OPEN-FILE REPORT 13-01

Hayden Gulch Quadrangle Geologic Map, Routt County, Colorado

Authors' Notes

John W. Hickenlooper, Governor
State of Colorado

COLORADO
DEPARTMENT OF
NATURAL
RESOURCES

Mike King, Executive Director
Department of Natural Resources

Vincent Matthews
State Geologist and Director
Colorado Geological Survey

by
David C. Noe, Michael J. Zawaski, Zachary D. Logan, and Daniel R. Hosler

Colorado Geological Survey
Department of Natural Resources
Denver, Colorado
2013

This mapping project was funded jointly by the Colorado Geological Survey and the U.S. Geological Survey through the National Cooperative Geologic Mapping Program under STATEMAP agreement number G10AC00410

FOREWORD

The purpose of Colorado Geological Survey's (CGS) *Hayden Gulch Quadrangle Geologic Map,Routt County, Colorado* is to describe the geology, mineral and ground-water resource potential, and geologic hazards of this 7.5-minute quadrangle located south of Hayden in northwestern Colorado. CGS staff geologist David Noe and field assistants Michael Zawaski, Zachary Logan, and Daniel Hosler completed the field work on this project during the summer of 2010. The geologic map plates and the Authors' Notes report were created using field maps, structural measurements, photographs, and field notes generated by the investigators.

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 G10AC00410, 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.

Vince Matthews
State Geologist and Director
Colorado Geological Survey

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

LIST OF PLATES

INTRODUCTION

The Hayden Gulch 7.5-minute quadrangle is located in Routt County, Colorado, south of the town of Hayden (**Figure 1**). Steamboat Springs, the county seat of Routt County, lies 24 miles to the northeast. Craig, the county seat of Moffat County, lies 14 miles to the northwest. Hayden Gulch and the town of Hayden were named after Professor F.V. Hayden (1829-1887), geologist-in-charge of the Geological and Geographical Survey of the Territories, which explored and mapped this area of Colorado in 1874.

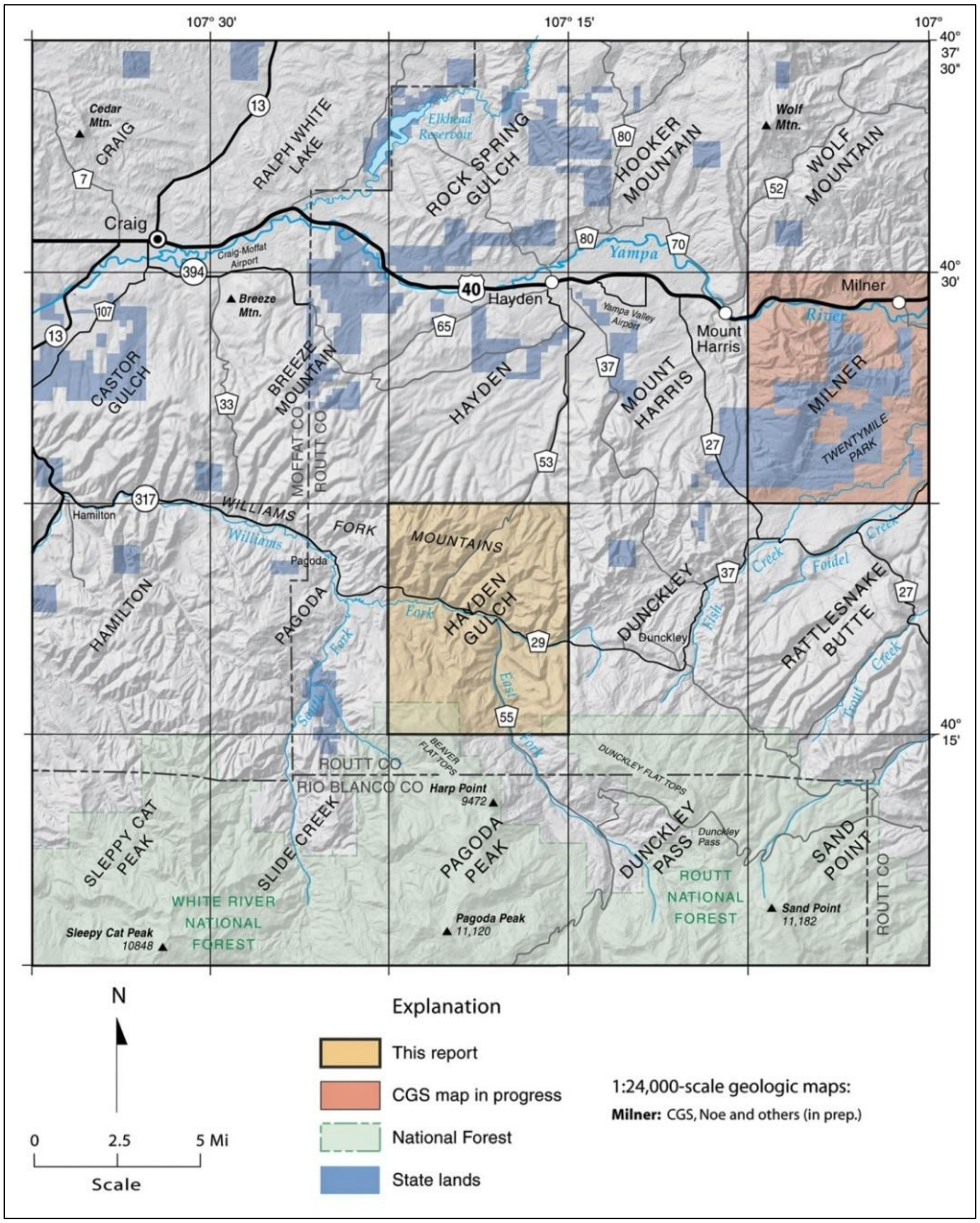


Figure 1. Index map of the Hayden Gulch quadrangle in northwestern Colorado.
The map shows federal- and state-owned land parcels and the status of 1:24,000-scale geologic mapping.

Figure 2 shows the major physiographic features of the quadrangle. The highest elevation in the quadrangle is on the Beaver Flat Tops (8,106 ft). The lowest elevation (6,660 ft) is where the East Fork Williams Fork River exits at the western border. A major bend in the river separates its upper reach, which flows northward from its headwaters in the Flat Tops mountain range, from its lower reach, which flows westward along the southern margin of the Williams Fork Mountains.

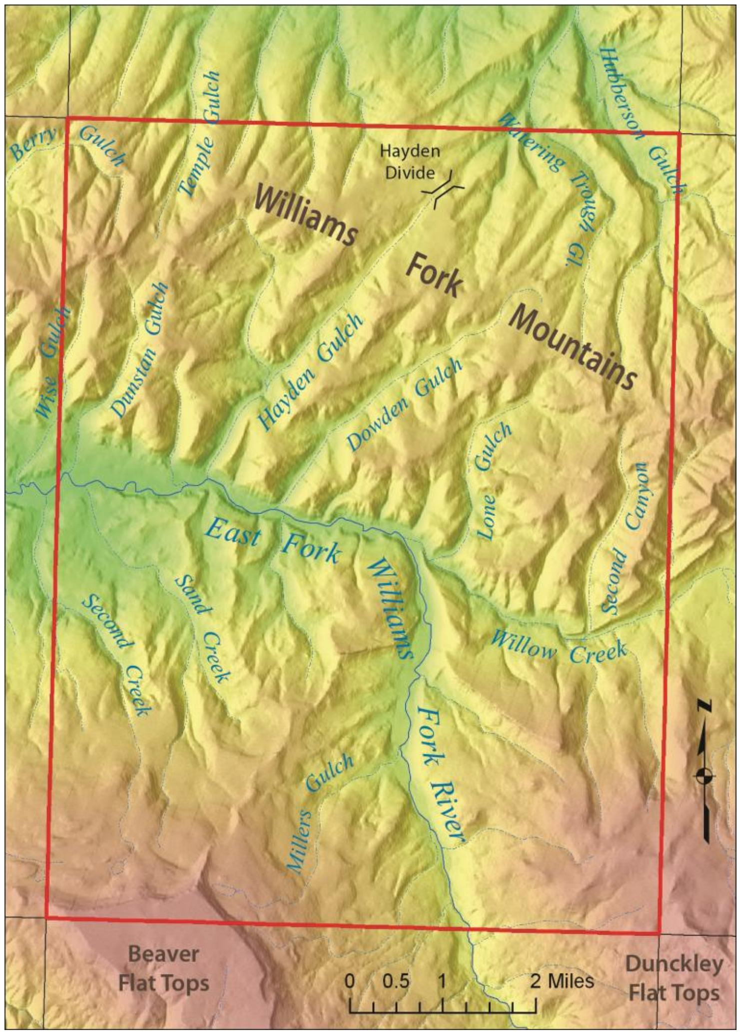


Figure 2. Shaded-relief index map of the Hayden Gulch quadrangle.
The map shows major physiographic features mentioned in the report.

The Williams Fork Mountains rise to an altitude of 8,300 ft. The crest of this east-west range forms a sinuous drainage divide, with gulches that drain southward and northward. Its lowest point is at Hayden Divide (7,468 ft). The landscape in the southern part of the quadrangle consists of slopes and small drainages that radiate away from Beaver Flat Tops and Dunckley Flat Tops, two basalt-capped plateaus. There are no towns or population centers within the quadrangle.

PREVIOUS MAPPING STUDIES

The earliest regional geological map of the region was published 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 Craig 1x2-degree sheet (Tweto, 1976) (1:250,000). Bass and others (1955) published a map and report on the region's coal resources (1:62,500). Madole (1989) mapped the surficial geology of the area (1:100,000).

Geologic mapping of the Hayden Gulch quadrangle was undertaken by the Colorado Geological Survey (CGS) as part of the STATEMAP program. STATEMAP is a component of the National Cooperative Geologic Mapping Act, administered by the U.S. Geological Survey (USGS). The purpose of the CGS STATEMAP program is to produce 1:24,000 scale geologic maps with a focus on surficial units, bedrock units, and structural features. The maps can be used for a variety of applications including land-use planning, geologic-hazard assessment, geotechnical engineering, mineral-resource development, and ground-water resource development. Additionally, the maps enhance our understanding of an area's unique geologic history. **Figure 1** shows the status of 7.5-minute (1:24,000-scale) quadrangle geologic mapping in the area. CGS previously mapped the Milner quadrangle (Noe and others, in prep.). (For the current status of CGS STATEMAP projects, see http://geosurvey.state.co.us/mapping/Pages/24,000-ScaleMappingProgram.aspx.)

MAPPING METHODOLOGY

The Hayden Gulch quadrangle geologic map is shown on **Plate 1**. The geologic interpretations are based on (1) CGS field investigations conducted from May to July 2010; (2) published and unpublished geologic maps and reports; and (3) interpretation of remote-sensing images. The image data include 1:20,000-scale, black-and-white aerial photography taken in 1962 by the Agricultural Stabilization and Conservation Service (ASCS); 1-m resolution digital orthophotos taken in 2005 and 2006 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 aerial photographs. 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. We were not allowed access to a large ranch that covers the most of the south-western quarter of the quadrangle. We mapped that area from surrounding overlooks using binoculars and aerial photos. Mapping from the aerial photos was digitized into ESRI ArcMap. Line work was digitized on a flat-screen computer monitor using the digital topographic map, DEM, and NAIP orthophotos to correctly locate the geologic features. We used MicroDEM 12.0 to project dipping unit-contact surfaces across covered terrain and ERDAS IMAGINE 2010 to create the 3-D map 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 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). 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 ("ft"), and miles.

SURFICIAL DEPOSITS

The surficial deposits in the Hayden Gulch quadrangle are Quaternary (Holocene and Pleistocene) in age. The deposits shown on the map are generally more than 5 ft thick but may be thinner locally. Certain contacts between surficial units may be gradational, and mapped units locally may include deposits of other types. None of these deposits have been age dated. 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 the 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 or other human-made structures.

dr **Disturbed and reclaimed land (late Holocene)** – Disturbed land includes areas such as surface coal mines, gravel pits, well-drilling pads, or other large excavations. Aggregate, coal, or waste overburden material are stockpiled at some sites. In reclaimed areas, the overburden material is replaced along the approximate contours of the original landscape, covered with topsoil cover, and revegetated. The material varies locally and may consist of gravel, sand, silt, clay, or rock debris. Fill properties vary as well. The fill may be engineered (controlled compaction) or completely uncontrolled.

ALLUVIAL DEPOSITS

Gravel, sand, silt, and clay deposited in stream channels and flood plains, and as alluvial fans and sheet wash along valley sides, in tributary drainages, and on terrace and pediment surfaces. Terrace alluvium and age-related, tributary stream deposits were formed mostly during periods of effective wet climate, periglacial frost weathering, or outwash flooding that coincided with Pleistocene glaciations.

Qa **Alluvium (Holocene to late Pleistocene)** – Sand, silt, and gravel in and underlying the modern flood plain of the East Fork Williams Fork River (**Figure 3**) and Willow Creek. The flood plain consists of active and abandoned meander channels and overbank plains. In stream bank exposures, the unit includes sand and gravel bar deposits. The gravel consists of sub-rounded to well-rounded pebbles and cobbles. Compositions include basalt (derived from the Flat Tops) and granitic-gneiss-quartzite (originally from the Park Range, derived from the conglomerate facies of the Browns Park Formation). Angular blocks of sandstone, ranging from a few inches to 12 ft long, are deposited in the flood plain from local tributary streams and as rock falls from adjacent cliffs and slopes. The flood plain is encroached upon by landslides and alluvial fans. Following Madole's (1989, 1991) work on the nearby Yampa River, we interpret most of unit **Qa** to be of latest Pleistocene age (10 to 30 ka), with Holocene reworking of the uppermost part. Thickness may be as much as 20 to 30 ft based exposures of older gravels in the area, but only the surface of the unit is exposed.

Figure 3. Alluvial deposit (**Qa**) in the East Fork Williams Fork River flood plain and active channel. The channel is eroding into shale, sandstone, and colluvium along the northern (left) valley edge. The flood plain is being used for agriculture. [UTMX: 302843, UTMY: 4465118]

Qac **Alluvium and colluvium, undifferentiated (Holocene to late Pleistocene) –** Silt, clay, sand, and variable amounts of gravel in the bottoms of valleys of tributary streams. The streams are age indeterminate but generally grade to **Qa**. Locally derived **Qac** alluvium takes its character from surrounding bedrock types. It is clay-and-silt rich in streams eroded into shale, sand-silt-clay rich in valleys eroded into sandstone, and clay-to-gravel rich in streams that drain landslide terrain. Most of the streams do not have a well-defined channel. The valley bottoms typically are gently rounded. This is a result of downslope encroachment of colluvium and slope-wash deposits at the valley margins. The margins are sharper where landslides encroach upon the valley floor (**Figure 4**). Thickness is poorly known but generally less than 10 ft.

Figure 4. Alluvium and colluvium deposit (**Qac**) in a small tributary stream valley, Dowden Gulch. Note the gently rounded valley bottom and lack of a stream channel. The valley margins are distinct where overrun by landslides from the steep side slopes. [UTMX: 303925, UTMY: 4467523]

Qg **Older gravel deposits (late to middle Pleistocene) –** Gravel deposits of various ages are scattered throughout the southern half of the quadrangle. They form a series of elevated and dissected gravel bodies having a variety of geometries and origins. Their upper surfaces range from 80 to 1,850 ft above modern stream levels. From younger to older, the remnant deposits stand at progressively higher elevations.

Many of the older gravel bodies appear to be stream-terrace deposits associated with periods of glacial outwash (**Figure 5**). They are typically found within a mile of the modern main stream valleys. The bodies are elongate parallel to the modern valleys and have similar down-valley gradients. The terrace deposits are comprised of sub-rounded to well-rounded basalt, granitic, and metamorphic rocks derived from the Flat Tops to the south. Basalt makes up less than 30% of the clasts, with diameters of up to 2 ft. Thickness is 20 to 50 ft.

Other types of older gravel bodies with fan-like or elongate geometries are found on slopes surrounding Beaver and Dunckley Flat Tops. Basalt makes up most of the gravel (60% to 95%). The deposits are poorly sorted and contain angular to sub-angular basalt boulders up to 6 ft long (**Figure 6**). The internal fabric is muddy and matrix supported. The fan-like gravel bodies appear to be relict alluvial fans, some of which encroached upon alluvial paleo valleys at their distal ends. The elongate gravel bodies appear to be debris-flow filled paleo valleys. We interpret that episodic debris flows filled both tributary stream valleys (high gradient) and landslide-scarp

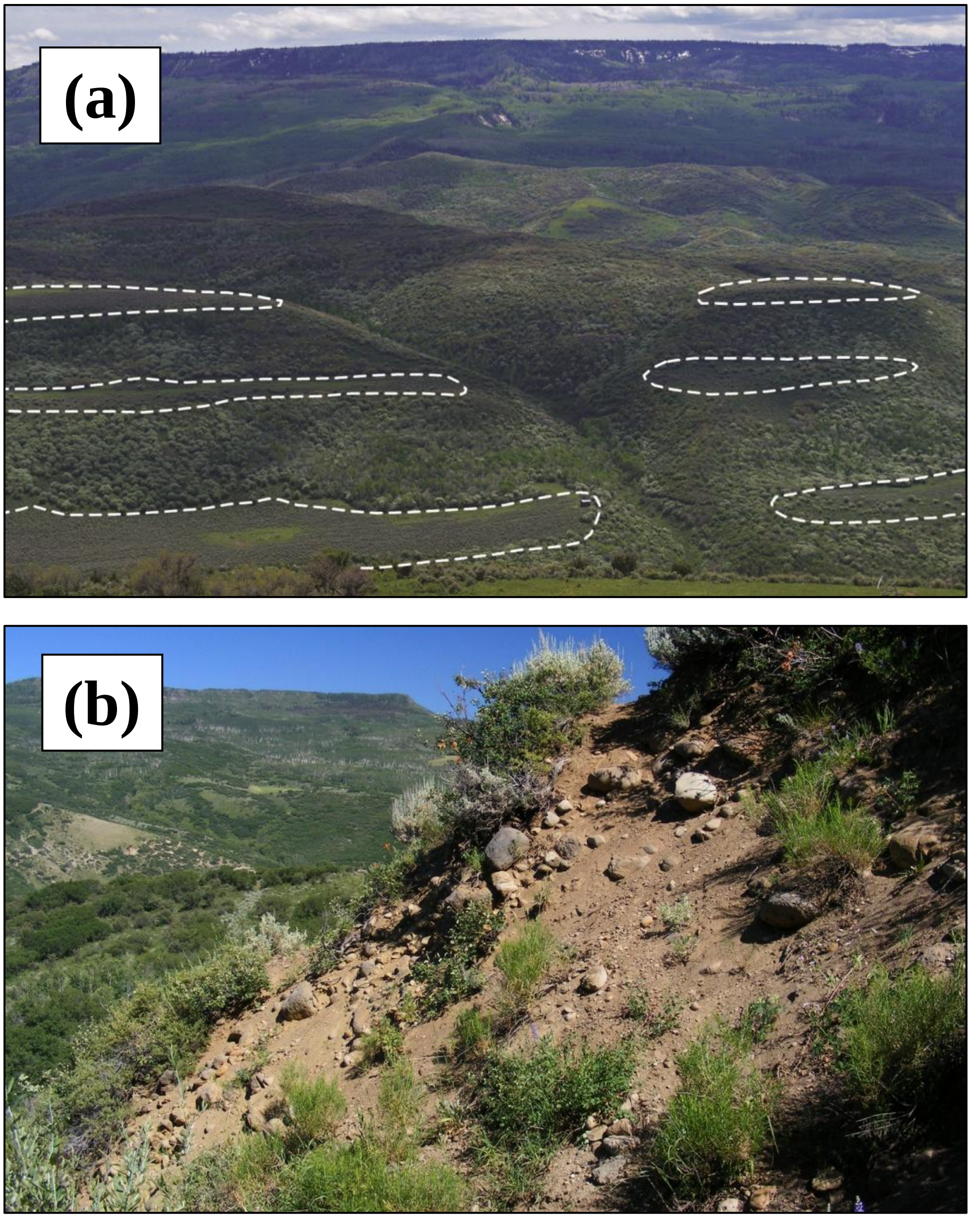


Figure 5. Older alluvial-terrace gravel deposits (**Qg**) along valley of the East Fork Williams Fork River.
(a) Terrace-gravel deposits to the southwest of the bend in the river, with upper surfaces at 680, 480, and 240 ft above the modern stream level. The oldest gravel body caps the hill, whereas the two younger bodies are inset into the hill slope. [UTMX: 304213, UTMY: 4466091]
(b) Cobbly coarse sand deposit 480 ft above the river. We interpret that this remnant terrace contains braided stream deposits emplaced by a sediment-choked, glacial outwash stream. [UTMX: 303996, UTMY: 4458328]

grabens (low gradient). The deposits were later topographically inverted as the shale substrate eroded away. Today they form high points along ridges and hills. Thickness is highly variable, and ranges from 15 to possibly more than 60 ft.

Figure 6. Elongate, older gravel body (**Qg**) on the slope of Dunckley Flat Tops.
Angular basalt boulders are strewn over the rounded hilltop. Their source is the basalt-capped plateau in the background. Also present are rounded metamorphic and granitic pebbles and cobbles that are either recycled from or are in-place Browns Park Formation gravels. [UTMX: 308552, UTMY: 4459182]

Qg **Surficial gravel lag deposits (Pleistocene) –** Several red "bulls'-eyes" mark the locations of small, thin, relict gravel deposits in the Williams Fork Mountains. They occupy the tops of hills and points and appear to be in place. They consist of sub-angular to sub-rounded basalt pebbles, cobbles, and boulders up to 3 ft long.

ALLUVIAL FAN DEPOSITS

Qf **Alluvial fan deposits (late Holocene) –** Poorly sorted sand, silt, gravel, and coarser fragments and blocks as large as boulder size. These deposits form at the mouths of ephemeral stream valleys where the streams lose confinement. They encroach onto modern flood plains of the main streams (**Figure 7**), where the fan aprons are typically reworked by migrating main stream channels. The fan sediments are deposited by flood, debris, and sheet flow processes. The unit is 5 to possibly 30 ft thick.

Qfo **Older alluvial fan deposits (middle Holocene to late Pleistocene) –** Composition and mode of deposition is the same as for **Qf**. An large, older fan is mapped along the southern map boundary. It covers an elevated alluvial terrace deposit (unit **Qg**) and has a fan-like geometry with an apex in landslide terrain (in the Pagoda Peak quadrangle). This fan is inactive. It is incised and bypassed by a younger tributary stream. Unit thickness is 5 to possibly 40 ft.

Figure 7. Alluvial fan deposit (**Qf)** encroaching onto the flood plain of the East Fork Williams Fork River. The fan issues from a tributary valley and spreads out over the flood plain (arrows). The main stream channel is forced against the opposite valley wall (at left), where it has completely removed fan deposits at the mouth of Dowden Gulch. [Helicopter position, UTMX: 301086, UTMY: 4465543]

MASS WASTING DEPOSITS

Qls **Landslide deposits (Holocene to early(?) Pleistocene) –** Non-sorted, heterogeneous mixtures of surficial materials and fragmented rock debris in a wide range of sizes. The matrix and rock types, compositions, and sizes of fragments present reflect the properties of the local source area. The unit includes material deposited in the lower part of the slide area or the zone of accumulation. We map the landslide head scarps as separate features. Several types of landslides are present in the Hayden Gulch quadrangle. The deposits vary in terms of their size and morphology. Dip-slope failures (**Figure 8a**) include block-glide landslides, where detached blocks of bedrock and surficial debris slide down a basal failure plane, and earth flow landslides. The failure plane is typically a weak layer such as a shale bed. Earth flow landslides occur where the slope materials are relatively fine grained and homogeneous, and develop in areas underlain by marine shale. Large earth flow complexes that cover many square miles occur on shale terrain in the southern part of the quadrangle (**Figure 8b**). Side-slope landslide failures occur along valley sides and are common where the valley has incised into shale strata. The deposits range from 5 to possibly greater than 100 ft.

Qscr **Sheet wash, colluvial, and rock fall deposits, undifferentiated (Holocene)** – 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 or blocks of resistant sandstone up to 20 ft long. They typically are wedge-shaped in cross section perpendicular to the slope, and thin at

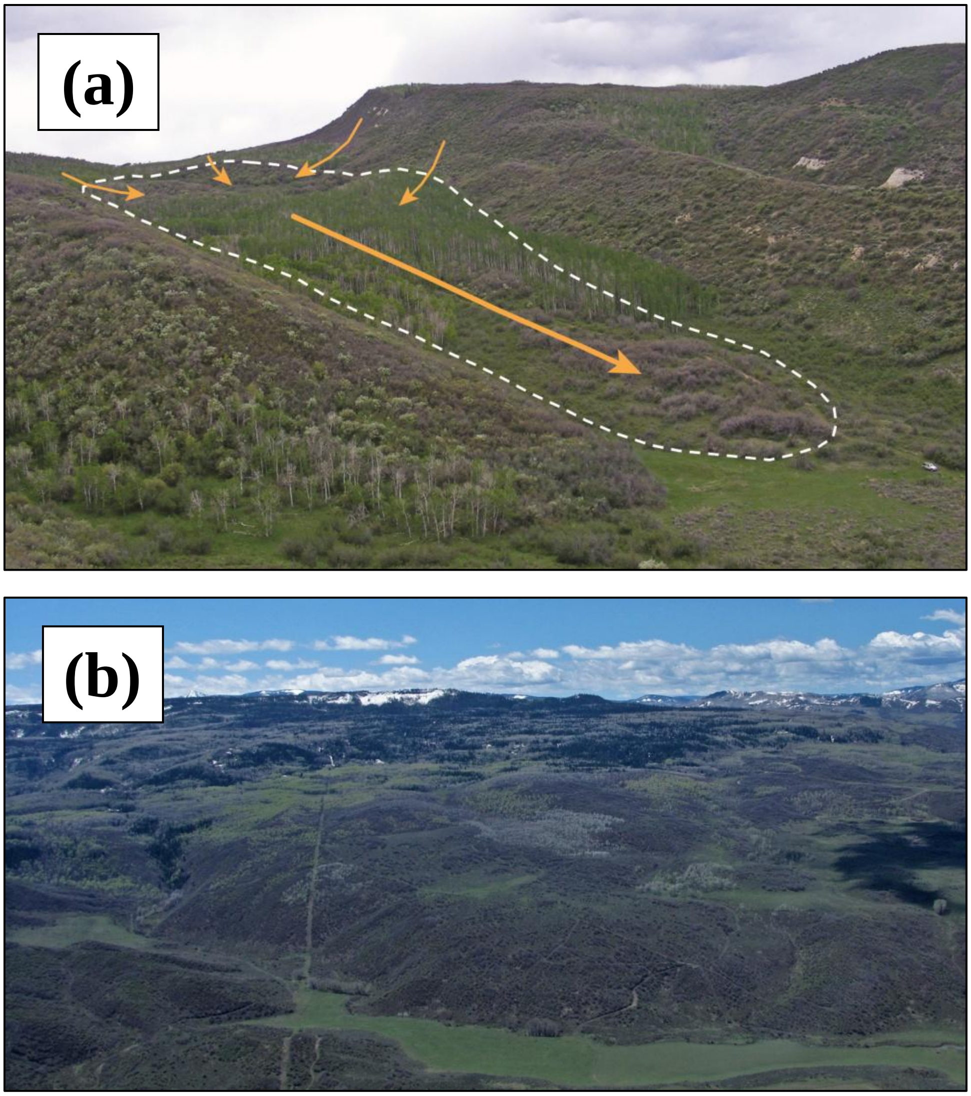


Figure 8. Landslide deposits (**Qls**) showing variations in size and morphologies.
(a) Dip-slope, earth flow deposit in Temple Gulch, Williams Fork Mountains. The slide plane is within a Lewis Shale tongue at the base of the valley. Side-slope failures of Twentymile Sandstone contribute large blocks to the slide mass. [UTMX: 300618, UTMY: 4471327]
(b) View looking south (from helicopter) over the Second Creek valley. The hummocky slope from Beaver Flat Tops on the skyline to the stream valley in the foreground is landslide terrain. The landslide complex contains intermediate scarps and coalescing earth flow lobes. [UTMX: 298596, UTMY: 4463958]

the slope toe. The sediments are poorly stratified to massive, and very poorly to extremely poorly sorted. Thickness is estimated to be 2 to 50 ft.

Qt **Talus deposits (Holocene) –** Deposits of broken and shattered rock blocks, cobble to boulder size, found generally on or at the base of steep slopes. We mapped one deposit beneath the exposed face of the basalt cap of Beaver Flat Tops. The sediment is transported and deposited primarily by raveling and rock fall, slope failure, and sheet wash processes. Unit thickness is estimated to be 5 to 50 ft. A similar deposit is shown in **Figure 9**.

BEDROCK UNITS

A 7,500-ft-thick sequence of Upper Cretaceous sedimentary formations is found in the Hayden Gulch quadrangle. Nearly 1,300 ft of Tertiary intrusive and sedimentary formations are found at higher elevations in the Beaver and Dunckley Flat Tops. These bedrock units are shown within a regional stratigraphic geologic context in **Appendix B**.

TERTIARY INTRUSIVE ROCKS

Tb **Basalt flows and necks (late Oligocene) –** Basalt flows cap the summit of Beaver Flat Tops in the southwestern corner of the quadrangle. We could not attain access to those outcrops. We did, however, examine basalt outcrops of Dunckley Flat Tops at its western point, just outside of the quadrangle (in the Dunckley quadrangle), and at its eastern point near Dunckley Pass (in the Dunckley Pass quadrangle). The basalt is dark gray and weathers to a dusky grayish purple. In outcrop it is highly fractured (**Figure 9a**). We did not observe any columnar structure. The hand samples from Dunckley Pass are composed of fine-grained ground mass of with occasional, clear to whitish, rounded phenocrysts of calcite (**Figure 9b**). The rocks contain abundant, fine vesicles. Certain layers contain larger, somewhat elongate vesicles of various sizes (**Figure 9c**). Kucera (1962) described the composition of basalts in the area as predominantly plagioclase, pyroxene, and opaque material (probably magnetite), altered olivine grains, and a small amount of glass. He also noted some secondary calcite.

Kucera estimated the age of the oldest basalt flows to be middle to late Miocene based on their equivalence with the Browns Park Formation. He estimated that the youngest flows were of Pliocene or early Pleistocene age. Andres Alsan (Colorado Mesa University, unpublished data) recently attained Argon-Argon age dates from two basalt samples collected from the uppermost flow near Dunckley Pass. The dates are 23.06 ± 0.05 My and 23.42 ± 0.06 My. These data show that the youngest basalt flow is approximately coeval with the Oligocene/Miocene boundary (23.0 ± 0.05 My; see **Appendix A**). Thus, the basalt at Dunckley Flat Top appears to be of late Oligocene age. We infer a similar age for the nearby basalt flows that cap Beaver Flat Tops.

Regarding the Beaver Flat Tops basalt flows, we estimate that the unit is 365 ft thick at the northern point, within the Hayden Gulch quadrangle. We could not approach close enough to the outcrops to recognize flow units. There may be a zone of sedimentary rock (representing interbedding with part of the Browns Park Formation?) lower in the unit. That zone is marked by a shelf of less-resistant strata in the blade-like northern ridge of the plateau.

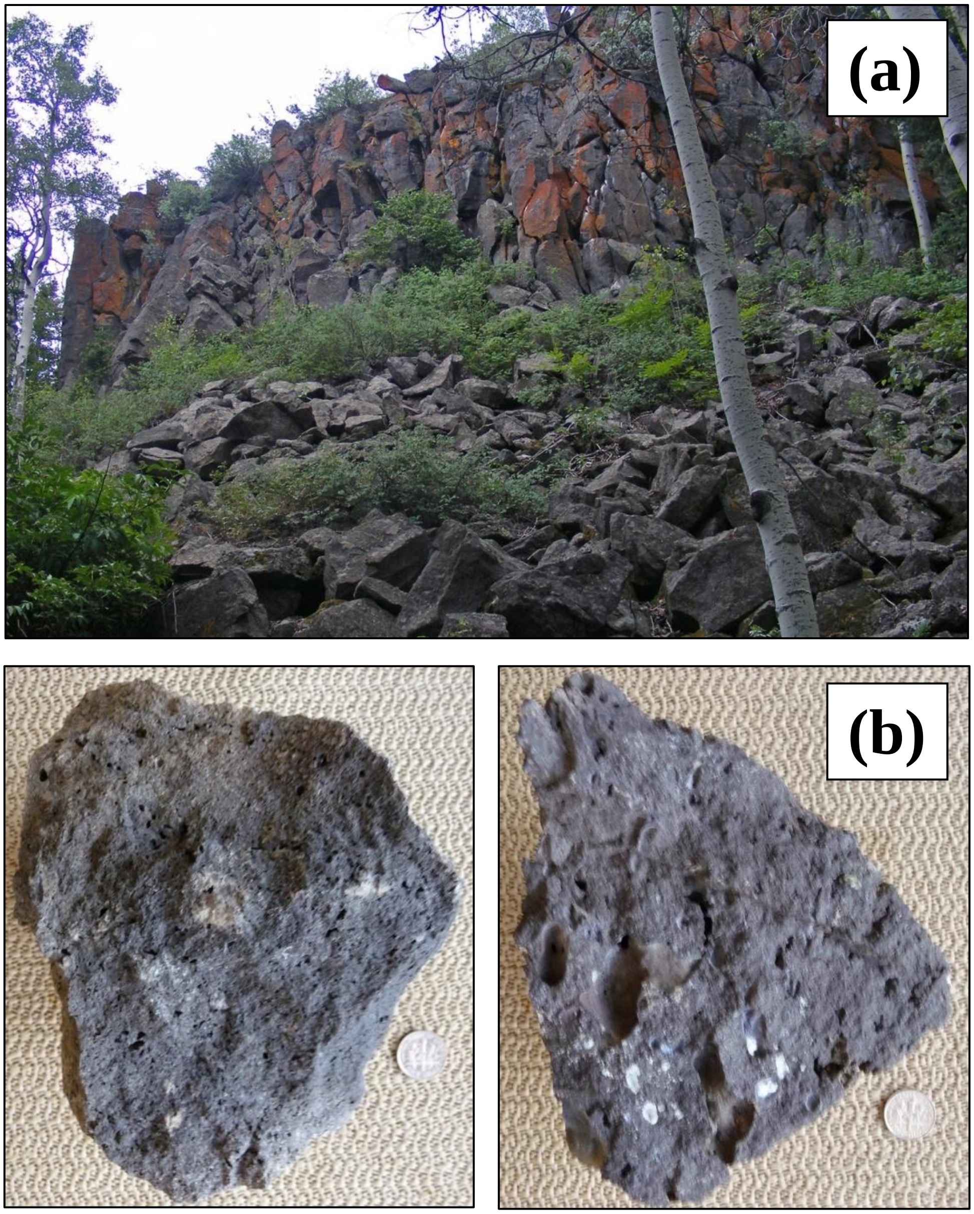


Figure 9. Basalt flows (**Tb**) exposed at Dunckley Flat Tops.
(a) Base of unit in outcrop at western point of the plateau. The slope below is covered with a coarse talus deposit of angular basalt blocks. [UTMX: 309013, UTMY: 4458210]
(b) Hand samples collected at eastern point of plateau near Dunckley Pass. Both display abundant small vesicles and a fine-textured, grayish-purplish ground mass. The sample on the right contains some larger vesicles and whitish calcite phenocrysts. [UTMX: 316132, UTMY: 4452431]

We found a previously unmapped neck of basalt to the east of the East Fork Williams Fork River at an elevation of 7,960 ft. It consists of two overlapping bodies of fine-grained, fractured basalt. Total extent is 300 x 600 ft. We estimate this basalt neck to be roughly age equivalent to the basalt flows at Beaver and Dunckley Flat Tops.

TERTIARY SEDIMENTARY ROCKS

Tbp **Browns Park Formation (late Oligocene) –** The Browns Park Formation is mostly covered with landslide deposits in the Hayden Gulch quadrangle. As a consequence, previous investigators mapped the basal contact of the unit in different locations. We were unable to gain access to much of the area of interest around Beaver Flat Tops. However, we were able to reach poorly exposed outcrops in upland hills near Dunckley Flat Tops. We also found an (apparently) in-place exposure in a landslide head scarp between Beaver Flat Tops and the East Fork Williams Fork River valley (**Figure 10**). Using these and off-quadrangle exposures, we map an inferred basal boundary on the basis of slope breaks and small erosion-scar exposures in landslide terrain. The unit is up to 900 ft thick near the northern tip of Beaver Flat Tops.

Luft (1985) compiled radiometric-age data from Browns Park tuffaceous strata in the region. The oldest reported age is 24.8 ± 0.8 My (late Oligocene) (Izett and others, 1970). The youngest age is 7.2 ± 0.6 My (late Miocene) (Naeser and others, 1980). Luft proposed that only the older part of the unit is present in Routt County and deposition had largely ceased by Miocene time. This appears to be correct based on recent age dating of the overlying basalts at Dunckley Flat Tops (in previous section). Those results indicate that the Browns Park Formation in Hayden Gulch quadrangle is late Oligocene in age.

Figure 10. Browns Park Formation (**Tbp**) exposed in landslide scarp, East Fork Williams Fork River valley. Here, a cross-bedded sandstone body is in erosional contact with an underlying ash-rich siltstone. The sandstone is coarse, feldspathic, poorly sorted, pebbly, and contains shale rip-up clasts. The siltstone is sandy, poorly sorted, and poorly stratified. Calcite-filled fractures cut the outcrop. A poorly exposed, basal conglomerate, containing well-rounded metamorphic and igneous pebbles and cobbles, occurs lower in the scarp, out of the photo frame. [UTMX: 303165, UTMY: 4459204]

CRETACEOUS SEDIMENTARY ROCKS

Cretaceous formations outcropping in the Hayden Gulch quadrangle include the Lewis Shale, Williams Fork Formation, Iles Formation, and Mancos Shale (**Figure 11**). The Williams Fork and Iles Formations comprise the Mesaverde Group in northwestern Colorado. They form three wedges of clastic, marginal-marine to continental sediments that prograded eastward into the Cretaceous Western Interior Seaway (**Appendix B**). The wedges contain three zones of coal-bearing strata: the lower, middle, and upper coal groups. They are bounded by and intertongue to the east with marine Lewis and Mancos Shales.

We map several persistent sandstone bodies within the Williams Fork and Iles Formations and the Mancos Shale. They include the Big White, Twentymile, and Sub-Twentymile (Williams Fork); Trout Creek, Double Ledge, and Tow Creek (Iles); and Loyd, Wise Gulch, and Berry Gulch (Mancos Shale) sandstone members. In addition, we map transgressive tongues of the Lewis and Mancos Shales that occur within the Iles and Williams Fork Formations.

These bedrock units are well described in the geologic literature. For nomenclature history and regional stratigraphic and depositional-systems studies of units within the Mesaverde Group, see Bass and others (1955), Masters (1965; 1967), Izett and others (1971), Bader and others (1983), and Johnson and others (2000). In addition, for the sandstone units at the Mesaverde/Mancos interface and within the upper part of the Mancos Shale, see Konishi (1959), Dyni and Cullins (1965), Gill and Hail (1975), Boyles and others (1981), Boyles (1983), Kiteley (1983), Kiteley and Field (1983), Crabaugh (2001), Hampson and others (2008), and Gomez-Veroiza and Steel (2010).

CGS STATEMAP geologic mapping includes the collection and cataloging of fossils. We collected only a few marine invertebrate fossils of Late Cretaceous age from the quadrangle. The fossils are potentially useful as paleo-environmental or biostratigraphic-age indicators. **Appendix C** contains a listing of fossils found in and near to the quadrangle by CGS and previous authors.

Lewis Shale (Upper Cretaceous)

Klsl **Lewis Shale, lower part of main body –** The lower part of the main body of Lewis Shale is present in the northern part of the quadrangle. In rare exposures, it consists of slightly sandy, non-calcareous, thin-bedded, shaley, marine mudstone. It is medium gray when fresh and weathers to pale to moderate yellowish brown. The maximum thickness of the lower Lewis Shale strata in the Hayden Gulch quadrangle is about 500 ft. We map the basal contact of the unit differently than Bass and others (1955). They chose the top of the Three White Sandstones Member of the Williams Fork Formation as their contact (see **Appendix B**). To the west, near Craig, Williams Fork continental deposits extend upward to that level. However, much of the upper part of the Williams Fork Formation pinches out eastward into the Hayden Gulch area. The Three White Sandstones are present in the quadrangle; however, here they consist of thin zones of hummocky cross-stratified sandstone beds encased in marine shale. We map that interval as part of the Lewis Shale, and accordingly, in our map the Lewis Shale is more areally extensive than was mapped by Bass and others. We place the contact lower in the section, at approximately 20 ft above the top of the Big White Sandstone Member (see **Figure 11**).

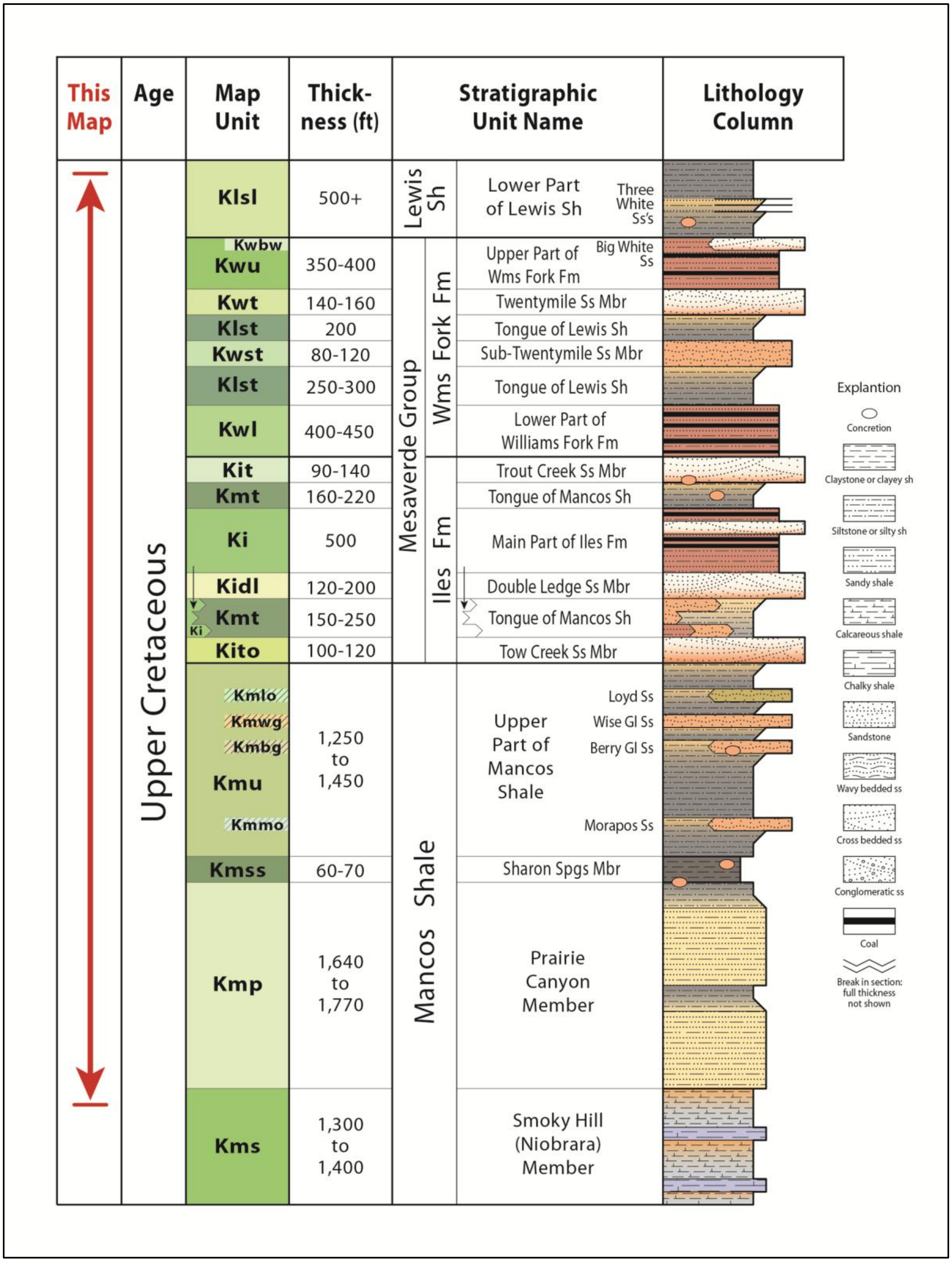


Figure 11. Generalized stratigraphic column of Cretaceous bedrock units for the Hayden Gulch quadrangle. Red arrow denotes bedrock units exposed in outcrops in the quadrangle. **Appendix B** shows how this column relates to the Upper Cretaceous and Tertiary geologic framework of northwestern Colorado.

Williams Fork Formation of the Mesaverde Group (Upper Cretaceous)

Kwbw **Big White Sandstone Member –** This unit is mapped in two locations in the northeastern part of the quadrangle. Where present, it forms a thick lens of whitish to very pale orange sandstone that contains low-angle to planar cross beds. The base is typically covered and the top is flat and horizontal. It is flanked and overlain by carbonaceous shale near the top of the upper Williams Fork Formation. The Big White Sandstone is 0 to 60 ft thick in the quadrangle and thickens to the north.

Kwu **Williams Fork Formation, upper part –** This unit contains interbeds of sandstone, siltstone, coal, and carbonaceous shale. It represents the uppermost of the three Mesaverde clastic wedges. The sandstone beds are grayish to yellowish orange, very fine to fine grained, lenticular, and contain trough cross beds and ripples. An exception is the Big White Sandstone (see above). The coal beds comprise the upper coal group of the Yampa coal field. The unit forms ledges and slopes. It is often a distinctive reddish color where the beds have been converted to clinker by burning of coal at the outcrop. Thickness is 350 to 400 ft.

Kwt **Twentymile Sandstone Member –** The Twentymile Sandstone forms a band of distinctive, pale-orange to whitish sandstone cliffs (**Figure 12**). The sandstone coarsens upward from very fine to fine grained. The unit consists of one to three, thick sandstone bodies that are sometimes separated by thin shale stringers. It has a gradational (often covered) contact with underlying marine shale strata and a sharp contact with overlying upper Williams Fork strata. According to Siepman (1985, 1986) and Benda (2000), the Twentymile Sandstone was deposited deltaic, strand plain, and barrier island settings. It is 140 to 160 ft thick in the Hayden Gulch quadrangle.

Figure 12. Twentymile Sandstone Member of Williams Fork Formation (**Kwt**) in Lone Gulch. Here, the unit forms a cliff with two to three, stacked sandstone bodies. Shrub-covered slopes above the white sandstone mark the upper part of the Williams Fork Formation (**Kwu**). A tongue of Lewis Shale (**Klst**) forms the grass-covered slopes below the cliff. [UTMX: 303470, UTMY: 4466747]

Klst **Tongue of Lewis Shale** – This tongue of the Lewis Shale represents a westward incursion of the Western Interior Seaway (**Appendix B**). The unit forms a distinctive band of gentle, grass-covered or forested slopes. In rare exposures, it contains silty, shaly to bioturbated, marine mudstone that looks similar to the main body of Lewis Shale. This is the uppermost of two Lewis Shale tongues that we mapped in the Hayden Gulch quadrangle. Its thickness is about 200 ft.

Kwst **Sub-Twentymile Sandstone Member –** The Sub-Twentymile Sandstone consists of light brown, hummocky to swaley to trough cross-bedded sandstone, with thin shale interbeds in the lowest part. This sandstone unit is both overlain and underlain by tongues of Lewis Shale. It forms a series of cliffs and resistant hogbacks. The unit thins from west to east. It is 120 ft thick near Dunstan Gulch and 80 ft thick in Lone Gulch.

Klst **Tongue of Lewis Shale** – This is the lowermost of two Lewis Shale tongues that we mapped. It is similar in composition to the previously described **Klst** unit. Its thickness is 250 to 300 ft.

Kwl **Williams Fork Formation, lower part –** This unit contains interbeds of sandstone, siltstone, coal, and shale. It represents the middle of the three Mesaverde clastic wedges. It is similar to the upper part of the Williams Fork Formation in terms of composition and lithofacies. The coal beds comprise the middle coal group, which is the major producing interval of the Yampa coal field (see **Mineral Resources** section). The unit contains the Yampa Bed, a 1-ft thick tonstein (volcanic ash) deposit that lies about approximately 120 ft above the base (Brownfield and Johnson, 2008). We did not see the ash bed in outcrop. The lower Williams Fork unit forms a series of hogback-capping bluffs. It contains abundant reddish clinker from burnt coal (**Figure 13**). The unit is 400 to 450 ft thick.

Iles Formation of the Mesaverde Group (Upper Cretaceous)

Kit **Trout Creek Sandstone Member –** The Trout Creek Sandstone forms a series of whitish cliffs below hogbacks of the overlying Williams Fork Formation (**Figure 13**). The sandstone coarsens upward from very fine to fine grained. The unit consists of one to three, thick sandstone bodies separated by thin shale stringers. It has a gradational to sharp (often covered) contact with the underlying marine shale and a sharp contact with overlying lower Williams Fork strata. The unit is similar to the previously described Twentymile Sandstone in terms of color, lithofacies, and thickness. Siepman (1985, 1986) interpreted the Trout Creek Sandstone as being deposited in deltaic, strand plain, and barrier island settings. The unit is 90 to 140 ft thick.

Kmt **Tongue of Mancos Shale** – This tongue of the Mancos Shale represents a westward incursion of the Western Interior Seaway (**Appendix B**). It forms a distinctive band of gentle, grass-covered or forested slopes. In rare exposures, it consists of silty to sandy, bioturbated to shaly mudstone that looks similar to the main body of Mancos Shale. This is the uppermost of two Mancos Shale tongues that we mapped within the Iles Formation in the Hayden Gulch quadrangle. It thickens to the southeast across the quadrangle, from 160 to 220 ft.

Figure 13. Trout Creek Sandstone Member of Iles Formation (**Kit**) west of Hayden Gulch. This distinctive, whitish sandstone forms a cliff in southern exposure (to left) but is hidden by heavy shrub cover in eastern exposure (to right). A reddish slope of coal-fire clinker above the cliff marks the lower part of the Williams Fork Formation (**Kwl**), which caps the hogback bluff. A tongue of Mancos Shale (**Kmt**) forms the shrub-covered lower slopes and the valley floor. [UTMX: 301774, UTMY: 4467675]

Ki **Iles Formation –** The main body of the Iles Formation contains interbeds of sandstone, siltstone, carbonaceous and marine shale, and coal. It represents the lowermost of the three Mesaverde clastic wedges. The sandstone is very fine to fine grained. The coal beds comprise the lower coal group of the Yampa coal field. The Iles Formation caps a series of prominent hogback bluffs that mark the southern edge of the Williams Fork Mountains. It forms a series of ledges, cliffs, and hogback slopes. The sandstone bodies are very fine to fine grained. They are light brown to whitish to very pale orange. Crabaugh (2001) investigated the formation in detail in this area. He defined 16 separate regressive-transgressive couplets within the Iles clastic wedge (which includes this unit and underlying **Kidl**, **Kmt**, **Kito**, and **Kmlo** units). Gomez-Veroiza and Steel (2010) found that the seaward part of the wedge (which includes the present-day Hayden Gulch quadrangle) is dominated by regressive, deltaic-shoreface and coastal-plain facies. The transgressive tracts contain nearshore marine, tidal, estuarine, and coal-swamp facies, and extend nearly 100 miles to the northwest into the Wyoming thrust-belt foreland. The main body of the Iles Formation is 500 ft thick in the eastern part of the Hayden Gulch quadrangle. It thickens to 650 ft near the western boundary, where **Kmt** marine shales pass laterally into **Ki** marginal-marine sandstones (Crabaugh, 2001).

Kidl **Double Ledge Sandstone Member –** The Double Ledge Sandstone forms a series of cliffs and shelves along the southern flank of the Williams Fork Mountains (**Figure 14**). The unit consists of one to three, thick, tabular sandstone bodies separated by shale and thin-bedded sandstone stringers. It has a gradational contact with the underlying marine shale and a sharp contact with overlying Iles Formation strata. The sandstone is pale grayish-orange to very pale orange in color. The unit is similar to the previously described Twentymile and Trout Creek Sandstone

Figure 14. Double Ledge Sandstone Member of Iles Formation (**Kidl**) near Dowden Gulch. To left, the unit forms two ledges of sandstone above the road cut. It continues eastward across the background, where it rises as a single, tabular sandstone body from a shallow syncline. The overlying upper slopes contain the main body of Iles Formation (**Ki**). A tongue of Mancos Shale (**Kmt**) forms the slope beneath the sandstone ledges. [UTMX: 302843, UTMY: 4465118]

units in terms of color, lithofacies, and thickness. Masters (1965) and Crabaugh (2001) show that this unit rises toward the east. In their cross sections, the type section for the member (Bass and others, 1955), 14.5 miles to the east near Fish Creek Canyon, is stratigraphically higher and younger than the strata that we mapped in the Hayden Gulch quadrangle. Thickness is 120 to nearly 200 ft, depending on the number of sandstone bodies present.

Kmt **Tongue of Mancos Shale** – This is the lowermost of two Mancos Shale tongues that we mapped within the Iles Formation in the Hayden Gulch quadrangle. It represents a minor, westward incursion of the Western Interior Seaway. The unit forms ledges and slopes. It is 250 ft thick in the east-central part of the quadrangle, where it is comprised of sandstone and shale interbeds. The sandstone beds are less than 2 ft thick, grayish orange, and hummocky cross-bedded. The shale interbeds are 0.5 to 5 ft thick, sandy to silty, and some are bioturbated. The thickness of the unit decreases to about 150 ft to the west as the shale tongue pinches out. This is due to the appearance of several lower-Iles, marginal-marine sandstones that intertongue with the shale (**Figure 11** and **Appendix B**) (see Masters, 1965; and Crabaugh, 2001).

Kito **Tow Creek Sandstone Member –** The basal unit of the Iles Formation in the Hayden Gulch quadrangle is the Tow Creek Sandstone. It forms a distinctive rim-rock cliff above the valleys of the East Fork Williams Fork River and Willow Creek (**Figure 15**). The unit consists of pale grayish-orange to very pale orange, very fine to fine-grained sandstone. Its basal contact is gradational with the underlying Mancos Shale. Its uppermost surface is planar and occasionally is eroded by channels in the overlying main body of the Iles Formation. The unit is similar to the previously

Figure 15. Tow Creek Sandstone Member of Iles Formation (**Kit**) near Dunstan Gulch. The unit forms a banded, sandstone cliff near the skyline. It is overlain by interbedded sandstone and shale of the main body of Iles Formation. Fallen sandstone blocks are strewn across the underlying slope, which consists of the upper Mancos Shale (**Kmu**). At left in middle ground is an outcrop of the Wise Gulch Sandstone (**Kmwg**), a marine sandstone encased in shale. [UTMX: 299555, UTMY: 4466089]

described Twentymile and Trout Creek Sandstone units in terms of lithofacies, and thickness. Kiteley (1983) and Kiteley and Field (1984) interpreted the Tow Creek Sandstone as a fluvial-dominated deltaic deposit comprised of channel-mouth bar and delta-front sheet sandstones facies. The unit is 100 to 120 ft thick in the Hayden Gulch quadrangle.

Mancos Shale (Upper Cretaceous)

Kmu **Mancos Shale, upper part of main body** — The upper part of the main body of Mancos Shale is present at the base of the Williams Fork Mountains, where it forms steep slopes beneath Tow Creek Sandstone rim-rock (**Figure 15**). South of the East Fork Williams Fork River valley, it covers an extensive area of low ridges and valleys on the slopes of Beaver and Dunckley Flat Tops. The unit consists mainly of olive-gray to pale yellowish-brown, non-calcareous, silty to sandy, marine mudstone. Certain intervals contain thin, sheet-like, hummocky cross-bedded sandstone beds, especially in the uppermost half of the unit. The unit contains occasional, dark yellowish-orange to light brown concretions. The overall thickness is 1,250 to 1,450 ft. Nearby oil and gas well logs show that the unit consists of at least five sequences of upward-coarsening shale (mud- to silt- to sand-rich). We mapped three marine sandstone bodies within the upper part of the Mancos Shale, coincident with the tops of the second, third, and fourth upward-coarsening sequences. These discrete members of the Mancos are described below.

Kmlo? **Loyd(?) Sandstone Member**

Kmwg **Wise Gulch Sandstone Member**

Kmbg **Berry Gulch Sandstone Member** — These three sub-units are found within the upper half of the upper Mancos Shale (**Kmu**). The highest, the Loyd Sandstone, occurs about 150 to 180 ft below the base of the Iles Formation. The Wise Gulch and Berry Gulch Sandstones occur about 400 to 440 ft and 600 to 650 ft, respectively, below the base of the Iles Formation. The three units are similar in appearance. Individual sandstone bodies are as much as 40 ft thick. They consist of very fine-grained to fine-grained, rippled to cross-bedded sandstone. They generally coarsen upward in grain size and bedding thickness. The thickest beds are 1 to 2 ft thick. The outcrops have a distinctive wavy and thin-bedded appearance. The sandstones may be slightly to intensely bioturbated in the lower strata. Their lower contacts are gradational with underlying sandy shale. Their upper contacts are sharply overlain by mud-rich shale.

The Loyd(?) Sandstone is light olive-brown. Kiteley and Field (1984) interpret it to be a slowly transgressed, deltaic deposit based on outcrops in other locations. The closest, known Loyd outcrop is 6.5 miles to the west, near Deakin Gulch in the Pagoda quadrangle. Noe and others (in prep.) mapped the Loyd Sandstone near Tow Creek in the Milner quadrangle, 18 miles to the northeast. There is a possibility that this sandstone body is equivalent to the Morgan Gulch Sandstone, which is stratigraphically higher and younger. The closest Morgan Gulch outcrop is near Jeffway Gulch, 8.5 miles to the west (Masters, 1965; Crabaugh, 2001).

The Wise Gulch and Berry Gulch Sandstones are light-brown to grayish-orange. Two levels of Wise Gulch sandstone are present in some areas (**Figure 16**). The Berry Gulch unit locally contains large, light-brown, often fossiliferous concretions. We collected *Baculites perplexus, B. haresi,* and *Cataceramus subcompressus* specimens from the Berry Gulch interval at three locations in the south-central part of the quadrangle (see **Appendix C**). The sandstone bodies form thin, lenticular sheets that are continuous for up to tens of miles along the bedding strike direction. Hampson and others (2008) interpret the Wise and Berry Gulch Sandstones to be nearshore shelf- bar complexes within estuarine river-delta systems.

Kmss **Sharon Springs Member** — This thin shale unit is typically poorly exposed. In the Hayden Gulch quadrangle it is mostly covered by landslides We identified it at one location on the western side of the East Fork Williams Fork River. It is a very dark gray to black, organic-rich, clay shale. Exposed surfaces contain abundant healed fractures. We mapped the unit elsewhere using Google™ Earth. Its outcrop was established on the basis of geomorphic indicators (scalloped ridges, landslide slip planes), and by making bedrock-plane projections from a known location using MicroDEM GIS software. The Sharon Springs Member contains a number of white to orange bentonite beds. The bentonite beds are 0.5 to 6 inches thick. In the subsurface, this unit forms a prominent, widespread bentonitic marker that is used for making well log correlations. The unit is 60 to 70 ft in outcrop and in nearby oil and gas well logs.

Kmp **Prairie Canyon Member** — This sandy shale is the offshore equivalent of the Blackhawk and Star Point Formations in central Utah (Cole and others, 1997). In the Hayden Gulch quadrangle it is mostly covered by landslides. In rare outcrops it is grayish orange to light brownish gray and

Figure 16. Wise Gulch Sandstone Member of Mancos Shale (**Kmwg**) near Detwiller Reservoir. This well-defined hogback contains two upward-coarsening bodies of sandy shale to rippled and cross-bedded, marine sandstone. It is encased in the upper part of Mancos Shale (Kmu), which forms the slope beneath the cliffs and in the right foreground. [UTMX: 302952, UTMY: 4462560]

contains small, rounded discs of very fine, bioturbated sandstone (**Figure 17**). The discs appear to be individual sand ripples that weathered out of the shale. In nearby oil and gas well logs the unit exhibits a rather homogeneous gamma-ray signature. Resistivity and porosity logs indicate several intervals that vary somewhat in sand and clay content. The uppermost 200 ft of the unit becomes less sandy. Total thickness of the unit from well logs is 1,640 to 1,770 ft.

Kms **Smoky Hill (Niobrara) Member** — Only the uppermost 200 ft of Smoky Hill (Niobrara) shale is exposed within the quadrangle. In outcrops along the East Fork road (C.R. 55) it is a medium-light-gray to dark-gray, calcareous mudstone that has a distinct silvery sheen (**Figure 18**). Examination of hand samples reveals a white-speckled appearance. The white specks are flattened and broken coccolith shells deposited along shale bedding planes. Total thickness of the unit from well logs is 1,300 to 1,400 ft.

Older Mancos Shale Members Shown on Geologic Cross Section A-A' Only

Cross Section A-A' runs from the summit of Beaver Flat Tops north to the East Fork Williams Fork River, and then to the northeast across the Williams Fork Mountains. The section line is shown on **Plate 1**. The cross section is shown on **Plate 2**. It shows the interpreted subsurface stratigraphy and structure of the Upper Cretaceous strata. In the south it includes the Tertiary sedimentary and igneous formations that form Beaver Flat Tops. We combined certain thinner, member-level units within the Mesaverde Group. The thin Sharon Springs Member of the Mancos Shale is shown as a line rather than an interval. Additional members of the Mancos Shale are included as subsurface units on the geologic cross section,

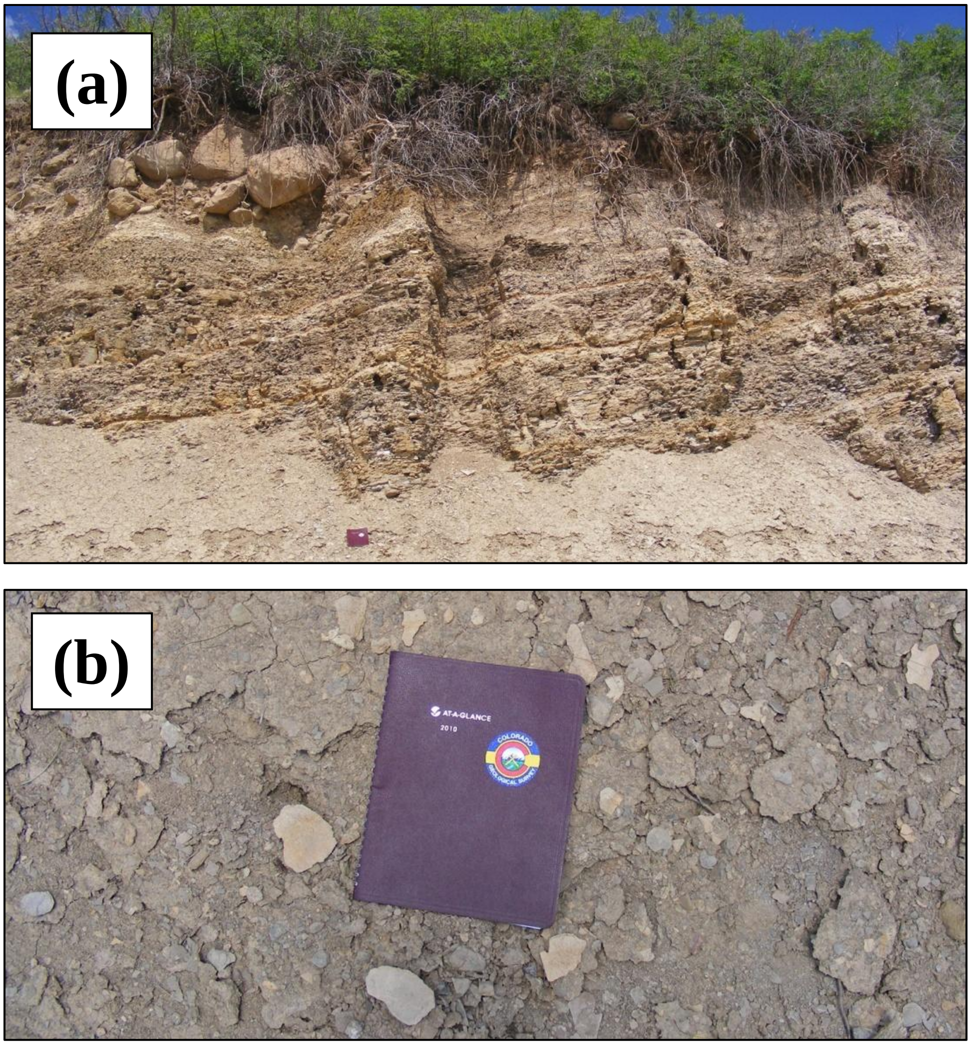


Figure 17. Prairie Canyon Member of Mancos Shale (**Kmp**) along County Road 55.
(a) Outcrop in road cut showing gently dipping, sandy shale. The light-orange bed that crosses the center of photo is a weathered bentonite seam. [UTMX: 305275, UTMY: 4458298]
(b) Surface of colluvium beneath the outcrop at same location. The scattered, thin discs of grayish to light-orange sandstone are weathered out of rippled, sandy shale beds. Notebook is 7.5 x 9 inches.

and are described below. They do not crop out within the Hayden Gulch quadrangle but occur in outcrops to the south. Reported thickness values are estimated from oil and gas well logs in the area.

Kms **Smoky Hill and Fort Hays (Niobrara) Members, undivided** — Niobrara-equivalent strata includes the Smoky Hill Member (only the uppermost 200 ft crops out within the quadrangle) and the underlying Fort Hays Member. It contains intervals of calcareous shale and marly, chalky limestone. The Niobrara interval is a favored oil-and-gas exploration target, especially the chalk-bearing intervals within the Smoky Hill Member. Thickness: 1,300 to 1,400 ft.

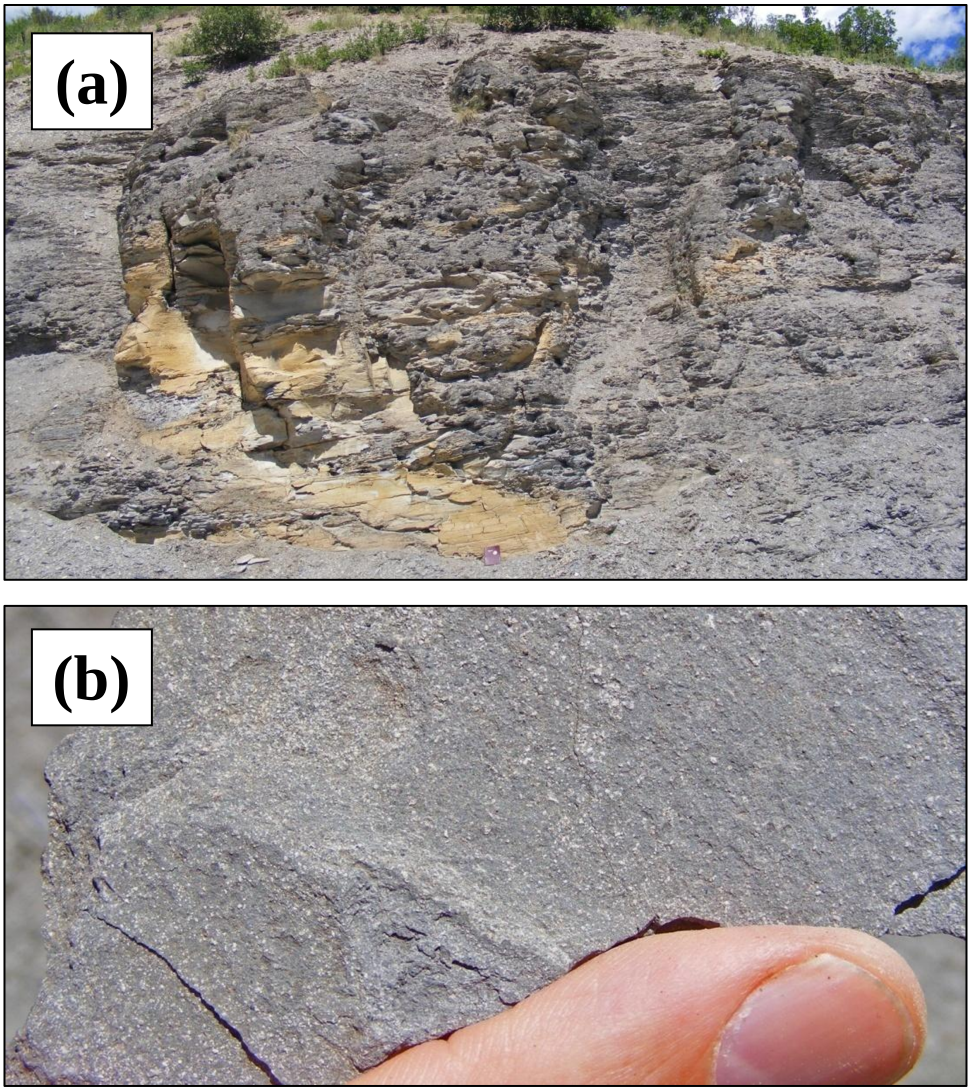


Figure 18. Smoky Hill Member of Mancos Shale (**Kms**) along the County Road 55.
(a) Outcrop in road cut showing gently dipping, calcareous shale. The light-orange patches at left are weathered fracture planes. [UTMX: 305449, UTMY: 4457932]
(b) Hand sample showing white-speckled bedding plane in a chip of calcareous shale. Closer inspection reveals the specks to be flattened and broken, calcareous coccolith shells.

Kml **Mancos Shale, lower part of main body** — This interval contains black shale and minor sandstone. It includes the upper Carlile, Frontier, and Mowry Members. Thickness: 700 ft.

OLDER SEDIMENTARY AND BASEMENT ROCKS

Approximately 2,500 to 3,500 ft of older sedimentary formations underlie the Mancos Shale in the vicinity of the Hayden Gulch quadrangle (RMAG Research Committee, 1977). Only the uppermost part of this interval is shown on the geologic cross sections as an undivided unit, "Older sedimentary rocks." It includes, from youngest to oldest, the Dakota and Lakota/Cedar Mountain Formations (Cretaceous); Morrison, Curtis, and Entrada Formations (Jurassic); Chinle, Shinarump, and Moenkopi Formations (Triassic); State Bridge/Park City/Phosphoria Formations (Permian); Weber, Maroon, Morgan, Minturn, Belden, and Molas Formations (Pennsylvanian); Madison/ Leadville Limestone (Mississippian); Dyer and Parting Formations (Devonian); Manitou Formation (Ordovician); and Dotsero and Ladore Formations (Cambrian) (Tremain Ambrose, 1998; New Mexico Bureau of Mines and Mineral Resources, 1993). The Paleozoic part of the section thins eastward; the Mississippian to Cambrian section may be missing in an unconformity at the top of the Precambrian basement rocks (RMAG Research Committee, 1977).

As inferred from the statewide map of Sims and others (2001), the Precambrian basement rock in the vicinity of the quadrangle consists of Uinta Mountain Group sedimentary and metasedimentary rocks (Mesoproterozoic) in the northern part and felsic and hornblende gneiss (Paleoproterozoic) in the southern part.

STRUCTURAL GEOLOGY

The Hayden Gulch quadrangle lies within the southeastern part of the Wyoming basin physiographic province (Fenneman and Johnson, 1946). It lies at the southeastern margin of the Sand Wash geologic basin. The Sand Wash basin is bordered by Precambrian basement-cored uplifts to the east (Park Range) and to the south (White River Plateau). The southeastern margin of the basin contains a series of ridges and valleys that mark the locations of tightly folded anticlines and synclines, interspersed with tilted basement-block ranges at the margins of the bordering uplifts. The basin formed during the Laramide orogeny, in Late Cretaceous to Eocene time (Tweto, 1977; Finn and Johnson, 2005). Later, during the Oligocene, Miocene and Pliocene Epochs, rifting, block faulting, and basaltic volcanism related to crustal extension occurred in central Colorado (Tweto, 1976; 1977). The study area contains north-west-southeast trending normal faults that may be related to this episode of extension.

We investigated the structure in the Hayden Gulch quadrangle as part of a regional structural-geology study of the Williams Fork Mountains (Colorado Geological Survey, 2010, unpublished data). A summary of our observations is shown in **Figure 19**. The figure shows folds and faults within and in the vicinity of the quadrangle. It also shows general bedding-strike orientation fields based on over 100 individual strike-and-dip readings. The primary structural feature in the western 2/3 of the quadrangle is the tilted bedrock block that forms the Williams Fork Mountains. In the Hayden Gulch quadrangle, the bedrock in the Williams Fork Mountains generally dips to the northeast at low angles (7° to 14°). We assume that this mirrors the upper surface of the underlying basement-rock block. Slight variations in strike/dip domains were noted. The variations may be due to basement sub-blocks having slightly different orientations. We map these as minor anticlines and synclines at the domain boundaries. They have axes that are oriented roughly perpendicular to the regional bedrock strike direction. In accordance with previous authors (Tweto, 1977; Finn and Johnson, 2005), we interpret the Williams Fork Mountains structural block to be a Laramide feature.

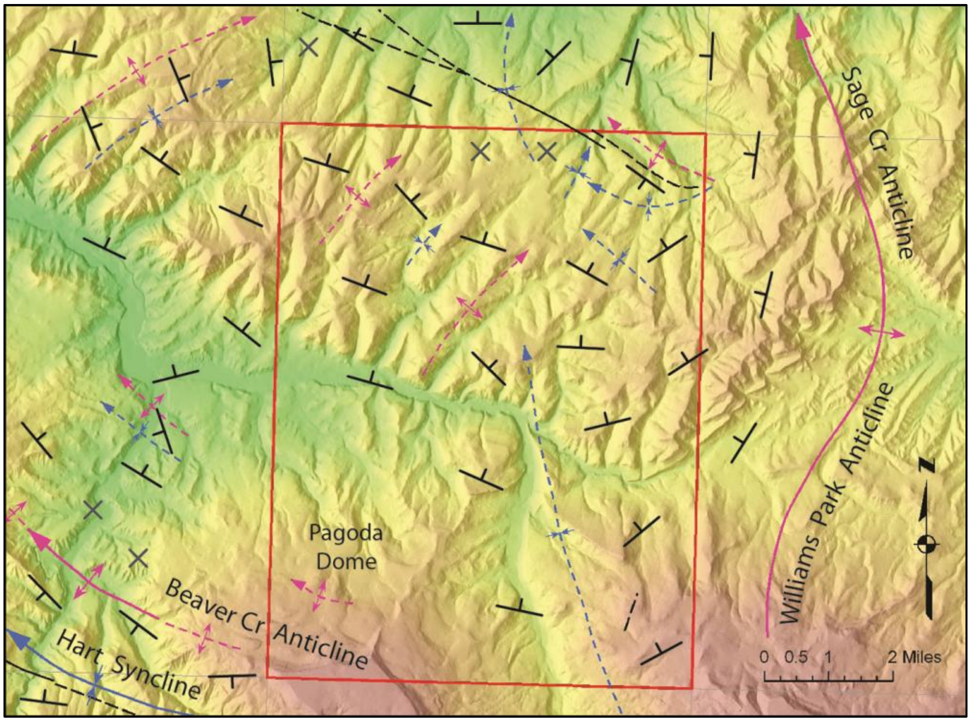


Figure 19. Shaded relief map showing structural elements in the Hayden Gulch quadrangle. Major folds shown as solid pink (anticlines) or blue (synclines); minor or concealed major folds shown as dashed pink or blue lines. Faults shown as black solid (certain) or dashed (inferred) lines. Strike/dip symbols show generalized strike-field orientations based on local bedding-surface readings. "X" symbols denote areas of unorganized structure having differing strikes in local bedding-surface readings.

At the eastern end of the quadrangle, the Williams Fork Mountains block merges with a major Laramide fold, the Sage Creek/Williams Park anticline (Crawford and others, 1920; Coffin and others, 1924; Bass and others, 1955; Severy, 1955). That fold is curvilinear and its axis is oriented in a general north-south direction. It has a very steep eastern limb. We measured low bedding dips (9° to 20°) on the gentle, west-dipping, western limb of the anticline. There is a bend of over 90° at the juncture of the Williams Fork Mountains block and the Sage Creek/Williams Park anticline. The re-orientation of Mesaverde strata across this juncture is seen in map view as a broad fold within most of the eastern 1/3 of the quadrangle (**Figure 19**). We map minor synclines in this area that separate different dip domains. This indicates that the folding may involve several, progressively reoriented basement sub-blocks.

In the northeastern corner of the quadrangle, where those two structural elements are folded together most tightly, there is a small structural basin. It features a zone of bedrock that dips to the southwest (4° to 22°) against the regional structural dip. The zone is bounded by a minor anticline and syncline pair with northwest-southeast orientation (**Figure 19**). We interpret that the basement blocks in this area were "popped down" relative to surrounding blocks due to lack of space at the tightest portion of the fold between the structures.

Pagoda dome, in the southwest corner of the quadrangle, underlies mostly landslide-covered terrain. Mobil Oil Company (1961) maps the structure as having 500 ft of closure. They and Masters (1965) project the axis to the northwest, toward a minor anticline (**Figure 19**). In contrast, Bass and others (1955) and Tweto (1976) project the axis to the southwest and join it with the major Beaver Creek anticline. In our regional structural study (Colorado Geological Survey, 2010, unpublished data), we found no conclusive surface evidence of a Pagoda dome and Beaver Creek anticline connection. Nor could we find evidence of an anticlinal axis to the east of the dome, within the north-south oriented reach of the East Fork Williams Fork River valley.

Surface faulting is rare in the Hayden Gulch quadrangle. We spotted offset bedding and calcite-filled fault planes at a few locations, but thick vegetation cover hindered extrapolation of the faults. The most continuous fault zone enters the quadrangle in the northeastern corner. It is part of a series of steep, down-to-basin faults along the margin of the Sand Wash Basin. The faults have a northwest-southeast orientation. In rare exposures, they cut cleanly through the Cretaceous sedimentary strata. Large-scale folding is absent. Tyler and Tremain (1994) describe the faults as Miocene to Pliocene in age. The faults display normal movement with indications of left-lateral, strike-slip movement (Tyler and Tremain). They are related to a left-oblique, extensional tectonic regime that existed during rifting (Chapin and Cather, 1994). Tertiary normal faults mapped within the quadrangle have offsets of 50 ft or less.

MINERAL RESOURCES

The Hayden Gulch quadrangle contains coal, oil-and-gas, and sand-and-gravel resources. The following paragraphs summarize historical and current production activities for those mineral resources.

Coal. The quadrangle lies within the Yampa coal field. Coal-bearing, Upper Cretaceous strata of the Iles and Williams Fork Formations were studied in detail over nearly 100 years. Reports and maps that consider coal resources in the Hayden Gulch area include those by Fenneman and Gale, (1906); Bass and others (1955); Dames and Moore (1979); and Johnson and others (2000). There are three productive coal zones or groups, the upper, middle, and lower (**Table 1**).

Table 1. Coal zones of the Yampa coal field, Mesaverde Group, Hayden Gulch quadrangle.

Formation	Coal Zones	Coal Beds	Primary Coal Mines
Upper Williams Fork (**Kwu**)	Upper coal group	Dry Creek, Sleepy Cat, K-S	Hayden Gulch
Lower Williams Fork (**Kwl**)	Middle coal group	F-J	Big Elk (planned)
Iles (**Ki**)	Lower coal group	Sun, Rice, A-E	Sun, Rice Pinnacle
Coal zone and bed terminology from Bass and others (1955)			

The extent of historic coal mining in the quadrangle, along with the names of the prominent mines, is shown in **Figure 20**. The Sun and Rice Pinnacle mines produced small amounts of coal from the lower coal group. The largest historic mine is the Hayden Gulch, a surface strip mine that produced from the upper coal group. The mines are closed and the Hayden Gulch mine has undergone surface reclamation. Future coal mining is in the works for the northern part of the quadrangle. Peabody Energy's Big Elk mine project is in the planning and permitting stage (R. Thompson, senior geologist, Peabody Energy, personal communication, 2010). Here, the feasibility for large-scale coal mining hinges on having large acreage and a relatively continuous, underground coal seam to mine. The Big Elk mine would be a longwall operation similar to Peabody's record-breaking Foidel Creek coal mine. The planned portal facility would be located in a side gulch to Hayden Gulch.

Oil and gas. A single gas field, Pagoda, is located in the southwestern part of the quadrangle (**Figure 21**). The field occupies the crest of Pagoda dome. It was discovered in 1948 and consisted of two producing gas wells. According to Mobil Oil Company (1961), the field produced from the Upper Triassic Shinarump Member of the Chinle Formation. They infer that there may be a pinch-out of porosity in the reservoir, as well. The gas zone thickness was 30 ft, although the dome has 500 ft of structural closure. Our **Cross Section A-A'** (**Plate 2**) crosses the eastern flank of Pagoda dome.

Early petroleum-prospecting studies in the region focused on structural anticlines and domes (e.g., Crawford and others, 1920; Coffin and others, 1924). Later studies integrated regional subsurface and surface stratigraphy, outcrop-facies relationships, and source and reservoir rock characterization (for example, Kiteley, 1983; Kiteley and Field, 1984; Siepman, 1985, 1986; Roehler, 1990; Benda, 2000; U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005; Gomez-Veroiza and Steel, 2010). Cummings and Potts (1962) and Vincelette and Foster (1992) established the importance of natural fractures and shear zones in the region, particularly those associated with Tertiary extensional tectonics, in enhancing shale-hydrocarbon accumulations.

There is currently oil-and-gas exploration activity in this part of northwestern Colorado. The main play involves the Niobrara-equivalent interval of the Mancos Shale. Horizontal drilling is being used to test calcareous, brittle, fractured Niobrara strata. In addition to the Niobrara, historical drilling targets in the region include the Dakota Sandstone, Salt Wash Member of the Morrison Formation, Entrada Sandstone, Shinarump Conglomerate, and Weber Formation (Dahm and others, 1955; Tremain Ambrose, 1998). The potential for new oil-and-gas discoveries in the Hayden Gulch quadrangle is not known. Exploration would involve new drilling and completion technologies. It is likely that new target areas were overlooked by earlier, conventional exploration programs.

Construction aggregates (gravel, sand, and crushed rock). Clinker and sandstone were produced from small quarries to the north of Hayden divide and in Hayden and Dunstan Gulches (Schwochow, 1981; Keller and others, 2002; Guilinger and Keller, 2004). The southern and central parts of the quadrangle contain a variety of gravel deposits (units **Qa** and **Qg**). To date, no commercial gravel-extraction operations exist. A few miles to the west of the quadrangle, a commercial pit produces from a low **Qg** gravel terrace above the South Fork Williams Fork River.

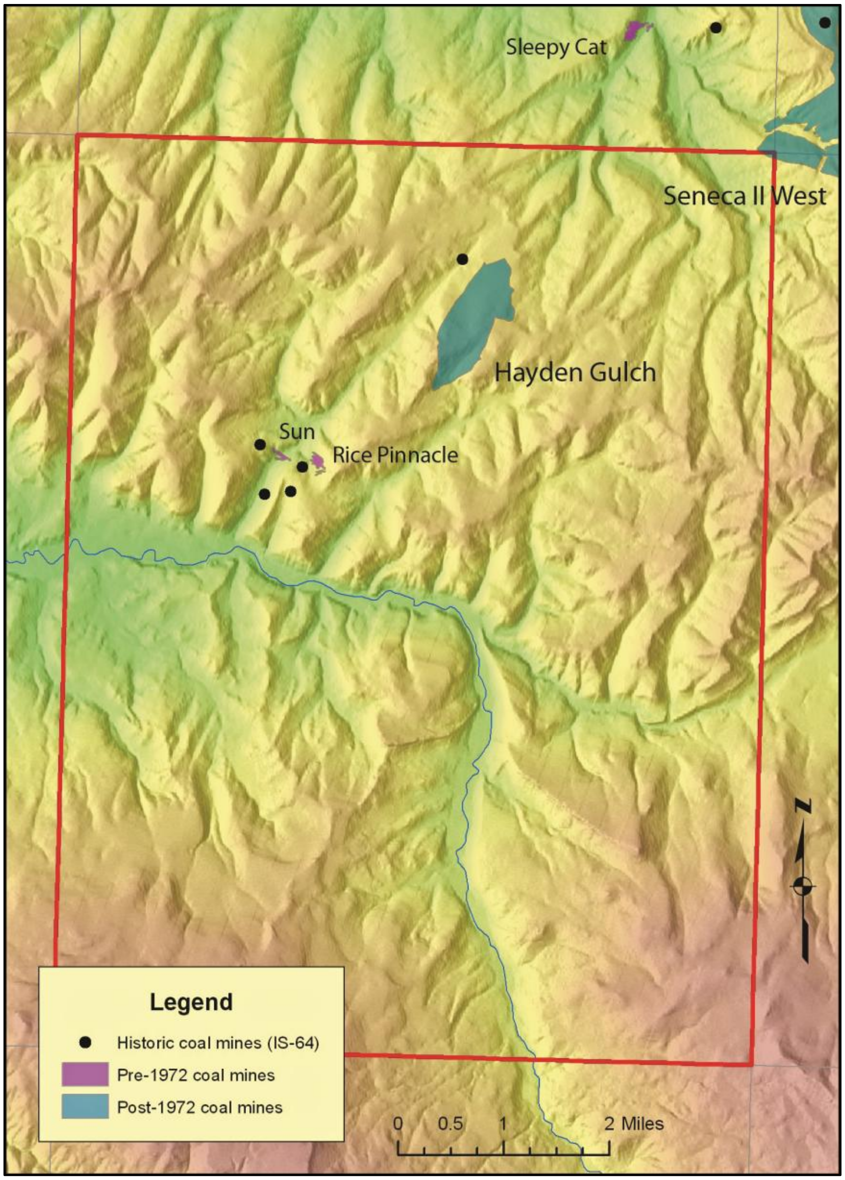


Figure 20. Shaded relief map showing coal mines in the Hayden Gulch quadrangle.
Black dots are historic (1864 to 2002) coal mines (Carroll and Bauer, 2002). Colored polygons show the extent of underground (light pink) and surface-strip (dark pink) coal mining (Keller and others, 2002). The proposed Big Elk underground coal mine would extend beneath the north-central part of the quadrangle. Its portal would be located in the gulch that curves northward above the "Sun" label.

GROUND-WATER RESOURCES

There are 16 ground-water wells in the Hayden Gulch quadrangle. They are permitted for stock, domestic, and industrial uses. The wells are scattered along the East Fork Williams Fork River, in some of the gulches in the Williams Fork Mountains, and on the upper slope of Dunckley Flat Tops. The primary sources are Quaternary alluvium or Cretaceous strata.

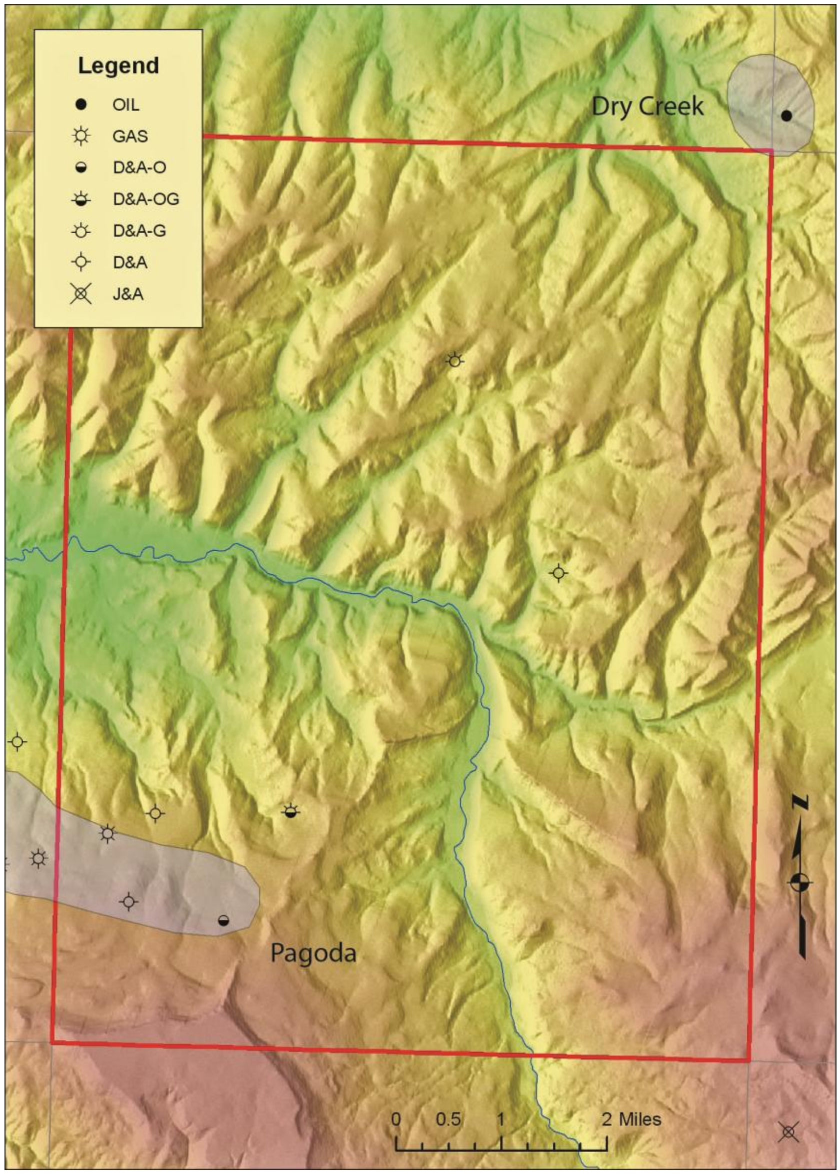


Figure 21. Shaded relief map showing oil and gas fields and wells in the Hayden Gulch quadrangle. Well data from Colorado Oil and Gas Conservation Commission (2007). Field boundaries from Wray and others (2005).

We examined GIS data from the Colorado Division of Water Resources to find the location, depth, and pump rate of ground-water wells in the quadrangle. The data show that about half of the wells are 100 to 400 ft deep. Shallower wells of less than 50 ft deep are found along the main stream flood plains. Reported pump rates range from 2 to 35 gpm.

Robson and Stewart (1990) identify the Twentymile and Trout Creek Sandstones (units **Kwt** and **Kit**) as major regional aquifers in the Sand Wash Basin region. Additionally, they found that sandstone and coal beds in the lower part of the Williams Fork Formation (unit **Kwl**; coincident with the middle coal group) constitute a significant aquifer of local extent. They report the average hydraulic conductivity of the local aquifer as being 20 times greater than that of the regional aquifers. Its mean transmissivity is 20 ft^2/day, superior to that of the Twentymile (4 ft^2/day) and Trout Creek (0.6 ft^2/day) aquifers. They attribute the greater water-yield potential of the local aquifer to the presence of fractured coal seams.

GEOLOGIC HAZARDS

We recognize several potential geologic hazards in the Hayden Gulch quadrangle. The hazards arise when naturally occurring geologic processes affect constructed facilities such as buildings and roads. Human 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.

Landslides (unit **Qls**) of many types and sizes are common within the quadrangle. Many are older features with movements dating to the late Pleistocene ice ages. Landslides are meta stable features. Modifications to the hill slope, such as removal of materials, loading, or changing the ground-water levels and pore pressures could reinitiate landslide movements. New landslides can be triggered by such activities as excavation of roads, pipelines, or borrow material. Potential landslide areas should be avoided where possible, or site should undergo proper geotechnical engineering investigations and mitigation. Mitigation may be expensive, but not nearly as much as the costs of damage and repairs to existing structures and facilities as a consequence of new or reinitiated landslide movements.

Stream flooding hazards and associated high water tables exist within the modern stream flood plains (unit **Qa**) and the valleys of tributary streams (unit **Qac**). In addition to annual snow melt, flooding along the through-flowing main streams and tributary streams may be initiated by occasional large rain fall events. Residences and critical facilities in those areas should be avoided.

Debris flow (also known as **mud flow**) hazards occur in hilly areas along confined stream reaches (unit **Qac**) and in alluvial fans (unit **Qf**). These flows are produced by large rain fall 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 flows present life-and-limb safety hazards, and they can cause damage to roads and buildings. Much of the hilly terrain in the Hayden Gulch quadrangle has the potential to generate debris flows. All areas meeting the above descriptions should be considered at risk, and construction in those areas should be avoided.

Rock fall hazards are prevalent at the toes of slopes that are capped with sandstone or basalt rim rock. The size of the falling blocks is a function of bedding thickness, fracture spacing, and exposure of the slope to ground-water seepage and freeze-thaw processes. Large precipitation events may trigger rock falls, as well. We observed several boulder-sized, angular blocks of sandstone up to 20 ft in diameter at the edge of agricultural fields below the Tow Creek Sandstone (**Figure 22**). The best mitigation is to avoid rock-fall slopes and roll-out zones.

Figure 22. Fallen blocks of Tow Creek Sandstone near the mouth of Hayden Gulch.
These sandstone blocks are up to 20 ft in long dimension. They came to rest on a colluvial deposit at the base of a slope after falling and rolling. The source cliffs are about 400 ft away and 400 ft higher (to right). **Figure 15** shows source cliffs in a similar setting. [UTMX: 300463, UTMY: 4465926]

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 matrices and the clay particles swell to accommodate the added water molecules (Noe, 2007). The resultant ground heaving may cause damage to buildings, roads, and underground utilities and pipelines. Upon drying, the clay particles lose water and shrink. This shrink-swell behavior may continue over numerous wetting and drying cycles. Potentially expansive soil and bedrock is found in the main bodies of Lewis and Mancos Shales (units **Klsl** and **Kmu**), in tongues of marine shale and continental-shale beds in the Mesaverde Group (units **Kwu**, **Klst**, **Kwl**, **Kmt**, and **Ki**), and in clay-rich surficial units derived from those shales. 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 and alluvial fans (units **Qac**, **Qf**, and **Qfo**). Collapsible soil also occurs in eolian deposits that sometimes overlie alluvial terraces. 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. No historical earthquakes are shown within the quadrangle in the CGS Colorado earthquake map server (Kirkham and others, 2004). An intensity V earthquake occurred in 1895 in the Yampa River valley (Hadsell, 1968). It was felt from south of Steamboat Springs to Hayden, and jarred windows, dishes, and spoons. The epicenter was near Mount Harris, about 8 miles to the northeast of Hayden Gulch quadrangle. Other notable earthquakes in the region include an intensity VI event in 1955, near today's Stagecoach Reservoir, and a magnitude 4.4 event in 1971, near the town of Clark. At least eight tremors of less than magnitude 2.0 are mapped in the Clark and Steamboat-Stagecoach areas.

ACKNOWLEDGMENTS

The authors offer sincere thanks to the following landowners who granted us access to their properties: Bernard Peterson (Cross Mountain Ranch); Mike Patterson and Mike Cosby (Beaver Valley Ranch); Dave and Kathy Smith; Jerry and Judy Green; Jim Floyd; Ted Myers; and Tim Gibson (Terrill's Cabin). Roy Karo (Peabody Energy) granted us access to the Big Elk mine-permit property.

We wish to thank the following colleagues for their assistance: Rocky Thompson and Scott Cowman (Peabody Energy) provided background GIS materials and generously shared previous mapping and their knowledge of the area. Jeff Crabaugh (ExxonMobil Production) reviewed the map and authors' notes. Bill Cobban and Irek Walaszcyk (USGS) provided identification of marine invertebrate fossils that we collected. Phyllis Scott (Scott Geological Consultants) generated electric logs and correlations of oil-and-gas wells in the area. Pilot John Witte (Zephyr Helicopter Company) facilitated our helicopter over-flight of the area. Andres Aslan (Mesa State College) provided new basalt age dates. Louise Kiteley (Colorado School of Mines) showed us key Upper Cretaceous outcrops in the region. Karen Morgan (CGS) provided GIS and cartographic support for the map plates. Larry Scott (CGS) provided the **Figure 1** index map and publication assistance. Finally, Dave wishes to thank Mike Zawaski, Zach Logan, and Dan Hosler for their work on this project as summer field assistants for CGS. I greatly appreciated their enthusiasm, curiosity, and uncanny ability to both encounter and avoid rattlesnakes at close quarters!

REFERENCES CITED

Bader, J.W., Gill, J.R., Cobban, W.A., and Law, B.E., 1983, Biostratigraphic correlation of some Upper Cretaceous rocks from the Lost Soldier area, Wyoming, to west of Craig, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1548, 1 plate.

Bass, N.W., Eby, J.B., and Campbell, M.R., 1955, Geology and mineral fuels of parts of Routt and Moffat Counties, Colorado: U.S. Geological Survey Bulletin 1027-D, 260 p., 1 map plate, scale 1:62,500.

Benda, T.L., 2000, Facies, architecture, and sequence stratigraphy of a fourth-order clastic wedge – Upper Cretaceous Twentymile Sandstone (Mesaverde Group), northwest Colorado: University of Wyoming, Master's Thesis, 138 p.

Boyles, J.M., 1983, Depositional history and sedimentology of Upper Cretaceous Mancos Shale and lower Mesaverde Group, northwestern Colorado - migrating shelf-bar and wave-dominated shoreface deposits: unpublished Ph.D. thesis, University of Texas at Austin, 270 p.

Boyles, J.M., Kauffman, E.G., Kiteley, L.W., and Scott, A.J., 1981, Depositional systems, Upper Cretaceous Mancos Shale and Mesaverde Group, northwestern Colorado: Society of Economic Geologists and Mineralogists, Rocky Mountain Section, 1981 Fall Field Trip Guidebook, 145 p.

Brownfield, M.E., and Johnson, E.A., 2008, The Yampa Bed—a regionally extensive tonstein in the Williams Fork Formation, northwestern Piceance Creek and southern Sand Wash Basins: U.S. Geological Survey Scientific Investigations Report 2008–5033, 32 p.

Brownfield, M.E., Johnson, E.A., Affolter, R.H., and Barker, C.E., 1999, Coal mining in the 21st Century – Yampa coal field, northwest Colorado, in Lageson, D.R., Lester, A.P., and Trudgill, B.D., eds., Colorado and adjacent areas: Boulder, Geological Society of America Field Guide 1, p. 115-133,

Carroll, C.J., and Bauer, M.A., 2002, Historic coal mines of Colorado, 2005: Colorado Geological Survey Information Series 64, CD-ROM.

Chapin, C.E., and Cather, S.M., 1994, Tectonic setting of the axial basins of the northern and central Rio Grande rift, in Keller, G.R., and Cather, S.M., Basins of the Rio Grande rift – structure, stratigraphy, and tectonic setting: Geological Society of America Special Paper 291, p. 3-25.

Cobban, W.A., Walaszczyk, I., Obradovich, J.D., and McKinney, K.C., 2006, A USGS zonal table for the Upper Cretaceous Middle Cenomanian-Maastrichtian of the Western Interior of the United States based on ammonites, inoceramids, and radiometric ages: U.S. Geological Survey Open-File Report 2006-1250.

Coffin, R.C., Perini, V.C., Jr., and Collins, M.J., 1924, Some anticlines of western Colorado: Colorado Geological Survey Bulletin 24, 68 p., 3 map plates, various scales.

Cole, R.D., Young, R.G., and Willis, G.C., 1997, The Prairie Canyon Member, and new unit of the Upper Cretaceous Mancos Shale, west-central Colorado and east-central Utah: Utah Geological Survey Miscellaneous Publication 97-4, 23 p.

Colorado Oil and Gas Conservation Commission, 2007, Well locations GIS downloads, NAD83 datum: http://oil-gas.state.co.us/. [Accessed 1/12/07]

Colorado State Board of Land Commissioners, 2009, Annual report, fiscal year 2008-09: trustlands.state.co.us/Documents\. [Accessed 3/4/11]

Crabaugh, J.P., 2001, Nature and growth of nonmarine-to-marine clastic wedges – examples from the Upper Cretaceous Iles Formation, Western Interior (Colorado) and the lower Paleogene Wilcox Group of the Gulf of Mexico (Texas): unpublished Ph.D. thesis, University of Wyoming, Laramie, 235 p.

Crawford, R.D., Willson, K.M., and Perini, V.C., 1920, Some anticlines of Routt County, Colorado: Colorado Geological Survey Bulletin 23, 59 p., 3 map plates, various scales.

Cummings, K.F., and Pott, R.L., 1962, South Craig area, Routt, Moffat, Garfield, and Rio Blanco Counties, Colorado, in Amuedo, C.L., and Mott, M.R., eds., Exploration for oil and gas in northwestern Colorado: Rocky Mountain Association of Geologists, Denver, p. 84-86, 2 map plates.

Dahm, J.N., White, C.E., and others, 1955, Penetration chart of oil and gas fields in northwestern Colorado and adjacent Wyoming, *in* Ritzma, H.R., and Oriel, S.S., eds., Guidebook to the geology of northwest Colorado: Rocky Mountain Association of Geologists, Denver, plate in pocket.

Dames and Moore, 1979, Coal resource occurrence and coal development potential maps of the Hayden Gulch quadrangle, Routt County, Colorado: U.S. Geological Survey Open-File Report 79-1395, 35 p., map plates, scale 1:24,000.

Dyni, J.R., and Cullins, H.L., 1965, Meeker and Loyd Sandstone Members of the Mancos Shale, Moffat and Rio Blanco Counties, Colorado: U.S. Geological Survey Bulletin 1194-J, p. J1-J7.

Fenneman, M.N., and Gale, H.S., 1906, The Yampa coal field, Routt County, Colorado: U.S. Geological Survey Bulletin 297, 96 p., 1 map plate, scale 1:125,000.

Fenneman, M.N., and Johnson, D.W., 1946, Physiographic divisions of the conterminous U. S.: U.S. Geological Survey Special Map Series, scale 1:7,000,000.

Finn, T.M., and Johnson, R.C., 2005, Niobrara total petroleum system in the Southwestern Wyoming province; Chapter 6 *in* U.S. Geological Survey Southwestern Wyoming Province Assessment Team, Petroleum systems and geologic assessment of oil and gas in the southwestern Wyoming province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series DDS-69-D, on CD-ROM.

Geological Society of America, 1991, Rock color chart with genuine Munsell color chips, 7th printing: Boulder, Colo., Geological Society of America.

Gill, J.R., and Hail, W.J., Jr., 1975, Stratigraphic sections across Upper Cretaceous Mancos Shale-Mesaverde Group boundary, eastern Utah and western Colorado: U.S. Geological Survey Oil and Gas Investigations Chart OC-68, 1 plate.

Gomez-Veroiza, C.A., and Steel, R.J., 2010, Iles clastic wedge development and sediment partitioning within a 300-km fluvial to marine Campanian transect (3 m.y.), Western Interior seaway, southwestern Wyoming and northern Colorado: American Assoc. of Petroleum Geologists, AAPG Bulletin, v. 94, no. 9, p. 1349-1377.

GretagMacbeth, 2000, Munsell soil color charts, year 2000 revised washable edition: New Windsor, N.Y., GretagMacbeth.

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

Hadsel, F.A., 1968, History of earthquake activity in Colorado, *in* Hollister, J.C., and Weimer, R.J., eds., Geophysical and geological studies of the relationship between the Denver earthquakes and the Rocky Mountain Arsenal well: Colorado School of Mines Quarterly, v. 63, no. 1, p. 57-72.

Hampson, G.J., Procter, P.M., and Kelly, C., 2008, Controls on isolated shallow-marine sandstone deposition and shelf construction, Late Cretaceous Western Interior Seaway, northern Utah and Colorado, in Hampson, G.J., Steel, R.J., Burgess, P.M., and Dalrymple, R.W., Recent advances in models of siliciclastic, shallow-marine stratigraphy: Society for Sedimentary Geology, SEPM Special Publication 90, p. 355-389.

Hancock, E.T., 1925, Geology and coal resources of the Axial and Monument Butte quadrangles, Moffat County, Colorado: U.S. Geological Survey Bulletin 757, 134 p., 1 map plate, scale 1:62,500.

Hayden, F.V., 1877, North-western Colorado and part of Utah, in Hayden, F.V., U.S. Geologist in Charge, Geological and geographical atlas of Colorado and portions of adjacent states: Department of the Interior, United States Geological and Geographical Surveys of the Territories, Sheet XI, scale 1:235,440.

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

International Commission on Stratigraphy, 2010, International stratigraphic chart: www.stratigraphy.org/cheu.pdf. [Accessed 12/28/10]

Izett, G.A., Denson, N.M., and Obradovich, J.D., 1970, K-Ar age of the lower part of the Browns Park Formation, northwestern Colorado: U.S. Geological Survey Professional Paper 700-C, p. C150-C152.

Izett, G.A., Cobban, W.A., and Gill, J.R., 1971, The Pierre Shale near Kremmling, Colorado, and its correlation to the east and west: U.S. Geological Survey Professional Paper 684-A, p. A1-A19.

Johnson, E.A., Roberts, L.N.R., Brownfield, M.E., and Mercier, T.J., 2000, Geology and resource assessment of the middle and upper coal groups in the Yampa coal field, northwestern Colorado, *in* Kirschbaum, M.A., Roberts, L.N.R., and Biewick, L.R.H., eds., Geologic assessment of coal in the Colorado Plateau, Arizona, Colorado, New Mexico, and Utah: U.S. Geological Survey Professional Paper 1625-B, Chapter P, 45 p., on CD-ROM.

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

Kirkham, R.M., Rogers, W.P., Powell, L., Morgan, M.L., Matthews, V., and Pattyn, G.R., 2004, Colorado Earthquake Map Server: Colorado Geological Survey Bulletin 52b, http://geosurvey.state.co.us/hazards/Earthquakes/Pages/Maps.aspx. [accessed 3/16/11]

Kiteley, L.W., 1983, Paleogeography and eustatic-tectonic model of Late Campanian Cretaceous sedimentation, southwestern Wyoming and northwestern Colorado, in Reynolds, M.W., and Dolly, E.D., eds., Mesozoic paleogeography of the west-central United States: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists Symposium 2, p. 273-303.

Kiteley, L.W., and Field, M.E., 1984, Shallow marine depositional environments in the Upper Cretaceous of northern Colorado, *in* Tillman, R., and Siemers, C., eds., Siliciclastic shelf sediments: Society of Economic Paleontologists and Mineralogists Special Publication 34, p. 179-204.

Konishi, K., 1959, Upper Cretaceous surface stratigraphy, Axial Basin and Williams Fork area, Moffat and Routt Counties, Colorado, *in* Haun, J.D., and Weimer, R.J., eds., Symposium on Cretaceous rocks of Colorado and adjacent areas: Rocky Mountain Association of Geologists, Eleventh Field Conference, Washakie, Sand Wash, and Piceance Basins, p. 67-73.

Kucera, R.E., 1962, Geology of the Yampa district, northwest Colorado: Ph.D. Dissertation, University of Colorado, Boulder, 675 p., 12 plates.

Kuiper, D.F., and others, 2008, Synchronizing rock clocks of Earth history: Science, v. 320, p. 500-504.

Luft, S.J., 1985, Airfall tuff in the Browns Park Formation, northwestern Colorado and northeastern Utah: The Mountain Geologist, v. 22, no. 3, p. 110-127.

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

Madole, R.F., 1989, Surficial geologic map of the Meeker 30 x 60 minute quadrangle, Garfield, Moffat, Rio Blanco, and Routt Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1823, scale 1:100,000.

Madole, R.F., 1991, Yampa River basin, *in* Reheis, M.C., ed., Quaternary history of some southern and central Rocky Mountain basins, Chapter 14 *of* Morrison, R.B., ed., Quaternary nonglacial geology, conterminous United States: Geological Society of America, Geology of North America, v. K-2, p. 427-432.

Masters, C.D., 1965, Sedimentology of the Mesaverde Group and of the upper part of the Mancos Formation, northwestern Colorado: Ph.D. dissertation, Yale University, New Haven, CT, 88 p.

Masters, C.D., 1967, Use of sedimentary structures in determination of depositional environments, Mesaverde Formation, Williams Fork Mountains, Colorado: American Association of Petroleum Geologists Bulletin, v. 51, no.10, p. 2033-2043.

Mobil Oil Company, 1961, Pagoda field, *in* Parker, J.M., ed., Colorado-Nebraska oil and gas field volume: Rocky Mountain Association of Geologists, Denver, p. 208-209.

Naeser, C.W., Izett, G.A., and Obradovich, J.D., 1970, Fission-track and K-Ar ages of natural glasses: U.S. Geological Survey Bulletin 1489, 31 p.

New Mexico Bureau of Mines and Mineral Resources, 1993, Sheet 2 - Stratigraphic correlation chart of major gas-producing basins and uplifts, in Hjellming, C.A., *ed*., Atlas of major Rocky Mountain gas reservoirs: Colorado Geological Survey Miscellaneous Investigations MI-40, 206 p., 10 plates.

Noe, D.C., 2007, A guide to swelling soil for Colorado homebuyers and homeowners, second edition: Colorado Geological Survey Special Publication 43, 52 p.

Noe, D.C., Busacca, A.J., and Zawaski, M.J., in preparation, Milner quadrangle geologic map, Routt County, Colorado: Colorado Geological Survey, scale 1:24,000.

RMAG Research Committee, 1977, Subsurface cross sections of Colorado: Rocky Mountain Association of Geologists Special Publication No. 2, 39 p., 24 plates

Robson, S.G., and Stewart, M., 1990, Geohydrologic evaluation of the upper part of the Mesaverde Group, northwestern Colorado: U.S. Geological Survey Water-Resource Investigations Report 90-4020, 125 p., 1 map plate, scale 1:62,500.

Roehler, H.W., 1990, Stratigraphy of the Mesaverde Group in the central and eastern greater Green River basin, Wyoming, Colorado, and Utah: U.S. Geological Survey Professional Paper 1508, 52 p.

Schwochow, S.D., 1981, Inventory of nonmetallic mining and processing operations in Colorado: Colorado Geological Survey Map Series 17, 30 p., 17 plates, scale 1:250,000. [Out-of-print publication. A digitally converted report and shapefiles are included in Keller and others (2002).]

Severy, C.L., 1955, Geology of the Williams Park-Fish Creek anticlines, Routt County, Colorado, *in* Ritzma, H.R., and Oriel, S.S., eds., Guidebook to the geology of northwest Colorado: Rocky Mountain Association of Geologists, Denver, p. 117-119.

Siepman, B.R., 1985, Stratigraphy and petroleum potential of Trout Creek and Twentymile Sandstones (Upper Cretaceous), Sand Wash Basin, Colorado: Colorado School of Mines Quarterly, v. 80, no. 2, 59 p.

Siepman, B.R., 1986, Facies relationships in Campanian wave-dominated coastal deposits in Sand Wash Basin, *in* Stone, D.S., ed., New interpretations of northwest Colorado geology: Rocky Mountain Association of Geologists, Denver, p. 157-164.

Sims, P.K., Bankey, V., and Finn, C.A., 2001, Preliminary Precambrian basement map of Colorado - a geologic interpretation of the aeromagnetic anomaly map: U.S. Geological Survey Open-File Report 01-364, digital text and two map plates, no scale given, http://pubs.usgs.gov/of/2001/ofr-01-0364/. [Accessed 12/6/12]

Tremain Ambrose, C.M., 1998, Penetration Charts of selected Colorado oil and gas fields: Colorado Geological Survey Resource Series 34, 5 p., 4 plates.

Tweto, O., 1976, Geologic map of the Craig 1 x 2 degree quadrangle, northwestern Colorado: U.S. Geological Survey, Miscellaneous Investigations Map I-972, scale 1:250,000.

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

Tyler, R., and Tremain, C.M., 1994, Tectonic evolution, stratigraphic setting, and coal fracture patterns of the Sand Wash Basin, *in* Kaiser, W.R., Scott, A.R., Hamilton, D.S., Tyler, R., McMurry, R.G., Zhou, N., and Tremain, C.M., Geologic and hydrologic controls on coalbed methane – Sand Wash Basin, Colorado and Wyoming: Texas Bureau of Economic Geology Report of Investigation 220; Colorado Geological Survey Resource Series 30; Gas Research Institute Topical Report 92/0420, p. 3-19.

U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005, Petroleum systems and geologic assessment of oil and gas in the southwestern Wyoming province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series DDS-69-D, on CD-ROM.

U.S. Geological Survey Geologic Names Committee, 2010, Divisions of geologic time – major chronostratigraphic and geochronologic units: U.S. Geological Survey Fact Sheet 2010-3059, 2 p.

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

Vincelette, R.R., and Foster, N.H., 1992, Fractured Niobrara of northwestern Colorado, in Schmoker, J.W., Coalson, E.B., and Brown, C.W., eds., Geological studies relevant to horizontal drilling in western North America: Rocky Mountain Association of Geologists, Denver, p.227-242.

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

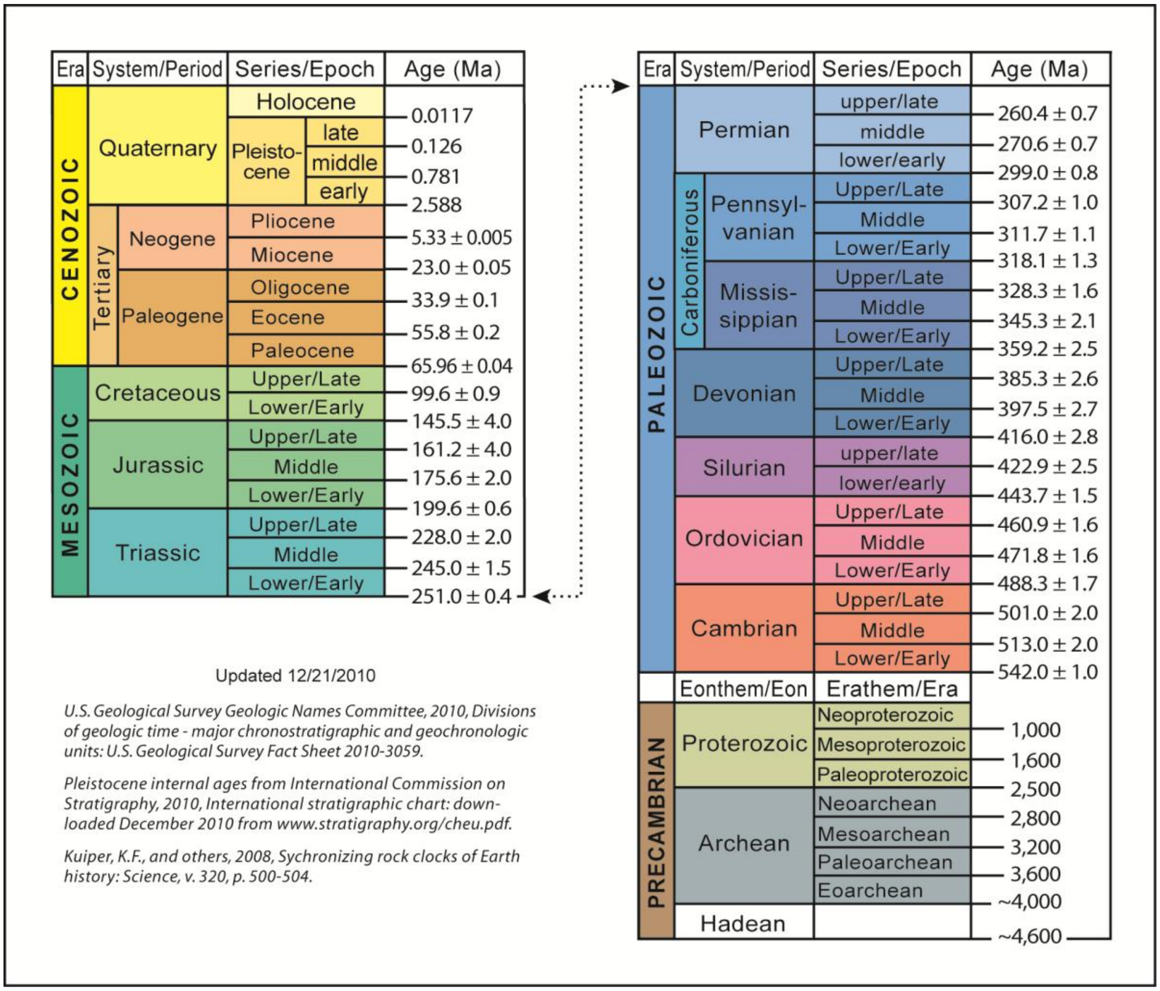
White, J.L., and Greenman, C.A., 2008, Collapsible soils in Colorado: Colorado Geological Survey, Engineering Geology 14, 108 p.

Wray, L.L., Apeland, A.D., Hemborg, H.T., Brchan, C.A., Morgan, M.L., and Young, G.B.C., 2005, Shapefiles for the 2002 oil & gas fields map of Colorado: Colorado Geological Survey Open-File Report OF05-09, CD-ROM.

38

APPENDIX A

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



APPENDIX B

Appendix B. Stratigraphic chart of Upper Cretaceous and Tertiary formations in northwestern Colorado

The schematic stratigraphic chart inserted at the end of this document was compiled by CGS as part of a regional study of the geology of the Williams Fork Mountains and surrounding areas in northwestern Colorado. It contains the basic geologic framework from the seminal, coal-stratigraphic studies of Hancock (1925) and Bass and others (1955), and regional mapping by Tweto (1976). The chart is augmented with information from stratigraphic studies by Boyles and others (1981), Boyles (1983), Kiteley (1983), Brownfield and others (1999), Johnson and others (2000), and Hampson and others (2008).

The chart shows (a) marine sands deposited within the Mancos Shale in the Cretaceous Western Interior Seaway; (b) the progradation of three regressive wedges of continental sediments (Iles and Williams Fork Formations of the Mesaverde Group) into the seaway, with minor marine transgressions; (c) a major transgression and deposition of marine Lewis Shale; (d) final regression and closure of the seaway, and deposition of Fox Hills Sandstone and Lance Formation; (e) deposition of coarse Tertiary deposits during the Laramide and later orogenic episodes; and (f) emplacement of Miocene igneous rocks in underground dikes and sills and as surface volcanic flows.

<u>Explanation</u>:

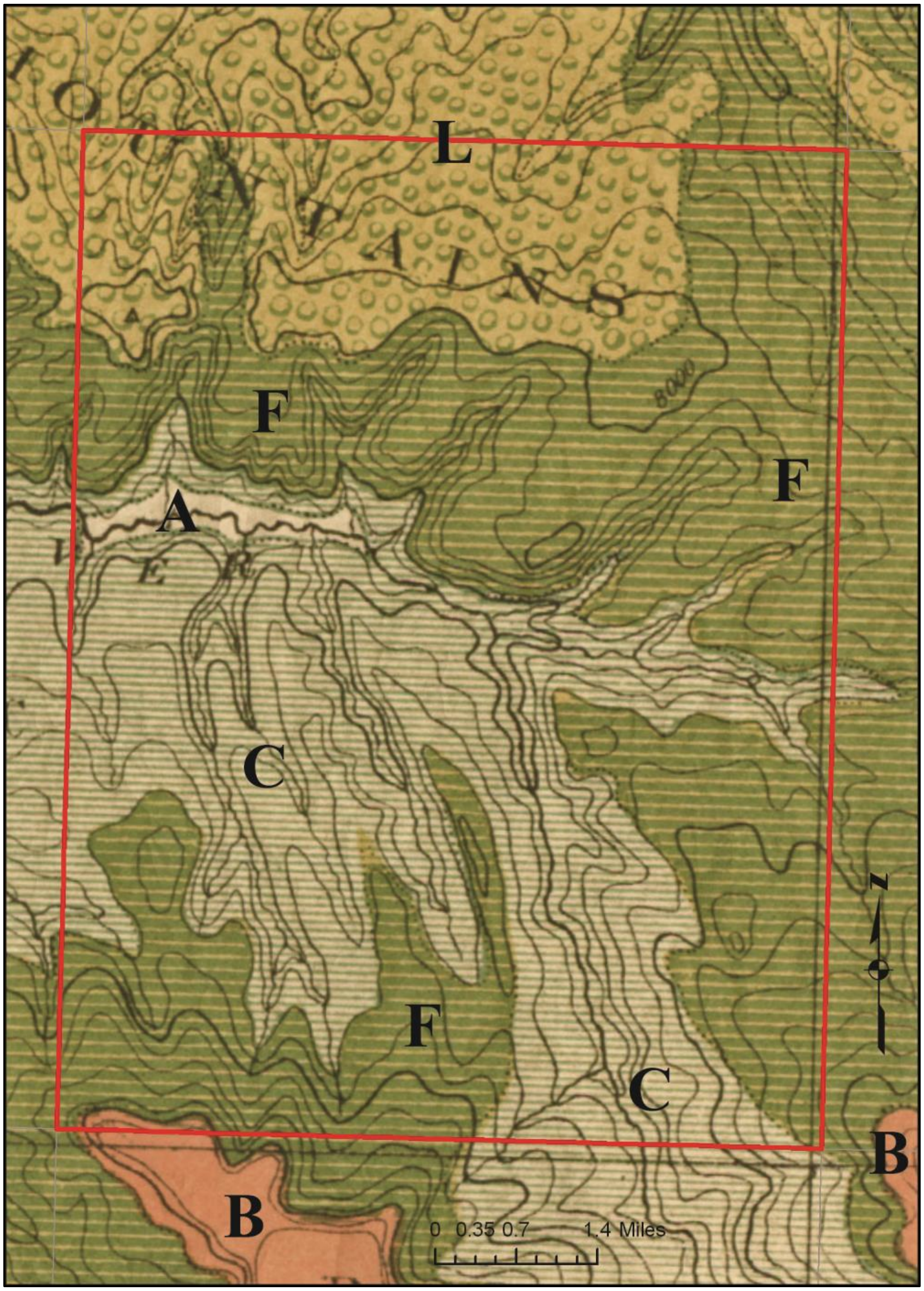
	Section of bedrock units mapped in the Hayden Gulch quadrangle
Kit	Unit abbreviation used for geologic mapping
	Volcanic flows (Tertiary)
	Continental deposits, synorogenic, coarse (Tertiary)
	Continental deposits, sandstone-shale-coal (Upper Cretaceous and Tertiary)
	Shoreline and marine sandstones (Upper Cretaceous)
	Marine shales (Upper Cretaceous)

APPENDIX C

Appendix C. Fossils collected from the Hayden Gulch 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 Hayden Gulch quadrangle by the CGS mapping crew during the 2010 and 2011 field seasons. 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 Hayden Gulch quadrangle map. Drs. William Cobban and Ireneusz Walaszczyk, USGS, provided identification of the fossils species and catalogued the specimens into the CWIS collection.

In addition, where possible, we add fossils collected in the immediate area (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.

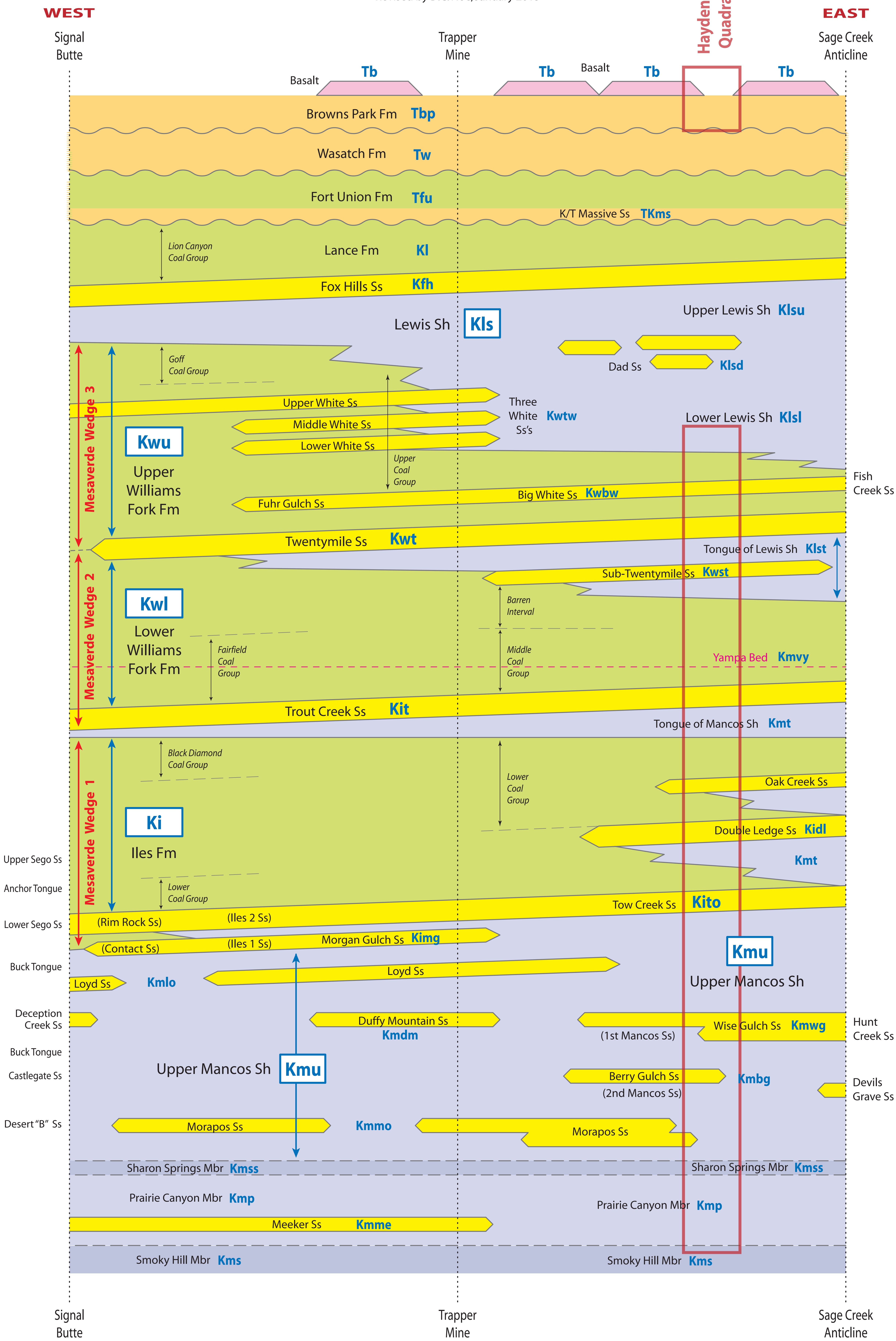


The first geologic map of the Hayden Gulch area, published by F.V. Hayden (1877) at a scale of 1:235,440. Fieldwork for the map was conducted during the 1874 Geological and Geographical Survey of the Territories (a precursor to the U.S. Geological Survey) under Professor Hayden. A portion of the map is shown, with a red box around the Hayden Gulch quadrangle. The map units are as follows:

A = Alluvium (Quaternary)
B = Basalt (Eruptive Rocks)
L = Laramie (Post-Cretaceous)
F = Fox Hills-Fort Pierre (Cretaceous)
C = Colorado (Niobrara-Fort Benton) (Cretaceous)

Upper Cretaceous and Tertiary Stratigraphy, Northwestern Colorado

Compiled by D.C. Noe, P.E. Barkmann, and C.J. Carroll
Colorado Geological Survey, May 2010
Revised by D.C. Noe, January 2013



Sources: Hancock (1925); Bass and others (1955); Konishi (1959); Dyni and Cullins (1965); Masters (1965); Izett and others (1971); Gill and Hail (1975); Bader and others (1983); Boyles and others (1981); Boyles (1983); Kitely (1983); Kiteley and Field (1984); Johnson and others (2000); Crabaugh (2001); Hampson and others (2008); and Brownfield and others (2009)

Appendix C: Fossils Collected From the Hayden Gulch Quadrangle and Vicinity

CGS Locality Number	USGS Locality Number	Fossils Collected and Identified	Ammonite or Mollusc Guide Fossil Zone	Age	Formation or Mancos Shale Member	Quadrangle	County	State	Land Survey Location	UTM83-X	UTM83-Y	Collected by	Date
---	6387	*???*	*Baculites grandis?*	Lower Maastrichtian	Upper Wims Fork Fm	Hayden Gulch	Routt	CO	sw ne sw 20-5N-88W	305574	4471687	Otis Edwards	1909
---	4049	*???*	*Baculites grandis?*	Lower Maastrichtian	Upper Wims Fork Fm	Hayden	Routt	CO	sw sw nw 16-5N-88W	306935	4473748	H.S. Gale, C.W. Harkness	1907
---	4048	*???*	*Baculites reesisei?*	Upper Campanian	Tongue of Lewis Sh	Hayden	Routt	CO	sw ne nw 22-5N-88W	308825	4472434	H.S. Gale, C.W. Harkness	1907
HDG-236	D15232	*Baculites perplexus; Inoceramus* fragments	*Baculites perplexus; Cataceramus subcompressus*	Middle Campanian	Berry Gulch Ss	Hayden Gulch	Routt	CO	e se nw 30-4N-88W	302950	4462564	David C. Noe	10/13/10
HDG-237	D15233	*B. perplexus; B. haresi; Cataceramus subcompressus*	*Baculites perplexus; Cataceramus subcompressus*	Middle Campanian	Berry Gulch Ss	Hayden Gulch	Routt	CO	ne se nw 30-4N-88W	303033	4462621	David C. Noe	10/13/10
HDG-244	D15221	*Baculites perplexus* (early form?); *Inoceramus* fragments	*Baculites perplexus; Cataceramus subcompressus*	Middle Campanian	Berry Gulch Ss	Hayden Gulch	Routt	CO	sw nw ne 29-4N-88W	304690	4463047	David C. Noe	06/26/11

CGS fossil collection identified by W.A. Cobban and E. Walaszcyk, 2/1/2012

Includes collection sites in and within one mile of the Hayden Gulch quadrangle. Sources of information for fossils collected previous to this study include unpublished USGS databases for Denver and Washington D.C. collections.

All GIS locations are reported using Universal Transverse Mercator (UTM), North American Datum 1983, Zone 13N projected coordinates, with units in meters. UTM83-X is the easting value; UTM83-Y is the northing value.

Collections from early 1900s not shown on geologic map; their exact locations could not be verified.