Geologic Map of the Whitewater Quadrangle
Mesa County, Colorado

Open-File Report 14-09

Authors' Notes

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FOREWORD

The purpose of Colorado Geological Survey's (CGS) *Geologic Map of the Whitewater Quadrangle, Mesa County, Colorado* is to describe the geology, mineral and ground-water resource potential, and geologic hazards of this 7.5-minute quadrangle located southeast of Grand Junction in western Colorado. CGS staff geologist Jon White and field assistant Rod MacLean completed the field work on this project during the summer and fall of 2012. Chris Carroll also assisted along the floor the Gunnison river canyon in the southern map area. The geologic map plates and the Authors' Notes report were created using field maps, structural measurements, photographs, and field notes generated by the investigators. A field review of the map area was conducted with Vince Matthews and Dave Noe. John Hodge and Dave Noe reviewed this map publication.

This mapping project was funded jointly by the U.S. Geological Survey (USGS) and CGS. USGS funding comes from the STATEMAP component of the National Cooperative Geologic Mapping Program, award number G12AC20229, authorized by the National Geologic Mapping Act of 1997, reauthorized in 2009. CGS matching funding comes from Colorado State severance taxes paid on the production of natural gas, oil, coal, and metals in Colorado.

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INTRODUCTION

The Whitewater 7.5-minute quadrangle is located in Mesa County, Colorado (**Figure 1**). The unincorporated community of Whitewater lies within the quadrangle. Grand Junction, the largest town and county seat of Mesa County, lies 8 miles to the northwest. The Whitewater community lies at the intersection of two major highways. U.S. Highway 50, the major western slope highway from Grand Junction to Montrose, passes through the quadrangle. Westward from its intersection with U.S. 50 State Highway 141 crosses the Gunnison River and passes through Unaweep Canyon to Gateway and southward to Naturita. Approximately two-thirds of the quadrangle is Federal lands administered by the Bureau of Land Management (BL M). The portion of the BLM land south of East Creek that includes the Gunnison River canyon lies within the Dominguez-Escalante National Conservation Area (DENCA). Private property is predominantly restricted to the flatter lands to the northeast around Callow Creek, Whitewater Creek, and the Kannah Creek valley. Increased development has recently occurred in Whitewater as it has become a bedroom community to Grand Junction. The major industry of the area is aggregate quarry operations in gravel deposits where the Gunnison River outlets the DENCA canyonlands in Whitewater.

PREVIOUS MAPPING STUDIES

Previous geologic mapping in the area was done at several different scales. The historical regional geological map was made by Hayden (1877) (scale 1:253,440). The study area is also included in four regional maps: 1) the Moab 1° x 2° geologic map (Williams, 1964) (1:250,000 scale), 2) a 30'x60' geologic map by Ellis and Gabaldo (1989) (1:100,000 scale), 3) a geologic map of the Grand Junction area by Lohman (1963) (1:31,680 scale), and 4) a geomorphic study by Sinnock (1978) of the Uncompahgre Uplift and Grand Valley region that included mapping of terraces and pediments in the Whitewater quadrangle. The extreme southwest corner of the quad was mapped as part of a 1:14,400-scale fault investigation by Livaccari and Hodge (2005a). 1:24,000-scale geologic quadrangle maps were completed to the north of Whitewater, including the Palisade quadrangle (Carrara, 2000), the Clifton quadrangle (Carrara, 2001), and the Grand Junction quadrangle (Scott and others, 2002). The nearby Colorado National Monument and vicinity map has also been mapped at the 1:24,000 scale (Scott and others, 2001).

Geologic mapping of the Whitewater quadrangle was undertaken by the CGS as part of the STATEMAP program. STATEMAP is a component of the National Cooperative Geologic Mapping Act, administered by the USGS. The purpose of the CGS STATEMAP program is to produce 1:24,000 scale geologic maps that focus on surficial units, bedrock units, and structural features. The maps can be used for land-use planning, geologic-hazard assessment, geotechnical engineering, and mineral and ground-water resource development. They can also be used to learn about an area's unique geologic history. (For the current status of CGS STATEMAP projects, see http://coloradogeologicalsurvey.org/geologic-mapping/124000-scale-mapping-program-index-maps/

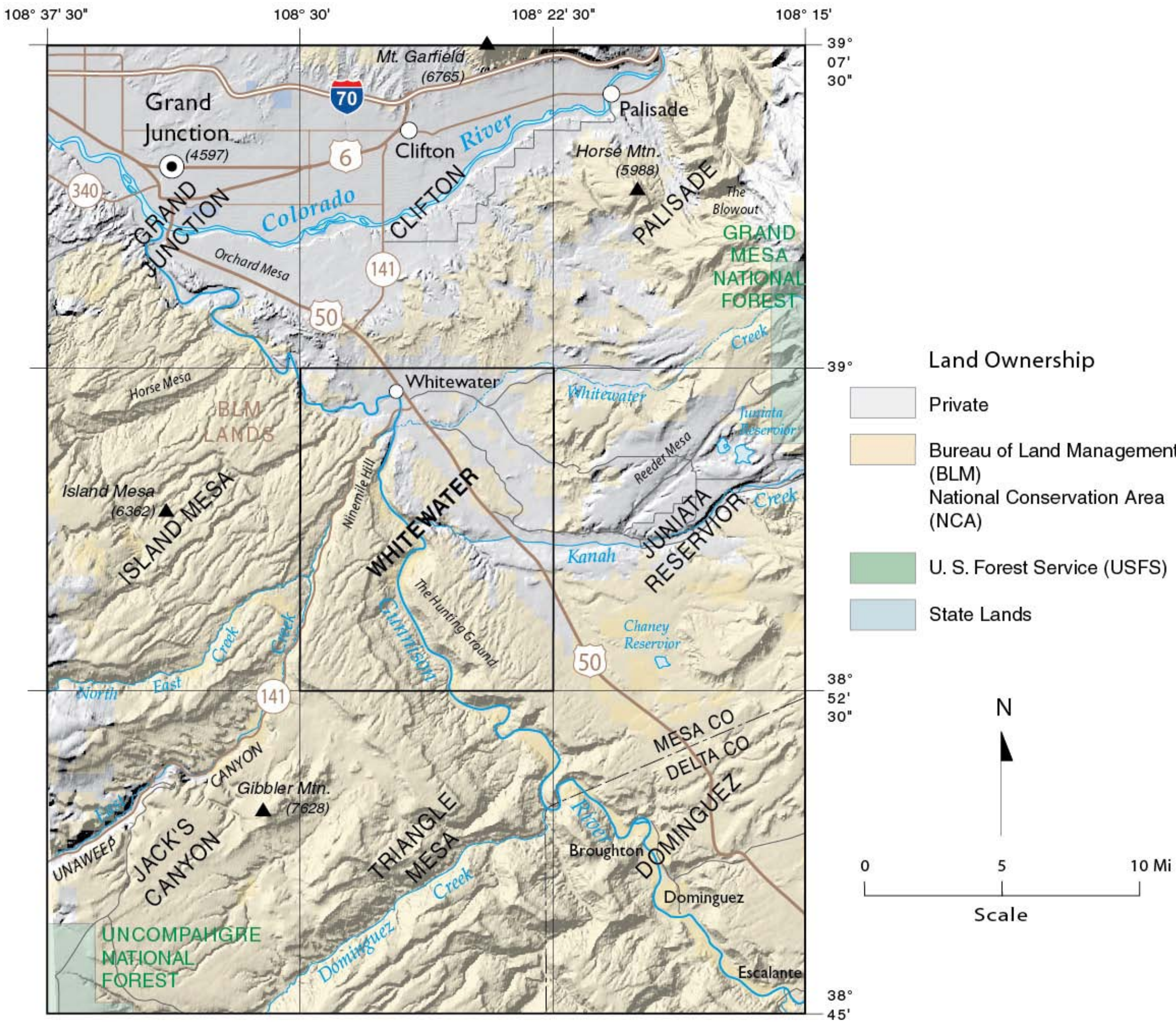

Figure 1. Regional map surrounding the Whitewater quadrangle.

MAPPING METHODOLOGY

The geologic map of the Whitewater quadrangle is shown on **Plate 1**. The geologic interpretations are based on: (1) CGS field investigations conducted from July to November, 2012; (2) published and unpublished geologic maps and reports; (3) NRCS soil survey data, and (4) interpretation of remote-sensing images. The image data include 1:20,000-scale stereo aerial photos created from 1-m resolution stereo digital photography taken in 2009 by the National Agricultural Imagery Program (NAIP); a 10-m resolution digital elevation model (DEM); and the Google™ Earth on-screen map viewer.

Bedrock geology and surficial deposits were mapped photogrammetrically in the field on stereo pairs of aerial photographs. Key geologic and photograph locations, and locations where geologic measurements were taken, were recorded with a portable GPS receiver. ***All GIS locations reported***

herein and in the GIS database are in Universal Transverse Mercator (UTM), North American Datum 1983, Zone 13N projected coordinates, with units in meters. Mapping from the aerial photos was scanned and re-traced photogrammetrically with the ERDAS Stereo Analyst extension for ESRI ArcGIS. Digitized map files were included in a GIS project file that also included the 1:24,000 USGS topographic base map, hillshade coverage generated from the 10-m DEM, and digital NRCS SSURGO data. Georeferenced 20011 NAIP orthophotography was also loaded into the GIS project to ensure the accurate map location of geologic features and contacts. Subtle spatial errors were found in the original USGS 1:24,000-scale topographic map. The final geologic mapping was indexed to the more accurately georeferenced digital stereo pairs and NAIP orthophotography so geologic contacts may not exactly match the contouring and stream locations. We used ERDAS IMAGINE 2010 to create the 3-D geologic map shown in **Plate 2**.

STRUCTURAL AND PHYSIOGRAPHIC SETTING

Whitewater quadrangle is located along the northeastern flank of the Uncompahgre Plateau. The plateau marks the location of ancestral mountains that uplifted during the Pennsylvanian Period and were eroded flat to be buried by deposits of Upper Triassic through Paleocene (?) rocks. The uplift was rejuvenated during the Laramide Orogeny and broadly uplifted again, likely along pre-existing basement faults. Structurally the sedimentary rock units dip gently and relatively consistently down to the northeast at about 3 degrees towards the Piceance Creek structural basin. At the extreme southwest corner of the quadrangle the gentle incline of the uplift terminates at a monocline that is likely related to the Cactus Park-Bridgeport Fault. This fault is one of several Laramide-age strike- and oblique-slip faults, reverse faults, and monoclines that link a basement cored, regional structural belt along the northeast edge of the Uncompahgre Uplift from Bridgeport, through the Colorado National Monument, to the Utah border (Livaccari and Hodge, 2005b). While the main fault mapped by Livaccari and Hodge (2005a) is off-map in Cactus Park, the strata at the monocline ridgeline is tilted up to 37° within the map area. The rock is disturbed there and contains evidence of bedding-plane strike-slip and flexural-slip movements, including abundant slickensides, deformation bands, and shear breccias (possibly Riedel structures) that are oblique to the assumed axis (**Figure 2**). Shale beds have pinched out or thinned along the ridgeline outcrop.

Figure 3 shows the major physiographic features of the quadrangle. The highest elevation (6,645 feet) is in the southwest corner of the quadrangle along the above-mentioned monocline. The lowest elevation (4,624 feet)) is located where the Gunnison River exits the quadrangle at the northwestern corner. Two geomorphic areas comprise the quadrangle: (1) The Uncompahgre Uplift in the southwest triangular two-thirds of the quad where the resistant Dakota Sandstone dip slope is exposed and canyons have been incised by the Gunnison River (the highest canyon wall is over 900 feet above the Gunnison River where it enters the map's southern boundary) and East, Kannah, and Bangs Canyon creeks; and (2) The broad dissected flatlands of the northeastern third of the quadrangle that is underlain by the easily eroded Mancos Shale. This area is characterized by Mancos shale badlands and the cuesta of the more resistant Juana Lopez and Blue Hill members that U.S. Highway 50 parallels. The badlands are known locally as the *Adobe Hills* or the *Adobes.* Many of the shale slopes are covered with variable thicknesses of reworked bouldery colluvium that is derived from the adjacent but off-map Reeder Mesa. Reeder Mesa is capped with old alluvium composed of basalt boulders eroded from the volcanic lava flows that cap Grand Mesa to the east. Along Kannah Creek above its canyon, the Mancos Shale slope has also been modified by the deposition of Pleistocene terraces.

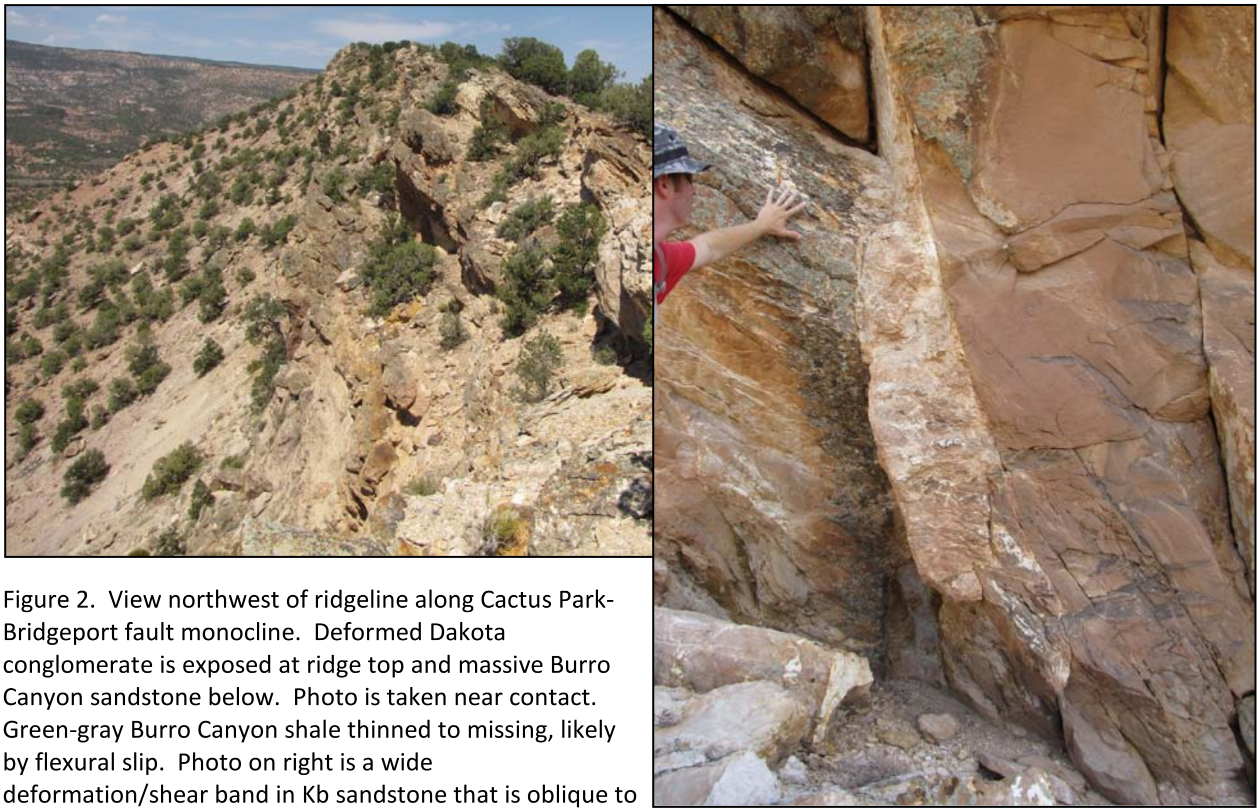

Figure 2. View northwest of ridgeline along Cactus Park-Bridgeport fault monocline. Deformed Dakota conglomerate is exposed at ridge top and massive Burro Canyon sandstone below. Photo is taken near contact. Green-gray Burro Canyon shale thinned to missing, likely by flexural slip. Photo on right is a wide deformation/shear band in Kb sandstone that is oblique to monocline axis [UTMX 197060, UTMY 4308760].

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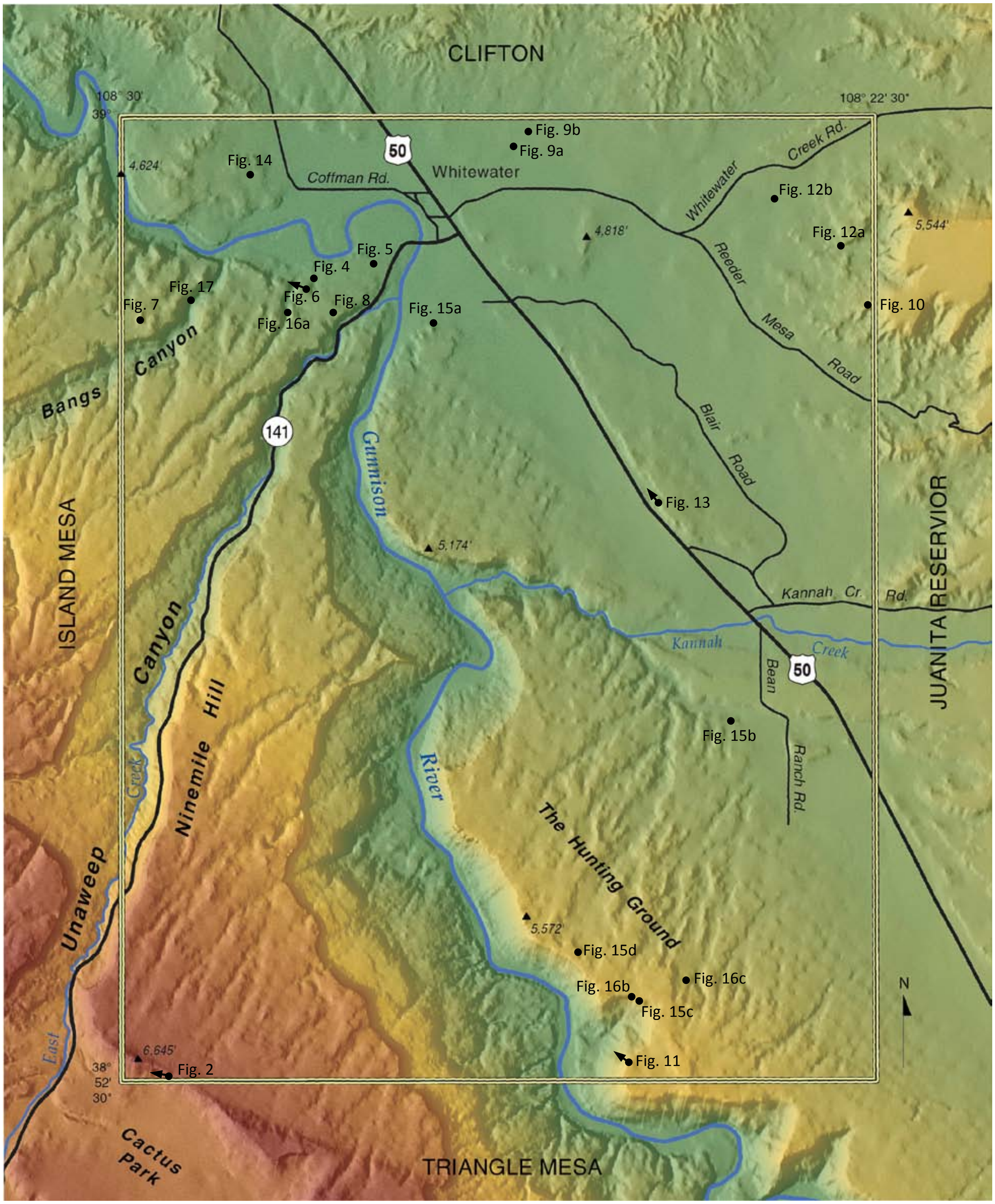


Figure 3. False-color shaded relief map of Whitewater quadrangle. Locations of photos in this report are shown by points and figure numbers.

DESCRIPTION OF MAP UNITS

This section contains descriptions of surficial and bedrock units from the geologic map. The surficial units are organized by the dominant process of deposition and by age, and are listed from youngest to oldest in terms of latest depositional activity. The bedrock units are organized by increasing age. The geologic time divisions and nomenclature used in this report are shown in **Appendix A**.

SURFICIAL DEPOSITS

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

HUMAN-MADE DEPOSITS

af **Artificial fill and disturbed land (latest Holocene)** – Gravel, sand, silt, clay, and rock or concrete debris emplaced to construct roads, dams, or other human-made structures. Fills may be engineered (built with controlled compaction) or completely uncontrolled. Their compositions and properties are varied. Unit also includes disturbed land and overburden spoils that include areas such as surface gravel pits, large excavations, or reclaimed areas covered with uncontrolled fill.

ALLUVIAL DEPOSITS

Gravel, sand, silt, and clay deposited in major river valleys and tributary drainages, in alluvial fans, and as older terrace deposits. The older alluvial deposits formed during Pleistocene glacial periods, particularly during episodes of outwash flooding from melting glaciers. Erosion of the landscape through time has formed *inverted topography*. This occurs when streams abandon their former courses and erode downward through the soft shale in the valley walls. A newer, lower, stream valley is formed. The abandoned deposits are somewhat resistant to erosion. They are preserved as remnant, mesa-capping gravel bodies. The highest deposits are the oldest. Terrace elevation heights represent the elevation difference between the modern river level (from the USGS topographic map) and the top of the terrace gravel. Thickness represents the maximum exposed thickness of the unit.

Qa **Alluvial deposits along tributary streams (Holocene)** – Sand, silt, clay, and gravel in and underlying the modern flood plain of tributary streams or incised into mud-flow alluvial fans (Qamf) forming arroyos. Within stream floors that are cut into tributary canyons, the unit is predominantly gravel and sand, and may include colluvial deposits along valley margins. Within the broad Qamf flats, the narrow arroyo flood-plain floor consists of active, low-sinuosity to meandering channels with poorly sorted sandy to clayey channel deposits. Thickness is poorly known but generally less than 15 feet.

Alluvial Deposits of the Gunnison River

Gravel, sand, and minor silt and clay deposited by the Gunnison River. The younger deposits (**Qag_1**) comprise the modern Gunnison River flood plain. Several levels of older deposits (**Qag_2** to **Qag_9**) are present as alluvial terraces that increase in age with increasing height above the modern river. Top-of-terrace elevation gradients are similar to the modern river gradient. Terrace treads are restricted to within the Gunnison River canyon at the southern boundary of the map. However, early Pleistocene/Pliocene(?) treads record the paleo river course along the paleo Dakota/Mancos Shale contact high on the uplift dip slope, and subsequent incision and lateral northeastward migration of the river down dip along the Dakota rim through the Pleistocene to recent times. We found accumulations of well-rounded river gravel in sporadic locations within landslide deposits high along the west bank of East Creek up to above the confluence with North East Creek. While most seemed to be Qaeo gravel, we did see basalt-clast cobbles and other lithologies that were tentatively attributed to Qag gravel. If these clasts are derived from a Qag terrace that was deposited on the Dakota dip slope above, which is now incorporated into the landslide deposit below, they represent a terrace tread that existed on the rim that is about 600 additional feet above the highest **Qag_9** remnant. Middle to Late Pleistocene terrace levels more clearly outlet from the canyon mouth near Whitewater. There, where underlain by Mancos Shale, the deposits have fanned out as the valley broadens.

The map includes many terrace-riser lines, which group and delineate same-elevation terrace-tread remnants within, along the rim, and at the mouth of the canyon. Most significantly, the risers also illustrate the migration of the river, northeastward, down the dip slope of the resistant Dakota Sandstone as it preferentially erodes the Mancos Shale at Whitewater. At the mouth of the canyon, the rapid nature of Mancos Shale incision and dip slope migration of the paleo river channel has left many strath elevations of terrace treads. We have assigned subunits (a, b, and c at lowest to highest elevation) to several enumerated deposits where clear strath changes occurred within that major terrace level.

Gunnison River gravel deposits are fairly consistent in texture and composition. The deposits are glacio-fluvial in origin and were deposited in aggrading, high-energy, braided-river-valley environments. The deposits are pebbly to cobbly gravel that consists of well-rounded, discoid to oval pebbles, cobbles, and rare small boulders just over 12" long (**Figure 4**). The clasts are river packed and typically encased in a clean, coarse-grained sand to granule matrix. Where vertical exposure are exposed in quarries, channel scour and cross-beds can be seen, as well as lenses of clean, well sorted, coarse-grained sand. Overbank deposits were only observed atop the higher Qag1 deposit in the current river floodplain, and consist of a thin top soil underlain by sand mixed with minor silt and clay. The Gunnison River gravels are an excellent aggregate resource and several abandoned and active quarries occur in several terrace remnants.

Figure 4. Prospect pit excavated in Qag_4 deposit. Note calcic soil development [UTMX 199390, UTMY 4320120].

The composition of Gunnison alluvium gravel indicates a mix of upstream source areas. Source areas include: 1) the Black Canyon of the Gunnison (gneiss, schist, amphibolite, pegmatite, granite); 2) San Juan Mountain volcanic field (tuffs, andesite, dacite, monzonite) and Uncompahgre Group quartzite clasts contributed by the Uncompahgre River; 3) central and northern West Elk Mountains (monzonite and granodiorite porphyries, hornfels, quartzite) contributed by the North Fork of the Gunnison, and 4) basalt from Grand Mesa. Along the Dakota dip slope in the northwest corner of the map area, local clast-provenance influence from East Creek of Unaweep Canyon and other dip slope canyons (e.g., Bangs Canyon) can be seen in the higher, older terrace deposits. Below the confluence of East Creek, old East Creek Alluvium deposits (Qaeo) have been found overlying Gunnison Alluvium.

Qag_1 **Alluvium one of the Gunnison River (Holocene-late Pleistocene) –** Deposit includes the current river level deposits (**Qag_{1a}**)and the first widespread terrace of the current floodplain (**Qag_{1b}**), that includes the elevations of several gravel-bar islands. The upper surface is about 8 feet above the current river level (in 2012 the river level was low due to drought conditions). Total thickness is not known but quarry operations indicate thicknesses up to 30 feet below the river level. OSL dating sampled from a quarry wall near Whitewater, 27 feet below the current river level, yielded a date of 11.8ka ±1.1 ka (written comm., Andres Aslan, Colorado Mesa University).

Typically, the floodplain deposits contain a thin upper deposit of overbank silty-clayey sand sediments and thin topsoil, and are generally covered with thick riparian vegetation. In Whitewater, the (**Qag$_{1b}$**) terrace is covered by variable thickness of finer-grained, clayey, mud-flow alluvium (Qamf) deposited at the mouth of Whitewater Creek, Callow Creek, and other intermediate shallow drainages from the Mancos Shale hills to the north.

Qag$_2$ **Alluvium two of the Gunnison River (late Pleistocene) –** The unit forms the first strath terrace remnants along the flanks of the modern river valley. Its upper gravel surface is 26 to 67 feet above the modern river. Thickness is 15 to 25 feet. Remnants of this terrace are currently being mined for aggregate in Whitewater. At this location, the 20-foot-high quarry wall also reveals a thin unmapped unit of old East Creek alluvium (**Qaeo**) overlying Gunnison alluvium (**Figure 5**). Samples of both were recovered from the wall of the quarry and submitted for optically stimulated luminescence (OSL) dating. Reported ages were 34.5ka ±2.3ka for the Qag$_2$ unit and 29.8ka ±1.8 ka for the overlying Qaeo unit (Steve Forman, University of Illinois-Chicago, written communication). See Appendix B for more information.

Figure 5. Quarry excavation in Gunnison River Qag$_2$ terrace overlain by Qaeo deposits sourced from East Creek of Unaweep Canyon. White arrows show sample location submitted for OSL dating (Appendix B) [UTMX 200440, UTMY 4320360].

Qag$_3$ **Alluvium three of the Gunnison River (late Pleistocene) –** The gravel unit forms terrace remnants at elevations ranging from 84 to 106 feet above the current river level. Remnants of this terrace have also been mined for gravel aggregate in Whitewater.

Qag$_4$ **Alluvium four of the Gunnison River (late middle Pleistocene) –** This unit formed strath terrace on the Entrada Sandstone within the Gunnison River canyon, and on the dip slope of the Dakota rim and forming small mesas on Mancos Shale at the mouth of the canyon. Its upper gravel surface is 127 to 165 feet above the modern river. Two distinct straths subunits were mapped. These subunits are designated **Qag$_{4a}$** and **Qag$_{4b}$** and are shown on the map divided by terrace risers. Gravel resource prospect pits **(see Figure 4)** in this unit reveal a Stage II$^+$ to sporadic Stage III calcic soil development (Machette, 1985). Remnants of this terrace have also been mined for gravel aggregate at the mouth of the canyon.

Qag$_5$ **Alluvium five of the Gunnison River (late middle Pleistocene) –** The unit forms dissected, remnant gravel terraces that occur below Whitewater on the Dakota Sandstone dip slope (**Figure 6**). Three distinct subunit strath risers (a, b, and c) were mapped within this unit. Its gravel surfaces are 180 to 260 feet above the modern river and are equivalent to the Qt60g unit of Scott and others (2002) in Grand Junction. Below the paleoconfluence of East Creek, this unit contains an increase in percentages of subangular to slabby Dakota Sandstone clasts. Unit can be selectively cemented with $CaCO_3$ to form a conglomerate. Clasts have calcic crusts but it appears that any major calcic soil development occurred in mixed fine-grained overbank, colluvium, and/or eolian sediment that once blanketed the gravel deposit but is now mostly eroded away. This terrace remnant has also been mined for gravel aggregate. Thickness is 15 to 20 feet.

Figure 6. View northwest of Qag$_5$ terrace treads on Uncompahgre Uplift dip slope. Rocks exposed below tread is the Dakota Sandstone. Gunnison River is to the right where fall colors occur in riverside trees [199380, UTMY 4319950].

Qag$_6$ **Alluvium six of the Gunnison River (middle Pleistocene) –** This unit forms 1) dissected remnant gravel terraces high on the dip slope of the Uncompahgre uplift, 2) high but small mesas overlying Mancos Shale on the northwest corner of the map area, and 3) small remnants where once was the paleo mouth of the canyon that was 1.5 miles up canyon from its current outlet. Along the Dakota dip slope a small-elevation strath terrace riser occurs within this unit. The gravel elevations of this unit range from 270 to 360 feet. Remnants of this tread on the east side of the canyon contain larger percentages of Grand Mesa basalt that were introduced by the paleo Kannah Creek whose east-side confluence was less than a mile up canyon. This terrace elevation likely corresponds with the Qt100 terrace alluvium in Grand Junction (Scott and others, 2002), as well as the Qt6G surface in Darling and others (2009), which they suggest is conformably overlain by Lava Creek B ash within a locally derived, fine-grained alluvium/slopewash overburden deposit. That superposition would assign a minimum 640 ka age to this deposit.

Qag_7 **Alluvium seven of the Gunnison River (early middle Pleistocene) –** This unit formed a terrace tread that occurs from 420 to 460 feet above the present river level. Terrace gravel occurs in remnants but the tread can be easily discerned on the Dakota dip slope below the mouth of the paleo canyon. Calcic crust was observed on clasts but worn and limited. Coarse crystalline igneous rocks at the surface shows evidence of decomposition. This tread also contains a small-elevation strath riser within it.

Qag_8 **Alluvium eight of the Gunnison River (early Pleistocene) –** This unit only occurs as sporadic gravel remnants between 490 and 540 feet above the current river level. Most prominent are high small mesas northwest of Bangs Canyon but very small relicts also exists on the east side of the canyon shown on the map as points. The paleo mouth of the Gunnison at the time of the deposition of this gravel unit was near the confluence of Kannah Creek above Milbern Bench and the relict deposits on the east canyon edge has noticeably higher percentage of larger vesicular Grand Mesa basalt clasts. The larger deposits downstream of Bangs Canyon have clast counts with as much as 30% that are atypical of Gunnison River provenance seen in the canyon rim relicts near Kannah Creek. Local lithologies, including redbed clasts (**Figure 7**), which would appear to indicate mixing of Colorado River gravels and the near proximity of the early-Pleistocene paleoconfluence. Calcic crust was observed on clasts but was worn and limited. It is likely that any calcic soil development has long since eroded. Many granitic-textured rocks on terrace surface shows evidence of decomposition. This terrace remnant likely corresponds to the Qt170 Colorado River terrace alluvium in Grand Junction (Scott and others, 2002).

Figure 7. Qag_8 terrace gravel. Note increase in redbed clasts that may indicate the paleoconfluence with ancestral Colorado River near this location [UTMX 197010, UTMY 4319660].

Qag_9 **Alluvium nine of the Gunnison River (early Pleistocene) –** Remnants of well-rounded river gravel on a small mesa at 720 feet above the river current level is shown by a single map point. No actual in-situ river gravel deposits exists but common Gunnison-river clasts were seen in slope float below a small hilltop in the Dakota Sandstone and scattered on the top of it. This site was the only location at this elevation level that was seen with Gunnison gravel in the map area.

Alluvial Deposits of Kannah Creek

Boulders, Cobbles, Pebbles, and Gravel in a silty to clayey sand matrix that was deposited by the ancestral Kannah Creek. These river-terrace deposits are almost 100 percent basalt clasts that eroded from the volcanic rocks that cap Grand Mesa. Trace amounts of chert and clasts of other lithologies were noted, likely reworked from Miocene (?) gravel (Aslan and others, 2008), Tertiary/Late Cretaceous Ohio Creek equivalent conglomerates (Ellis and Gabaldo, 1989), or pebble conglomerates in the Tertiary Wasatch Formation that occur below the Grand Mesa basalt flows. Kannah Creek clasts are subangular to round and range in size from pebble to boulders up to 3 feet in diameter. Imbrication of clasts can be seen showing a westward flow towards the Gunnison River confluence. The alluvial deposit description is the same for all the various elevations of Pleistocene Kannah Creek terrace units enumerated below, except the current floodplain deposits. Terrace deposition show a general narrowing of the Kannah Creek valley when it passes from being underlain by the Mancos Shale to a gorge incised into the Dakota and Burro Canyon sandstones at the Uncompahgre Uplift dip slope.

Qak_1 **Alluvium one of Kannah Creek (Holocene) –** fine grained current floodplain unit, a and b subunits, up to 8 feet above current creek level

Qak_2 **Alluvium two of Kannah Creek (late Pleistocene) –** Gravel strath terrace at 26 feet above the current creek level.

Qak_3 **Alluvium three of Kannah Creek (late Pleistocene) –** Gravel strath terrace at 75 to 100 feet above the current creek level. This unit has been subdivided into a and b subunits.

Qak_4 **Alluvium four of Kannah Creek (late middle Pleistocene) –** Gravel strath terrace 130 to 155 feet above current creek level. This terrace is being actively quarried for aggregate near Highway 50, south of Kannah Creek.

Qak_5 **Alluvium five of Kannah Creek (late middle Pleistocene) –** Gravel strath terrace 185-200 feet above the current creek level.

Qak_6 **Alluvium six of Kannah Creek (middle Pleistocene) –** Gravel strath terrace remnant forms mesa on north side of creek where underlain by Mancos Shale. This terrace remnant is 256 feet above the current creek level.

Qak_7 **Alluvium seven of Kannah Creek (early middle Pleistocene) –** Small terrace remnants on the north rim of Kannah Creek gorge near the confluence with Gunnison, 365 and 419 feet above current stream level.

Alluvial Deposits of East Creek

East Creek flows eastward from the drainage divide in Unaweep Canyon. The stream has incised a canyon though the Dakota/Burro Canyon rim rocks into the Morrison Formation. The Morrison Formation mudstones are weak so large landslide complexes occur in the lower East Creek valley basin where the valley has widen, from rim to rim, up to 8/10ths of a mile. The older deposits reflects both riverine and alluvial-fan deposition concurrent with the Pleistocene landsliding. Concentrated mud, debris, and earthflows occur from the landslides into the creek so rocky alluvial-fan and mud-flow type deposits were seen at different paleoconfluences elevations at the Gunnison River. East Creek gravels contain very high percentages from local sources (Dakota, Burro Canyon, and Morrison Formation sandstone). Some reddish sandstone and siltstone clasts were also seen that may be Wingate Sandstone, Chinle Formation, and/or Entrada Sandstone in origin. Also observed were some well-rounded volcanic and igneous cobbles that appear to be reworked Qag alluvium clasts that washed into the creek basin from higher and much older terraces remnants along the adjacent canyon rims. Clasts size and shape of this deposit are mixed, from subrounded to angular with shapes ranging from blocky, slabby, bladed, to ovoid. There also can be boulders of sandstone in the deposit.

Qae **Alluvium of East Creek (Holocene) –** Rocky flood plain deposits composed of boulder, cobbles, and pebble gravel in clayey to silty sand. Clasts are generally angular to subrounded and derived mostly from ancient landslide deposits that are actively being eroded by the creek. Banks of the currently flood plain are choked with rocky colluvium that have slumped, rolled, or washed down to the creek side. Within the current narrow flood plain there are thin remnants of an earlier gravel terrace, approximately 8 feet above the creek floor, which is also included in this unit. Thickness is variable but likely thin; locations were seen where creek flow is directly on the Morrison Formation bedrock.

Qaeo **Old alluvium of East Creek (late to late middle Pleistocene) –** Older alluvium of East Creek was seen at several elevations near the mouth of East Creek/Unaweep Canyon at the confluence with the Gunnison River. In each case, old cobbly gravel alluvium of East Creek was overlying Gunnison River terrace gravel. The superposition is easily seen compositionally by differences in clast lithology, and texturally by degree of sorting and angularity of clasts. The highest was at 225 feet that was deposited over the **Qag_{5b}** terrace tread (**Figure 8**). A prominent gravelly mud-flow deposit buries **Qag_2** gravel at a paleoconfluence fan elevation 75 feet above the Gunnison River. Another Qaeo remnant unit previously discussed overlies the Qag2 terrace about 1,800 feet below the confluence (**See Figure 5**). This thinner and more fluvially textured deposit is 62 feet above the current river level and has been OSL dated an age of 29.8ka ±1.8 ka (Steve Forman, University of Illinois-Chicago, written communication). See Appendix B for more information.

Mud-Flow Dominated Alluvial and Alluvial Fan Deposits

Qamf **Alluvial mud-flow and mud-fan deposits (Holocene to late Pleistocene) –** Light gray, moderately to poorly sorted, poorly consolidated, clayey to sandy silt. The deposits primarily consist of poorly defined silt layers, typically less than an inch to a few inches thick. The muddy sediments are principally derived from the Mancos Shale. The deposits are formed by channelized to laterally unconstrained mud flows or mud-and-gravel debris flows. The deposit can be locally gravel-bearing but where it appears to contain over 50 percent gravel and exhibits riverine sorting (i.e., clast-to-clast contacts), it is mapped **Qgo** instead. The gravel clasts are derived locally, reworked from the erosion of older river and pediment gravel terrace deposits and rocky colluvium. Alluvial floods may rework the sediments.

Figure 8. Prospect pit in Qaeo gravel deposit near East Creek. Note difference in lithology, color, sorting, and clast shape compared to Qag terrace gravel shown in Figure 4. View is to the north toward the Books Cliffs seen in background [UTMX 199700, UTMY 4319770].

The unit forms valley-head and valley-side alluvial fans and tributary-stream valley fills. It forms low-gradient mud fans and coalesced-fan aprons that cover large areas of the modern Gunnison River floodplain at the village of Whitewater. The unit is best developed within the "Adobe hills" areas of the quadrangle and typically is incised by latest Holocene arroyos. Thickness is 5 to 10 feet in valley-head areas and may exceed 20 feet along valley reaches and in terminal fans.

The unit is also prone to soil dispersion and piping erosion, forming pseudokarst features such as sinkholes. Where this deposit is dry and has low density, it may be susceptible to soil collapse and settlement if wetted.

Qamfo **Old alluvial mud-flow and mud-fan deposits (late Pleistocene) –** These deposits are very similar to **Qamf** but are better consolidated by soil development to form slightly higher topographic bumps and low subtle ridgelines, generally in proximity to, or adjacent to, **Qamf** deposits. Deposits generally contain higher percentages of gravel than the Qamf. Where deposits contain over 50 percent gravel and the gravel exhibits clast to clast contact, this deposit has been mapped as **Qgo**.

Qgo **Old gravel-rich alluvial, mud flow, and mud fan deposits (late Pleistocene) –** Gravel-rich mudflow deposits. Gravel clasts are usually in direct clast-to-clast contact or concentrated within a silt and clay matrix that is principally derived from the Mancos Shale. In certain areas, gravelly Qamfo units may be included in this deposit. Deposits are extensive along the wide Callow Creek drainage flats where the clasts were noted to be predominantly of Colorado River provenance. We interpret this gravel to be reworked from headward erosion into older Colorado River gravel terraces mapped to the north (Carrera, 2001). In the lower Whitewater Creek basin, Colorado-River provenance gravel makes up about 40% of the **Qgo** composition with the remaining basalt clasts from Grand Mesa. Higher along the Whitewater Creek in the northeast corner of the quadrangle, as well as in other isolated erosional remnants on the east side of the map area, the gravel clasts are almost 100% Grand Mesa basalt reworked from Reeder Mesa pediment gravels to the east. The deposits tend to be thin, less than 5 feet, but topographic reversal occurs where they are deposited on the Mancos Shale. Winnowing of the fine-grained clayey matrix also leads to an armoring of a cobbly gravel veneer on the ground surface (**Figure 9**).

Figure 9. Old gravel deposits (Qgo) overlying weathered Mancos Shale. Contact is shown by dashed red line. Note the deposit is poorly sorted but clast imbrication can be seen [UTMX 202530, UTMY 4322030]. Photo on left shows surface of deposits where finer-grained matrix has washed away leaving an armored surface of cobble to pebble sized gravel [UTMX 202820, UTMY 4322270].

Qf **Alluvial fan deposits (Holocene) –** Poorly to moderately sorted, angular, cobbly gravel-sized rock fragments, sand, silt, and clay. The fan sediments are deposited by flood, debris, and sheet flow processes. In the map area, most alluvial fans form at the mouths of intermittent drainage channels and swales along the flanks of the Gunnison river canyon where the drainage channel or swale loses confinement. Most of these deposits are rocky fan aprons that formed along the base of extensive landslide complexes or steep colluvium where surficial materials on the steeper slopes above have been disturbed, loosened, and are easily eroded. Many of these fans encroach onto modern floodplains. Fans outletting the dip slope ravines of the Dakota Sandstone are sandier and the clasts more slabby to tabular, reflecting the widespread thin-bedded sandstone exposed in the basin.

Qfo **Old alluvial fan deposits (late to middle Pleistocene) –** Composition and mode of deposition is the same as for **Qf** other than the deposits may have higher percentages of boulder-sized rock fragments. However, this unit occurs as individual, dissected remnants that overlie bedrock or older river-gravel terraces. The deposit caps the higher ground between drainageways. This deposit may include ancient landslide earthflows where the fine-grained constituent has winnowed out, leaving the coarse angular rocky fraction exposed. The fans are inactive, incised, and are bypassed by modern streams or arroyos. Thickness is 5 to 30 feet.

COLLUVIAL, ALLUVIAL/COLLUVIAL, AND MASS-WASTING DEPOSITS

Unconsolidated surficial materials that were transported downslope primarily by gravity and not within or under another medium, such as water or ice. These deposits are formed in combinations of the following depositional systems: 1) downward transport of slope material by gravity creep and sheetflooding (slope wash) into colluvial wedges at the base of slopes, 2) rockfall forming talus slopes, 3) landsliding along zones of weaknesses in underlying bedrock or unconsolidated sediments, and 4) clay-rich earthflows where the entire sliding mass is very wet, wholly or partially fluidized, and flowed down the slope. This category also includes those undifferentiated hillside surficial units that exhibit both colluvial and alluvial (usually limited - such as from rill-type erosion) depositional environments.

Qc **Colluvial deposits (Holocene) –** Unsorted, non to very poorly stratified, very bouldery to cobbly gravel-sized rock fragments deposited primary by gravity on and along the base of steeper slopes. The deposits include talus slopes within the canyons in the map area. This unit also includes deposits in some areas in Gunnison canyon where erosion of existing terrace gravels atop steeper bedrock bluffs has formed rockfall-debris cones below. These deposits generally have an unsorted sandy to clayey matrix that was transported by overland sheetflooding and rills that washed fine-grained material into the deposit.

Qco **Old colluvial deposits (Pleistocene) –** Older unsorted, unstratified, bouldery to cobbly gravel in a sandy clay matrix, deposited primary by gravity and slope wash processes on steeper slopes. The deposit is most commonly found in the northeast portion of the map area where reworked subrounded boulders to cobble gravel-sized rocks covers side slopes that are underlain by the

Mancos Shale. These slopes mark earlier slope margins of pediment and alluvial-fan mesas that were capped with thick gravel deposits composed of subrounded Grand Mesa basalt rocks. Headward erosion of the softer Mancos Shale has resulted in the formation of relict facets and ridge remnants that are capped by the more resistant **Qco** deposit that armor the slope **(Figure 10)**. In some locations one can see a series of armored older colluvial slopes that mark punctuated erosion and retreat of the mesa edge. The deposit generally has a well-developed, consolidated Bk calcic soil horizon and the underlying Mancos has been weathered at depth to what is referred to as the Mancos "blonde." Other locations of this deposit include slopes that

Figure 10. Smoky Hill Member (Kms) shale slopes mantled by old colluvial deposits (Qco). These ridgelines were originally the side slopes of early to mid Pleistocene, gravel-capped mesas that have now been removed by headward erosion into the shale. The weathered Mancos “blonde” below the surface colluvium and above the dark gray shale is best seen in left photo where the Uncompahgre Uplift is in the background. Right photo shows basalt clasts and the thick Bk horizon near the slope edge. The high mesa just visible in center background is Grand Mesa, the original source of the basalt rocks in the Qco deposit. [UTMX 207520, UTMY 4319500].

mark the risers between Pleistocene-aged terraces along the Gunnison River. There, the slope deposit is composed of mixed terrace gravel eroded from above and regolithic rocks from the Dakota Sandstone that thinly (±5 feet) cover the riser slope surface between successive strath terraces.

Qac **Alluvial and colluvial deposits, undifferentiated (Holocene) –** Tan, light gray, to sometimes reddish tan, poorly sorted, pebbly sand deposit formed primarily by the disaggregation of Dakota sandstone and pebbly conglomerate that are exposed as bluffs and cliffs in many subparallel side valleys that have incised into the Dakota Sandstone rim rock. The minor side valleys, most notable in *The Hunting Grounds*, are generally oriented parallel to the dip-slope direction and have eroded into either Dakota shale intervals, or the upper shale unit of the Burro Canyon Formation. The sediments accumulate and are deposited down slope by rilled slope-wash processes to where underlying weak shale beds have influenced topography and the slopes have flatten and widen below the sandstone cliffs. This unit may also include reworked windblown sediments that can give the deposit a reddish hue. The deposit can be gradationally stratified, which likely reflects differing climatic conditions. These deposits can exceed 15 feet where it thickens towards the valley floor. Typically these deposits are scoured along the active drainage channel. The cut bank exposures reveal little or no soil development.

Qaco **Older alluvial and colluvial deposits, undifferentiated (Pleistocene) –** Older slope-wash deposits composed of unsorted cobbly gravel and sand with minor silt and clay. They include the down-slope transport of reworked river gravel and bedrock regolith that can include larger rock slabs and blocks of sandstone. This deposit may include some alluvial fan sediments. Distal edges of Qaco deposits also commonly cover the valley-side margins of lower, but earlier deposited, gravel-terrace treads.

Landslide deposits

Landslides occur by gravity-influenced movement of surficial sediment and bedrock materials down a slope. Moving, shearing, and breaking of the ground materials result in an unsorted, loose, chaotic deposit of rock and soil rubble. Further mobilization of the loose material can also commonly occur as earth/debris flows. Landslides occur in two geomorphic systems in the Whitewater map area. The most widespread are very large and older landslide complexes below canyon rims where weak mudstones of the Brushy Basin and Tidwell members of the Morrison Formation have failed and slid down the slope. The most extensive of these landslides complexes generally occur on the west canyon sides of the Gunnison River and East Creek where strata dip direction is towards the canyon floor (see **Figure 11**). These old landslides deposits show evidence of significant erosion and age, as well as localized areas of recent reactivation. Sinkholes and mud tunnels were also noted in the landslide mass. In many locations, sufficient erosion has occurred that the stronger and more resistant sandstone interval of the Salt Wash Member of the Morrison Formation is now exposed and topographic benches in the landslides deposits have been created (e.g., Milbern Bench and Hallock Basin).

The second landslide geomorphic system, which occurs to a lesser extent and at a much smaller scale, are slump-block failures of Mancos Shale bluffs that underlie terrace gravels along Kannah Creek. Ground water passes easily through the gravel and will perch on the claystone. In time, the weakened and saturated claystone, usually in seep areas along the bluff, will slump and create small landslides.

Qls **Landslide deposits (Holocene to middle Pleistocene) –** Unsorted landslide debris that can range from disturbed and remolded clayshale of only limited downslope movement to very large, angular, rock blocks and boulders emplaced in a gravelly matrix of clay, silt, and sand that have moved hundreds of feet. The deposits record retrogressive failures in mudstone strata of the Brushy Basin and Tidwell members of the Morrison Formation, which then slumps down into the canyons. The canyon rim recedes as the rim rock (Dakota and Burro Canyon sandstones) becomes undermined and destabilized. Large joint-defined sandstone blocks detach and become incorporated within the landslide deposit, either as slumped blocks or toppling rockfall. Sandstone blocks of Salt Wash member are also included in the landslide. Reactivations were noted in several areas, including relatively fresh, lobate earth flows and landslide toes overriding and burying Gunnison River terraces. Thicknesses may exceed 150 feet.

BEDROCK UNITS

A 3,300-foot-thick interval of Upper Cretaceous to Middle Jurassic sedimentary formations is exposed in the Whitewater quadrangle. The oldest units are found in the lower Gunnison River canyon in the south-central part of the map (**Figure 11**). There, the main units are the Entrada Formation at the floor of the canyon, Wanakah Formation, and Morrison Formation that makes up the canyon walls within the lower Gunnison River Gorge. The Burro Canyon Sandstone and overlying Dakota Sandstone, being highly resistance to erosion, form the rim of the Gunnison River canyon and the gentle dip slope of the Uncompahgre Uplift that covers two-thirds of the map area. The remaining northeastern third of the map area lies within the down-dip outcrop belt of the Mancos Shale that strikes roughly southeast to northwest. Approximately the lowermost third of the 4,000-foot thick shale formation occurs within the quadrangle with the youngest strata in the far northeastern corner. Reported thickness ranges of the bedrock units are derived from section measurements in the field or nearby references.

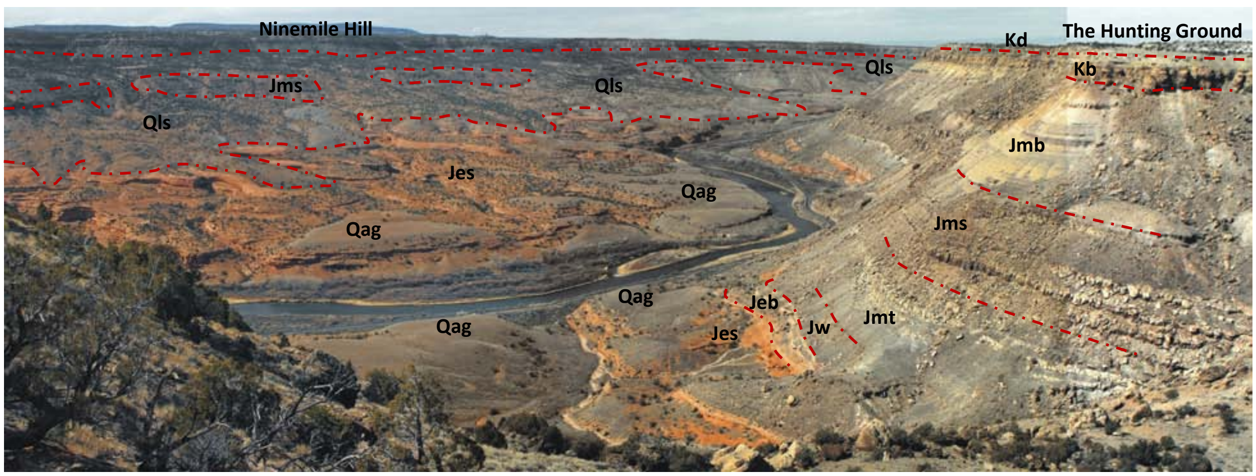


Figure 11. View northwest of Gunnison River canyon near southern boundary of quadrangle. Dashed lines on right show approximate location of bedrock contacts on east wall. The extents of the landslide complex are also shown on the west side. Note benches of intact Jms exposed within landslide complex. Gray flat areas on slopes above river are Pleistocene river-gravel terrace remnants (Qag) [UTMX 203780, UTMY 4308880].

Mancos Shale (Upper Cretaceous)

The Mancos Shale is marine in origin (Cross and Purington, 1899; McGookey and others, 1972). It consists of clayey to sandy to calcareous shale with minor limestone, sandstone, and bentonite beds. We recognize five map units of the Mancos Shale in the quadrangle. They are distinguished on the basis of composition, color, and marine fossil assemblages. Their contacts are conformable unless indicated. Some of the units contain thinner members that have been grouped together on the geologic map (**Plate 1**).

Kms **Smoky Hill and Fort Hays (Niobrara) Members, undivided** — Dark-gray to light-gray, calcareous to very calcareous, fissile to subplaty shale. The Smoky Hill Member is distinguished by the calcareousness and presence of thick-shelled *Inoceramus* fragments, often encrusted with *Pseudoperna congesta* oysters. The inoceramus fragments can be so abundant locally that small reefs or bioherms can form that differentially outcrop as humps in the shale slope (**Figure 12a**). The Inoceramus fragments emit a petroliferous odor when freshly broken. Freshly exposed bedding planes are speckled with small, white, forams and coccoliths. There are occasional shaly limestone beds (peloid-rich mudstone or packstone) up to 1 foot thick. A 50-foot-thick, sandy zone is present in the lower middle part (**Figure 12b**). The sandy zone contains individual sandstone beds up to 8 inches thick. Marine fossils were also noted in the sandstone. Where surface outcrops exists of the Smoky Hill, the shale is both heavily fractured and split along fissile planes and commonly filled with secondary fibrous gypsum. Although widespread in outcrop, the Smoky Hill Member is often covered by thin residuum or mud-flow deposits (Qamf) and is poorly exposed. This surface residuum can exhibit "popcorn" surface texture related to shrink-and-swell clay mineralogy. The Fort Hays Member forms the basal strata of the Niobrara interval. It is highly calcareous but very poorly exposed. In outcrop, it consists of very light gray to gray-white residuum. The unit overlies a regional unconformity (Weimer, 1983). Thickness of the Smoky Hill Member is 650 to 720 feet.

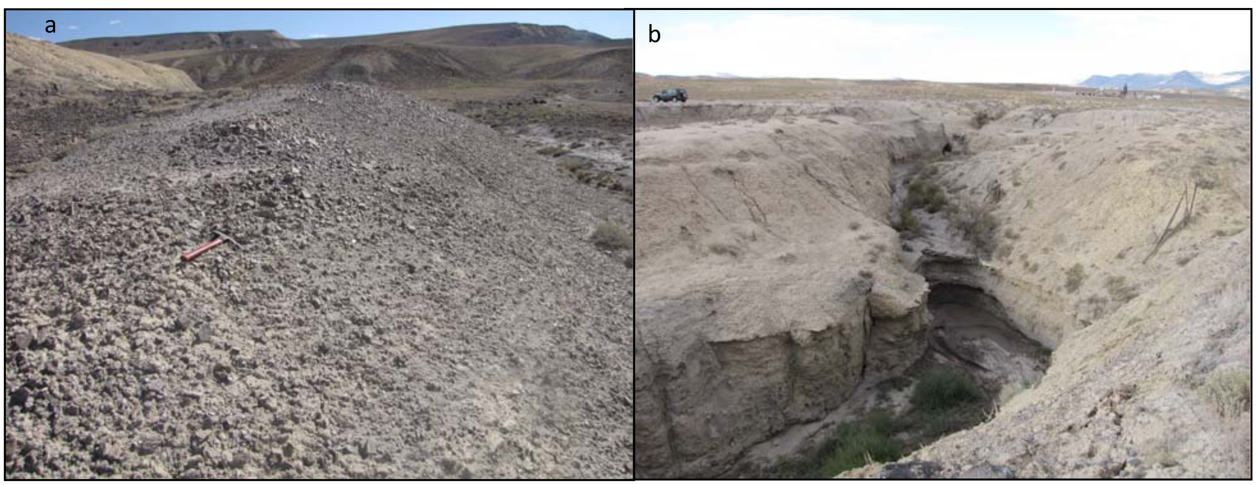


Figure 12. (a) Location of reef of inoceramid fossil fragments that are more resistant to weathering and form small mounds on hillsides [UTMX 206750, UTMY 4320440]. (b) Resistant sandy interval of the Smoky Hill Member (Kms) of the Mancos Shale that has formed a knickpoint where a sandstone ledge and 7-foot deep plunge pool has formed on the floor of the arroyo. Upper surface deposits are mud-flow deposits (Qamf) [UTMX 206110, UTMY 4320960].

Kmj **Montezuma Valley and Juana Lopez Members, undivided** — The Montezuma Valley Member is a medium-dark-gray shale. The sub-unit is very poorly exposed or covered in **Qamf** deposits. The underlying Juana Lopez Member is much more conspicuous in outcrop. It is a medium gray to black subfissile shale and thinly bedded very fine to fine grained, sometimes calcarenitic sandstone. There are common football-sized fossiliferous concretions and, in outcrop, the unit weathers to orange-brown to orange-tan. It consists of interbeds of rippled calcarenite, very fine-grained sandstone, and gray-black organic-rich shale. Sandstone and calcarenite beds are thin but rarely can be up to 2 inches thick. The calcarenite beds contain shell hash and broken pieces of inoceramids shells, small oysters (*Lopha lugubris*), and coiled ammonites (*Prionocyclus sp., scaphites sp.*). Fossils were collected at three locations shown on the map (#6043, #6188, and #6399). The Juana Lopez Member is more resistant to erosion and, with the underlying Blue Hill Member, forms a prominent cuesta in the map area that parallels the east side of U.S. Highway 50 (**Figure 13**). Thickness of the Montezuma Valley Member is reported to be 50 to 60 feet. The Juana Lopez Member is 40 to 60 feet thick.

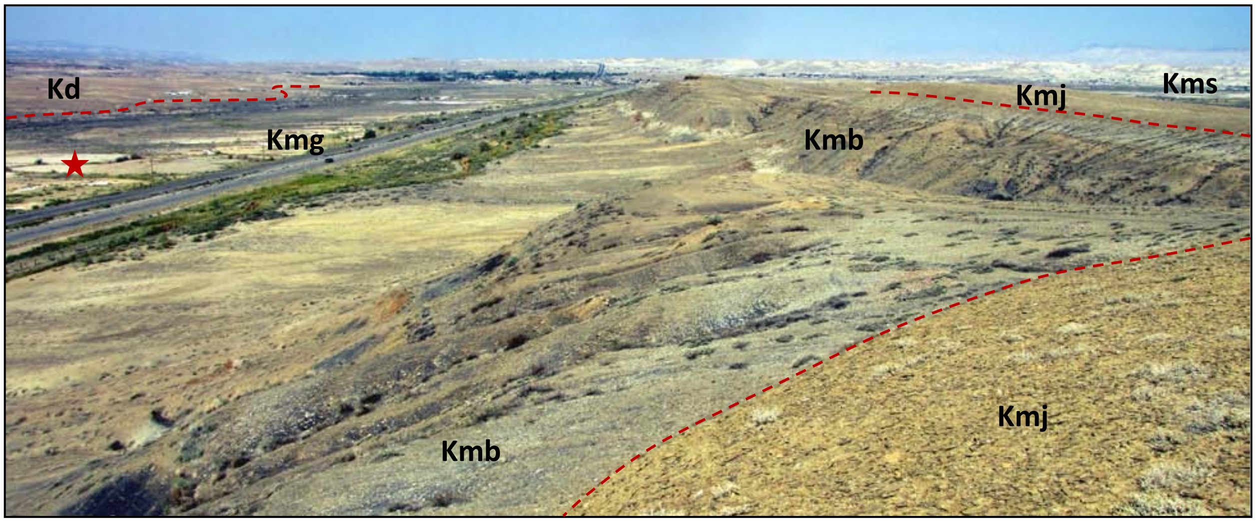


Figure 13. Low ridgeline adjacent to Highway 50 is a cuesta of the Juana Lopez (Kmj) and Blue Hill (Kmb) members of the Mancos Shale. View is to the northwest towards town of Whitewater. Note abundant orange-brown, thin bedded, slabby Kmj sandstone fragments exposed in lower right corner of image. Also note prominent Kmb concretion zone below and near base of slope along light gray color band in the shale. Contact with underlying Kmg is obscured by highway and irrigation canal vegetation. Uncompahgre Uplift dip slope of Dakota Sandstone (Kd) can be seen rising in far left of image. Red star marks fossil collection site of *Pycnodonte aff. P. newberryi* oysters [UTMX 204430, UTMY 4316670].

Kmb **Blue Hill Member** — Medium-gray to dark olive-green gray to black, glauconitic, pyritic, non-calcareous shale. The upper part weathers at the surface to a light gray to light yellow-gray colored slope, which easily contrasts against the orange-brown Juana Lopez above. The shale is fissile to platy, silty, and commonly contains secondary fibrous gypsum along bedding planes and fractures where outcrops are exposed. The bedding surfaces often contain coatings of yellow residue, presumably related to sulfide (pyrite) oxidation. Siltstone interlaminations, starved glauconitic-sand ripples, and very thin beds of olive green-gray brown to tan gray, very-fine grained fossiliferous sandstone is common in the uppermost 40 feet. In that interval we collected beddings lamina specimens of broken marine shell hash that included several small (5-20mm), tightly sutured, likely immature *Prionocyclus hyatti* ammonites (map fossil location #6341).

Within the upper section are small concretions with cone-in-cone structure that commonly disaggregate to buff colored splintery shards. The middle part is fissile shale with distinct bedding planes. Two horizons of much larger orange brown concretions occur (~6 feet dia.) in the lower middle part of the unit that are prominently exposed along the western flank of the Juana Lopez cuesta and easily seen from Highway 50 (**see Figure 13**). The concretions are commonly septarian. Cloudy white crystalline calcite fills the septaria at their cores. The surrounded concretionary carbonate material (dolomite and siderite?) sometimes exhibits outward radiating, cone-in-cone structure. The lower part of the Blue Hill Member is slightly silty, wavy-bedded, finely fissile shale. It becomes brownish black on surface slopes near the base of the unit. Thickness is 120 to 165 feet.

Kmg **Fairport, Bridge Creek, and Graneros Members (undivided)** — The lower members of the Mancos Shale are poorly exposed, the contacts were obscured, and so they were mapped as a single undivided unit. Shale outcrop exposures are non-existent for both the Fairport and Bridge Creek members; the zone is typically deeply weathered to claystone-fragment residuum. However, these members can be distinguished from the overlying Blue Hill Member because it weathers to a light-colored, grayish-white zone that separates predominantly darker shale sections in slope-residuum surface exposures. This color contrast is most noticeable in NAIP aerial photography and Google Earth™ imagery. Within this zone, we collected many *Pycnodonte aff. P. newberryi* oysters at map locations #6154 and #6326. These fossils differentially weather out of the residuum and litter the slope, as do noncalcarous fossiliferous sandstone chips and gray micrite limestone that appear to be concretion fragments. The *newberryi* molluscan guide fossil lies within the Bridge Creek Limestone Member in this area (Merewether and others, 2006). Digging deeper within this fossiliferous zone, the shale was found to be dark gray and finely fissile. Shale becomes a darker, olive-green gray, to brown gray to dark gray with stratigraphic depth and is indistinguishable on open slopes. Near the contact with the underlying Dakota Sandstone, thin zones in the lower Graneros equivalent unit exhibit some characteristics of the Mowry Shale member (**Figure 14**) seen in northern Colorado (White and others, 2013), becoming blocky, more siliceous, and containing interlaminated light gray siltstone. The base of the unit was marked by the first occurrence of thin beds of tan to light-brown, fine-grained sandstone interpreted to be a marine-environment facies of the Dakota Sandstone.

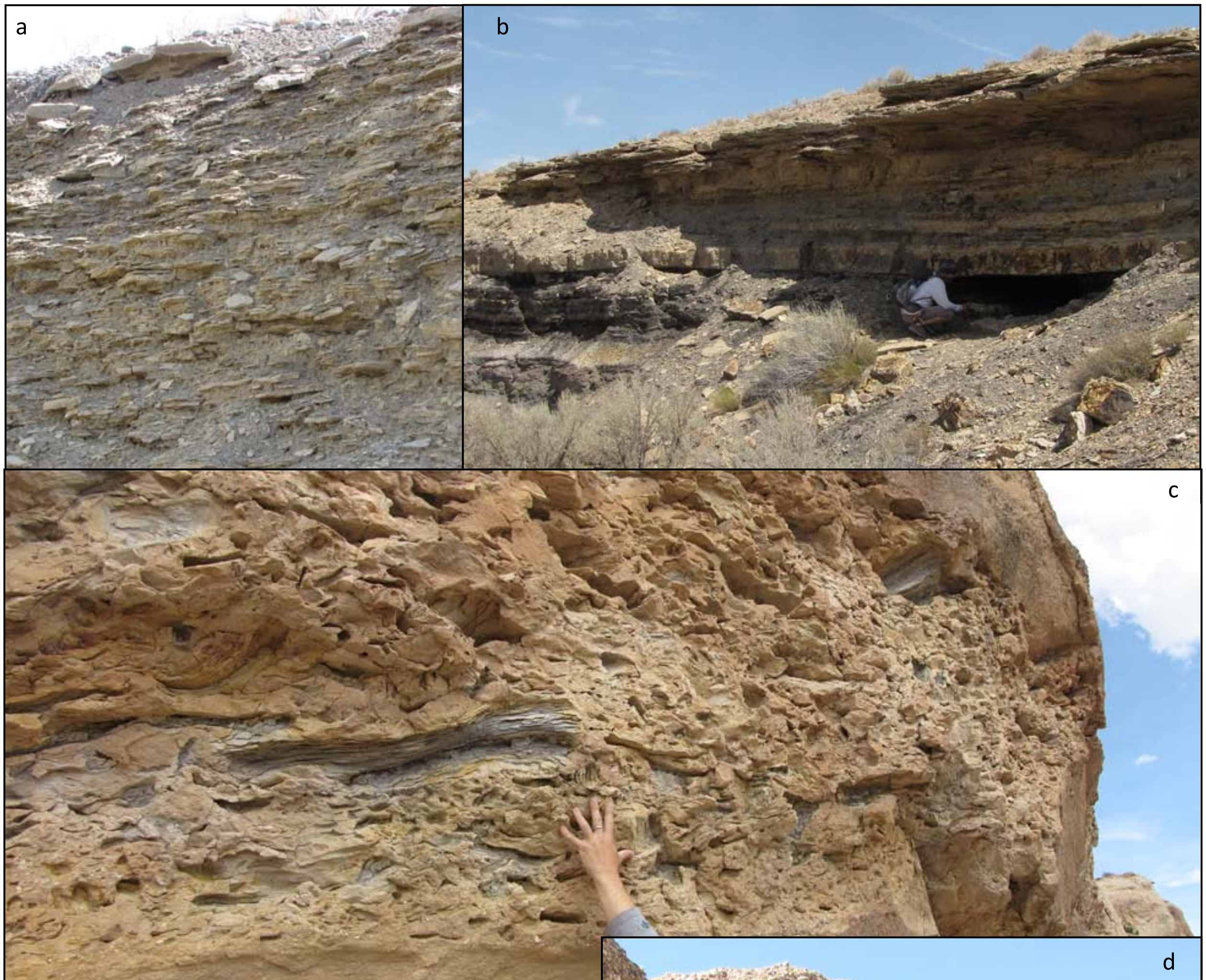
Figure 14. Mancos Shale mapped in the Graneros Member near contact with first Dakota Sandstone beds contains light-gray siltstone laminations and has a banded appearance similar to the Mowry Shale [UTMX 198780, UTMY 4321650].

Kd **Dakota Sandstone (Upper and Lower? Cretaceous)** — Surface exposures of the Dakota Sandstone cover wide areas on the Whitewater quadrangle map. It forms the uppermost rim rock of the Gunnison River Canyon and East Creek of Unaweep Canyon, and the dip slope of the Uncompahgre Uplift that comprises the southwestern two-thirds of the quadrangle.

The sandstone formation consists of interbedded sandstone, conglomerate, shale, and minor coal. Broadly speaking there are two sub-units that reflect a paleo transgressive depositional environment that transitions, up section, from terrestrial alluvial plain to an estuarine and near-shore marine settings as the mid-continent Cretaceous seaway flooded the area and the marine Mancos Shale was subsequently deposited.

The upper interval consists of marine influenced interbedded shale, sandstone, and thin coal (**Figure 15a and 15b**). The shale is dark gray to dark olive gray and contains thin beds of sandstone. Shale intervals, very similar to the Graneros Shale, are up to 10 feet thick near the top. This upper package of thicker shale and thin sandstone beds have mostly been eroded and striped away on the Dakota dip slope. The thin sandstone beds are light brown to tan to grayish red, and very fine to fine grained. It is locally sparsely bioturbated with *Skolithos*, *Ophiomorpha*, and *Thalassianoides* borrows. The sandstone beds can be up to 5 feet thick and have tidally influenced mud-draped flaser bedding and hummocky to planar cross stratification. Coal seams are subbituminous to bituminous and thin; less than two feet thick. Some of the sandstone beds have siliceous cement and are light gray and looks quartzitic in fresh exposures. Occasionally, thicker channel-like sandstone bodies occur in the lower part of the upper sub-unit. They contain trough cross beds that have mud-draped, rippled foresets and locally abundant mud rip-up clasts.

The lower Dakota Sandstone sub-unit is terrestrial, and variable in thickness and lateral facies changes. It contains tabular beds, channels, and lenses of tan to buff sandstone, prominent conglomerate, gray to dark gray mudstone, and gray-black carbonaceous shale. The sandstone is medium to very coarse grained, with beds up to 25 feet thick. The sandstone can contain trough and planar cross-bedding with occasional soft sediment deformation. Differential weathering lattice-type erosion forms occur in some exposures. Medium to very coarse, chert-pebble (≤ 2 in.) conglomeritic beds are common in the lower unit (**Figure 15d**). Within *the Hunting Grounds*, the conglomerate is thick and friable. Where exposed at bluffs on the dipslope, it is commonly altered to a bleached-white color that is stained with yellow, pink, and red splotches. The carbonaceous shale beds are typically less than 4 feet thick and contain sporadic thin coaly stringers. The sandstone beds are tan to gray tan, sometimes exhibiting a salt-and-pepper-type appearance but as brown speckles in a light tan-gray groundmass. Thin reddish-brown iron-oxide cemented seams can be extensive. There can also be orange-brown liesegang bands. The basal chert-pebble conglomeritic sandstone is laterally variable, revealing depositional environments from channel-based riverine to matrix-supported hyperconcentrated (mud/debris) flows with dispersed, matrix-supported pebbles and rip-up clasts up to 2 feet in width (**Figure 15c**). Petrified wood fragments are very common in the basal unit. The basal beds can also have an ashy appearance, be very friable, and split with a rotten slabby appearance. In those circumstances, the basal sandstone can be a slope former, or poorly outcropping as thin, discontinuous ledges above the green mudstone slope of the Burro Canyon Formation (**Figure 16a**). In other locations the sandstone is more resistant, more thickly bedded, and forms steep cliffs above the Burro Canyon mudstone slope (**Figure 16b and 16c**).



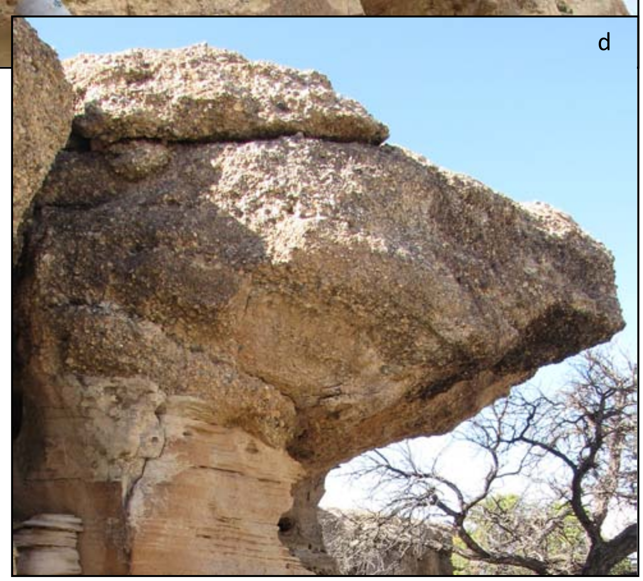


Figure 15. Various lithofacies of the Dakota Sandstone. (a) Tidally-influenced flaser-bedded sandstone near top of the unit [UTMX 201270, UTMY 4319570]. (b) Adit in coal seam within thin–bedded sandstone deposited in estuarine to near-shore floodplain environments [UTMX 205260, UTMY 4313560]. (c) Large clay rip-up clasts in poorly sorted conglomeritic sandstone with dispersed pebbles that mark a hyperconcentrated channel fill within larger amalgamated channel sandstone. Note hand for scale. [UTMX 203740, UTMY 4309620]. (d) Very coarse to coarse-pebble chert conglomerate [UTMX 202670, UTMY 4310440].

Figure 16. Typical Dakota Sandstone (Kd) and Burro Canyon (Kb) exposures at the K-2 unconformity. (a). Where lower Kd is interbedded and basal conglomeritic sandstone is thin, contact can be obscured. Compare contact at hillside colluvium in left of photo to where the stream has cut into the hillside and exposed green Kb shale [UTMX 199040, UTMY 4319940]. (b). Thick basal Kd sandstone. Person shown by red arrow is standing at green-shale contact [UTMX 203810, UTMY 4309570]. (c) Small basin of Kb mudstone surrounded by bleached Kd conglomeritic sandstone. Note small hill in center of photo that contains resistant carbonate concretionary mass and reddish mudstone below [UTMX 204300, UTMY 4310180].

The Dakota Sandstone is Upper Cretaceous (Cenomanian) in age in west-central Colorado (Merewether and Cobban, 1986) but increases in age to the west. Tetrapod track sites have been reported nearby in Dakota Sandstone strata (Lockley and others, 2014). The Dakota-Burro Canyon contact marks the regional K-2 unconformity. Thickness varies from 100 to 130 feet.

Kb **Burro Canyon Formation (Lower Cretaceous)** — The Burro Canyon Formation contains sandstone, green and lavender-red mudstone, and minor conglomeritic sandstone. It generally forms the thickest, more massive, sandstone unit that cliffs out along the walls of the Gunnison River canyon and its tributary gorges within the map area **(Figure 11**). The unit is bound by the K-2 and K-1 unconformities. The upper K-2 unconformity at the Dakota Sandstone is marked by the first occurrence of mottled green to green gray and less often, lavender-red mudstone **(see Figure 16**). This mudstone can be between 5 and 30 feet thick and shows evidence of paleosol development. Where the top mudstone bed is thicker, there are irregular lumpy intervals of chert, and calcic nodular and concretionary masses (**See Figure 16c**). Where quality chert is exposed or litters the slope, there is widespread evidence of lithic scatter (e.g., knap shards and worked edges) to indicate Native American tool making. Below the mudstone is a package of massive to thickly bedded, buff to light brown, amalgamated-channel sandstone. Conglomerate in the Burro Canyon was not widely seen in the map area. Only thin, discontinuous, channel-migration-type, cross bedded, fine granule-sized conglomeratic lenses were observed, typically with abundant clay rip-up clasts. The conglomerate lenses typically occur where the sandstone beds are scoured into the green mudstones, and at the base of the unit where the thick sandstone unit is in disconformable contact with the scoured top of the underlying Morrison Formation (K-1 unconformity). This main sandstone of the Burro Canyon Formation forms cliffs up to 85 feet thick along the Gunnison River gorge and East Creek of Unaweep Canyon. The top of this thick sandstone package also forms the floor of the many subparallel side valleys that have incised through the Dakota rim rock on the *Hunting Grounds* and on Ninemile Hill. Dark brown ferrous nodules commonly occur. *Thalassinoides isp.* trace fossils were noted on bedding surfaces. Chert replacement and silcrete zones were also noted within the top of the sandstone.

Morrison Formation (Upper Jurassic) — Member units include the upper **Brushy Basin Member,** middle **Salt Wash Member,** and the lower **Tidwell Member**. The best exposures of the Morrison Formation are on west-facing exposures on the east wall of the Gunnison River canyon near the southern boundary of the map area (**Figure 11**) and, to a lesser extent, the east rim of Unaweep Canyon at East Creek. It is typically obscured by talus and colluvium from above or by extensive landsliding within the formation. The formation top was selected at the first significant occurrence of bright red shale below the massive lower Burro Canyon Formation sandstone. The total thickness of the Morrison Formation was measured at 625 feet within the Gunnison River canyon.

Jmb **Brushy Basin Member** — This unit generally forms smooth benchy slopes composed of banded red, grayish-purple, and green-gray mudstone, coarse siltstone, and thin to thickly bedded reddish-tan to tan sandstone. The mudstone is generally mottled and contains bentonite and swelling clays that can form popcorn textures on the slope residuum. Paleosol horizons are common, containing lumpy chert and calcrete bodies, and bioturbated sandstone beds with burrows and vertical root casts. The sandstone is mostly fine- to medium-grained and occurs as lenticular bodies and as thin, tabular beds interbedded with shale. It often has a salt-and-pepper appearance of dark and light sand grains. Some of the sandstone channels are amalgamated and up to 30 feet thick. These thick sandstone beds, if near the top of the unit, can appear to be part of the massive Burro Canyon Formation sandstone in canyon-rim cliff exposures. Some of the sandstone beds have lenticular, crossbedded, granule to medium pebble-sized (< ½") conglomerate. The clasts are subrounded to subangular and composed of reddish brown, gray, jade green, and yellow chert, as well as similar sized rip-up clasts (**Figure**

17). Along East Creek canyon in the upper Brushy Basin, there is an old prospect slash on the canyon side exposing altered zones of mudstone and sandstone, including siliceous replacement, iron veining, agate inclusions, and large bodies of chert. According to the BLM, this site was prospected for uranium and vanadium (written communication, David Scott Gerwe, BLM geologist) and an adit is back-filled at the site. This prospect is labeled on the USGS 1:24,000-scale topographic. Contact with the underlying Salt Wash Member was picked by the transition to major sandstone beds that cliff out along the Gunnison River canyon. The Brushy Basin Member is prone to mass wasting and is usually covered by landslide deposits. Thickness was measured between 338 and 266 feet.

Figure 17. Thin conglomeritic sandstone beds in the Brushy Basin Member (Jmb). Left photo shows close up of fine-pebble, chert conglomerate [UTMX 197820, UTMY 4319950].

Jms **Salt Wash Member** — The Salt Wash Member contains thick persistent sandstone beds that are conspicuous between the mudstone-rich Brushy Basin Member above and the Tidwell Member below. The unit is exposed as a line of benchy cliffs along the east side of the Gunnison River canyon composed of thick to massive-bedded, tan-gray with red staining, fluvial and channel sandstones with minor thinly interbedded, mottled red to green-gray mudstone (see **Figure 11**). Member thickness was measured from 136 to 149 feet.

Jmt **Tidwell Member** — The Tidwell member is primarily a gray mudstone and gypsiferous shale, with thin beds of sandstone and gray, hard, dense, micritic limestone. The unit is poorly exposed except for sandstone benches. On many slopes, and in old landslide deposits derived from the unit, the clay has winnowed out by slopewash processes and left a light-gray residuum of angular limestone fragments on the surface. One to two prominent, but discontinuous, beds of light-colored, gray-white, fine to medium grained, eolian sandstone occurs in the top third of the Tidwell at the southern boundary of the map area. Where exposed along the east face of the Gunnison River canyon at the southern map boundary, this sandstone unit quickly thins and pinches out northward (**See Figure 11**). This eolian facies in the Tidwell may represents a dune field or small erg in the same desert paleoenvironment as that of the Junction Creek Sandstone that was mapped to the south, and by Hansen (1968, 1971) in the vicinity of the Black Canyon of the Gunnison where he included the entire Tidwell Member package of rocks within the Wanaka Formation. In the Whitewater map area, the Tidwell base is marked by another thin (3-4 feet) but prominent basal sandstone bench. This sandstone can be very-coarse grained to granule conglomeritic at its base and lies unconformably on the Wanakah Formation, marking the regional J-5 unconformity (Pipiringos and O'Sullivan, 1978; O'Sullivan, 1992; O'Sullivan, 2004). Total thickness of the Tidwell Member was measured from 141 to 153 feet.

Jw **Wanakah Formation (Middle Jurassic)** — Red and green-gray, thin to medium bedded, mudstone, siltstone, and very fine-grained sandstone. O'Sullivan and Pipiringos (1983) described an upper green unit and lower red unit and stratigraphically placed them within the Tidwell Member of the Morrison Formation. This package of strata was later reclassified the Wanakah Formation in nearby mapping by Scott and others (2001) and later stratigraphic section work by O'Sullivan (2004). These two color bands are easily discerned in the Whitewater map area. The lower reddish band at the contact with the underlying Entrada "board beds" is composed of very fine-grained sandstone and siltstone beds that are generally mottled in color and lumpy bedded. Discontinuous, dark lavender-gray shale seams were noted at the lower contact with the Entrata "board beds." The upper green-gray colored band below the J-5 unconformity is comprised more of soft mudstone and shale. The Wanakah Formation contains an interval called the *Carnelian sandstone marker bed* (O'Sullivan, 2004) that contains autochthonous irregular masses of granule-textured, red to reddish light-gray chalcedony. More resistant to erosion, fragments of these irregular masses are commonly seen in slope residuum (**Figure 18**). While not seen in the map area, fossils in the Wanakah Formation have been reported in nearby tributary canyons of the Gunnison River between this map area and Delta (O'Sullivan and others, 2006). Total unit thickness was measured at 40 feet.

Figure 18. Sample of red chalcedony typically found in Wanakah (Jw) Formation residuum.

Entrada Sandstone (Middle Jurassic) — Two members of Entrada Sandstone were mapped in the Whitewater quadrangle: the Slick Rock Member and the *board beds*. The *board beds* is an informal unit but is easily seen in outcrop so the term was carried over from the same package of rocks described by O'Sullivan and Pipiringos (1983) that was mapped in the vicinity of the Colorado National Monument and Grand Junction by Scott and others (2001 and 2002) and described in nearby stratigraphic sectional work by O'Sullivan (2004).

Jeb **"Board Beds" (informal member)** — Pale, pinkish light-gray to light red, thin to medium bedded, very fine to fine grained sandstone. Beds are water deposited and planar bedded. There are some shaly partings and thin mudstone interbeds that separate the individual sandstone beds, resulting in the outcrop morphology that resembles a stack of books or boards **(**see **Figure 11**). Thickness was measured from 35 to 41 feet.

Jes **Slick Rock Member**— Prominent red sandstone exposed at the floor of the Gunnison River canyon in the southern part of the map area (see **Figure 11**). The unit is composed entirely of eolian, large-scale crossbedded sandstone that weathers to a rounded appearance and erodes to steep-walled box canyons and grottos. The sand is very fine to medium grained. Differential weathering lattice-type erosion forms occur in sandstone exposures and in some areas, abundant small granule-sized concretions stand out in relief and give the surface exposure a rough gritty appearance. The Slick Rock Member is the lowest formation in the map area. A thickness of over 100 feet was exposed in the map area.

Older Bedrock Units Shown on Geologic Cross Section A-A' Only

Cross Section A-A' runs northeast from the southwest corner of the map area, across the Gunnison River canyon and Kannah Creek to the adobe hills of the Mancos Shale. The section line is shown on the map in **Plate 1**. The cross section is shown on **Plate 2**. Additional, older bedrock units are included as subsurface units on the cross section. They do not crop out within the Whitewater quadrangle but are exposed to the south in the Gunnison River gorge (Livaccari and Hodge, 2005a). The thickness of the Entrada Slick Rock Member exposed in the map area approximates the total thickness reported by Scott and others (2001 and 2002) so suggests that the Kayenta Formation is incised by the Gunnison River in the map area but is hidden by canyon floor, flood-plain alluvium.

J₸ **Undivided formations of the Lower Jurassic and Upper Triassic** — Includes the Kayenta Formation, Wingate Sandstone, and the Chinle Formation. The Chinle Formation unconformably overlies Precambrian rocks that marks the erosional surface of the ancestral Uncompahgre Mountains.

Xu **Undivided meta-igneous gneiss and migmatitic meta-sedimentary rocks (Proterozoic)**

For more detailed descriptions of the lower formations and the Precambrian rocks, see the map of the Colorado National Monument by Scott and others (2001) where they are exposed.

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GEOLOGIC HAZARDS

This section of the author's notes contains descriptions of the geologic hazards identified that could pose a potential risk to people, structures, and property. Geologic hazards have been defined in Colorado by Rogers and others (1974). In the Whitewater quadrangle, the following hazards have been either mapped or identified: rockfall, landslides, debris/mud flows, and problematic soils and bedrock that have the potential to swell (expand) or subside (collapse or settle).

ROCKFALL

Rockfall occurs where rock is exposed and slopes are sufficiently steep that when a rock detaches from the slope, the gravitational force causes the rock to fall, bounce, rapidly slide, and/or roll down the slope. The rock comes to rest when the slope angle flattens and the frictional forces of the rocks hitting the surface increase, and/or the surface roughness of the slope "catches" the rock. In the Whitewater quadrangle, rockfall hazards occur below the cliff lines of the Gunnison River, East Creek, and Kannah Creek canyon rims, as well as some of the smaller canyons near Bangs Canyon. Most of the rockfall hazard locations occur on public property within the BLM Dominguez-Escalante National Conservation Area but the public is exposed along State Highway 141 and private landholdings near the East Creek confluence and in the lower Kannah Creek/Indian Creek area. Many sections of the railroad tracks through Gunnison Canyon are also exposed to rockfall hazard.

LANDSLIDES

Landslides form where geologic materials in a slope do not have the strength to support itself against the force of gravity. The ground ruptures and the downward movement of rock and soil generally slide on subsurface shear planes, or in a saturated state, become an earthflow. Typical landslide morphology includes scarps, slumps, slip planes, intermediary scarps and traverse pressure ridges, hummocky terrain, and spreading earthen toes. The rates of these movements can range from rapid earth flows to slow creeping ground movements that are only perceptible over months or years. Hummocky terrain includes closed depressions and irregular drainage patterns. Human structures, which are not designed for earth movements, generally, do not survive if landslides are moving.

In the Whitewater map area, landslides form in two general geomorphic conditions. The most extensive are very large, ancient landslide complexes within the canyons of the Gunnison River and East Creek, Bangs, and Kannah Creeks. There, the weak claystones of the Morrison Formation are exposed below the rim rocks and have failed, causing retrogressive failures of the Dakota Sandstone and Burro Canyon Formation rim rocks. For the most part, these landslides are ancient, activated when climatic conditions were wetter during Pleistocene glacial cycles. The broadest landslide complexes are on the west canyonsides where downcutting into the Uncompahgre Uplift has daylighted northeast-dipping bedding planes. For the future, the existing chaotic landslide rubble and sheared broken land is now even further weakened and prone to additional movements if they become saturated. There are reactivated areas of more recent landslides within these ancient landslide complexes. Fortunately, impacts to the public are minimal because most of these landslides lie on public lands. State Highway 141 lies mostly on landslide deposits from about 1½ miles above the Gunnison River confluence where the Morrison Formation begins its exposure along the canyon floor. There is some private land exposure to this type of landslide in the lower Kannah Creek near its confluence with the Gunnison River.

The second system is much smaller in area but important since it lies on mostly private property. Smaller landslides and soil slips occur near Kannah Creek along mesa bluffs where Pleistocene gravel (Qak) caps high terrace remnants that are underlain by Mancos Shale. The gravel is permeable so water passes easily downward to the contact with the relatively impermeable shale. The perched groundwater migrates laterally to the mesa edge forming seeps in the slope. Sufficiently weakened and saturated, the shale shears and slips, forming small landslides. These types of landslides are very common along the Uncompahgre River valley where extensive irrigation occurs on mesas underlain by the Mancos Shale (White and others, 2011). New development should avoid the mesa edges where the underlying bedrock is the Mancos Shale.

DEBRIS/MUDFLOWS

A debris/mud flow is a geologic phenomenon whereby a wet, viscous, fluid mass of entrained fine- to course-grained material flows rapidly and turbulently downslope, initially within a basin drainageway. This typically results from torrential rainfall that initiates rapid erosion (including shallow soil-slip-type landslides) and transport of poorly consolidated surficial materials that have accumulated in the upper reaches of the drainage area. The unconsolidated sediment, rock fragments, and other debris is entrained within a sufficient amount of water that it behaves as a viscous fluidized mass that has the ability to rapidly flow down a drainage channel. At the mouth of steep basin channels, these fast-flowing hyper-concentrated flows have the ability to jump the banks of existing channels and fan out over the flatter ground terrain and can cover large areas. For that reason, mud/debris flows are categorized as a geologic hazard and not a flooding hazard. Mud is composed predominantly of silt- and clay-sized particles, whereas the term “debris” is commonly applied to material that consists mostly of boulder- and cobble-sized rocks mixed with displaced soil and vegetation. It is a potentially damaging geologic hazard in semi-arid Colorado where poorly vegetated, hillside slopes exist, and intense, cloud-burst-type rainfall events can occur (White and others, 2011).

Areas in Whitewater that may be prone to overland mud flows include the adobe hills of Mancos Shale in the northeast corner. Mancos Shale is impermeable and, where exposed, is essentially barren of vegetation. Storm run-off quickly concentrates in swales and drainage channels. While those flows will eventually enter the deep arroyos of Whitewater and Callow Creeks, some overland mud flows would be expected in the flatlands, swales, and gullies that exit the adobe hills above.

PROBLEMATIC SOIL AND BEDROCK

Problematic soils and bedrock contain properties that cause volumetric changes, generally when they become wetted beyond their original natural condition. There are two basic mechanisms: Swelling or expansive soil and bedrock, and compactive (collapsible) or settling soil and bedrock. Problematic soils derived from shale bedrock can also be corrosive to certain metals and concrete. Subsurface soil investigations are recommended for foundations design of new construction in problematic soil areas. These investigations should include sampling and swell/consolidations testing that measure the swell or collapse potential of the load-bearing soils, as well has addressing the corrosive nature of the soil.

Swelling Soils

Swelling soil and expansive bedrock are soil and rock that contain clay minerals that attract and absorb water (Rogers and others, 1974). The rock or soil swells in volume when wet and shrinks when dry. The swelling is caused by the chemical attraction of water to certain clay minerals, predominantly smectite and, to a lesser extent, illite. At the molecular level, clay minerals form micron-sized sheets or plates. Within the crystalline lattice of these clay minerals, layers of water molecules have an affinity to be incorporated between the clay plates. As more water is made available to the clay, more layers of water molecules are added between the plates and the adjacent clay plates are pushed farther apart. The overall soil-swell pressure from the addition of water at the molecular level can be quite high and can easily heave typical foundations and slabs, resulting in severely damaged structures (Noe, 2007).

The swelling of expansive-clay soil is a mineralogical phenomenon as available water is taken in and clay particles swell. Expansive soils can also shrink when desiccation occurs and the soil volume reduces as evaporation pulls water molecules out of the clay particles. The terms swelling soil, expansive soil and bedrock, heaving soil, and shrink-swell soils are used interchangeably to describe the mineralogical volume expansion process described above. Very commonly, repeated shrink-swell cycles in surface exposures of expansive-clay soil results in desiccation cracks and what is called “popcorn texture” commonly seen in the Mancos abobe hills (White and others, 2011).

The major bedrock units that contain expansive clay minerals in the project area are the Mancos Shale and shales of the Morrison Formation. Most of the private property in the northeast corner of the map area near Whitewater and Kannah Creek is underlain by Mancos Shale, or sediment (soils) that are derived from it so there is highly probability that swelling clay minerals are present. Shales of the Morrison Formation are of lesser concern because they lay mostly on public lands of the BLM Dominguez-Escalante National Conservation Area, except for private-land inholdings within Kannah Creek canyon near the confluence with the Gunnison River.

Settling or collapsible soils and bedrock

Collapsible soils are broadly defined as soils that can rapidly settle when exposed to water. These soils can be a significant geologic hazard in semiarid to arid climates. The collapse can occur under the weight of the soil alone (overburden pressure) or under the additional load of a building or other structure. Most collapse occurs through mechanical means where dry, low-density, high-porosity soil becomes denser when the soil-particle binding agents weaken or break after wetting. The destruction and recompaction of the soil structure at moister denser conditions cause soil-volume loss and settlement of the ground surface. Because the introduction of water brings about such collapse, the terms “hydrocompactive” and “hydrocompressible” are commonly used to describe collapsible soils.

Other processes of ground subsidence and collapse occur in certain soil and bedrock through (1) suspension and removal of particles in dispersive soil by flowing water (soil piping and pseudokarst formation) and (2) actual chemical dissolution of gypsiferous soils and secondary gypsum in Mancos Shale bedrock (White and Greenman, 2008).

Collapsible soil forms in specific, geologically recent (Holocene) sediments that have been deposited in arid to semiarid environments. In the Whitewater area those finer-grained accumulations of rapidly deposited, unsorted, water-borne mud are Qamf and finer-grained Qc. Where soil collapse can exist, an open and inherently unstable skeletal fabric characterizes the soil structure of these sediments. The common factor in the water-laid sediments is rapid deposition. In a generally arid climate, wet sediments quickly desiccate (dry out) in their original condition, without the benefit of further reworking to pack the sediment grains. Locally, groundwater levels generally never rise into these mantles of soil, which can remain unsaturated until land development. During and after development, moisture can be introduced to the subsurface soil through field irrigation, lawn and landscaping irrigation, capillary action under impervious slabs, leaking or broken water and sewer lines, and altered surface and subsurface drainage (White and Greenman, 2008).

The above definition states that soil collapse is a mechanical phenomenon as soil grains shear against each other, physically moving and re-orienting into a denser configuration, which results in a one-time reduction of soil volume. This is an important distinction from expansive soils that can experience repeated cycles of swelling and shrinking, depending on periods of wetting and desiccation.

Other processes of soil settlement and collapse can also present problems, as it does in similar terrain in the Uncompahgre River valley in Montrose County (White and others, 2011). Dispersive soils have soil chemistry high in sodium-ion concentrations. This occurs because most of the mud-type alluvial sediments (**Qamf**) are derived from the Mancos Shale, which can have a high salt content. Other impacts of high salt content and high total-dissolved-solids content of the Mancos Shale and soils derived from it include corrosiveness and salt/selenium loading of irrigation waters. Soil dispersion occurs when clay particles deflocculate in the presence of water and go into suspension. Moving water flushes the suspended clay and silt away and soil pipes, fissures, and small caverns can open, generally near existing arroyos. Collapse of these types of features can form psuedokarst landforms such as sinkholes and ground fissures.

The dissolution of gypsum in weathered shale bedrock and soil can also result in ground settlement. Complex biogenic and oxidation-weathering chemistry results in the abundant gypsum fracture-filling observed in weathered zones of the Mancos Shale. Arid-climate soils can also be gypsiferous. In the presence of introduced water, gypsum dissolves, which can then result in void creation and micro-piping in soil and enlargement of openings in gypsum-filled fractures. Under load and in the presence of additional water, the weathered shale bedrock can recompress and cause ground settlement. A case history of this circumstance in recent land development in the Whitewater area is discussed in White and Greenman (2008).

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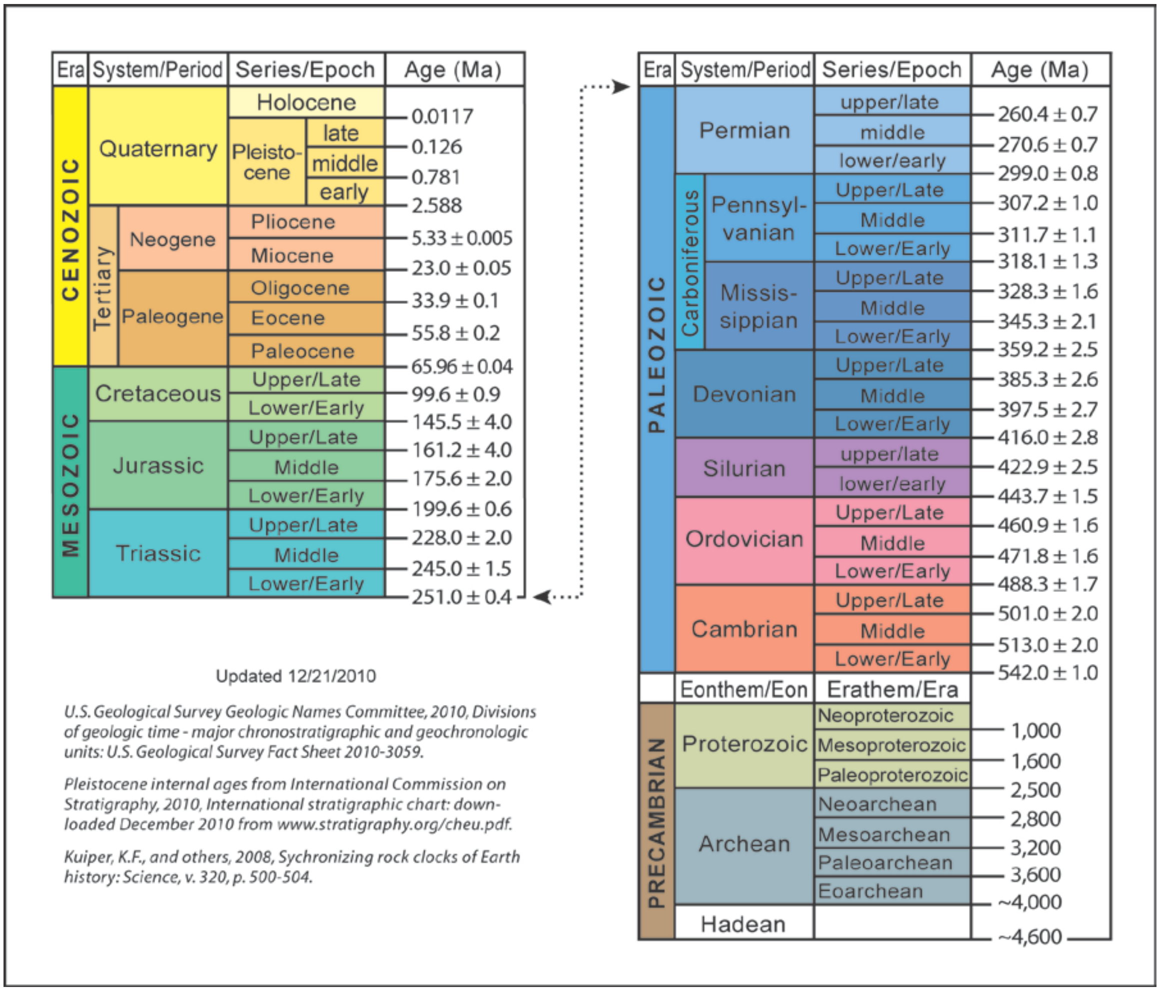
APPENDIX A

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



APPENDIX B

Appendix B. Age dates of material samples collected from the Whitewater quadrangle

Optically stimulated luminescence (OSL) ages and associated chronologic data for fluvial sediments high country, western Colorado (10/7/2013)

Field number	Laboratory number	Quartz grain size (µm)	Equivalent dose (Grays) [a]	Uranium (ppm)[b]	Thorium (ppm)[b]	K20 (%)[b]	H20 (%)	Cosmic dose (mGrays/yr)[c]	Total dose rate (mGrays/yr)	OSL age (ka)[d]
WW#6457A	UIC3421	250-355	69.15 ± 3.67	2.5 ± 0.1	5.3 ± 0.1	1.61 ± 0.02	10 ± 3	0.16 ± 0.02	2.32 ± 0.12	**29,790 ± 1840**
WW#6457B	UIC3439	150-250	90.19 ± 5.09	1.4 ± 0.1	8.2 ± 0.1	1.89 ± 0.02	10 ± 3	0.19 ± 0.02	2.62 ± 0.13	**34,490 ± 2310**

[a] Equivalent dose determined by the multiple aliquot regenerative dose method under blue (470 nm) excitation (Jain et al., 2003). Blue emissions are measured with 3-mm-thick Schott BG-39 and one, 3-mm-thick Corning 7-59 glass filters that blocks >90% luminescence emitted below 390 nm and above 490 nm in front of the photomultiplier tube.

[b]U ,Th and K_20 determined by ICP-MS, Activation Laboratory Ltd., Ontario.

[c] Cosmic dose rate component from Prescott and Hutton (1993).

[d]All errors are at one sigma and ages are calculated from AD 2010. Analyses performed by Luminescence Dating Research Laboratory, Dept. of Earth & Environmental Sciences, Univ. of Illinois-Chicago.

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