. Rock avalanches are possible in certain areas, particularly where the rock is steep and weathered or chemically altered. Examples of recent rock avalanche initiation zones include "the Lamb" on Mt. Lamborn and part of the western slope of Second Creek Ridge. Large rockfall or rock avalanche failures are capable of producing very large rock blocks, up to 20 feet long (**Figure 30**).

Figure 30. A large rockfall block of monzonite porphyry on the side of Elephant Hill. This 16-foot-long block, which was originally part of Mt. Lamborn, has a complex geologic history. It originally fell from the mountainside in a rockfall or rock avalanche event. During the Pleistocene glacial ages, it was carried nearly 3 miles away in a debris flow. During subsequent erosion, it became exposed at the edge of a mesa-capping gravel deposit, and later it fell from the rim of the mesa. Currently, it is part of a landslide on the side of the hill. The geologist is 6 feet tall. [UTMX: 278618, UTMY: 4303162]

Snow avalanche hazards are prevalent around the high peaks of the West Elk Mountains. The paths of recurrent avalanches are marked by steep chutes or slopes that are lacking in tree growth (**Figure 28**). These paths may be rockfall areas during the summer months. The snow avalanche run-out zones may be somewhat coincident with the rockfall talus or upland debris flow fan deposits (**Qt** or **Qg**).

Expansive soil and bedrock hazards occur in clay-rich materials. These materials are relatively dry under natural climate conditions. Upon wetting, water is drawn into crystal lattices. The clay particles swell to accommodate the added water molecules (Noe, 2007). Resultant ground heaving may cause damage to buildings, roads, and underground utilities and pipelines. The clay particles lose water and shrink upon drying. This shrink-swell behavior may continue over numerous wetting and drying cycles. Potentially expansive soil and bedrock is found in the Mancos Shale (particularly in units **Kmu**, **Kmss**, **Kmp**, and **Kms**), and in clay-rich surficial deposits derived from those units (especially **Qls** and **Qamf**). These heave-prone earth materials are found throughout lower and middle elevations of the Paonia quadrangle, particularly in the “adobe hills” area and on the sides of shale-cored mesas and hills near Paonia. The hazard and ground heave movements may be significantly reduced if proper geotechnical engineering studies and designs are employed at potentially affected construction sites.

Collapsible soil hazards occur in silt-rich sediments that are relatively quickly deposited and have high internal porosity (White and Greenman, 2008). Such deposits include tributary stream alluvium, alluvial fans, and mudflow valley fills and fans (**Qa**, **Qf**, **Qfo**, and **Qamf**). Ground collapse and settlement occurs as a result of wetting or loading of the soil. Collapsible soil may occur in eolian deposits (**Qe**) that sometimes overlie alluvial terraces. All of these earth materials tend to be highly erodible, and may be additionally susceptible to bank instability, sedimentation, piping and sinkholes, and erosive fissure development (**Figure 31**). All areas containing the above-listed deposits should be considered at risk for collapsible soil conditions. Ground collapse hazards may be reduced if proper geotechnical engineering studies and designs are employed at potentially affected sites.

Seismicity and earthquake hazards are generally difficult to assess. We did not see evidence of younger faulting or offsets of Quaternary-age deposits while mapping. The CGS *Colorado Earthquake Map Server* (Morgan and others, 2012) shows one historical earthquake within the quadrangle, which occurred in May, 2007. It was located 5 miles to the southeast of Paonia, at an approximate depth of 1 km (3,280 feet), and had a magnitude of 2.8. At least 45 tremors of less than magnitude 4.0 and one of magnitude 4.4 are mapped in the Bowie-Somerset area (just to the north, northeast, and east of the quadrangle). Many of these are attributed to ground movements and collapses within coal mines, or “coal bumps.” The nearest fault suspected of having Quaternary movement is located to the south of the Black Canyon of the Gunnison River (15.5 miles to the south of the quadrangle). An updated, online version of the Kirkham and Morgan maps is available for viewing on the CGS web site, at http://coloradogeologicalsurvey.org/geologic-hazards/earthquakes-2/maps/.

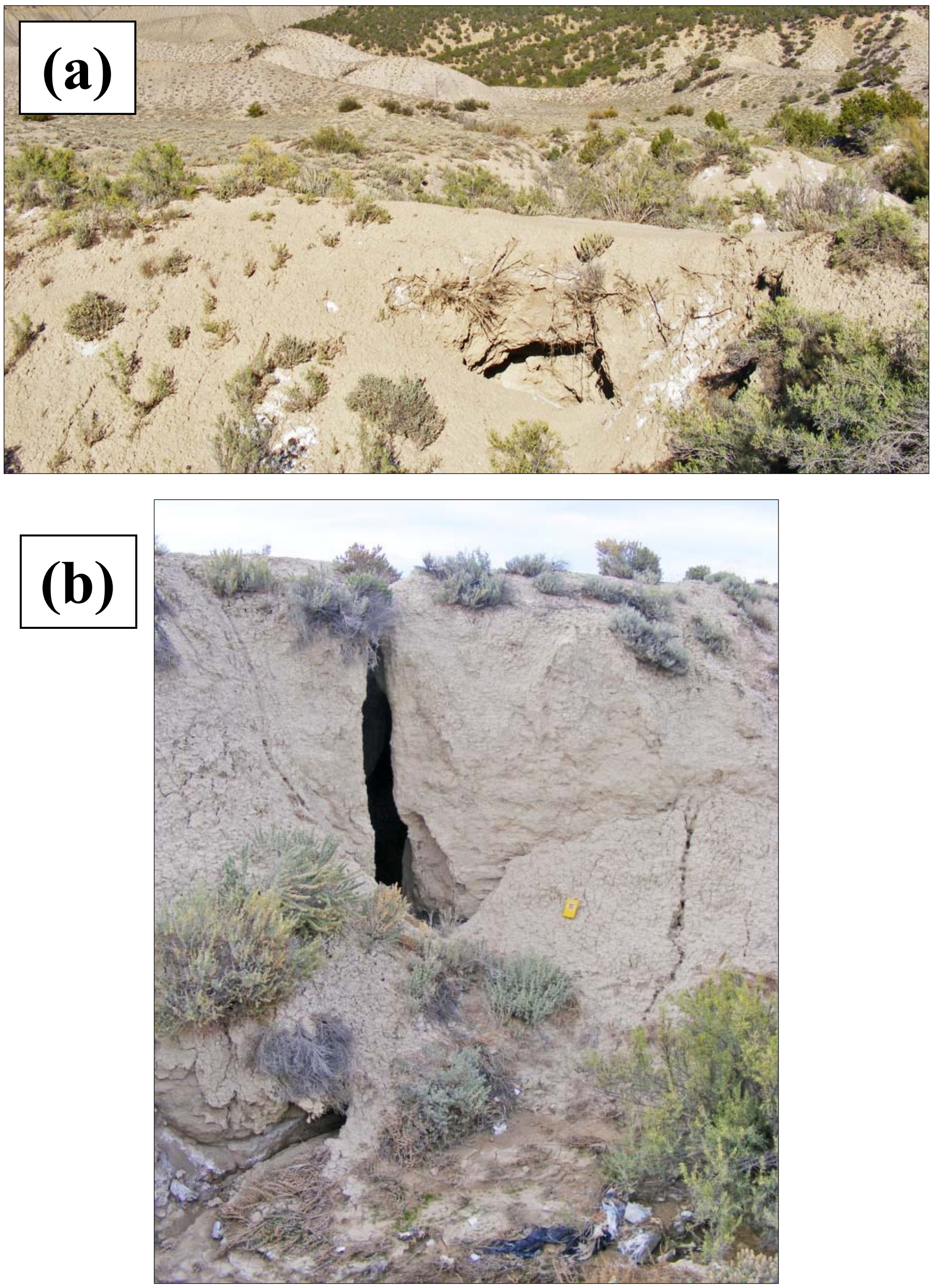

Figure 31. Collapsible and highly erosive surficial deposits in the "adobe hills" area.
(a) Piping, collapse, and sinkhole development in an abandoned, earthen dam near Cottonwood Creek. The dam was constructed, and shares physical properties and collapsible-soil behavior, with surrounding mud flow deposits (**Qamf**). [UTMX: 273689, UTMY: 4292874]
(b) An erosive fissure in mud flow deposits (**Qamf**) near McDonald Creek. The water that eroded this fissure began as sheetwash that flowed across the top of the deposit during a flash rain storm. The original stream bank in front of the fissure has collapsed as a result of flash flooding along the arroyo floor in the foreground. [UTMX: 271965, UTMY: 4296396]

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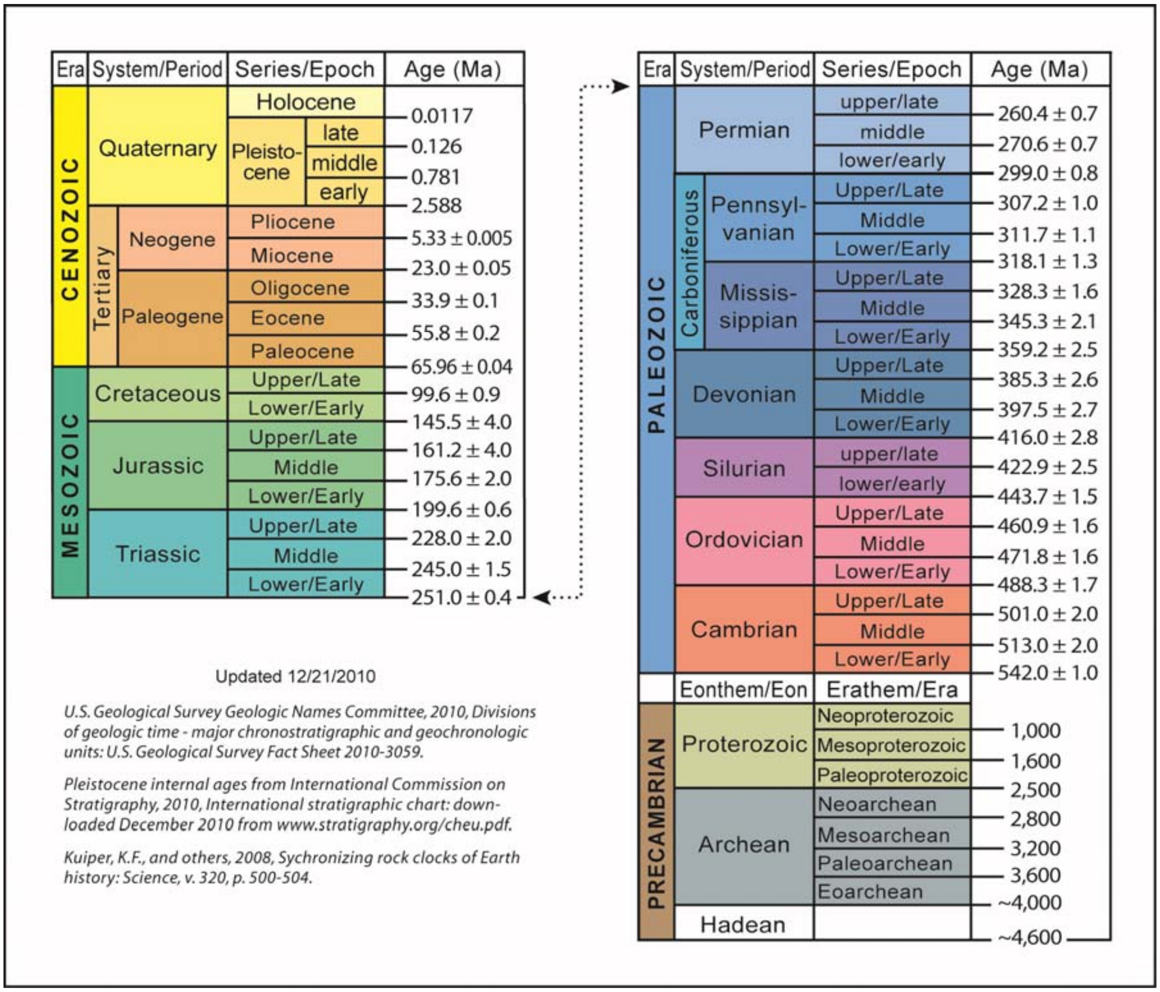
APPENDIX A

Appendix A. Geologic time chart adopted by the Colorado Geological Survey



APPENDIX B

Appendix B. Fossils collected from the Paonia quadrangle and vicinity

The table inserted at the end of this document contains a listing of marine invertebrate fossils collected within or near to the Paonia quadrangle by the CGS map author during the 2013 field season. The fossils were donated to the U.S. Geological Survey (USGS) for their Cretaceous Western Interior Seaway (CWIS) collection. USGS collection numbers (beginning with a "D" for Denver collection) were assigned and are shown on the geologic map. Dr. William Cobban (USGS) provided general identification of the fossil species, with additional identification provided by Dr. Stephen Hook (Atarque Geologic Consulting, Socorro NM) and Dr. Irek Walaszczyk (University of Warsaw). K.C. McKinney (USGS) catalogued the specimens into the CWIS collection.

In addition, where possible, we add fossils collected in the immediate area (that is, from within the quadrangle or within 1 mile of the quadrangle) by other investigators and authors. Those additions are the result of a technical-literature search. The table includes ages and guide-fossil zones from Cobban and others (2006). All of the specimens are Late Cretaceous in age.

Figure 32. The town of Paonia, as seen from the summit of Cedar Hill (known locally as "P Hill"). The town occupies the south bank of the North Fork Gunnison River at its confluence with Minnesota Creek. The river flows from northeast (right) to southwest (left), beyond the town. On the far side are several levels of flat-topped mesas (in sunlight) that are remnants of Pleistocene river terraces. This view looks northward to the downtown district along Grand Avenue. [UTMX: 274594, UTMY: 4304394]

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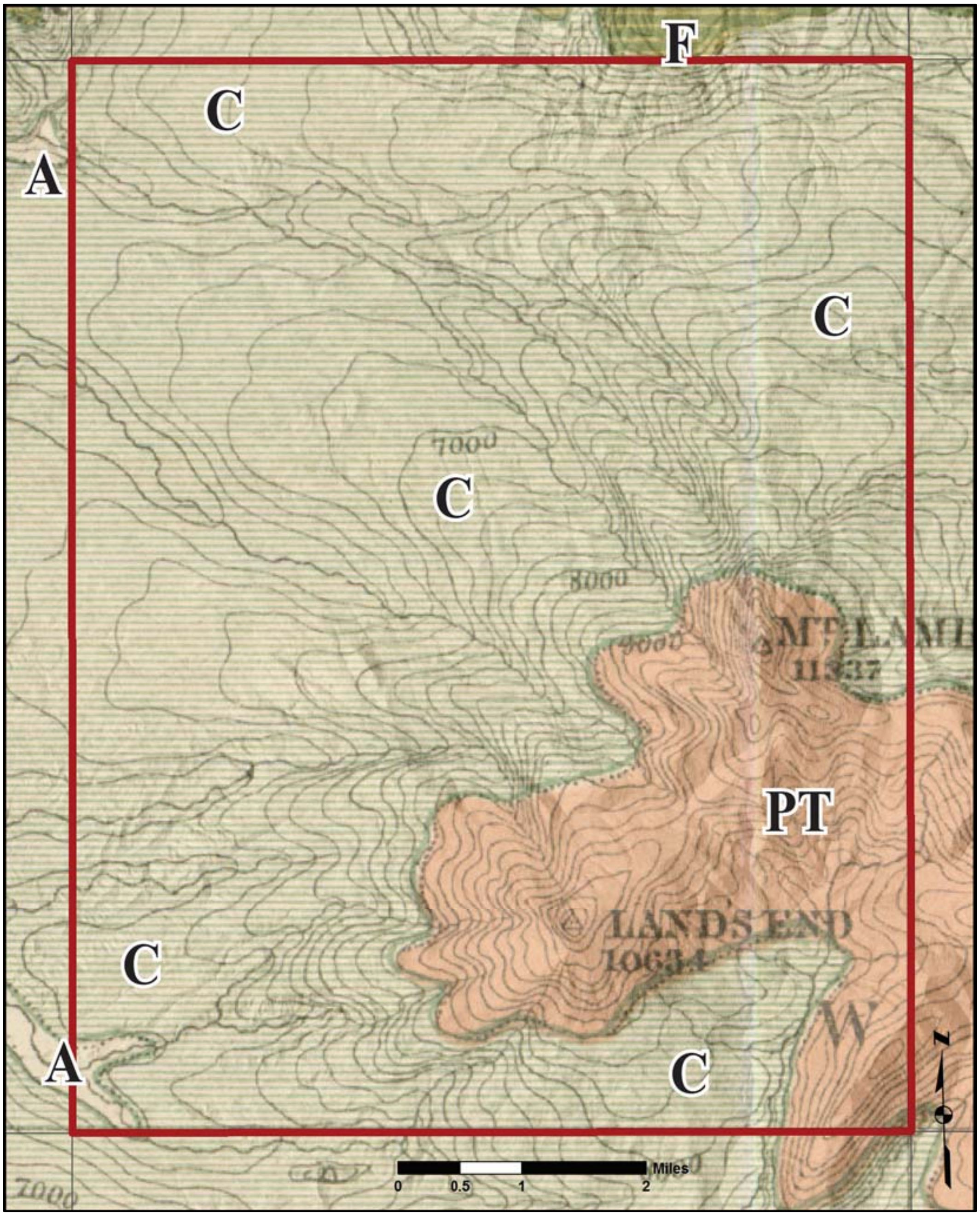

Back Cover. The first geologic map of the Paonia area, published by F.V. Hayden (1877). Fieldwork for this regional map was conducted during the 1874-1876 Geological and Geographical Survey of the Territories (a precursor to the U.S. Geological Survey) under Professor Hayden. A portion of the map is shown, with a red box around the Paonia quadrangle. The map units are as follows:

A	Alluvium (Quaternary)	**F**	Fox Hills-Fort Pierre (Cretaceous)
PT	Porphyritic Trachyte (Eruptive)	**C**	Colorado (Niobrara-Fort Benton) (Cretaceous)