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Meeker Quadrangle Geologic Map, Rio Blanco County, Colorado

Authors' Notes

Includes Description of Map Units, Structural Geology, Geologic Hazards, Mineral Resources, and Ground-Water Resources

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Northward view of the Grand Hogback escarpment with Agency Park to the right. Meeker is on the north bank of the White River shown by the treed areas in the middle right of the photo. Agency Park is underlain by the Mancos Shale. The escarpment is the Iles Formation and the most prominent white line in the hills above is the Trout Creek Sandstone member. The high reddish ridgeline in the middle right of the photo is the Fairfield Coal Group Clinker Zone of the Williams Fork Formation. [UTMX 248757, UTMY 4431928]

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FOREWORD

The purpose of Colorado Geological Survey's (CGS) *Meeker Quadrangle Geologic Map, Rio Blanco County, Colorado,* is to describe the geology, mineral and ground-water resource potential, and geologic hazards of this 7.5-minute quadrangle located in the vicinity of the town of Meeker in northwestern Colorado. CGS staff geologist Jon White and field assistant John Hodge completed the field work on this project at the end of the summer of 2009. Jon White, the principal mapper and author, created this report using field maps, photographs, structural measurements, and field notes generated by both investigators. Signficant knowledge was also gained by a compilation of the available published geologic literature listed in the references.

This mapping project was funded jointly by the U.S. Geological Survey (USGS) and the CGS. USGS funding comes from the STATEMAP component of the National Cooperative Geologic Mapping Program, award number 09AC00192, 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 taxes paid on the production of natural gas, oil, coal, and metals in Colorado.

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INTRODUCTION

The Meeker 7.5-minute quadrangle is located in Rio Blanco County, Colorado, along the valley of the White River **(Figure 1)**. On the north bank of the White River, the Town of Meeker lies along State Highway 13 just southeast of the center of the quadrangle. Meeker is the county seat of Rio Blanco County.

Figure 2 is a false-color shaded relief map that shows the major physiographic and structural features of the Meeker quadrangle. The formal topographic names have also been labeled. The most striking physiographic and structural features are the ridges of the Grand Hogback and the water gap where the White River has incised through them. The highest elevation is in the northeast portion of the quadrangle (8,197 feet) on the highest ridge of the Grand Hogback. The lowest elevation (6,055 feet) occurs on the floor of the White River valley where it exits the quadrangle near the southwestern corner.

Geologic mapping of the Meeker 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). Geologic maps produced by CGS through the program are intended as general-purpose maps that can be used for land-use planning, civil and geotechnical engineering, geologic-hazard assessment, mineral-resource development, and ground-water exploration.

The purpose of the CGS STATEMAP program is to produce 1:24,000-scale geologic maps with approximately equal focus on surficial units, bedrock units, and structural features. The intended benefits of this mapping approach for the Meeker quadrangle include the following:

1. The surficial units were not previously studied or mapped in any detail. The map adds appreciably to understanding the Quaternary geologic history of the area, especially dip-slope failures and landslide deposition along the ridges of the Grand Hogback, tributary valley-fill deposition, and alluvial deposition concurrent with Pleistocene glacial periods and the successive lowering of the White River base level. The map shows the locations of alluvial deposits on the valley floors that may be suitable sources of sand and gravel, as well as potential for shallow ground-water aquifers. Many of the surficial unconsolidated deposits (soils) may be problematic for geotechnical engineering by settling or heaving and may be considered potential geologic hazards.

2. The Meeker quadrangle bridges the available 1:24,000 geologic mapping of the Northern Piceance Basin to the northwest with the mapping of the eastern margin of the basin along the Grand Hogback to the south. Most importantly, it reconciles mapping differences in Tertiary-age and Upper Cretaceous formations and sheds some insight into the initial mountain-building pulse of the early Cenozoic Laramide Orogeny.

3. The bedrock units in this area are well known and extensively studied. The map shows the extent of those bedrock outcrops at a more detailed scale and with more accuracy than

previous maps. In addition, the individual formational members of the Mancos Shale were subdivided and delineated on the map, including several member sandstones not shown in previous mapping.

4. The map shows more bedding strike-and-dip readings and more faulting than previous maps that will improve the understanding of the structural geologic conditions of the area.

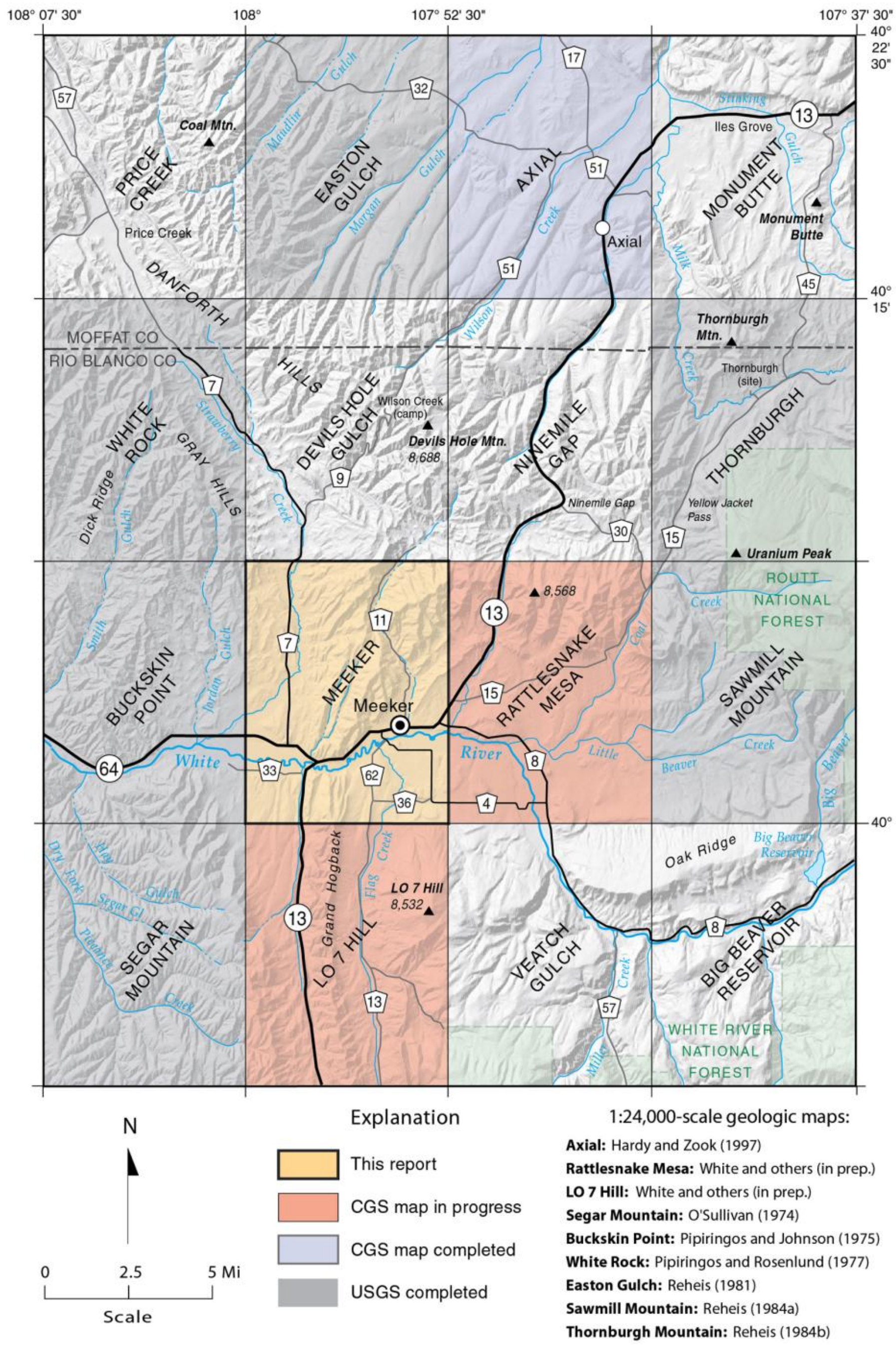

Figure 1. Map key of geologic quadrangles in Meeker area.

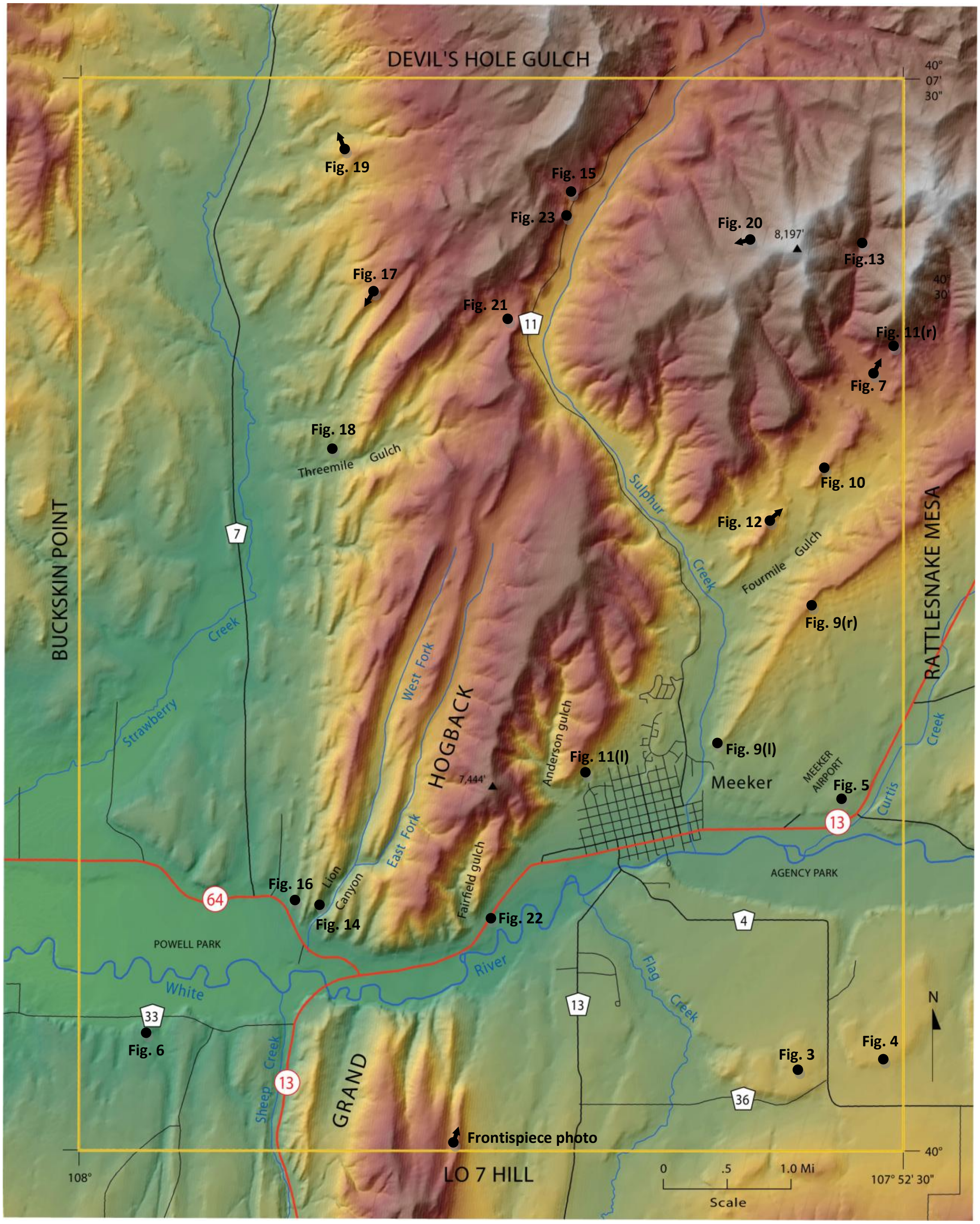

Figure 2. False-color shaded-relief map of the Meeker quadrangle showing major physiographic and topographic features. Figure numbers (l-left, r-right image), if they are photographs, are shown by black dots. Vectors are included if photo is a panoramic view.

PREVIOUS MAPPING STUDIES

The Meeker quadrangle study area is included in a regional geologic map of the Craig 1x2° sheet (Tweto, 1976) at a scale of 1:250,000. Tweto (1976) relied heavily on the earlier work by Hancock and Eby (1930), who produced a seminal geologic map and coal-resources report on the 15-minute (1:62,500 scale) Meeker quadrangle. Murray (1962 and 1966) completed his University of Colorado thesis and dissertation of the stratigraphy and structural geology of the Grand Hogback Monocline. HIs work includes a 1:63,360-scale black-and-white geologic map and cross sections, which included the Meeker area. Madole (1989) mapped the surficial geology of the area at a scale of 1:100,000. **Figure 1** shows the status of 7.5-minute (1:24,000-scale) quadrangle geologic mapping in the area. Three reconnaissance-level preliminary quadrangle maps were completed on the west side of the Meeker quadrangle: Segar Mountain (O'Sullivan, 1974), Buckskin Point (Pipiringos and Johnson, 1975), and White Rock (Pipiringos and Rosenlund, 1977). These maps were published as black-line, miscellaneous field study maps and made no attempt to subdivide the unconsolidated Quaternary deposits. To the east, two full-color 1:24,000-scale coal investigations maps were completed by Reheis (1984a, 1984b) for the Sawmill Mountain and Thornburgh quadrangles. Two other 1:24,000-scale coal resource maps were completed in the Danforth Hills to the north: The Easton Gulch quadrangle by the USGS (Reheis, 1981), and the Axial quadrangle by the CGS (Hardie and Zook, 1997). These maps emphasized coal resources and provided little or no differentiation of Quaternary and Holocene surficial deposits. The Meeker quadrangle is the second geologic map done by CGS in the region. Field mapping has been completed for two other adjacent quadrangles, Rattlesnake Mesa (White and others, in prep.) and LO7 Hill (White and Warden, in prep.).

MAPPING METHODOLOGY

The geologic interpretations shown on the Meeker geologic map are based on the following sources: (1) CGS field investigations conducted from June to September 2009; (2) published and unpublished geologic maps and reports; (3) interpretation of remote-sensing data; and (4) the NRCS Soil Survey Geographic (SSURGO) database for Rio Blanco County. The data used to map the geologic contacts include stereo pairs of black and white 1:20,000-scale Agricultural Stabilization and Conservation Service (ASCS) aerial photography flown in 1966, a 10-meter resolution digital elevation model (DEM), the USGS 1:24,000-scale topographic base map, and 1-meter resolution National Agricultural Imagery Program (NAIP) digital orthophotos taken in 2006 and 2009.

Bedrock geology and surficial deposits were mapped photogrammetrically in the field on stereo pairs of aerial photographs. Key geologic and photograph locations were recorded with a portable GPS receiver, using Universal Transverse Mercator (UTM; North American Datum 1983, Zone 13) coordinates. Upon the completion of fieldwork, the annotated aerial photos were scanned and georeferenced into an ESRI ArcMap GIS project file. The line work on the scanned photo images was then digitized on a computer monitor where the digital topographic map, DEM, and GPS point data were visible layers. Locations were also indexed to georeferenced 2009 NAIP orthophotography that was also loaded into the GSI project to ensure the accurate map location of geologic features and contacts.

Because of subtle errors found in the original 1:24,000-scale topographic map, the final geologic mapping was indexed to the more accurately georeferenced NAIP photography.

The following conventions are used for describing the surficial deposits and bedrock units. Clast sizes are based on the modified Wentworth grain-size scale (Wentworth, 1922) using a chart from the American Geological Institute (Ingram, 1989). Stages of calcic soil development are described using the classification system of Machette (1985).

Bedrock structural measurements, including bedding and fracture orientations, were taken using a Brunton compass. In most cases, bedding strike-and-dip were determined by direct measurements of rock strata surfaces where favorable facies were present, such as tabular and sheet-like sandstone bodies, and uniformly bedded shale and limestone. We avoided taking readings from cross bedding or channel scour surfaces, and within landslides, or in areas of obvious slope creep unless the intent was to map the disturbance or displacement of very large blocks of strata.

The Meeker quadrangle is well vegetated as a result of higher precipitation in the higher terrain, the shading of north-facing slopes, and the abundant irrigation on the many mesas and “parks” in the valley bottoms. Well exposed outcrops are present in the Grand Hogback but more poorly exposed in the valley bottoms, along the mesa edges where it is mostly easily erodible shale. The mapping involved interpolation of geologic boundaries between known points. Many of the bedrock and surficial units have distinctive geomorphic signatures, lithologies, and fossil assemblages that assisted the authors in mapping the various strata. Many smaller faults, especially in shale bedrock, become untraceable where buried by valley-fill deposits or river alluviums. Where possible, we used subsurface data and geomorphic clues to infer fault traces, such as topographic lineations, offset of cuestas and hogbacks on opposite sides of valley floors, and presence of linked valleys and ridge-line saddles.

PHYSIOGRAPHY AND GEOLOGIC SETTING

The Meeker quadrangle lies at the junction of three physiographic provinces where the southern part of the Wyoming basin intersects the boundary of the Colorado Plateau and the Southern Rocky Mountains (Fenneman and Johnson, 1946). This physiographic intersection occurs at the Grand Hogback Monocline, the main structural feature of the Meeker quadrangle, which tectonically defines the northeast margin of the Piceance Basin against the White River Uplift. Lower Tertiary and older geologic strata are tilted steeply at the front (west side) of the Hogback but dip more gradually on the back side (east side). At the north end of the quadrangle, the south to north-trending Grand Hogback terminates against the east-west trending Sulphur Creek synclinal fold. The strike of the formation bedding quickly changes from a north-south, to an east-west orientation on the southern limb of the syncline, the axis of which mostly lies off map, north of the quadrangle boundary. This syncline defines the northern end of the Grand Hogback and the regional structural transition to the southwest flank of the southeast to northwest-trending Axial Basin Uplift in the Danforth Hills.

The Piceance Basin, Grand Hogback Monocline, White River Uplift, Axial Uplift, and the interbasin folds were formed during the Laramide Orogeny, in Late Cretaceous to Eocene time (Tweto, 1975; Finn and Johnson, 2005). The paleoenvironment during this geologic time interval transitioned from epeiric seas of the Cretaceous North American Western Interior Seaway, to Late Cretaceous shoreface, near-shore swamp, and deltaic environments where extensive coastal plains developed that rose towards highlands of the Sevier Thrust belt to the northwest. Sediment-source direction reversed as the initial pulse of the Laramide Orogeny began. The seaway regressed, regional elevations rose, and fault blocks of the Gore and Sawatch Range uplifted to the east. Clastic sediments, eroding from the emerging mountains were deposited in Tertiary foreland braidplain, strandplain, and paludal environments (see *Structural Geology* section).

Bedrock exposed in the Meeker quadrangle consists of Upper Cretaceous to Lower Tertiary formations. From oldest to youngest, they are the Mancos Shale, the Mesaverde Group, Ohio Creek Conglomerate, Fort Union Formation, and the Wasatch Formation. The Mesaverde Group is subdivided into separate formations: the Iles and Williams Fork formations. The shale and mudstone units are nonresistant and form valleys and topographic basins. The sandstone-bearing strata are more resistant, and form the cuestas, hogbacks, and ridges that easily express the geologic structure across the landscape. The main sandstone-bearing strata (Iles, Williams Fork, and Fort Union Formations) also contain coal beds (see *Mineral Resources* section).

The White River, the region's major stream, flows from east to west across the southern part of the quadrangle. It cuts through the Grand Hogback monocline southeast of Meeker where the intersection of Highway 13 and Highway 64 occurs. Structural offsets in the Williams Fork and Iles Formation strata indicates the White River water gap was preferentially cut at a fault location; the precise location not known beneath the river floor. Powell Park and Agency Park are large topographic basins where the White River valley widens in the erodible bedrock of the Mancos Shale on the east side and the Wasatch Formation on the west side. Several mesas in these parks are strath terraces that record episodic Pleistocene glaciations of the White River Uplift-Flat Top highlands and the resultant glacio-fluvial gravel alluviation of the White River valley, as well as local fluvial gravel deposition of tributary streams at their paleoconfluences. In addition to these broader mesas along the White River, Quaternary erosion and base-level lowering of all streams has also formed smaller mesas and ridges along tributary valleys slopes, which are capped with more resistant valley-fill gravel and rocky mud-flow deposits (See *Surficial Deposits* in *Description of Map Units* sections).

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 (human-made, alluvial, and mass-wasting deposits) and by age, with the younger units preceding older units. Bedrock units are organized by increasing age. Geologic time divisions and nomenclature used in this report are shown in **Appendix A**.

SURFICIAL DEPOSITS

The surficial deposits in the Meeker quadrangle are Quaternary (Holocene and Pleistocene) in age. They are wide spread on the Meeker quadrangle because of the erodible nature of the local bedrock and topographic elevation differences that can foster rapid and extensive deposition of sediments in alluvial, colluvial, and mass-wasting environments. The deposits shown on the map are generally more than five feet thick but may be thinner locally. Certain contacts between surficial units may be gradational, and mapped units locally may include deposits of other types. Only a few of these deposits have been absolutely age-dated by radiometric or luminescence methods. Relative age assignments (early, middle, late) for the Holocene and Pleistocene deposits are based primarily on relative age-dating techniques: degree of erosional modification of original surface morphology, height above modern stream levels, degree of dissection and slope degradation, and degree of soil development.

HUMAN-MADE DEPOSITS

af **Artificial fill and disturbed land (latest Holocene)** – Generally unsorted gravel, sand, silt, clay, and rock or concrete debris emplaced as fill to construct highways, airport runways, and other human-made structures. Also includes stockpiled materials, excavations, and overburden spoils that are associated with aggregate mining at gravel pits, as well as overlot grading where the ground topography has been obscured.

ALLUVIAL DEPOSITS

Clay, silt, sand, gravel, cobbles, and boulders deposited by flowing water in major and tributary stream channels and floodplains. Terrace alluvium and age-related tributary stream deposits were formed mostly during periods of wetter climate that coincided with Pleistocene glacial epochs. These sediments are generally unconsolidated but cemented zones were noted in some of the older units.

ALLUVIAL DEPOSITS OF THE WHITE RIVER

The White River flows from east to west across the southern part of the Meeker quadrangle. Its alluvium consists of gravel, cobbles, small boulders, sand, silt, and clay transported and deposited by the river. Alluvium deposited from confined-channel flows is the principal sediment underlying the modern floodplain. Clast sizes range from silt, sand, and some granule gravel in recent over-bank deposits while larger clasts predominate in the older and higher-elevation glacial-derived deposits on the adjacent mesas. In the four elevated and dissected, older alluvial-terrace deposits of the White River, the depositional environment was higher energy and the glacio-fluvial outwash sediments were deposited as an aggrading braidplain on the valley floor with common cross-bedding and cut-and-fill channels **(Figure 3)**. The dominant sediment is a clast-supported pebbly to cobbly gravel in a coarse sand matrix with scattered small (<2 feet diameter) boulders. Thin lenses of clean well-sorted coarse-grained sand sometimes occur within the gravel. Clast imbrications generally show an east to west flow of water.

Figure 3. Quarry wall exposure revealing cross bedding of pebbly to cobbly gravel in White River alluvium (Qaw_4). Note white Stage IV calcic soil horizon and later deposition of valley fill on gravel surface. Largest rocks in pile are approximately 18 inches (long axis). [UTMX 253172, UTMY 4433071]

Volcanic, crystalline, and lower-Paleozoic sedimentary rocks are exposed in the White River Uplift highlands and this distinct assemblage of lithologies dominates the gravel and larger size fractions of all Quaternary deposits of the White River. Lithologic gravel-count average about 50% Tertiary basalt, 30% Cambrian Sawatch quartzite, 10% Precambrian igneous and metamorphic crystalline rock, and the remaining 10% is other early Paleozoic sedimentary rocks including red clasts from the Maroon Formation. The gravel, cobble, and boulder clasts are generally well rounded to round. The older river alluvium deposits are relatively devoid of fine-grained silt and clay, and clast lithologies are hard and resistant to weathering. Subsequent differential erosion and downcutting of the surrounding weaker bedrock has caused topographic reversal so that mesas and terrace bluffs have formed in the greater White River valley. Most of the terrace gravel deposits that cap these mesas are now mantled with variable thicknesses of more recent valley fill, including alluvial/alluvial fan deposits, slopewash, and windblown loess. These subsequent deposits can be quite thick, over 50 feet in some areas. In certain areas of the map, the thickness of the overlying valley fill has covered and obscured the river terraces along the valley slopes. In those areas the buried White River terrace gravel is mapped as only a line trace along the slope bluff where well-rounded clasts of White River lithologies were noted in the surface float in side drainageways along the valley bluff.

These older mesas have aggregate-mine value (see *Mineral Resources* section). There are several active and abandoned gravel pits in the White River alluvium.

Qaw$_1$ **Alluvium one of the White River (Holocene to late Pleistocene)** – Brown to dark brown sand, silt, and gravel of the modern, active floodplain of the White River. This glacial unit occupies the current valley floor, generally from bedrock valley wall to bedrock valley wall. In areas near smaller ephemeral tributary channels and ravines, this unit has been covered by alluvial fans that have been deposited out onto the valley floor. The river channel apparently has been actively migrating across this unit throughout much of the Holocene, so that the floodplain consists of abandoned oxbow meander channels and over-bank plains. Many of the alluvial fans have also been truncated by this meandering. The channel bed load is predominantly cobbly gravel while the adjacent over-bank floodplain deposits and meander in-fill sediments are finer grained silty to clayey sand. Maximum thickness is unknown but exceeds 55 feet based on the deepest water-well logs.

Qaw$_2$ **Alluvium two of the White River (late Pleistocene) –** Gray cobbly pebbly gravel in a very coarse sandy matrix. These deposits exist as prominent strath terraces remnants 50-65 feet above the modern floodplain. Stage II+ calcite development (Machette, 1985) in Bk soil horizons was observed in gravel pit exposures. This unit has a measured thickness of 28 feet at the Berry Pit quarry. Old quarry cut slopes of this unit are very well exposed along S.H. 13 at the CDOT maintenance yard. At this location there are zones or horizons where the coarse sand matrix is prominently cemented, to an extent that the unit could be called a conglomerate. The Meeker airport buildings on the mesa west of town are underlain by Qaw$_2$ gravel. OSL dating of a clean coarse sand layer near the middle of this unit yielded an age of 76.4±5.0 ka (Steven Foreman, University of Illinois at Chicago, written communication).

Qaw$_3$ **Alluvium three of the White River (late to middle Pleistocene) –** Gray cobbly gravel in a very coarse sandy to pebbly matrix with scattered small boulders deposited on strath terraces 120 to 140 feet above the modern floodplain. This unit is from 15 to 20 feet thick. The top of the unit contains terrace risers and undulations consistent with a braided stream morphology. The Qaw3 terraces are the most extensively preserved on the Meeker quadrangle. The large mesa across the river from Meeker is a Qaw$_3$ gravel terrace. The Meeker Town cemetery is located on this unit. Pit exposures reveal a Bk horizon with Stage III+ calcic soil development. Based on the height above the modern floodplain and calcic soil development, this unit has been assigned a late to middle Pleistocene age. This unit is mantled by a thin discontinuous veneer of loess.

Qaw4 **Alluvium four of the White River (early middle Pleistocene) –** Gray cobbly pebbly gravel in a densely packed, very coarse sandy matrix with scattered small boulders deposited on strath terraces 325 to 350 feet above the modern floodplain. This unit caps two prominent mesas of Mancos Shale that rise above the Qaw_3 surface, southeast of Meeker. They are being actively mined by Meeker Sand and Gravel, Inc. When the Meeker pit was much smaller, Izett and Wilcox (1982) reported the identification of a Lava Creek B (LCB) volcanic ash by J. W. Whitney (USGS). The 640ka age of the LCB ash would place this gravel as early middle Pleistocene. Gravel pit exposures reveal a Bk soil horizon with stage IV calcic development (**Figure 3**). The unit thickness was measured at 35 feet at its deepest but the Qaw_4 braided channel thins to only about 5 feet along the southern edge where the Mancos Shale paleo-valleyside once rose. Large blocks of Mancos Shale occur where the gravel thins (**Figure 4**). For blocks of extremely weak Mancos Shale to remain intact in this energy of deposition, the source area must have been an immediately adjacent cut bank. Also at this location, this unit is mantled by up to 10 feet of shale-clast-rich Qafo deposits that were shed out onto the terrace from the adjacent paleovalley side, now eroded away. This unit is predominately unconsolidated but there are horizons of cementation of sufficient hardness to create conglomerate.

Figure 4. Block of Mancos Shale in Qaw_4 deposit. Note upside down ball cap for scale. [UTMX 254210, UTMY 4432881]

Qaw_5 **Alluvium five of the White River (early Pleistocene to Pliocene(?)) –** Heavily stained cobbles and small boulders in a sandy gravel matrix. This unit is represented by one isolated strath terrace bench high on the sides of the Grand Hogback at the White River water gap, 640 feet above the modern floodplain. Clast lithologies are White River provenance but are heavily stained where exposed at the surface. Height of the unit above the modern floodplain, and 300 feet above the early middle Pleistocene Qaw_4 unit (with the 640ka LCB ash) suggest a early Pleistocene to possibly Pliocene age to this unit.

ALLUVIAL DEPOSITS OF TRIBUTARY-STREAM AREAS

Alluvium of the tributary-stream areas consists of cobble, gravel, sand, silt, and clay transported and deposited by perennial first-order tributary streams of the White River throughout the Meeker quadrangle. The main perennial streams are Strawberry Creek, Sulphur Creek, Flag Creek, and Curtis Creek (**Figure 2**). Clast provenance is very distinctive between the different tributary streams. The Flag Creek basin from the south along the Mancos Shale strike valley extends into Early Cretaceous, Triassic, Jurassic, and late Paleozoic rocks. Higher lithology percentages are seen of hard dark-gray siliceous siltstones of the Mowry Shale, Dakota and Morrison sandstone and pebble conglomerate, older red sandstone and siltstones, and reworked quartzitic pebbles and cobbles from conglomerate beds of the Maroon Formation. The provenances of Sulphur and Curtis Creeks are the Iles and Williams Fork formations so they contain almost nothing but sandstone and common red clinker clasts. The Strawberry Creek basin west of the Grand Hogback extends into the Wasatch, Fort Union, and Ohio Creek formations. Its distinctive clast lithologies include sandstone but with high percentages of reworked pebble to small cobble-sized chert and petrified wood. Higher-order enumerated alluviums roughly correspond with the enumerated alluviums of the White River. Except for the base level Qa_1 sediments, these alluviums are gravel rich and form terrace remnants. These tributary deposits generally can be traced down to a paleoconfluence where mixing of clast lithologies can be identified with the main-trunk sediments of the White River.

Qa_1 **Alluvium one of tributary streams (Holocene)** — A dark brown to brown, weakly stratified, unconsolidated sediment composed of poorly to moderated sorted, silty to clayey sand with scattered pebbly to cobbly gravel lenses. Deposits of this unit were mapped at and near the base-level floodplains in tributary streams. In most circumstances, these stream are generally well incised (up to 30 feet) into earlier valley-fill alluviums on tributary valley floors, forming steep-walled channels and arroyos. Where actively eroding the river valley, these sediments are likely thin. However, in major tributary streams, this map unit also includes a middle to late-Holocene terrace level. These narrow and discontinuous terrace remnants are most noticed where subsequent stream downcutting has abandoned earlier Holocene meanders within the arroyo. At those exposures, multiple weakly-developed Bt horizons were observed that show the aggraded nature of the deposit . Where remnants of this terrace exist, it is 6 to 8 feet above the base-level channel.

Qa_2 **Alluvium two of tributary streams (late Pleistocene) –** Tan to buff colored alluvium that ranges gradationally from cobbly gravel in very coarse silty sand to a finer grained silty sand with only scattered gravel. This unit is poorly exposed at very discontinuous strath terrace remnants along all the major tributary valleys. In most locations, the exposure is just a subtle bump in the valley slopes where the slope surface is gravel and cobble rich. Thicknesses may be up to 15 feet. Along Curtis Creek, the Qa_2 alluvium has been deposited over the Qaw_2 alluvium and has enough fine contents and matrix support to suggest that Curtis Creek formed an alluvial fan over the White River braided floodplain before subsequent lowering and incision of the White River could occur. At this location a well developed chalky-white Bk horizon is developed in this unit, which has been subsequently buried by windblown loess deposits. This depositional relationship can be seen at the Berry Pit and the roadcut adjacent to the CDOT maintenance yard on State Highway 13 (**Figure 5**).

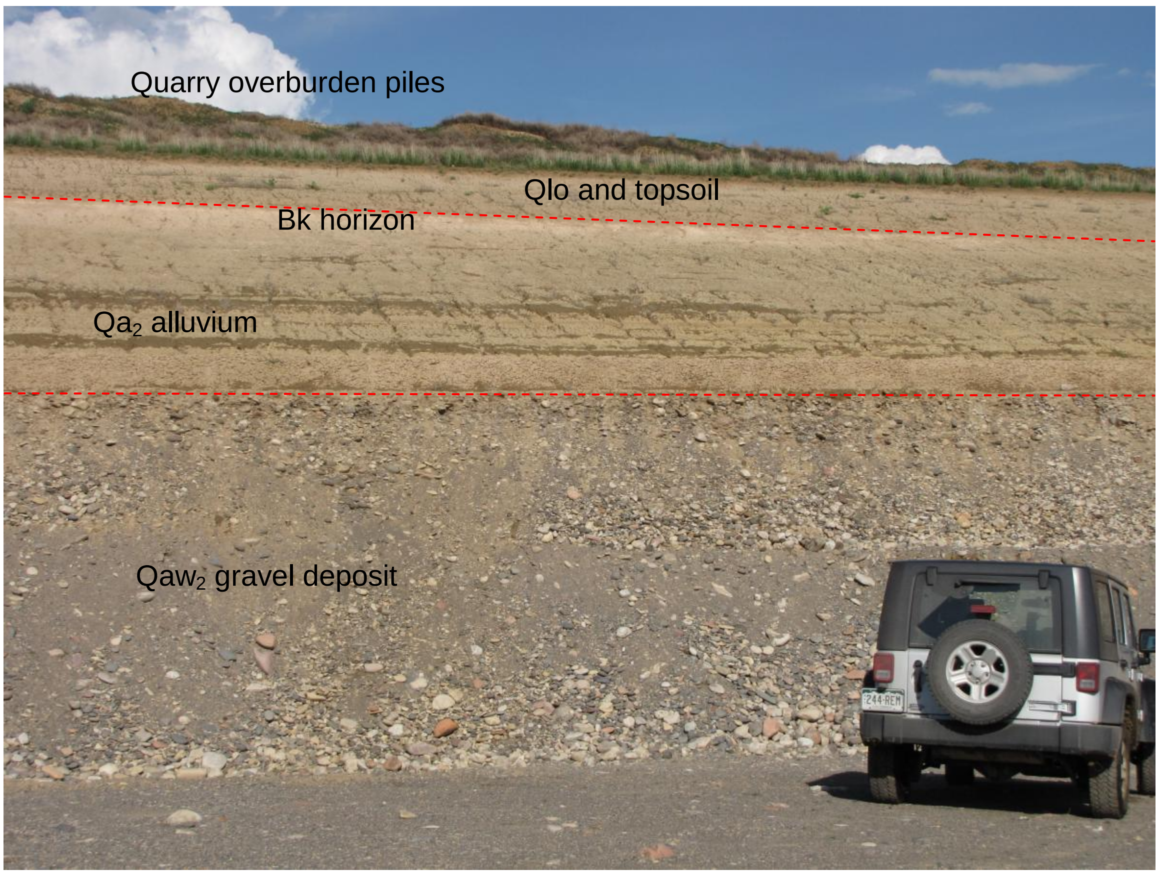

Figure 5. Quaternary deposits exposed at the Berry Pit east of Meeker near confluence of Curtis Creek with the White River. Red dashed lines delineate the separate deposits. [UTMX 253706, UTMY 4436275]

Qa_3 **Alluvium three of tributary streams (late to middle Pleistocene) –** Tan to brown, cobbly to pebbly gravel in medium to very coarse sand. This unit was mapped only in the Strawberry Creek and Flag Creek basins. In good exposures excavated along irrigation canals and roadcuts, the exposed cobbly gravel is river sorted and clast supported. In Flag Creek, there is a thin layer in this unit that has been selectively cemented to a conglomerate. Imbrications of the clast reflect a water-flow direction toward the confluence with the White River. This river terrace gravel is 70 feet above the adjacent Flag Creek floodplain and 90 feet above the Strawberry Creek floodplain

Qa$_4$ **Alluvium four of tributary streams (early middle Pleistocene) –** Tan to buff-colored cobbly to bouldery gravel in very coarse silty sand. This unit is only exposed as a terrace remnant 105 feet above the adjacent base-level floodplain of Flag Creek. This unit is very similar to Qa$_3$ with the exception that there is more extensive calcic soil development.

Qa **Alluvial deposits, undifferentiated (Holocene) –** A dark brown to brown, weakly stratified, unconsolidated sediment composed of poorly to moderated sorted, silty to clayey sand with scattered pebbly gravel lenses. Unit is mapped in bottoms of swales and third-order ephemeral streams.

MUDFLOW-DOMINATED ALLUVIUM AND ALLUVIAL-FAN DEPOSITS

The second most common surficial deposits that cover broad areas within the Meeker quadrangle are associated with complex alluvial-valley-fill and alluvial-fan systems along tributary streams and in broad basins at the perimeter of the Grand Hogback. In these systems, channelized to laterally unconstrained mud and gravel debris flows have been the dominant depositional processes. Depending on the energy of deposition, these widespread Holocene to late Pleistocene deposits can range from fine-grained mudflow-dominated sandy to silty clay, to clast-supported pebbly to cobbly gravel more typical of bed-load riverine environments. These deposits are poorly to moderately stratified and channelized. Most of the source material is derived from Cretaceous Iles Formation, Williams Fork Formation, and Mancos Shale on the east side of the Grand Hogback, and from the Wasatch and Fort Union Formations on the west side of the hogback. Smaller fans have been deposited from the many gullies that have incised the high terrace mesas underlain by Mancos Shale. These latter deposits reflect erosion from the terrace gravels and the underlying shale, and so form a darker, more clayey deposit with dispersed reworked White River gravels.

Qaf **Alluvial and alluvial-fan deposits (Holocene)** — Brown, tan to light-gray, poor to moderately sorted, unconsolidated, stratified clayey silt and sand with sporadic gravelly to cobbly lenses. This unit was deposited as an aggrading valley fill in larger tributary basins where the surrounding bedrock is relatively weak and prone to rapid erosion. This unit was separated from the Qa and Qf map units because it fills the entire valley and doesn't have the morphological boundary from an alluvial fan slope to a flat alluvial floodplain. The stratification records episodic and dynamically differing energies of deposition as sediments aggraded the valley floor. This unit is best exposed in arroyo escarpments of Strawberry Creek and Fourmile Gulch. Soil development reflects the aggrading nature of the deposit with multiple poorly developed Bt soil horizons. The highest arroyo escarpment in this unit was measured at 37 feet. Actual unit thickness may exceed 40 feet. The sediments of this unit may subside when wet, which is a problematic engineering property for structures. See the "Geologic Hazards" section for further discussion on low-density hydrocompactive soils.

Qafo **Old alluvium and alluvial-fan deposits (late to middle Pleistocene)** — Reddish tan, buff, brown, and tan-gray, poorly to moderately sorted, moderately consolidated, stratified silt, sand, gravel, cobbles and boulders deposited as coalescing valley fill in both alluvial fans and alluvial channel settings. Near the ridges of the Grand Hogback, Qafo deposits are typically much coarser and bouldery than the Qaf deposit, reflecting the climatic conditions of the Pleistocene glacial periods. The typical sediments deposited near steeper bedrock slopes ranged from clast-supported cobbles and boulders in a silty to pebbly sand matrix to sandy gravel interlayered with finer-grained clayey to silty sand. Where this unit has spread over flatter slopes of existing pediments and terraces, the primary deposit is a mudflow to stream-deposited, moderately sorted, interlayered silt to coarse grained sand with sporadic sandy granule lenses (**Figure 6**).

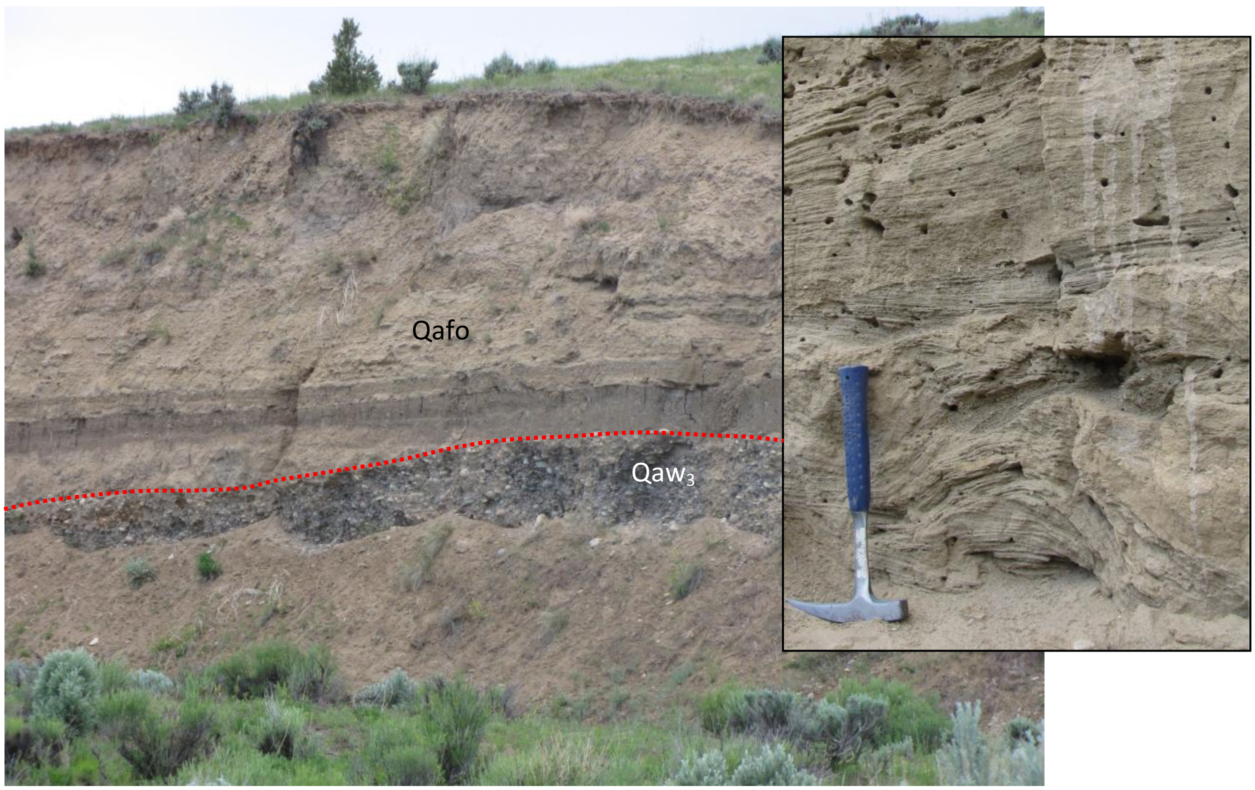

Figure 6. Thick Qafo deposit overlying Qaw_3 White River gravel. Note inset photo showing interlaminated deposition and folded load-deformation structures right of hammer. Pock marks are insect burrows. [UTMX 244915, UTMY 4433540]

The individual layers in the unit record episodic and dynamically differing alluvial and alluvial fan depositional events as sediments aggraded the tributary valleys and terraces of the White River. This deposit may also be mantled by a thin discontinuous veneer of loess. Where this unit is a coarse-grained cobbly to bouldery deposit, it is more resistant than the underlying bedrock so topographic reversal occurs as the base-level downcutting of streams continued. The Qafo unit includes various aged deposits at five elevation base levels. These very coarse cobbly to bouldery gravel deposits exist on narrow ridgelines and small mesas. The highest and oldest

Qafo surface near the Grand Hogback lies atop the Morapas Sandstone ridge, 400 feet above the Fourmile Gulch base level.

In the White River valley, the highest Qafo unit was deposited on the Qaw_4 terrace gravel. Near where figure 4 was taken, this interesting alluvial and alluvial fan deposit contains large percentages of Mancos Shale fragments, from very small sand-gravel sized shale fragments to large intact blocks. The nature of this deposit indicates the middle-Pleistocene valley side in Mancos Shale was immediately adjacent to this terrace at the time of Qaw_4 gravel deposition. This valley side, long since lowered hundreds of feet by later erosion, was the source areas for the shale-clast-rich debris flows and alluvial sediments.

This unit has highly variable thicknesses, from five feet to over 50 feet. Maximum measured thickness near location of figure 6 was 53 feet. In some ridge-line locations, erosion has winnowed away the finer portions of the deposit leaving only the bouldery fraction exposed on the underlying bedrock surface.

Qf **Alluvial-fan deposits (Holocene)** — Tan to light brown, poorly to unsorted, unconsolidated, roughly stratified, sandy silt with dispersed matrix-supported gravel that is gradational with a much coarser sandy to cobble gravel with scattered small boulders. This unit is deposited in alluvial fans from the mouths of ephemeral steams that outlet from small tributary valleys. The deposits can have a fan-shaped morphology but generally have coalesced and aggraded the edges of the valley floors at low surface gradients. The sharply angular to subrounded clasts are from local sandstone sources eroded from high bedrock ridges and hillsides. Boulders can exceed five feet in diameter near the mouth of the larger ephemeral streams. Deposit may exceed 50 feet in thickness near the apexes of the larger fans. Sediments are deposited primarily as muddy debris flows, hyperconcentrated flows, and earth flows. The sediments of this unit may subside when wet, which is a problematic engineering property for structures. Upon saturation, theses deposits may also be susceptible to soil shear and experience lateral ground movements. See the *Geologic Hazards* section for further discussion on low-density hydrocompactive soils and landslides.

Qfo **Old alluvial-fan deposits (late to middle Pleistocene)** — Tan to orange-tan to light reddish brown, poorly to unsorted, unconsolidated, sandy silt with dispersed gravel that can range to a much coarser sandy to bouldery gravel. Through erosion and topographic inversion, only remnants of these deposits occur at higher elevation than the younger Qf deposits. Clast composition and shape vary depending on source areas. This unit is poorly exposed, but clasts near the surface are coated by a discontinuous rind of $CaCO_3$, indicating that a calcic Bk horizon is present. Rapid mud deposition is indicated by the unsorted nature of the deposits, with angular to subangular clasts generally dispersed and supported within a finer-grained matrix. The unit thickness may locally exceed 40 feet. This deposit may be mantled by a thin discontinuous veneer of loess.

ALLUVIAL/COLLUVIAL AND MASS-WASTING DEPOSITS

These deposits were transported downslope primarily by gravity and not within or under another medium, such as water or ice, except where noted in mixed alluvial and colluvial deposits. These deposits are formed in combinations of the following depositional systems: 1) downward transport of slope regolith by creep and sheetflooding into colluvial wedges at the base of slopes, 2) rockfall forming talus, 3) shear-plane landsliding along defined zones of weaknesses in the underlying bedrock or unconsolidated sediments, and 4) clay-rich earthflows where the entire sliding mass was very wet and has partially fluidized and flowed down the slope. See the *Geologic Hazards* section for further discussion of landslides.

Qac **Alluvium and colluvium, undifferentiated (Holocene)** —Tan to tan-gray unconsolidated silt, clay, and sand with lesser amounts of dispersed, matrix-supported gravel and larger rocks, up to small boulder in size. Unit is poorly sorted, very weakly stratified, and clasts are angular and of local up-slope origin, reflecting the in-situ weathering of soft bedrock slopes and formation of residuum and regolith. These deposits are derived by sheetwash processes and smaller mudflows where fine-grained sediments accumulate at the base of steeper slopes. Stratification, when present, is rough and likely reflects short-term climatic changes when the down-slope movement and deposition of sediment was enhanced. These deposits are found on flatter slopes at the base of steeper slopes, including valley fills and along upland mesa edges. Soil development is weak. The sediments of this unit may subside when wet, which is a problematic engineering property for structures. See the “Geologic Hazards” section for further discussion on low-density hydrocompactive soils.

Qaco **Old alluvial and colluvium, undifferentiated (Pleistocene)** —Reddish tan to tan, unconsolidated silt, clay, and sand with lesser amounts of dispersed, matrix-supported gravel with scattered larger rocks up to small boulder in size. Deposit is poorly sorted, very weakly stratified, and the angular clasts are of local upslope origin. Mapped only in the Strawberry Creek basin, these deposits cap flatter-sloped tops of upland hills in the easily eroded Wasatch Formation. These flatter slopes are old surface remnants of the Pleistocene valley sides that are now dissected and isolated by the erosion and base-level lowering of Strawberry Creek. This unit may also include reworked windblown dust (loess). Exposures are poor, but chalky-white exposure along slope breaks and ridgeline saddles reveal a well-developed calcic Bk horizon. That soil development, the reddish hue of the surface soils, and elevation above the base level stream assign this deposit a late Pleistocene age. Thickness is highly variable and likely does not exceed 10 feet. In some areas in may thin to only zones of regolith and top soil atop near-surface erodible bedrock. The sediments of this unit may subside when wet, which is a problematic engineering property for structures. See the *Geologic Hazards* section for further discussion on low-density hydrocompactive soils.

Qc **Colluvial deposits (Holocene)** — Heterogeneous tan to tan-gray deposits consisting of unsorted and unstratified clay, silt, and sand, with dispersed matrix-supported angular gravel to boulder-sized rock fragments. Colluvium is generally very rocky where it mantles the base of steep or cliffy valley sides and ridgelines. Unit may include areas of accelerated creep. Unit thickness averages about five feet but can thicken to over 20 feet at the base of slopes, and may include areas much thinner or where weathered bedrock is at or near surface.

Qco **Old colluvial deposits (late Pleistocene)** — Heterogeneous tan, reddish tan, tan-gray deposits consisting of clast-supported bouldery-pebbly gravel in an unsorted sandy clay matrix. These older colluvial deposits typically occur as facets that partially cover the Mancos Shale slope below the Iles Formation escarpment along the east side of the Grand Hogback. These very rocky deposits contain sandstone clasts, so they are more resistant to weathering than the underlying Mancos Shale. Where they exist, this unit has formed relict faceted slopes that are commonly covered with vegetation compared to the nearby bare Mancos Shale slopes (**Figure 7**). Some Qco units may include ancient, small landslide deposits where the diagnostic landslide morphology has been obscured by subsequent erosion. As the underlying shale weakens, the Qco slope edges may become unstable. See the *Geologic Hazards* section for further discussion.

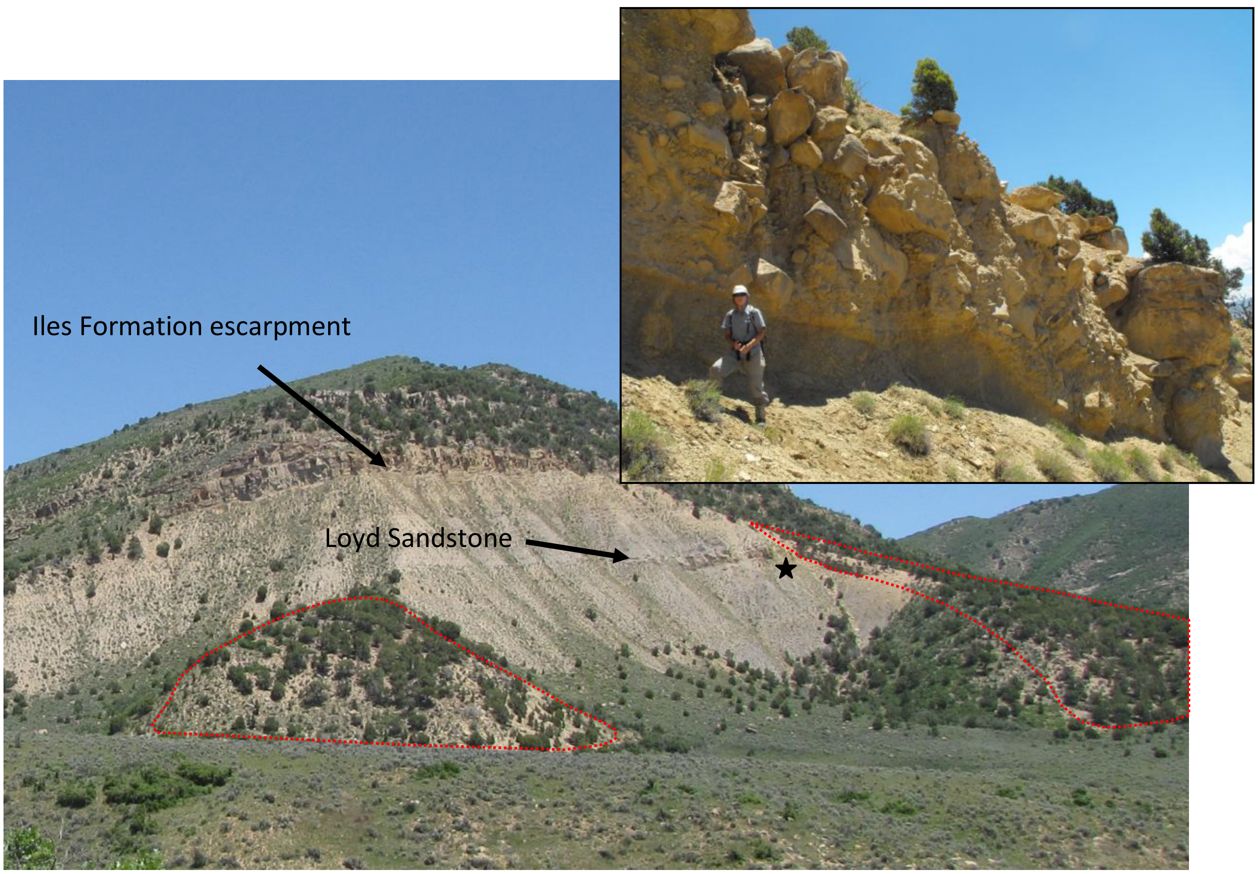

Figure 7. Two Qco facets (enclosed in dashed red lines) are erosional remnants protecting the soft upper Mancos Shale below the Iles Formation rim rock escarpment. The Loyd Sandstone Member is also visible in the shale slope. The inset photo, taken where star symbol is shown, illustrates the bouldery unsorted nature of the colluvial deposit. Location is near the mouth of Ryan Gulch in the Fourmile Gulch valley northeast of Meeker. [UTMX 254595, UTMY 4441987]

Qls **Landslide deposits (Holocene to late Pleistocene)** — Landslide deposits in the Meeker quadrangle are found along dip slopes of tilted interbedded formations within the Grand Hogback and steeper bluffs of gravel-capped mesas that are underlain by weak Mancos Shale. This map makes no age distinction of the mapped landslides. Lateral ground movements have also occurred in weak sandy-clay deposits in alluvial fans (Qf).

The dark gray to gray landslide deposits along the mesa edges consist of chaotic, unsorted and unstratified, unconsolidated, highly weathered and disturbed Mancos Shale rubble, derived clay, and transported and reworked terrace gravel. Gravel becomes incorporated into the slide mass where scarps form in the gravel deposit above and the underlying shale begins to mobilize and incorporate the surface gravel. Thickness of landslide deposits in Mancos Shale may locally exceed 20 feet. Vegetation is generally thicker in landslide deposits due to the amount of water seeping into and running off of the deposits.

The landslide deposits within the tilted bedrock formations of the Grand Hogback are quite different. The Williams Fork and Fort Union formations are composed of hard brittle sandstone beds interbedded with thicker beds of low shear-strength shale, mudstone, and minor coal seams. Dip-slope failures occur when tilted strata bedding planes shear and slip. Any formational material above this slide plane then slides down the dip slope. The disturbed and sliding bedrock is transformed into a mass of chaotic, unsorted, unconsolidated rubble. This landslide rubble of broken rock can include very large sandstone blocks, tens of feet across. See the “Geologic Hazards” section for further discussion of landslides within the mapped area.

EOLIAN DEPOSITS

Eolian deposits are fine-grained sediments (dust and very fine grained sand) that are transported and deposited by wind. They are a homogenous deposit that mantle relatively flat-lying ground surface. Eolian deposits were only mapped where there was a suitable thickness that exceeded five feet. Many old alluvial and colluvial deposits on flatter terrain may also be covered by thin discontinuous veneers of eolian deposits, much of which has been reworked as Qac and Qaco slopewash that usually contain small regolithic chips of sandstone.

Qlo **Loess deposits (late Pleistocene)** — Reddish tan silt and minor very fine grained sand deposited by wind. This homogenous deposit is located on broad flattened hills and mesas in the vicinity of the Meeker Airport. This unit has a reddish hue and contains a chalky white, moderately developed Bk soil horizon. The sediments of this unit may subside when wet, which is a problematic engineering property for structures. See the *Geologic Hazards* section for further discussion on low-density hydrocompactive soils.

BEDROCK UNITS

From the youngest to the oldest, the bedrock exposed in the Meeker quadrangle consists of the Tertiary Wasatch and Fort Union Formations, Tertiary to Upper Cretaceous Ohio Creek Conglomerate, Upper Cretaceous Iles and Williams Fork Formations and the Upper Cretaceous Mancos Shale. The Upper Cretaceous units have been mapped showing member units that could be identified in the field. **Figure 8** contains a stratigraphic column for the Meeker quadrangle that includes the individual formational members.

TERTIARY ROCKS AND THE K/T DISCONFORMITY

There is some uncertainty in the literature with the stratigraphic hierarchy and mapping of early Tertiary Rocks (Ohio Creek, Fort Union, and Wasatch Formations) in the vicinity of the Meeker quadrangle. This is best illustrated In the USGS Northern Piceance Basin geologic map compiled by Hail and Smith (1994). This map has the Fort Union Formation being mapped along the northern rim of the Piceance Basin to the northern limb of the Sulphur Creek Syncline where their map ends at the west boundary of the Meeker quadrangle. However, the Fort Union is absent along the Grand Hogback to the south, where Hail and Smith (1994) state that the correlative strata is in the basal Tertiary Wasatch Formation, which lies disconformably on the Williams Fork. Early work by Hancock and Eby (1930) mentioned the striking lithologic resemblance of Meeker area Lower Tertiary rocks to post-Laramie rocks of the Yampa field, which are mapped as Fort Union Formation (Brownfield and others, 2000). Donnell (1961) mentioned an unnamed Paleocene unit between the Mesaverde Group and the Wasatch Formation that contains massive sandstone beds that is likely correlatable with the Fort Union Formation. Franczyk and others (1992) also show a somewhat nebulous contact of the Fort Union and Wasatch sediments in their paleogeographic reconstructions.

The same is true for the basal Tertiary conglomerate in this area. The relatively thin (<50 feet) conglomerate has been referred to, or mapped, by various authors as the Ohio Creek Conglomerate (Hancock and Eby, 1930; Donnell, 1961; Tweto, 1975) or defined as the Ohio Creek Formation (Gaskill and Godwin, 1963). It has also been included as a basal sandstone and conglomerate facies of the Fort Union Formation in mapping of the northern Piceance Basin (Hail, 1973; Pipiringos and Rosenlund, 1977; Izett and others 1985). The same strata has been included in the basal Wasatch Formation in USGS mapping of the Grand Hogback south of Meeker to the Colorado River (O'Sullivan and Smith, 1985; O'Sullivan, 1985; Shroba and Scott, 1997; Shroba and Scott, 2001; and Perry and others, 2003). The Tweto (1975) description of a thinner conglomerate north of the Colorado River is more accurate to what was seen in this map area than the description in Gaskill and Godwin (1963). To further complicate the issue there are other interpretations: Johnson and May (1980) postulated the dropping of the Ohio Creek Formation to member status within the Cretaceous Hunter Canyon (Williams Fork) Formation in the southwestern Piceance Creek Basin based on kaolinitic zones and perceived paleosols, though later work by Johnson does indicate his agreement with a basal unnamed Paleocene conglomerate (Johnson and Flores, 2003). More recent work has also postulated a thicker Ohio Creek Formation – up to 250 feet thick, in the northern Piceance Basin. Patterson and others (2003) propose a

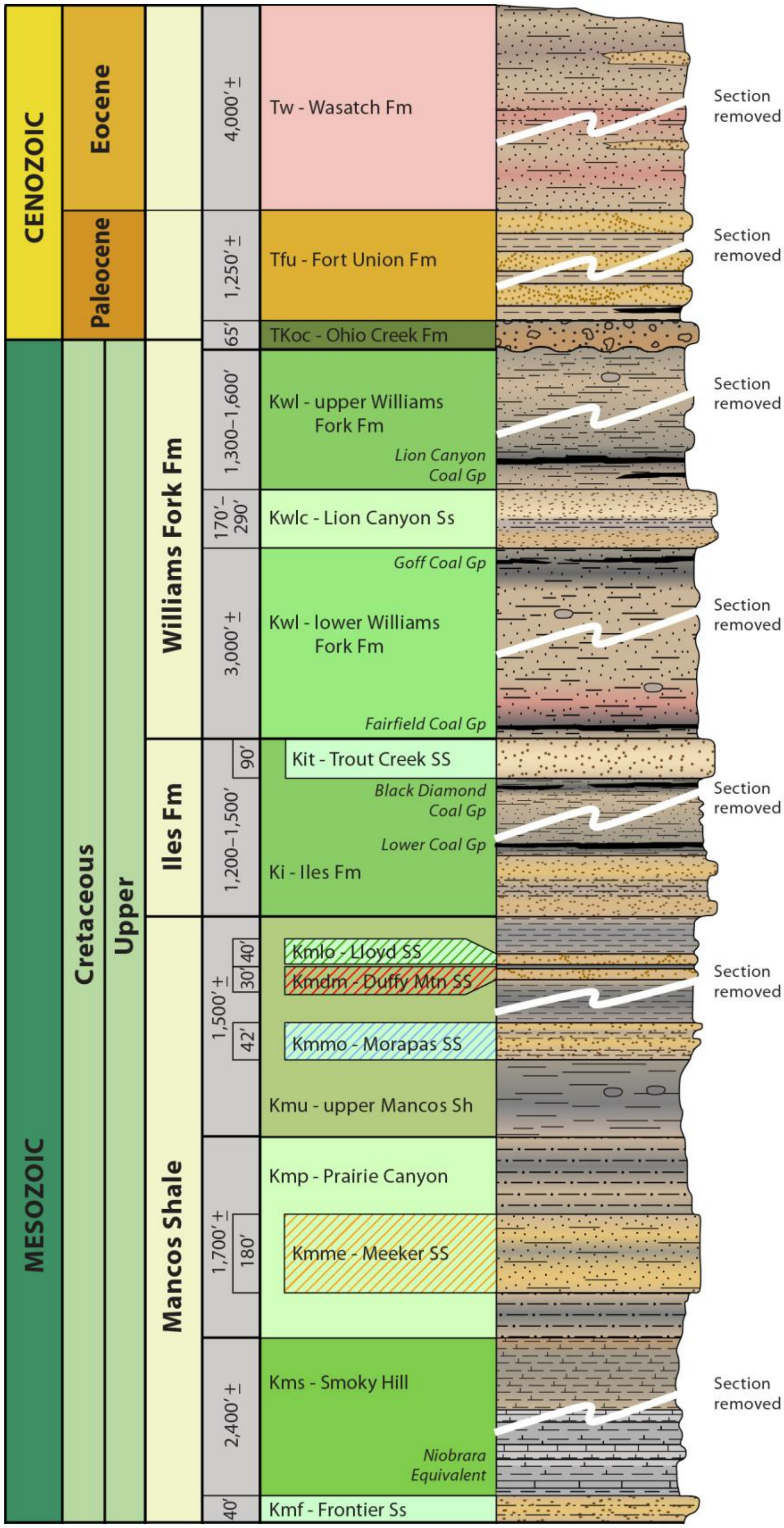

Figure 8. Stratigraphic/geologic column of the Meeker quadrangle with approximate thicknesses. Not to scale.

much thicker Ohio Creek Formation that is Late Paleocene and reclassified the age of the uppermost Williams Fork to Lower to Middle Paleocene. Analysis of earlier fossil pollen collections of Newman (1965) and fossil pollen data collected for this map (Nichols, written communication in **Appendix B** of this report) and the LO7 Hill quadrangle immediately south (White and Warden, in prep.) would appear to refute this. In his paleontological work along Crooked Creek near the White River in the Smizer Gulch quadrangle, Burger (2007) agreed with Patterson and others (2003) and also expanded the unit originally mapped by Hail (1973) so that the conglomerate is the base of a thicker unit where he recovered late Paleocene vertebrate faunal fossils. The Johnson and May (1980) nomenclature was used in some respect by Shroba and Scott (1997), Scott and Shroba (1997), Shroba and Scott (2001), and Perry and others (2003) in the USGS mapping of the Grand Hogback from New Castle to Rifle. The USGS mappers placed conglomeratic strata in both the basal Atwell Gulch Member of the Wasatch Formation and/or the top of the Cretaceous Williams Fork Formation, based on where the chalky-white kaolinitic zones occurred. This kaolinitic horizon has been theorized to be stacked palesols that represent the nondepositional hiatus of the K/T disconformity (Johnson and May, 1980 and Johnson and Flores, 2003), which they reported are quite thick in exposures along the southern Piceance Basin. Patterson and others (2003) consider the kaolinitic zone in-situ alteration and not pedogenic. Farther to the north, a thick package of basal Tertiary sandstone is typical in the Sand Wash Basin where it is called the Massive K/T Sandstone Unit (Tyler and McMurray, 1994).

During the field work for the Meeker quadrangle, examinations of mapped Fort Union strata were made in the White Rock quadrangle to the northwest (Pipiringos and Rosenlund, 1977) and basal Wasatch rocks to the south (O'Sullivan and Smith, 1985; O'Sullivan, 1985, Perry and others, 2003). The lithofacies of the Paleocene package in the Meeker quadrangle differs from the exposure near Rifle and suggests that the continued subdivision of the Fort Union Formation is warranted, as was done by the USGS in adjacent quadrangles along the north and northwest margin of the Piceance Basin (Hail, 1973; Pipiringos and Rosenlund, 1977; Izett and others, 1985).

The Fort Union Formation is composed of thick, laterally extensive, sandstone units interbedded with drab-colored olive-brown mudstone, carboniferous shale, and minor lignitic coal. It lies conformably on the resistant basal Ohio Creek Conglomerate that, in turn, rests disconformably on the Cretaceous Williams Fork Formation. The pebble to cobble conglomerate is correlatable with the Ohio Creek Conglomerate of Hancock and Eby (1930), Murray (1966), Tweto (1975), the Ohio Creek Formation of Gaskill and Godwin (1963), and the unnamed basal Tertiary conglomerate of Johnson and Flores (2003). The tilted sandstone and conglomerate beds form prominent fins and hogbacks where they are well exposed along the western side of the Grand Hogback as it approaches the southern limb of the Sulphur Creek Syncline. The basal conglomerate hogback forms the highest ridgeline between Sulphur and Strawberry creeks in the north portion of the quadrangle. This conglomerate/Kwu disconformity is regionally widespread and marks the Cretaceous/Tertiary (KT) boundary. The authors found no indications of a precise KT-boundary lithofacies on this quadrangle. In the tilted exposures along the Grand Hogback, the late Cretaceous to early Paleocene Ohio Creek Conglomerate has disconformably scoured into underlying Kwu strata and, depending on the location and level of scour, either sandstone or mudstone occur below the disconformity. In those sandstone contact areas, there can be a thin discontinuous chalky-white kaolinitic zone at the scoured Kwu surface. The thick kaolinitic zones and paleosols described by Johnson and May (1980) and Johnson and Flores (2003) are not present in the Meeker area. Further to the north on the Meeker quadrangle the tilted conglomerate bed lies directly on Kwu mudstone.

The Ohio Creek Conglomerate facies is interpreted to mark the initial, Late Cretaceous, early-Laramide syntectonic interior basin deposition of coarse sediments eroding from the emerging basement-cored Gore/Sawatch Ranges to the east. Erosion into early Paleozoic and Precambrian basement provinces in the actively uplifted mountains to the east and southeast provided the coarse sediments to form an extensive syntectonic braidplain that scoured into, and was deposited on, the underlying Williams Fork surface. The Fort Union deposits reflect continued strandplain and paludal environments. This early Paleocene deposition predates the formation of the Grand Hogback monocline, and possibly the differentiation of the early eastern Laramide basin into the separate Piceance and Sand Wash Basins.

As mentioned earlier, palynological evidence supports the disconformity as closely marking the K/T boundary in the Meeker area. In his collection sites on the Meeker quadrangle, Newman (1965) noted that typical Cretaceous fossil pollen assemblages are found below the conglomerate and what appear to be Paleocene assemblages are found just above it. This has been confirmed by pollen samples collected for this mapping. Pollen from Kwu coaly shale 20 feet below the conglomerate base (TKoc) was identified as Late Cretaceous Campanian to Maastrichtian age while samples in drab-colored carboniferous shales immediately above the conglomerate bed yield P1 and P2, early to middle Paleocene, dates (Doug Nichols, written communication in **Appendix B** of this report). New palynological data from mapping the LO7 Hill quadrangle (White and Warden, in prep) just south of the Meeker quadrangle would appear to indicate that an undefined basal portion of the conglomerate remains late Cretaceous.

The laterally extensive Fort Union sandstones beds thin and disappear southward towards the White River water gap, and south of the gap this stratigraphic interval is progressively obscured and buried by valley-fill deposits. For convenience, this map is using the thick cover of alluvium at the White River water gap as an arbitrary southern boundary where mapping of the Fort Union Formation ceased and equivalent Paleocene-age strata has been included in the basal Wasatch Formation as was done in geologic maps of the Grand Hogback to the south. However, unlike the maps to the south, the Ohio Creek Conglomerate remains a distinct and mappable unit (Tweto, 1975) so it continues to be separated from basal Wasatch strata. The package of rocks that include basal Tfu and TKoc units is coeval with the lower Wasatch Formation of the southern Piceance Basin as it was mapped further to the south along the Grand Hogback, including an unnamed Paleocene gravel defined by Johnson and Flores (2003).

WASATCH FORMATION (LATE PALEOCENE TO EOCENE)

The Wasatch Formation was mapped as a single undifferentiated unit on the Meeker quadrangle. The formation top contact occurs outside of the Meeker quadrangle on the adjacent Buckskin Point quadrangle (Pipiringos and Johnson, 1975). The formation is poorly indurated and generally erodes easily. Exposures are generally obscured to very poor, except where more resistant channel sandstones form ridges. The unit is usually covered with variable thicknesses of valley-fill deposits (Qafo and Qaf), colluvial/alluvial slope-wash (Qaco and Qac), and unmapped regolith and topsoil. Preferential erosion of Wasatch Formation rocks has directed the longitudinal profile of the Strawberry Creek valley northward along the west side of the Grand Hogback from its confluence with the White River in Powell Park. The Wasatch Formation was deposited in fluvial systems in a broad alluvial plain within the Eocene synorogenic Piceance depositional basin as the Rocky Mountains continued to rise.

Tw **Wasatch Formation** — Banded gray-white, red, reddish tan, pink, yellow-gray, and purple sandy mudstone containing lenses and channels of sandstone. Mudstones are soft, and typically contain reddish paleosols horizons that give outcrops a banded appearance. Horizons of dark purple-blue siderite and iron nodules also impart a banded appearance. Sandstones are gray-white to orange-tan to tan and range from fine to coarse grained. Sandstones are generally friable but can contain calcareous beds that are much harder. Sandstones can contain pebbles, both dispersed and in thin conglomeritic lenses where clasts can be up to 4 inches in diameter. Pebbles are well rounded to rounded white, black, gray, and occasional red chert, as well as petrified wood, andesites, and orange-brown iron-stained clay rip-up clasts. Sandstone beds are predominantly cut-and-fill fluvial channels with curved bottoms that pinch out within the mudstone (**Figure 9**). Cross bedding is common. Sandstone outcrops also commonly exhibit soft-sediment deformation. Plant and wood fossil imprints are common, some of which are carbonized (black). The top of the Wasatch Formation does not occur on the Meeker quadrangle. Thickness within the map boundary is around 4,000 feet.

Figure 9. Typical channel sandstone in Wasatch Formation near axis of Sulphur Creek Syncline. Note termination of channel where sandstone pinches out into mudstone. Off-map flatirons in background are steeply dipping Fort Union Formation sandstone strata on northern limb of Sulphur Creek Syncline. [UTMX 247698, UTMY 4444681]

FORT UNION FORMATION (EARLY TO MIDDLE PALEOCENE)

Tfu **Fort Union Formation** — Orange-brown to buff to light gray sandstone and banded tan-brown, olive-brown, mustard yellow, gray-brown, to gray-black mudstone, carbonaceous shale, and lignitic coal. Unit contains three major ridge-forming sandstone beds composed of trough cross-bedded, moderately well sorted, medium to coarse sandstone with common clay rip-up clasts. Sandstones are commonly limonite stained, with some zones so heavy to becomes iron-oxide cement. Iron concretions are common, some are up to three feet in diameter. The base of the lowest sandstone bed contain sparse and discontinuous, thin (<6" thick), very coarse to gravelly lenses that contains mixed clay rip-up clasts and chert (<1 inch). Fossil wood casts and sand-filled molds are common. The three major sandstone beds are generally thick (25-45 feet) and laterally extensive, forming prominent fins and ridges on the west side of the Grand Hogback (**Figure 10**). Generally, the sandstone is noncalcarous, but can be moderately calcareous where the unit is more resistant.

Figure 10. Major sandstone beds of the tilted Fort Union Formation on the west side of the Grand Hogback. Lowlands to right is the Strawberry Creek valley that is underlain by Wasatch Formation. Lowest major sandstone is exposed as bare dip slope seen on left. Photo is taken from second major sandstone. [UTMX 247962, UTMY 4442955]

The slope-forming intervals between the major sandstone beds are composed of drab-colored banded mudstone, carbonaceous shale, lignitic coal, and thin beds of very fine to fine-grained sandstone that range from very friable yellow-white to gray-white, to better-cemented orange-brown color. Fossil plants occur in the thin sandstone beds, including large *Platanites marginata* leaf imprints identified by Ian Miller, Denver Museum of Nature and Science (written communication). Siderite concretions and cemented horizons occur in the mudstone, as do thin sandy fresh-water limestone. Pollen assemblages extracted from the carbonaceous shales and shaly coal above the Ohio Creek Conglomerate were identified as early to middle Paleocene, biozones P1 and P2 (**Figure 11**). Other samples from stratigraphically higher, between the prominent sandstone beds, had pollen dated at middle Paleocene, Zone P3 (Doug Nichols, written communication in appendix). Approximate thickness of this unit is 1,250 feet.

Figure 11. Basal drab-colored shale interval in Fort Union Formation between Ohio Creek Conglomerate and lowest major sandstone unit. Coal seam on right (arrow) is where fossil pollen sample #368 was taken. Rocks are dipping about 35°. [UTMX 247412, UTMY 4441001]

OHIO CREEK CONGLOMERATE (LATE CRETACEOUS TO EARLY PALEOCENE)

TKoc **Ohio Creek Conglomerate** —Tan to gray, conglomerate with a very coarse grained sand matrix. Clasts sizes are typically pebble but small cobbles (<6 inches) are common. Unit also contains thin beds and lenses of well-sorted very-coarse-grained to granule sandstone with dispersed pebbles. Unit is generally well cemented and forms ridgelines. Casts of petrified tree branches are common in the gravel (**Figure 12**), Clasts are well rounded, multicolored, and include black, gray, red, and white chert, tan to brown petrified wood, and pink to red andesites. Also fairly common were white to pink quartzites and arkosic quartzites that have been identified by the authors as originating from the Cambrian Sawatch Quartzite. While less common, early Paleozoic and Precambrian pebbles were also identified, including crystalline metamorphic and granitic igneous rocks, and early Paleozoic silicified algal limestone. Rare fossilized bone fragments were also noted. This unit scours into and disconformably overlies the upper Williams Fork Formation (Kwu). The conglomeritic unit was measured at a maximum thickness of 65 feet.

Figure 12. Underside of steeply dipping Ohio Creek Conglomerate. Note linear mold of fossil branch on bottom left of outcrop (arrow). Inset photo shows close-up taken at arrow location. [UTMX 246740, UTMY 4435174]

WILLIAMS FORK FORMATION (UPPER CRETACEOUS)

The Williams Fork Formation was deposited in terrestrial coastal plain and near-shore estuary environments. In the Meeker quadrangle the Williams Fork Formation has been subdivided into an upper unit (Kwu), the Lion Canyon Sandstone Member (Kwlc), and a lower unit (Kwl). The Lewis shale is not present in the Meeker area as the Cretaceous paleoshoreline was further northeast. The seaway did transgress into the Meeker area briefly when the middle marine unit of the Lion Canyon Sandstone was deposited. The Lance Formation is equivalent to the upper Williams Fork Formation above the Lion Canyon Sandstone. Palynological data in Newman (1965) strongly suggest an age correlation between the lower Lance Shale near Hayden and the upper Williams Fork at Meeker.

Kwu **Williams Fork Formation, upper part** — Interbedded gray to dark gray mudstone, buff to tan sandstone, brown carbonaceous shale, and minor coal deposited in terrestrial near-shore and coastal-plain environments. This unit correlates with the Lance formation to the northeast, across the Axial Basin Uplift. The top of this unit has been differentially eroded prior to the nonconformable deposition of the Ohio Creek Conglomerate. At the base of the unit near the contact with the Lion Canyon Sandstone Member, a package of coal seams exists that Hancock and Eby (1930) call the Lion Canyon coal group. Petrified wood and unidentified fresh to brackish water oyster fossils were noted near coal beds, as was the ichnofossil *Teredolites* (**Figure 13**). At the disconformity with the overlying Late Cretaceous to Paleocene conglomerate, if the lithofacies is sandstone, there may be a thin (<5 feet) chalky-white friable kaolinitic zone. Fossil pollen from a Kwu coaly shale sample, 20 feet below the disconformity with the Ohio Creek Conglomerate base, was identified as Campanian to Maastrichtian (Doug Nichols, written communication in **Appendix B** of this report). Thickness ranges from 1,300 to 1,600 feet.

Figure 13. Wood-boring *Teredolites* trace fossil in base of sandstone bed in upper unit of Williams Fork Formation exposed near entrance of Coal Canyon. [UTMX 246905, UTMY 4434935]

Kwlc **Lion Canyon Sandstone Member** — The Lion Canyon Sandstone is divided into three units; upper and lower thickly bedded, buff to light gray, well sorted, cross-stratified, fine to medium-grained sandstones that are separated by a middle interval composed of thinly interbedded finer-grained sandstone and mudstone (**Figure 14**). The upper major progradational sandstone of this unit correlates with the Fox Hills Sandstone across the Axial Basin Uplift (Brownfield and Johnson, 1984). The thickness of the Lion Canyon Sandstone varied from 170 feet to 290 feet. The top sandstone (Fox Hills equivalent) is 75 feet thick and generally thick bedded but contains hummocky, thinly bedded to interlaminated zones with bioturbated mudstone and heavy concentrations of marine ichnofossils. The 35 to 50-foot-thick middle zone consists of thinly interbedded very-fine-grained tan sandstone, gray sandy mudstone, and dark gray shale that were deposited in a near-shore marine environment. This middle unit has been correlated as the westward terminus of the Lewis Shale marine transgression (Brownfield and Johnson, 1984, and Brownfield and others, 2000). The basal sandstone interval is another thickly bedded, fine- to medium-grained sandstone unit that is over 60 feet thick, which marks the conformable shoreface transgression of the seaway over the lower Williams Fork terrestrial deposits. In the map area, the middle, thinly interbedded, marine section of Kwlc thins to the south as the entire unit progressively thickens to about 290 feet.

Figure 14. Exposure of Lion Canyon Sandstone in Sulphur Creek valley. For scale, field geologist is shown by circled area in middle. This middle unit is composed of marine sandstone and interbedded shale that is more of a slope former. Thickness at this location is 170 feet. [UTMX 250539, UTMY 4444085]

Kwl **Williams Fork Formation, lower part** — Interbedded buff to tan sandstone, gray siltstone, dark gray clay shale, red clinker, brown carbonaceous shale, and coal. This unit rest conformably on the Trout Creek Sandstone. There are two coal groups within the lower Williams Fork Formation; the upper Goff Group and the more significant basal Fairfield Group (Hancock and Eby, 1930). Within and above the Fairfield Coal Group there is an extensive zone of red clinker that is shown on the map as the Fairfield Coal Group Clinker Zone. This deformed, baked and fused rock zone, related to the burning of coal beds, is more resistant to erosion and supports the highest ridge of the Grand Hogback where the radio towers and FAA facilities are located. Within this Fairfield clinker zone, the Yampa bed was observed approximately 325 feet above the top of the Trout Creek (Kit) Sandstone . The altered volcanic ash deposit described by Brownfield and Johnson (2008) has been further altered by coal burning to a yellow-cream to peach colored porcellanite. The Yampa bed was dated at 72.5±5.1 Ma using K-Ar methods on andesite minerals (Brownfield and Johnson, 2008). Above the Fairfield clinker zone, the Kwl unit becomes increasingly finer-grained mudstone with fewer and thinner sandstone beds. Easily eroded, this interval underlies the valleys of the east and west forks of Lion Canyon and where Sulphur Creek doglegs northward from where the lower valley followed the Sulphur Creek fault. Where steeply dipping along the Grand Hogback, this interval is also prone to instability and dip-slope landslides are common. A fossil assemblage of fresh-water mollusks was found in lower unit sandstone that were identified as the pelecypod *Proparreysia letsoni* and the gastropod *Campeloma sp.* (W. Cobban, written communication in appendix A). Thickness of the lower Williams Fork is about 3,000 feet.

ILES FORMATION (UPPER CRETACEOUS)

The Iles Formation represents a major depositional cycle where sediments changed from shallow-marine lithofacies to progradational shoreface and coastal-plain lithofacies, and then back to a marine depositional setting. This cycle reflects the first major regression and transgression sequence of the Cretaceous Western Interior Seaway in the map area. Terrestrial coastal-plain sediments, sourced from the Sevier orogenic belt to the west and northwest, were conformably deposited onto the Mancos Shale as the Cretaceous seashore regressed southeastward. Estuarine, deltaic, and swamp conditions occurred where coal could form. Marine interbedded shale and sand below the Trout Creek Sandstone Member marks the end of this cycle as the Cretaceous seaway, through a combination of eustatic sea-level rising and subsidence of the Cretaceous coastal plain, again transgressed westward over this package of terrestrial sediments. The base of the Iles Formation was selected at the first thin sandstones seen of a basal progradational shoreface sandstone sequence that occurs on the Mancos Shale. The top of the Iles Formation is the distinctive and easily traced Trout Creek Sandstone member. The thick sandstone units of the Iles Formation mark the eastern edge of the Grand Hogback ridgeline and form the major rim rock escarpment above the town of Meeker. Thickness of the Iles Formation is about 1,250 to 1,500 feet.

Ki **Iles Formation** — Interbedded sandstone, mudstone, clay shale, carbonaceous shale, and coal. The base of the Iles is composed of prominent ridge-forming sandstones that mark three to four progradational shoreface sequences. These sequences are composed of basal thin bedded sandstone interbedded with mudstone; transitioning to thicker beds of coarser-grained hummocky to trough cross-bedded sandstone; thinly bedded mudstone and carbonaceous shale; and minor coal. The coal zone is referred to as the “Lower Coal Group” by Hancock and Eby (1930). Tidal deposits were noted in the major sandstones that contained both marine mollusk fossils, mudstone rip-up clasts, and petrified wood and plant fragments. The upper section of the Iles is finer grained, which reflects a cyclic coastal swamp, tidal-influenced estuary, and lower-energy fluvial environments. Sandstone beds are thinner, becoming interlaminated with mudstone, with channel cuts and fills. Some thicker sandstones beds have soft-sediment deformation. Several thin coal beds exist in this unit, referred to as the “Black Diamond Coal Group” by Hancock and Eby (1930) after the Black Diamond Coal Mine located up Anderson Gulch near the town of Meeker. Sporadic red clinker zones also occur in the upper section of the Iles related to these coal beds. Below the Trout Creek Sandstone Member, the Iles Formation becomes increasingly shaly, related to a major Late Cretaceous marine transgression. This marine shale unit is better developed in the Rifle area and Yampa Coal field region where it is referred to as the Tongue of Mancos Shale. Thickness of the Iles Formation ranges from 1350-1500 feet, including the Trout Creek Sandstone member.

Kit **Trout Creek Sandstone Member** — Very light gray to gray-white, fine to medium grained, moderately well sorted, cross-stratified sandstone. The sandstone is predominantly noncalcarous and somewhat friable with common orange-tan staining. In outcrop, the unit has a general rounded, massive appearance, compared to the more angular, blocky outcrops of the lower Iles Formation sandstone beds (**Figure 15**). The Trout Creek Sandstone is a prominent gray-white ledge former that is very conspicuous and easily traceable along the Grand Hogback in the Meeker area. Maximum thickness measured was 90 feet.

Figure 15. Typical exposure of Trout Creek Sandstone. Location is in Ryan Gulch northeast of Meeker. [UTMX 254275, UTMY 4443319]

MANCOS SHALE (UPPER CRETACEOUS)

The Mancos Shale was deposited during the marine transgression of the Cretaceous North American Western Interior seaway with member subunits deposited in various deep shelf, shelf-bar, and near shore environments. Surface exposures of the Mancos Shale were generally poor on the Meeker quadrangle because the shale is easily eroded and there is widespread cover of Quaternary terrace gravels, alluvial fans, and other types of valley-fill sediments. Exposures improve on the slope below the Iles Formation escarpment, and those sandstone members resistance to weathering that have created hogbacks and subdued ridgelines where they are exposed east of the Grand Hogback Monocline. For most units, there are diagnostic lithologic changes where unit boundaries were located. However, there was some estimation of contacts between the varied members where exposures were poor, the contact is gradational, or the contact was covered by surficial deposits. From youngest to oldest, the mapped Mancos Shale members include undifferentiated upper Mancos Shale, Loyd Sandstone, Morapas Sandstone, Meeker Sandstone, Prairie Canyon, Smoky Hill , and the Frontier (sandstone facies).

Kmu **Mancos Shale, upper unit** — Gray to dark gray, non calcareous shale and claystone with minor sandstone in the upper part of the unit and orange-tan limey concretions. This unit is undifferentiated shale that exists between the contact of the overlying Iles Formation and the top of the sandy Prairie Canyon Member. It contains marine sandstone members in the upper part of the Mancos Shale: the Loyd and Morapas. There are other unnamed tan noncalcarous marine sandstone within this unit that are poorly exposed or occur as sporadic lenses. Fossil marine shell fragments were found in certain beds, as were oscillating ripple marks and animal-burrow ichnofossils. A terrestrial seed pod was recovered from one cross-laminated very-fine grained sandstone 20-30 feet below the contact with the Iles Formation. A very dark gray claystone interval occurs between the Prairie Canyon and Morapas Sandstone, characterized by large limonite-stained calcareous concretions and high percentages of swelling clay minerals. This unit, a valley former and very poorly exposed, appears to share lithologic similarity with the Sharon Springs Member in the same stratagraphic interval in west-central Colorado (Noe and others, in prep). This stratigraphic interval is buried along the floor of Fourmile Gulch. The thickness of this unit from the base of the first Iles sandstone to the approximate top of the Prairie Canyon Member is 1,700 feet, including the upper Mancos sandstone members (**Figure 16**).

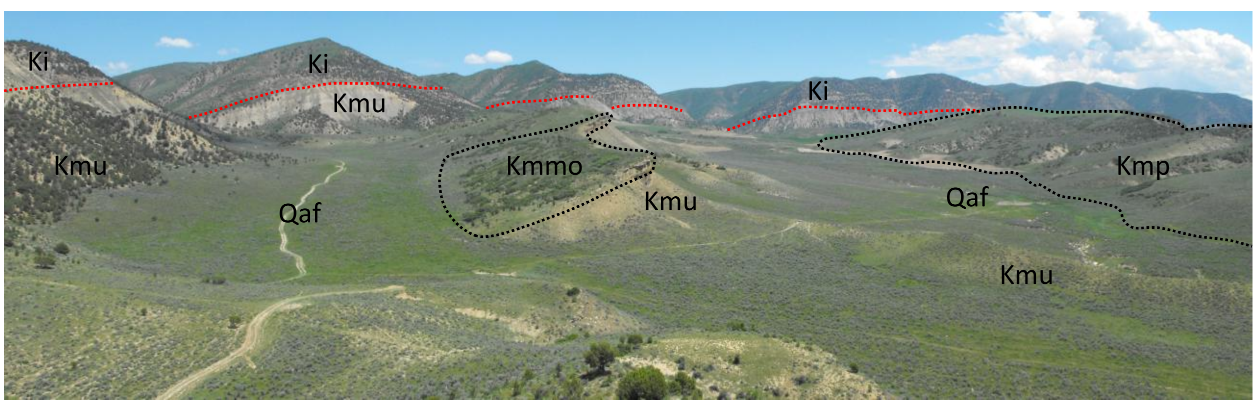

Figure 16. Typical erosional profile of the upper Mancos Shale in Fourmile Gulch. The dipping upper Mancos Shale (Kmu) is mostly covered by valley fill (Qaf) except where protected by the Iles Formation (Ki) escarpment (red dashed line) or the Morapas Sandstone (Kmmo) hogback in center of photo. Low hills on right are dip slopes of more resistant, sandy, Prairie Canyon Member (Kmp). [UTMX 253044, UTMY 4439894]

Kmlo **Loyd Sandstone Member** — Green-gray to olive-tan with orange-tan staining, non to moderately calcareous, sandstone and minor mudstone. Unit weathers tan-gray to orange-brown in outcrop. Near the town of Meeker this sandstone has two sharply contrasting marine lithofacies. The upper unit is interbedded to interlaminated tan sandstone and dark gray shale. The lower unit is a massive, greenish gray, moderately calcareous, very fossiliferous, very fine to medium-grained sandstone that fines downward to a shaly coarse siltstone. The upper interbedded sandstone beds are well sorted, non calcareous, but better indurated. The beds range up to eight inches in thickness and typically exhibit hummocky cross-laminations and oscillation-ripple laminations. Sandstone beds may thin and become interlaminated with mudstone. Upward in the unit the sandstone beds become fewer and thinner, separated by thicker beds of mudstone. The top was chosen where the first well developed tabular sandstone bed was observed in outcrop. The upper unit lithology closely approximates the description by Boyles and Scott (in Boyles and others, 1981). The lower unit exhibits no distinct bedding, likely from bioturbation and closely approximates the description in Dyni and Cullins (1965) and Kiteley (in Boyles and others, 1981). It is typically less indurated, and very fossiliferous with marine fossils dispersed in the sand matrix and clumped in brown calcareous concretions. Several articulated inoceramid bivalves were collected that were identified belonging to the *Cataceramus subcompressus* Western Seaway Inoceramid Interval Zone of the Middle Campanian Series (W. Cobban, written communication in appendix A). *Baculities sp.* fragments were also found. Unique to the lower unit of this Mancos member sandstone is its weathering profile. Where exposed in outcrop, the lower unit weathers to either a rounded lump-like mass or a nodular/spheriodal appearance. (**Figure 17**) . Outcrops of this unit are generally obscured or only poorly exposed on steeper slopes below the Iles Formation escarpment (**Figure 7**). In many areas it is buried by thin unmapped colluviums, regolith, and slope-hwash sediments. This unit is mapped only by a line trace where reliable exposures could

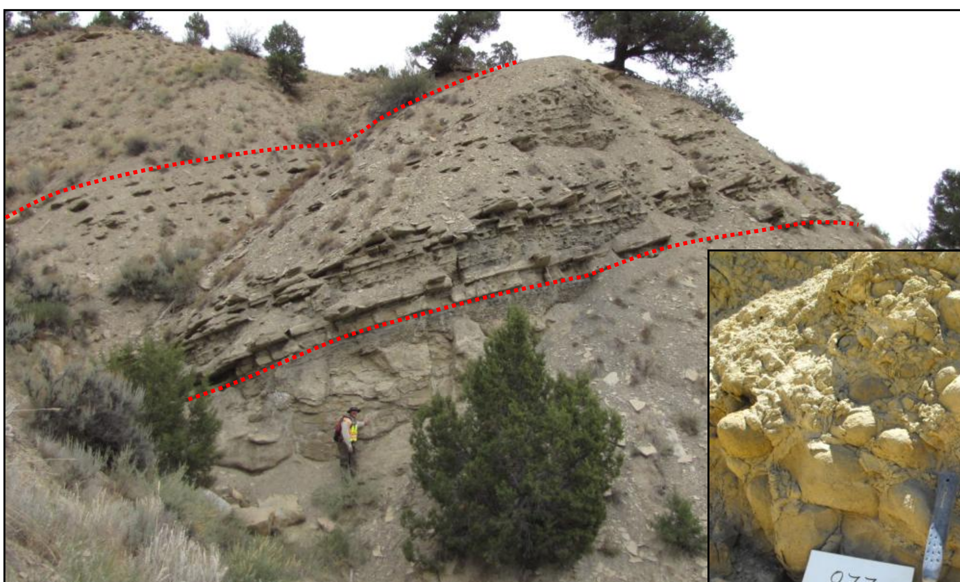


Figure 17. Outcrop of Loyd Sandstone above town of Meeker. Red dashed lines show top of interbedded sandstone unit and top of massive bioturbated unit below where field geologist is standing [UTMX 250596, UTMY 4436790]. Inset photo shows typical spheriodal weathering of the lower massive unit. [UTMX 254766, UTMY 4442188]

be determined. The trace line approximates the contact between the lower massive sandstone and the interbedded sandstone and shale unit above. Upper unit and lower units thickness are variable and appear to be based on the extent of bioturbation where exposed elsewhere in the map area. Average unit thickness is about 40 feet.

Kmmo **Morapas Sandstone Member** — tan to buff to tan-gray slightly calcareous marine sandstone that occurs as two distinct coarsening upwards sequences (**Figure 18**). This coarsening upwards sequence begins with the upper Mancos Shale. The shale transitions to bioturbated silty to sandy mudstone interlaminated with poorly to moderately sorted, very fine grained, sandstone and sandy mudstone. Upwards, the sandstone beds become more numerous and thicken, becoming well sorted, medium grained, sandstone that exhibits both hummocky cross-stratification and tabular to trough cross-bedding. There are common mud rip-up clasts in the coarser sandstone intervals. The second coarsening upwards sequence is in a similar facies system but the mudstone base is much sandier. The shale just above the top of the Morapas Sandstone contains small plant fossils along bedding planes. Baculites fossils collected from a concretion in upper Mancos Shale (Kmu) approximately six feet above the top of this sandstone was identified belonging to the *Baculites obtusus* Ammonite Taxon Range Zone in the lower Middle Campanian Series by Cobban (written communication in **Appendix A**). The Morapas Sandstone is wholly enclosed within the upper Mancos Shale. It has been interpreted to have been deposited in a marine shelf-bar environment. This unit was measured at 42 feet thick.

Figure 18. Two locations of the Morapas Sandstone ridgeline in Fourmile Gulch, northeast of Meeker. Note the two distinct upward-coarsening sequences in outcrop. [UTMX 253689, UTMY 4440454]

Kmme Meeker Sandstone Member — tan to tan-gray, rarely red stained, non to slightly calcareous, very fine to medium grained, wavy to cross-stratified marine sandstone and interlaminated bioturbated gray sandy mudstone. Individual sandstone bed thicknesses range from laminations to 8-10 inches. The Meeker Sandstone contains up to four upward-coarsening sequences similar to the Morapas Sandstone but do not appear to be continuous or don't outcrop as well. The thicker, coarser beds become medium grained with tabular and trough cross bedding. Individual beds generally do not exceed 12 inches in thickness. Marine mollusk fossil shell fragments were seen, and marine animal burrow and track ichnofossils are abundant. Northeast of Meeker, the thickest sandstone forms a prominent hogback ridge northeast of town above the airport. The thin bedded to wavy interlaminated nature of the sandstone is also well exposed at the County Road 14 roadcut near the bridge crossing the White River. The Meeker Sandstone is a geographically restricted shelf-bar sand facies that lies entirely within the Prairie Canyon Member. Its top and bottom boundaries are gradational. The type section of the Meeker Sandstone is just east of the quadrangle boundary where State Highway 13 passes through the sandstone cuesta. At that location, the Meeker sandstone was reported as 180 feet thick (Dyni and Cullins, 1965). Near the town of Meeker, only one coarsening upwards sequence is exposed on the ridgeline above town and at that location it is only about 25 feet thick. At that location above the new elementary school (under construction in 2009), the exposed sandstone includes a lenticular siliceous zones that crosses primary bedding (**Figure 19**).

Figure 19. Meeker Sandstone. Left image shows coarsening upwards of sand and siliceous zone (arrow) in lower interlaminated muddy zone [UTMX 252324, UTMY 4437066]. Image on right shows most developed sandstone interval in map area. [UTMX 253468, UTMY 4438710]

Kmp Prairie Canyon Member — Dark gray to tan-gray, noncalcareous, platy, sandy to silty, bioturbated marine shale with interlaminated, buff to tan-gray, very fine-grained, non to moderately calcareous, sandstone. There are occasional thin bentonite beds. The sandstone is usually interlaminated, but in some strata it thickens to discontinuous lenses up to 1.5 inches thick. Ripple marks form lenticular "pinch-and-swell" changes in bed thicknesses. Marine mollusk fossil fragments are rare. There is usually very common marine animal burrow ichnofossils in the sandstone beds, including *Ophiomorpha isp*. Some carbonized plant fragments were seen in the upper part of the unit above the Meeker Sandstone lentil. The main field identifier of the Prairie Canyon Member is sandstone chips and thin slabs that litter ground exposures. These sandstone fragments are not seen in the underlying Smoky Hill Member or the overlying undifferentiated upper Mancos Shale. Where the sandstone beds thicken, there is generally an increase in topographic relief (low hills as shown in Figure 12). At those locations, small (<6-inch dia.) slabs of thin sandstone typically litter the slopes. The Meeker Sandstone is wholly enclosed, stratigraphically, within the Prairie Canyon Member. Top and basal contacts of the Prairie Canyon were obscured on the Meeker quadrangle and were estimated based on the first notice of sandstone chips in slope float and increase in calcareousness of the underlying Smoky Hill shale.

The unit is equivalent to the sandy Mancos "B" interval in the Douglas Creek Arch area (Kellogg, 1977), the Prairie Canyon Member (Cole and others, 1997) in the Book Cliffs area, and to the Cortez Member (Leckie and others, 1997) in southwestern Colorado. The thickness of this unit is approximately 1,700 feet, including the Meeker Sandstone lentil.

Kms **Smoky Hill Member** — Light gray to very dark gray, calcareous shale, marlstone, and shaly limestone. The upper contact with the overlying Prairie Canyon Member is marked by a cessation of interlaminated very fine-grained sandstone and silty mudstone and a transition to very calcareous, homogeneous, fissile to platy, shale with common *Inoceramus sp.* fragments; the larger fragments of which are typically encrusted with *Pseudoperna congesta* oysters. Bentonite beds occur and there can be stratigrahic intervals with high percentages of swelling-clay minerals. In the middle and lower intervals, the shale becomes increasingly limy, becoming argillaceous limestone with a speckled appearance from ostracode fossils. Where limy, the shale exposures become increasingly blocky and weather with a subspheroidal appearance. Discontinuous slabs of secondary very-coarse crystalline calcite also occur along bedding planes, up to two inches in thickness. The last prominent limestone bed near the base of the unit is considered the Fort Hays Limestone equivalent along the Front Range of Colorado. Below this prominent limestone is a thin basal interval of dark gray to gray-black shale that is equivalent to the Carlile Shale along the Front Range.

In most surface exposures, the shale is highly fractured with common crystalline gypsum (selenite) fracture filling. Where secondary gypsum is heavy, the shale has a tan-brown staining.

Pseudoperna congesta fossils were identified by Cobban (written report in **Appendix A**). This oyster and the *Inoceramus sp.* fragments it encrusts are good index fossils for the Cretaceous late Coniacian and early Santonian Stages. This fossil assemblage is also seen in the Smoky Hill Member at Mesa Verde in southwestern Colorado (Leckie and others, 1997), the Uncompahgre and Gunnison valleys (Noe and others, in prep; Morgan and others, 2008; and White and others, 2008), as well as in the Grand Junction area (Livaccari and Hodge, 2009). Petroliferous odor was noted when the large *Inoceramus sp.* fragments were broken to reveal the prismatic crystalline structure.

Along the Front Range the Smoky Hill Member is stratigraphically equivalent to the Niobrara Formation, which includes the upper Smoky Hill member, the Niobrara limestone, and the basal Fort Hays limestone. The depositional environment of this unit is considered the deeper shelf of the Cretaceous North American Western Interior seaway. The larger inoceramid fossil fragments in the Smoky Hill are petroliferous and breaking the fragments to reveal the prismatic crystalline structure releases a strong oil odor. The lower limy interval is of interest to oil and gas exploration using horizontal well-completion techniques. For this reason, most oil and gas wells in the Meeker area refer to the lower shaly limestone as the Niobrara Formation in their stratigraphic picks. The thickness of this unit is approximately 2,300 feet.

Kmf **Frontier Member (sandstone facies)** — Buff to tan to gray sandstone, and minor olive-tan gray mollusk-shell calcarenite interbedded with dark gray to gray-black noncalcareous fissile shale. The unit contact with the overlying Smoky Hill Member is marked by the first occurrence of thin beds of calcarenite and very calcareous gray sandstone interbedded in shale. The fossil "hash" in the calcarenite is composed of broken and intact marine mollusk shells that range in size from coarse sand to shells three inches long. *Prionocyclus sp., Lopha sp.*, and Inocermid fragments were seen. The collection of a *Nacaisolopha lugubris* fossil was identified by W. Cobban (see written report in appendix A) and indicates a biostratigraphic equivalent to the Juana Lopez Member of southwest and west-central Colorado Mancos Shale (Scott and others, 2001). Lithology and fossil content of the upper thin calcarenite beds are also similar to the Juana Lopez calcarenite described in the Uncompahgre and Gunnison valleys (White and others, 2008, Noe and others, in prep.).

With stratigraphic depth, the calcarenite and calcarenitic sandstone is replaced by thicker beds of tan to dark gray, moderately sorted, fine-grained, noncalcareous, marine sandstone interbedded with thinner beds of dark gray to gray-black noncalcareous shale. Shale can become only wavy interlaminated partings within the sandstone. The sand is tightly packed with predominantly subrounded to subangular, clear to cloudy, white quartz grains and rare pink grains. Abundant small black grains or pellets give the sandstone a salt-and-pepper appearance under the microscope. The sandstone may be cross-stratified, contains oscillation ripple marks, and locally abundant horizontal and vertical animal burrow ichnofossils (*Thalassinoides isp., Planolites isp., Skolithos isp.*). Sole mark sedimentary structures are also common, mostly flute and groove casts on the underside of individual sandstone beds. The cleaner, better-sorted sandstone beds contain much fewer marine fossils. With increasing depth in the unit, the sandstone becomes increasing gray and finer-grained, becoming a muddy siltstone with increasing thicknesses of interbedded dark gray to gray-black shale. A prominent horizon of large limy, tan-brown concretions occur where the Frontier becomes mostly shale. The Frontier sandstone is found in the Meeker quadrangle in two locations: 1) as dip slope exposures along the southern map boundary and in excavations for Miller Creek Ditch, and 2) an exposure along the north side of the White River on the east map boundary, as strata begins to rise towards the Meeker Dome on the Rattlesnake Mesa quadrangle (White and others, in prep.).

STRUCTURAL GEOLOGY

The main structural feature in the Meeker quadrangle is the Grand Hogback. This major monoclinal fold is considered the structural boundary between the Colorado Plateau and the Southern Rocky Mountain provinces (Fenneman and Johnson, 1946). It marks the deformation boundary of the White River Uplift, a part of the Laramide orogenic belt in Colorado (the modern-day Rocky Mountains), and the Piceance syntectonic basin. Near the north boundary of the quadrangle the Grand Hogback monocline ends against the southern limb of the Sulphur Creek Syncline. The axis of this asymmetrical syncline, from where it is mapped in the northwest corner of the Meeker quadrangle, runs west to east just north of the Meeker quadrangle boundary. At this structural interface, the major ridge-forming strata of the lower Williams Fork and Iles formations transition from a south-north strike, dipping to the west, to an east-west trend with a dip direction to the north. The syncline plunges to the west so prominent ridges of Lion Canyon Sandstone, Ohio Creek Conglomerate, and Fort Union and Wasatch sandstones within the map boundary dog-leg around the syncline axial limbs from a northeast strike to a northwest strike (as shown by background flatirons in **Figure 9**). This linear trend of outcrops continue northwestward to the Danforth Hills-Wilson Creek anticlinal structure (Izett and others, 1985). These fault-propagation fold structures are part of the Danforth Hills-White River Uplift basement-involved thrust-fault structural trend along the northeastern boundary of the Piceance Basin that extend to the Uinta Mountains from the White River Uplift (Stone, 1990).

Where the Grand Hogback ends, several accommodation faults were created where dips flattened and strata were structurally deformed by curvature to the east. Two major faults with the most displacement have been previously mapped by Hancock and Eby (1930) and Murray (1966), and are also shown on the Craig 1:250,000-scale geologic map (Tweto, 1976). The most prominent is the Sulphur Creek fault that controls the location of the lower Sulphur Creek valley. The normal Sulphur Creek fault has approximate 200 feet of throw and may have a left-lateral (sinistral) oblique-slip component (**Figure 20**). The other fault, approximately 3,000 feet to the south, has a normal throw of about 40 feet. Where this fault intersects another inferred shear zone that is concealed by Threemile Gulch, the Lion Canyon Sandstone strata has been overturned and dips to the east. This overturning of strata is likely the result of recent gravitational deformation in response to downcutting of the Threemile Gulch drainage and rotational creep of this fault-bound rockmass. Both prominent faults die out within the upper Mancos Shale at the confluence of Sulphur Creek and Fourmile Gulch and could not be reliably traced to small-scale faulting in the Meeker sandstone ridgeline. These and other low-displacement near-vertical normal faults and shear zones are generally perpendicular to the strike and tend to radiate like spokes of a tire where the regional strike curves to the east. Some are simple normal faults while others show some localized drag folding within a boarder shear zone as the strata was wrenched to curve to the east. A small-scale compressional thrust fault is seen in outcrop in the Meeker Sandstone below the Meeker cemetery near the bridge crossing the White River. Many of these minor displacement faults (<6 feet) are difficult to see. Minor offsets are only discernible in sandstone exposures along rim rock sandstone beds of the Iles Formation, and the Morapas and Meeker ridgelines in the Mancos Shale.

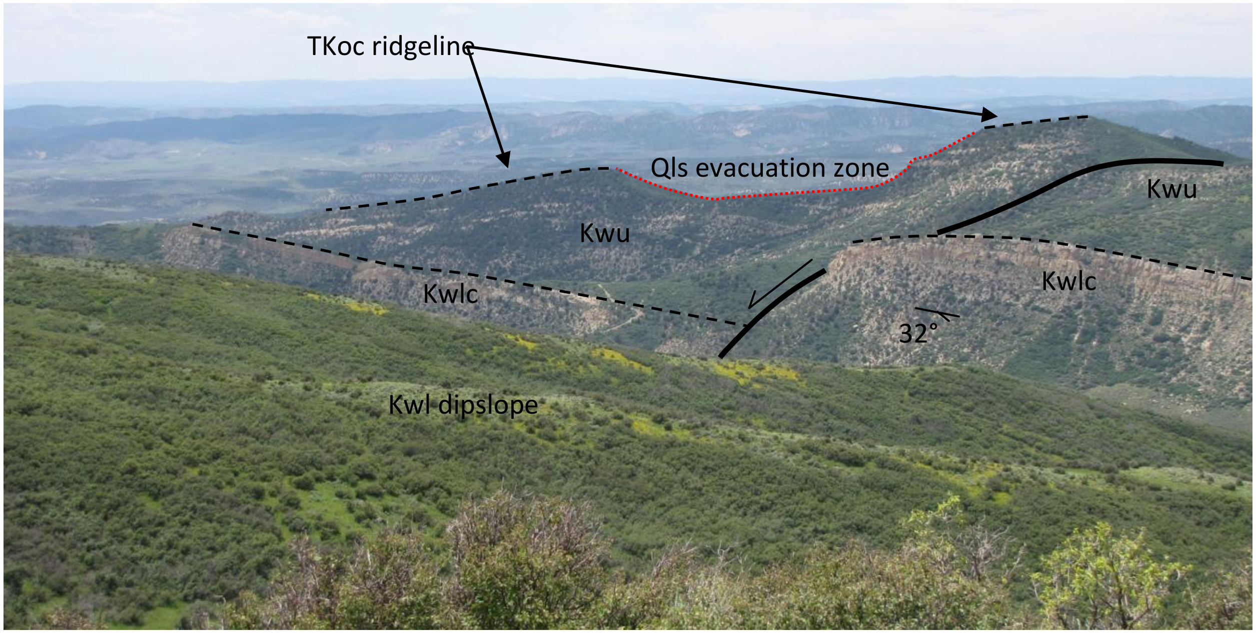

Figure 20. View west to southwest of Sulphur Creek fault offsetting Lion Canyon Sandstone (Kwlc). Highest ridge is capped by the Ohio Creek Conglomerate flatiron (TKoc) except at bowl (red dotted line) where large dip-slope landslide occurred on back side of hogback. Formation tops shown by black dashed lines. Background horizon is the Tertiary Uinta and Green River Formations in the Piceance Basin. Sulphur Creek valley is hidden by foreground slope of lower Williams Fork Formation (Kwl). Swales in foreground slope contain dipslope landslides. [UTMX 252916, UTMY 4443550]

Comparative measurements of strata across the White River water gap indicate spatial displacement between the north and south sides of the gap, and strongly suggests that a fault controlled the location of the water gap. Burial and concealment by river alluvium allows only an approximation of the fault location on the map, as well as the extent of the fault into Agency and Powell parks. It is unknown whether this fault is normal or left-lateral oblique slip.

Another structural change in the Meeker quadrangle is along the lower easternmost edge of the map area where strata have begun to deform as they rises to the Meeker Dome structure that lies on Rattlesnake Mesa quadrangle to the east. Notable changes in strike and dip of strata were seen in this area and paired anticline and syncline axes from recent mapping of Rattlesnake Mesa extend westward onto the Meeker quadrangle (White and others, in prep.).

The rock along the Grand Hogback has pronounced near-vertical jointing (J1) that is approximately normal (range is 75° to 120°) to the strike. The J2 joint pattern is orthogonal to J1, oriented about 100° from it. Jointing orientation is best seen on dip slope surfaces of resistant sandstone where erosion has stripped away overlying strata (**Figure 21**).

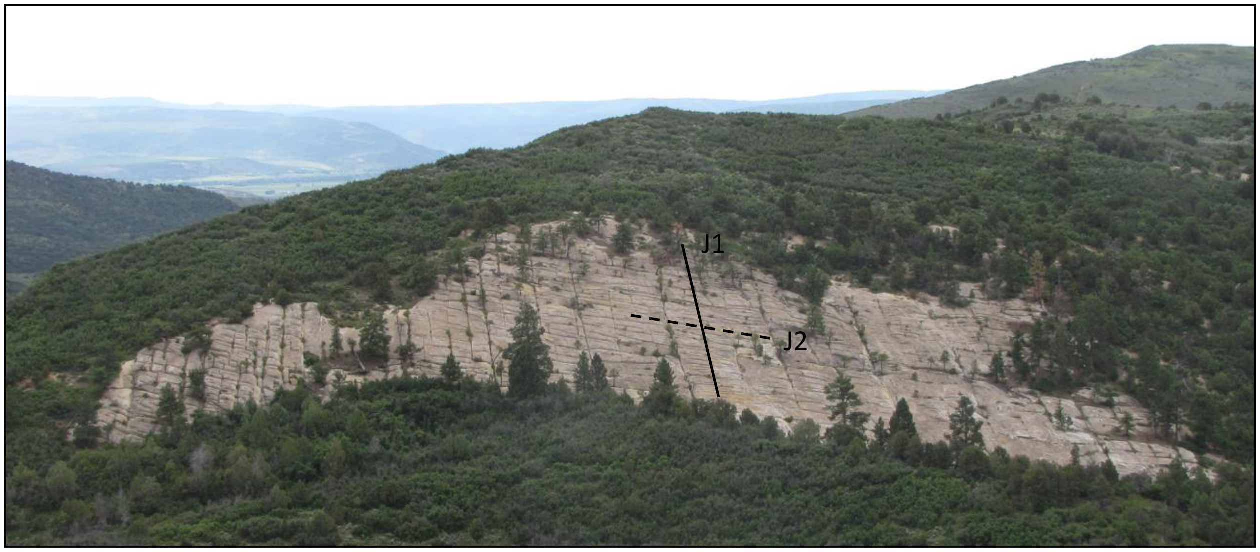

Figure 21. Lion Canyon Sandstone dipslope showing orthogonal jointing. The near-vertical J1 set is wider spaced but more persistent, oriented at 325° (solid line). The J2 set is fainter but tighter spaced, oriented at 224° (dashed line). Strike and dip at this location is 208°, 27°.

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GEOLOGIC HAZARDS

Geologic hazards are adverse geologic conditions or a natural geologic event that can either endanger human lives or threaten human property. Bedrock structure, hydrology, topography, surface drainage, lithology, depositional processes, soil development, and clay mineralogy are important controls on the development of geologically hazardous areas within the Meeker quadrangle. In this section of the Author's Notes, the term "soil" is used in the geotechnical or civil engineering sense to describe an unconsolidated geologic material or nonlithified sediment. Landslides, debris/mudflows, hydrocompactive (collapsible), and swelling soils have the most potential to impact infrastructure and residential and commercial structures in the Meeker area. Other significant and potentially damaging hazards in the mapped area include rockfall, and corrosive and erodible soils.

Landslides

Landslides occur in the Meeker quadrangle in three major geomorphic conditions: 1) along the mesa edges underlain by Mancos Shale in the White River Valley and 2) dip-slope failures in steeply dipping interbedded bedrock within the Grand Hogback ridges, and 3) saturated weak zones in sandy clay deposits in mud-flow alluvial fans.

In the recent geologic past during the Quaternary Period, downcutting and lowering of stream levels was punctuated by periods of river gravel deposition on weathered Mancos Shale. Topographic reversal occurs when successive downcutting of the White River erodes the surrounding weaker shale and leaves the area with a gravel cap to form mesas. Landslides are prevalent on the steeper slopes that flank these gravel-capped mesas. The slope failures are mainly rotational and translational slides where shearing failure typically occurs within the heavily weathered, fractured, and weakened shale. Accelerated ground creep and earth flows may also occur if slopes become fully saturated. Ground water infiltrates through the permeable gravel that caps the mesas and perches on the more impermeable shale. The groundwater flows laterally to the flank of the mesa where springs and ground seeps occur. Unlined irrigation canals also contribute seasonal water to the steeper mesa slopes. Water slowly seeps into the shale causing further weakening of the bedrock by additional weathering, increased pore pressure, and/or dissolution of gypsum fracture filling. Pore pressure and weathering of the shale meet a threshold where steep slopes are unable to support themselves and the earth materials begin to shear and move downward. The resulting landslides typically occur along gullies or steep hillsides that rim the mesas. The landslide debris is almost exclusively a mixture of weathered and disturbed Mancos Shale and gravelly alluvium. In most places, these landslides show obvious geomorphic expression that disrupts the profile of the mesa slopes. Generally, head scarps (near-vertical detachment scars exposed at the top of and sides of the landslides) are readily recognizable; however, some scarps may be eroded or covered and not pronounced. Other common diagnostic features may include hummocky topography, closed depressions, ponds, fissures, tension cracks, and pressure ridges at the toe of the mobilized mass.

Occurrences of landslides within the White River valley follow the mesa edges. Landslide activity can be accelerated by agricultural practices in the White River valley. Irrigation water infiltrates the gravel and percolates downward, further "lubricating" the weathered bedrock and increases the pore pressure, which reduces the inherent stability of the slope. All steep mesa-edge terrain should be considered susceptible to future ground movements.

The second geomorphic system where landslides commonly occur are within steeply dipping formations of the Grand Hogback where the bedrock is composed of interbedded sandstone, mudstone, shale, and minor coal. These different rock types have different mechanical properties. Sandstone is hard and relatively strong. Shale and mudstone are soft and composed of high percentages of clay minerals. These are weak rocks with very low shear strength, especially parallel to bedding planes. Within the Grand Hogback monocline, formation strata tilt up to 75° on the west side before flattening to around 35° to 40° in the center. The top of the monocline is 1,800 feet higher than the White River valley so it received more annual precipitation. In the ridges of the hogback, the gravitation pull on the rock along the tilt of the strata exceeds the strength of the weakest unit, usually a weathered claystone bed. The bedrock can also be further weakened by water and when stream channels downcut along the strike of the strata, exposing these planes of weakness. This undermining further destabilizes the slope since it is not buttressed any longer. The weak rock shears, and the overlying bedrock slides down the dip slope deforming and rubblizing into a chaotic landslide deposit at the base of the slope.

The third system where landslides can occur are on alluvial fans slopes where fine-grained clayey deposits become saturated and weaken to the point where soil shear can occur. The town of Meeker is having problems with ground movements on alluvial fan deposits at Pinyon Street between 10th and 12th Streets. While much of the ground movements were initially attributed to hydrocompaction and settlement (see *Collapsible Soils* section) there now appears to be a down-slope lateral component to the movement of the now-wetted soil. At the time of this mapping, the town had commissioned an investigation of these ground movements by a geotechnical consultant (Yeh and Associates, 2011). The landslide boundary from their investigation in this area is shown on the map. If introduction of groundwater is severe, such as uncontrolled irrigation, blow-outs can also occur where the very wet soil of an alluvial-fan slope rapidly mobilizes as a fluidized mass and flows down slope (**Figure 22**).

Figure 22. Earthflow of unconsolidated alluvial-fan soil near Meeker in 1996. Scarp is at irrigation ditch. Cause was over-irrigation and saturation of slope near river-meander bluff. Note the throat of failure where the bluff failed, mobilization and flowage of soils occurred towards it, and the resultant mud fanned out over the lower field adjacent to the White River. [UTMX 249177, UTMY 4434934]

Landslide areas may be subject to future movement during episodes of heavy rain or snowfall, or rise in groundwater levels, or when critical weathering thresholds that weaken clay minerals in the shale are met. They may also be reactivated by human-made disturbances such as alteration of slopes by excavation or loading with fill and introduction of water. Poor irrigation practices commonly initiate new landslides or remobilize older landslide deposits. In addition to potential for further reactivations, landslide deposits are prone to lateral creep movements and settlement when disturbed, loaded, or wetted during development.

Debris Flows (Mudflows)

Debris flows are dense, heterogeneous mixtures of water, mud, rock fragments, and plant materials that typically follow preexisting ephemeral streams. As hyperconcentrated flash floods move down its valley, its size and power increase, and it hydraulically incorporates additional loosened soil, rock, and other debris. Once the flow reaches an area of lower gradient, usually at the mouth of the ephemeral stream, the flow drops its suspended-sediment load near the mouth of the drainage. Sediments from successive flows coalesce and form an alluvial fan. They are caused by torrential rainfall or very rapid snowmelt runoff in steeply sloped areas where sediment supply is abundant and easily mobilized. At times, small soil-slip landslides may also contribute materials to debris flows.

Most of the mapped alluvial fans (Qf and Qaf) are composed of sediments that were deposited by debris and mud flows. The channel floor and mouths of all the ephemeral streams that outlet the narrow canyons of the Grand Hogback should be considered at risk of potential debris flooding. Residents living within or in close proximity to these areas and their associated drainageways should be aware of the possibility that large precipitation events may trigger future debris/mud flows that may inundate these areas with dangerous amounts of water and sediment. Another factor that has been focused on recently in Colorado is the physiographic changes in a drainage basin that occurs after a wildfire. Almost universally, risk of debris flows becomes much higher in a burn area when the vegetation has been removed and the soil mantle loosened.

Rockfall

Rockfall deposits are included in colluvium deposits (Qc) and old colluvial deposits (Qco) but may also fan out over other map units. Rockfall occurs in the Meeker quadrangle where there is a steep slope (generally steeper than 30 degrees) and rocky source areas such as a high sandstone ridge or cliff. The slope needs to be steep enough that if a rock where to detach at the source area, it would fall, bounce, or roll down the slope. Most rockfall-hazard areas exist below high ridge lines and cliffs within the Grand Hogback. Minor rockfall also occurs where loose cobbles and boulders are exposed along mesa edges, especially if exposed by excavation. Large precipitation events, freeze-thaw processes, and undercutting of shale where interbedded with sandstone may trigger rockfall. A large rockfall from the upper bench of the Lion Canyon Sandstone fanned across County Road 11 in the Sulphur Creek valley in early 2009 (**Figure 23**). Locations at the base of the Iles Formation rim-rock escarpment of the Grand Hogback can be at potential risk of rockfall.

Figure 23. Rockfall from top of Lion Canyon Sandstone in Sulphur Creek valley. Note scarring of rock face and scattered rock blocks around County Road 11. Some of these blocks are the size of cars. [UTMX 250588, UTMY 4443745]

Earthquakes

The Meeker quadrangle lies in an area that is seismically quiet. No Quaternary or late Cenozoic (<23.7 Ma) faults have been mapped within 20 miles. The closest are some unnamed late Cenozoic faults south of Maybell and near Elk Springs, which partially delineate the southeast structural extension of the Uinta Mountains to the Axial Basin Uplift. The next closest group of Quaternary and Late Cenozoic faults occurs over 40 miles southeast in the Glenwood Springs area. These faults are related to salt tectonism, dissolution, and regional collapse (Kirkham and Scott, 2002). Several early Cenozoic faults were mapped on the Meeker quadrangle but none showed any recent movement that offset overlying Quaternary deposits.

The same is true for actual reports of earthquakes. Only one earthquake event has been measured near Meeker. This magnitude 2.2 event was reported by the USGS on June 30, 1989. Within 15 miles were two additional earthquakes: a magnitude 3.4 event to the west on November 3, 1994, and a 4.3

magnitude event to the northwest in the Axial basin on January 31, 2002. The closest other earthquakes is the swarm around Rangely that has been attributed to well injection for tertiary oil recovery in the Rangely oil field.

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

Swelling Soils

Certain parts of the Mancos Shale, as well as derived clay soils, may undergo volumetric swelling when wetted due to the presence of smectite, an expansive clay mineral. Smectite is prevalent in reworked and altered volcanic ash (i.e., bentonite) widely found in mudstones and marine shales of Cretaceous age in the North American mid-continent. Upon wetting, these clay minerals, which are relatively dry under the natural semi-arid climate conditions of the area, draw water into their crystalline matrices and expand to accommodate the added water molecules (Noe and others, 2007). These types of high-plasticity clay are generally greasy and slippery when wet and tend to clump on shoes and tires. Surface exposure of swelling clay soils exhibit a popcorn-like texture from the repeated shrinking and swelling of clay soil agglomerations. The wetting of subsurface expansive-clay soils can result in high swell pressures, which result in ground heave that can damage structure foundations, paved roads, concrete flatwork, and underground utility pipes.

In the Meeker quadrangle, shale beds throughout the Mancos Shale contain clay-rich zones that contain these expansive clay minerals and may be prone to swelling. If Cretaceous volcanic eruptions were extensive with heavy ash fall, actual thin beds of bentonite occur within the shale. Where the Mancos clay shale is steeply dipping along the Iles rim-rock escarpment, there may be linear steeply-dipping bedrock heave zones. This circumstance occurs when tilted Mancos shale beds have different percentages of swelling clay minerals and so different heave potential. This differential can be problematic for structure foundations at the surface that span across tilted strata that have different swell potential. Most residential foundations are not able to withstand even a 1-inch heave differential. In such a situation, the foundation would crack and a portion of the house would heave, forming cracks, gaps, and jamming doors and windows.

Derived clay-rich soils of the Mancos Shale on the valley sides and floor, particularly the alluvial fan (Qf and Qaf), landslides (Qls), slope colluviums (Qc), and tributary alluvium (Qa) deposits, may contain pockets or zones of swelling clays. Because of the lateral material-property variability in tilted claystone and derived clay soils in the above-mentioned mapped units, the detection of swelling soil conditions is best accomplished on a site-specific basis. This involves the drilling of exploratory boreholes, recovering samples from critical strata and depths, and testing the engineering properties of those samples. A number of tests including Atterberg limits and swell/consolidation may be used to assess the plasticity and swell potential of the samples. For more information on expansive soil and bedrock, the reader is encouraged to see the CGS swelling soil publication, SP-43 (Noe and others, 2007).

Collapsible Soils

Surficial deposits in the Meeker quadrangle can be especially prone to hydrocompaction. In these dry and low-density deposits, the addition of water causes soil-binding agents to weaken and the loose soil skeletal fabric to collapse, which allows the soil particles to reorient into a more compact structure. This soil densification and collapse often results in localized ground settlement. The town of Meeker has had significant problems with hydrocompactive soils that have severely damaged infrastructure and destroyed residential structures (White and Greenman, 2008). Collapse typically occurs in matrix-supported deposits where clay- and silt-sized particles dominate the matrix. These soils tend to have a similar characteristic where the depositional environment has caused the soil particles to be deposited in a meta-stable condition with high void-space ratios. These soils are usually very dry because of the semi-arid climate. Rapidly-deposited alluvial fan (Qf), valley fill (Qaf), sheetwash deposits (Qac), the fine-grained tributary alluviums (Qa), colluviums (Qc), and windblown deposits (Qlo) in the Meeker quadrangle should be considered potentially susceptible to the occurrences of collapsible soil.

Some soil deposits may have both collapse and swelling properties. Collapse is a mechanical settlement property while swelling is a mineralogical phenomenon. The soil reaction to wetting depends on its porosity and internal skeletal fabric, in addition to clay mineralogy, moisture contents, and applied load. Instances occur where certain clay soils may slightly swell upon wetting but quickly settle or collapse upon further incremental loading (White and Greenman, 2008).

Collapsible or hydrocompactive soil conditions need to be assessed by professional engineering geologists and geotechnical engineers and taken into account during the engineering design of structure foundations, concrete slabs, and road pavements. Water management in collapsible soil areas is very important. Dry density, moisture content, and swell-consolidation tests are commonly performed to determine the collapse potential and whether mitigation design is needed. Knowing the thickness of the collapse-prone soil is also very important. For more information on hydrocompactive soil, the reader is encouraged to see the CGS collapsible soils publication, EG-14 (White and Greenman, 2008).

Erodible Soils

Wind and water runoff are the biggest causes of erosion; however, these are amplified by development and grazing of vegetated lands where the soil is exposed and easily eroded. Exposed bedrock of the Mancos Shale and the Wasatch Formation and their surficial derivatives are susceptible to moderate erosion, especially where vegetation is naturally absent or has been removed (National Resources Conservation Service, 2009), and where slopes are at least moderately steep. Soils with a high silt fraction are the easiest to erode and produce higher rates of runoff. The least susceptible areas of erosion correspond to the gravel-capped mesas and where hard sandstone bedrock exists.

Erodability indices using Rio Blanco County Soil Survey Geographic database (National Resources Conservation Service, 2009) shows that the Wasatch Formation (Tw), the thick valley fill sediments (Qaf, Qa) in the tributary streams, and windblown loess areas (Qlo) have a higher potential for erosion.

Another type of erosion, which can be also considered a type of soil collapse, is dispersion. Dispersive soils are clay and silt-rich soils with high ratios of saline (sodium) ions. In the presence of fresh water, the soil particles rapidly go into colloidal suspension. The dispersed soil washes away and soil pipe voids and fissures occur. Many times these soil pipes can enlarge and reach the surface to create small depressions and sinkholes. These are referred to as pseudo-karst landforms. Valley fill alluviums and windblown loess have the highest potential for dispersion. Steep-walled arroyos commonly occur where soil is dispersive.

Corrosive Soils

Corrosive soils may damage typical concrete and buried metal. The Mancos Shale, and sediments derived from the Mancos Shale, and alluviums and fine-grained valley fills can have elevated salt and sulfate content and should be considered potentially corrosive. Sulfate-resistant concrete is typically specified in high-sulfate areas. The use of PVC pipes and plastic tanks, cathodic protection, or corrosion-resistant coatings is highly recommended for metal corrosion. Geotechnical consultants should specify the degree of corrosion protection that is recommended for all site specific investigations.

Mine subsidence

Coal-mine subsidence occurs when the roof of underground mine workings collapse after the coal has been removed. This failure propagates to the surface to form subsidence features such as ground depressions and sinkholes. Several small inactive and abandoned underground coal mines exist in the Meeker quadrangle within the mapped coal-bearing formations of the Grand Hogback. These are small shallow workings that follow the tilt of the strata. The location and names of these mines are shown on the map. There may be subsidence hazards areas at the ground surface above these mines. The Subsidence Library at the Colorado Geological Survey has files on inactive coal mines in Rio Blanco County that includes the extent of underground workings on the Meeker topographic quadrangle (Sullivan, 1984). Company mine maps of the actual underground workings are also available for the following mines that are located on the Meeker Quadrangle: Black Diamond, Fairfield, Johnny Boy, Lion Canyon, Oldland, Pollard, and Sulphur Creek. These maps are available to the public. Unfortunately, mine-workings maps are not available for several other smaller mines shown on the quadrangle. These have very small areas of underground workings, or may only be prospects so mine subsidence hazard is very small.

MINERAL RESOURCES

The Meeker quadrangle contains coal, oil and gas, and aggregate mineral and mineral-fuel resources.

Coal

Bituminous coal was historically the most economically significant mineral resource in the Meeker quadrangle (**Figure 24**). The Iles and Williams Fork formations exposed along the Grand Hogback contain very important coal-bearing sequences. They are the major coal resources of west-central and northwest Colorado. Coal mines in the Meeker quadrangle have been worked from the late 1800s until the early 1940s. The coal resources of the Meeker area have been extensively reported by Hancock and Eby (1930), Collins (1976), and Brownfield and others (2000). The Meeker area is located within the southern spur of the Danforth Hills Coal Region. The stratigraphic column in **Figure 8** shows the approximate location of the major coal groups as they were originally defined by Hancock and Eby (1930). Though quality coal is locally present with beds thicker than 10 feet, it is uneconomical to mine because the steep structural dips makes surface strip mining or underground long-wall mining impossible with current mining technology. More information about the historic mines and their production in the Meeker area can be found in the CGS historic coal mine publication by Carroll and Bauer (2002).

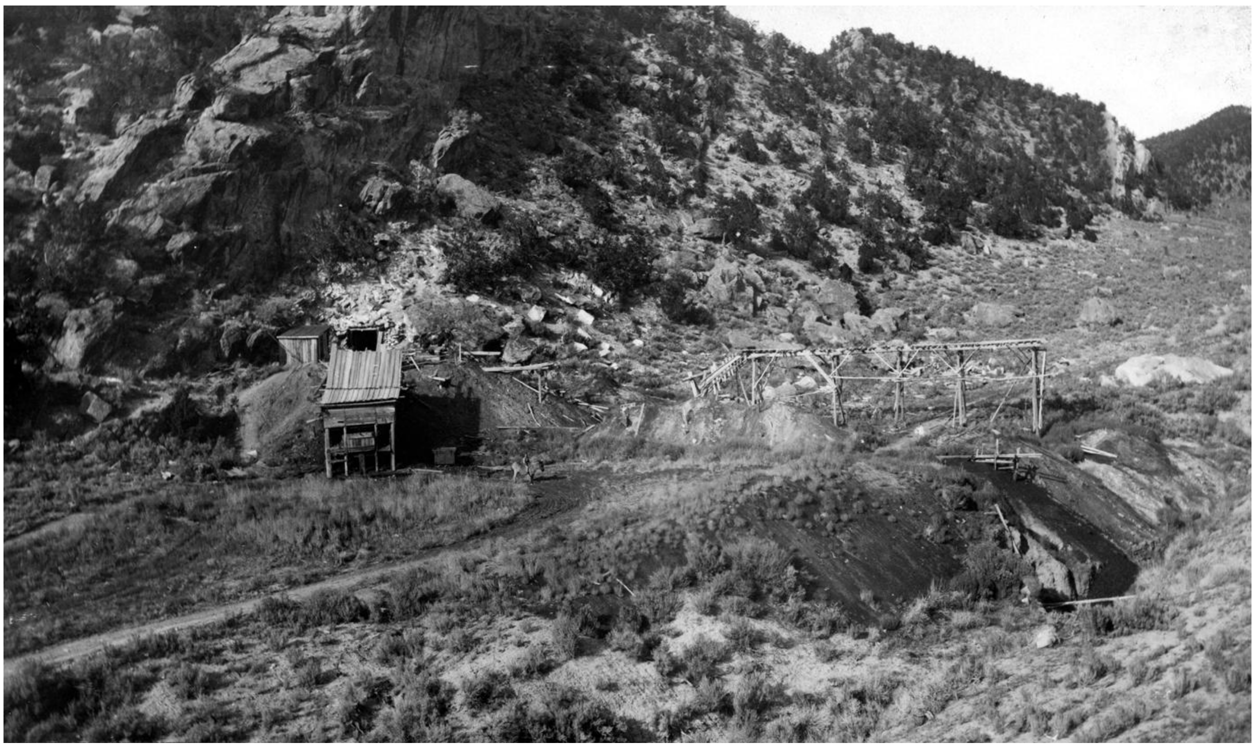

Figure 24. Historic photo of the Lyon Canyon Coal Mine (historic spelling) taken in 1911 near mouth of Lion Canyon. USGS archival photo downloaded from: http://libraryphoto.cr.usgs.gov/. [UTMX 247039, UTMY 4435077]

Oil and Gas

The monoclinal structure of the Grand Hogback apparently does not create decent traps for the accumulation and exploitation of oil and gas. Coal methane is also not viable where tilted coal beds are exposed along the hogback. Nonetheless, Shell Oil conducted experimental testing of coal gasification by downhole heating and vacuum extract of a major coal seam near the old Fairfield Mine in 1999 (Larry Moyer, consulting petroleum geologist, personnel communication). A review of Colorado Oil and Gas Conservation Commission (COGCC) data show the closest oil and gas fields to be 1) the Powell Park gas field one mile west of the west map boundary in the White River valley producing from the Fort Union and the Mesaverde Group, and 2) the McHatton oil field five miles east of the eastern boundary on

Rattlesnake Mesa producing from the Niobrara (Smoky Hill), and 3) the Wilson Creek oil field in the Danforth Hills, 3 miles north of the map boundary. The Wilson Creek field is the second largest oil producer in Colorado. Discovered in 1938, oil production comes from a large anticlinal trap where oil pools formed in sandstones of the Morrison Salt Wash Member, Entrada Sandstone, and, more recently discovered, the Minturn Formation (Stone, 1986). Very few explorations wells have been drilled on the Meeker quadrangle and only one, Meeker #1-4, horizontally completed in the Niobrara limestone and calcareous shale, currently produces oil and gas. Production information for this well can be found in the Colorado Oil and Gas Information System (COGIS), which can be accessed at the database tab of the COGCC website at http://cogcc.state.co.us. To avoid confusion, the oil and gas play called the Niobrara Formation in the subsurface has been mapped as the Smoky Hill member of the Mancos Shale. It is exposed at the surface in Agency Park in the White River valley. Increased attention is being given to the Niobrara play using horizontal well-completion techniques.

Aggregate Resources

The White River alluvial gravels are generally an excellent aggregate resource. The White River gravels contain very small percentage of fines (silt and clay) and high percentages of hard basalt, sedimentary, and crystalline intrusive and metamorphic rocks. Many active and inactive quarries are located in the mapped area on these terraces (i.e., Qaw_2, Qaw_3, and Qaw_4) and excellent potential exists for the development of additional sand and gravel operations in the widespread alluvial terrace deposits of the White River within the mapped area. However, in many map areas the thickness of overburden (up to 50 feet) from later deposition of valley fill is a constraint that may make recovery of this gravel expensive (**Figures 5 and 6**). Tributary gravels have also been mined (Qa2) along Strawberry Creek for local road base. These gravels are of local less-indurated sandstone sources so they do not crush well (they pulverize to sand), and do not have the durability for quality aggregate recommended for concrete.

GROUND-WATER RESOURCES

The primary source of domestic drinking water within the Meeker quadrangle comes from the White River aquifer. The town of Meeker water supply is via wells on the river floodplain drilled into the Qaw_1 gravel near where County Road 4 crosses the White River off the map area to the southeast. Outside the White River Aquifer, the other sources of domestic drinking water are from bedrock aquifers. Depending on location, ground water has been found and utilized from consolidated sandstone bedrock aquifers in the following hydrogeologic units: Wasatch Formation, Fort Union Formation, Williams Fork Formation, Iles Formation, and sandstone members of the Mancos Shale. The Colorado Division of Water Resources' website, http://water.state.co.us/Home/Pages/default.aspx, has both map viewer and well-permit search tools that include well locations, depths, production intervals, yields, and scans of the original water well applications for all adjudicated water wells in Colorado. The following sections briefly describe the alluvial and bedrock hydrogeologic units in the map area. Additional information on ground water in Colorado is in the CGS Ground Water Atlas of Colorado (Topper and others, 2003).

Alluvial Aquifers

Groundwater for domestic use comes from the Quaternary alluvial deposits associated with the White River. Theses gravels have high permeability and can produce high yields. The existing floodplain alluvium (Qaw_1) is in direct hydraulic connection with the river and is normally saturated with ground water to very near the elevation of the river level. Those older, higher-elevation gravels that cap the adjacent terraces and mesas are now isolated from the river by shale bluffs. They are not necessarily saturated with groundwater, unless recharged from upland areas, or are only seasonally and when heavily irrigated. The areal extent of the alluvial aquifers roughly coincides with the areal extent of the alluvium. Along the edges of the valley, the river gravel can be buried with aprons of alluvial fan and valley-fill deposits. In those locations, deeper wells, possibly to 70 feet, are needed to reach the underlying water-bearing gravel.

Bedrock Aquifers

Where groundwater from alluvial aquifers is not feasible or available, permitted water wells on the Meeker quadrangle also utilize aquifers in bedrock sandstone beds. Bedrock wells are generally drilled deeper to find both an adequate sandstone aquifers and an adequate sustained yield from the less permeable rock. Several Cretaceous sandstone formations may be aquifers. In the Meeker area, deeper sandstone aquifers have been found to be high in total dissolved solids. In almost all cases, water law stipulates that groundwater from sandstone aquifers is considered “tributary” and directly connected to surface water (Hobbs, 2004).

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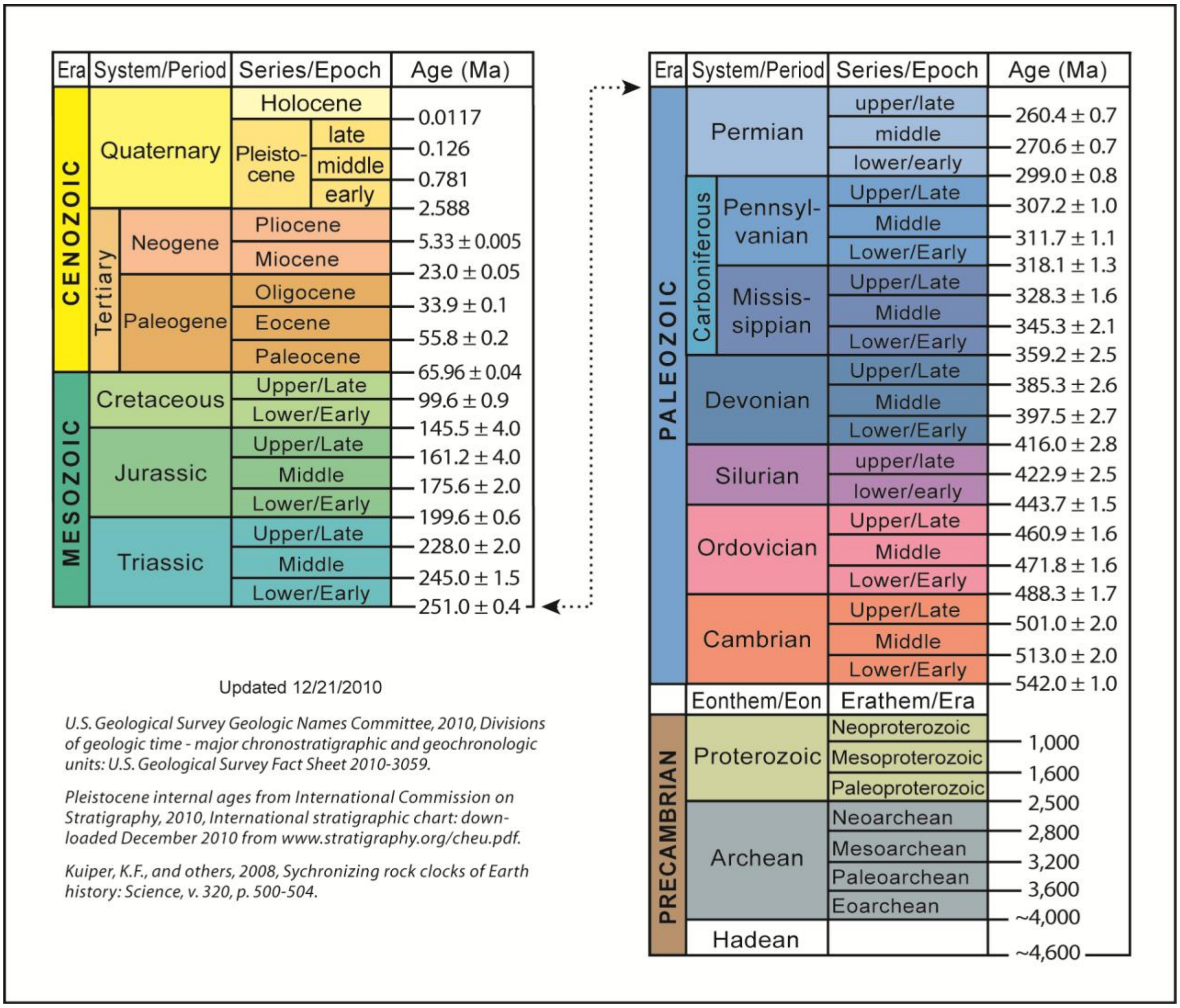
APPENDIX A

DIVISION OF GEOLOGIC TIME ADOPTED BY THE COLORADO GEOLOGICAL SURVEY



APPENDIX B

FOSSILS COLLECTED FROM THE MEEKER QUADRANGLE

Marine invertebrate fossils were collected during field mapping of the Meeker quadrangle. The fossils were donated to the U.S. Geological Survey for their Cretaceous Western Interior Seaway (CWIS) collection kept in Building 810 at the Federal Center in Lakewood, CO. USGS collection numbers (beginning with a "D" for Denver collection) were assigned and are shown on the geologic map. William Cobban, USGS, provided identification of the fossil species and catalogued the specimens into the CWIS collection. The following table is from a written list by Dr. Cobban submitted December 28, 2009.

USGS No.	Location	Formation	Specie or interval zone
D14888	SW¼SE¼NE¼, Sec. 25, T1N, R94W	Mancos Sh (Kms - Smoky Hill/Niobrara)	*Inoceramus sp.* *Pseudoperma congesta*
D14889	SE¼SE¼NE¼, Sec. 25, T1N, R94W	Mancos Sh (Kms -Smoky Hill/Niobrara)	*Inoceramus sp.* *Pseudoperma congesta*
D14890	NE¼SE¼NE¼, Sec. 1, T1S, R94W	Mancos Sh (Kmf -Frontier)	*Nicaisolopha lugubris*
D14891	Center W½NE¼, Sec. 35, T1N, R94W	Mancos Sh (Kms -Smoky Hil/Niobrara)	*Inoceramus sp.* *Pseudoperma congesta*
D14892	NW¼NW¼SE¼, Sec. 11, T1N, R94W	upper Mancos Sh - Kmu (between Kmmo and Kmlo)	*Cataceramus balticus*
D14893	Center E½, Sec. 1, T1N, R94W	upper Mancos Sh -Kmu, just above Kmmo	*Baculites obtusus*
D14894	Center NE¼, Sec. 33, T1N, R94W	upper Mancos Sh - Kmu (between Kmmo and Kmlo)	*Baculities sp., Glyptoxoceras sp.*
D14895	Center N½NW¼, Sec. 32, T1N, R94W	upper Williams Fork - Kwu (near coal seam)	bits of brackish-water? bivalves
D14896	SW¼SW¼SE¼, Sec. 36, T1N, R94W	Mancos Shale (Kms - Smoky Hill/Niobrara)	*Inoceramus sp.* *Pseudoperma congesta*
D14897	SE¼NE¼NE¼, Sec. 4, T1N, R94W	lower Williams Fork -Kwl	*Proparreysia letsoni* (a fresh-water unio)
D14898	NE¼SE¼SE¼, Sec. 2, T1N, R94W	Mancos Shale (Kmlo - Loyd)	*Cataceramus balticus*
D14899	NW¼SW¼SW¼, Sec 31, T2N, R93W	upper Mancos Sh - Kmu (between Kmmo and Kmlo)	*Baculites sp.*
D14900	SW¼SW¼SE¼, Sec. 24, T2N, R94W	lower Williams Fork - Kwl,	Bits of small fresh-water gastropods
D14901	NE¼SE¼NW¼, Sec. 22, T1N, R94W	Mancos Sh -ss near Ki (Kmdm?)	Seed pod
D14902	SW¼NW¼NE¼, Sec. 2, T1N, R94W	Mancos Sh - Kmlo	*Cataceramus subcompressus*
D14903	SE¼SW¼SW¼, Sec. 14, T1N, R94W	upper Mancos Sh (just below Kmmo)	*Baculites asperiformis*?

APPENDIX C

PALYNOLOGY REPORT FOR SAMPLES COLLECTED FROM THE MEEKER QUADRANGLE

Dark gray and carbonaceous shale samples were collected along the Cretaceous/Tertiary boundary and within Paleocene strata in the Meeker Quadrangle to recover, identify, and date fossil pollen. Sample locations are shown on the geologic map. Dr. Douglas J. Nichols at the Denver Museum of Nature and Science provided the palynological analyses of the sample pollen yield. The following is a written report by Dr. Nichols dated November 9, 2009.

REPORT ON PALYNOLOGICAL ANALYSES OF SAMPLES FROM THE MEEKER QUADRANGLE COLORADO

Douglas J. Nichols
Research Associate, Denver Museum of Nature & Science
9 November 2009

This report covers seven samples submitted for palynological analysis by Jonathan White of the Colorado Geological Survey. Age determination was requested. Samples were from outcrop localities in the Meeker quadrangle, Moffat(sic) and Rio Blanco Counties, Colorado. Sample preparation was conducted by Global Geolab of Alberta, Canada. DBP numbers, field numbers, and results are given below.

DBP no.	Field no.	Results
DBP-2009-45	M310	The sample yielded a low-diversity assemblage of pollen. Presence of *Aquilapollenites quadrilobus* indicates an age of Campanian to Maastrichtian. Species identified are: *Aquilapollenites quadrilobus* (common) *Pandaniidites typicus*
DBP-2009-46	M366	The sample yielded a moderately diverse assemblage of pollen. The assemblage indicates an age of middle Paleocene (Zone P3). Species identified are: *Momipites anellus* *Momipites leffingwellii* *Momipites ventifluminis* *Taxodiaceaepollenites hiatus* *Tilia vescipites* *Ulmipollenites krempii*
DBP-2009-47	M368	The sample yielded a sparse but reasonably diverse assemblage of pollen and spores. The assemblage indicates an age of Paleocene, probably early Paleocene (Zone P1 or P2). Species identified are: *Arecipites columellus* *Gleicheniidites senonicus* *Momipites inaequalis* *Momipites tenuipolus* *Reticuloidosporites pseudomurii* *Stereisporites* spp. *Tricolpites* sp. *Triporopollenites granilabratus* (common) *Triporopollenites subtriangulus*

Ulmipollenites krempii
trilete spores

DBP-2009-48	M452	The sample yielded only a small amount of organic matter and few pollen or spores. No age-definitive species were recovered, so the age of the sample is uncertain. Taxa identified are: *Ulmipollenites* bisaccate pollen monolete spores trilete spores triporate pollen
DBP-2009-49	M722	The sample yielded only a small amount of organic matter and few pollen or spores. The age of the sample is uncertain because among the few specimens of pollen recovered are two that respectively indicate Cretaceous and Paleocene age. If the Cretaceous specimen is reworked, the Paleocene age is more likely, but the evidence is weak. Species identified are: *Aquilapollenites quadrilobus* *Erdtmanipollis cretaceus* *Momipites* sp. triporate pollen
DBP-2009-50	M925	The sample yielded a sparse assemblage that lacks age-definitive species. Thus, its age is uncertain. However, my best estimate is that the sample is Paleocene in age. Taxa identified are: *Tricolpites* *Ulmipollenites* bisaccate pollen monosulcate pollen triporate pollen
DBP-2009-51	M947	The sample yielded a diverse assemblage indicative of middle Paleocene age (Zone P3). Species identified are: *Classopollis* sp. *Cyathidites* sp. *Laevigatosporites* sp. *Momipites actinus* *Momipites anellus* *Momipites leffingwellii* *Pityosporites* sp. *Tricolpites* sp. *Triporopollenites granilabratus*