OPEN-FILE REPORT 09-04

Authors' Notes

Geologic Map of the Fruita Quadrangle
Mesa County, Colorado

by
Richard Livaccari and James Hodge

Bill Ritter Jr., Governor
State of Colorado

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Colorado Geological Survey
Department of Natural Resources
Denver, Colorado
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Geologic Map of the Fruita Quadrangle Mesa County, Colorado

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

by
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Image looking north at Dinosaur Hill. Dinosaur Hill is composed of the Brushy Basin Member of the Morrison Formation. The Brushy Basin member is partly covered with large blocks of sandstone that are remnants of landslide deposits derived from the overlying Burro Canyon and Dakota Formations. [UTM83 12S UTMX: 695913, UTMY: 4333509]

This mapping project was funded jointly by the Colorado Geological Survey and the U.S. Geological Survey through the National Geologic Mapping Program under STATEMAP Agreement No. 08HQAG0094

FOREWORD

The purpose of Colorado Geological Survey Open File Report 09-04, *Geologic Map of the Fruita Quadrangle, Mesa County, Colorado* is to map and describe the geologic setting, structure, geologic hazards, and mineral and ground-water resources of this 7.5-minute quadrangle located northwest of Grand Junction in western Colorado. Geologists Richard Livaccari and James Hodge completed the fieldwork on this project during the Spring, Summer, and Fall of 2008. Richard Livaccari was the principal investigator and author of this report and James Hodge was the principal mapper and author of the geologic map (Plate 1).

This mapping project was funded jointly by the U.S. Geological Survey (USGS) and the Colorado Geological Survey (CGS). USGS funds were received under STATEMAP award number 08HQAG0094. STATEMAP is a component of the National Cooperative Geologic Mapping Program, which is authorized by the National Geologic Mapping Act of 1997. Matching funds were drawn from the Colorado Department of Natural Resources Severance Tax Operational Funds, which are obtained from the Severance Tax paid on the production of natural gas, oil, coal, and metals in Colorado.

Vince Matthews
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INTRODUCTION

The Fruita 7.5-minute quadrangle is located in the Grand Valley of Mesa County, western Colorado (Figures 1 and 2). The Grand Valley, along with Fruita, has historically been a major fruit-growing region with a large number of orchards and small farms. The name “Fruita” is derived from the fruit producing potential of this area. Except for the city of Fruita, the Fruita quadrangle area is dominated by agricultural land use. This is changing, however, as agricultural lands throughout the Grand Valley are rapidly being converted to urban uses. This is reflected in the population growth of this area. The population in all of Mesa County was approximately 139,000 in 2007 (U.S. Census Bureau, 2007). The 2005 population of the City of Fruita was 9,416 (Figure 3). The population of the City of Fruita has more than doubled in the past fifteen years (from about 4,000 residents in 1990 to over 9,000 residents in 2005; Figure 3). This represents a “boom” growth rate.

The Colorado River runs through the southernmost portion of the quadrangle (Figure 2). Since 1900, irrigation canals have provided ample and inexpensive water from the Colorado River for agriculture (Mayo, 2008). These canals run roughly northwest-southeast across the Fruita quadrangle

(Figure 2). Irrigation water is available in the valley from mid-April through November each year (Mayo, 2008). The Grand Valley and Main Line Grand Valley canals are privately owned and managed by local companies. The Government Highline Canal is federally owned and operated by the Grand Valley Water Users Association (Leib, 2008).

The highest point in the quadrangle (elevation 5,080 feet) is found in the broken hills of the Mancos Shale in the northeastern corner of the quadrangle. The lowest point is along the Colorado River valley (elevation 4,480 feet) in the southwestern part of the quadrangle (Figure 2).

Geologic mapping of the Fruita 7.5-minute quadrangle was undertaken by the Colorado Geological Survey (CGS) as part of the STATEMAP component of the National Cooperative Geologic Mapping Act, which is administered by the U.S. Geological Survey (USGS). Geologic maps produced by the CGS through the STATEMAP program are intended as multi-purpose maps useful for land-use planning, geotechnical engineering, geologic hazards assessment, mineral resource development, and ground-water exploration.

The geologic interpretations shown on the Fruita quadrangle are based on: (1) field investigations from April through November of 2008; (2) prior published and unpublished geologic maps and reports, in particular the USDA National Resources Conservation Service (NRCS) Soil Survey was used as a guide in areas where geologic exposures were limited; (3) interpretation of 2007 natural color aerial photography provided by Mesa County; (4) supplemental interpretation of older black and white and infrared aerial photography flown in 1937, 1954, 1977 and 2003 provided by Mesa County;

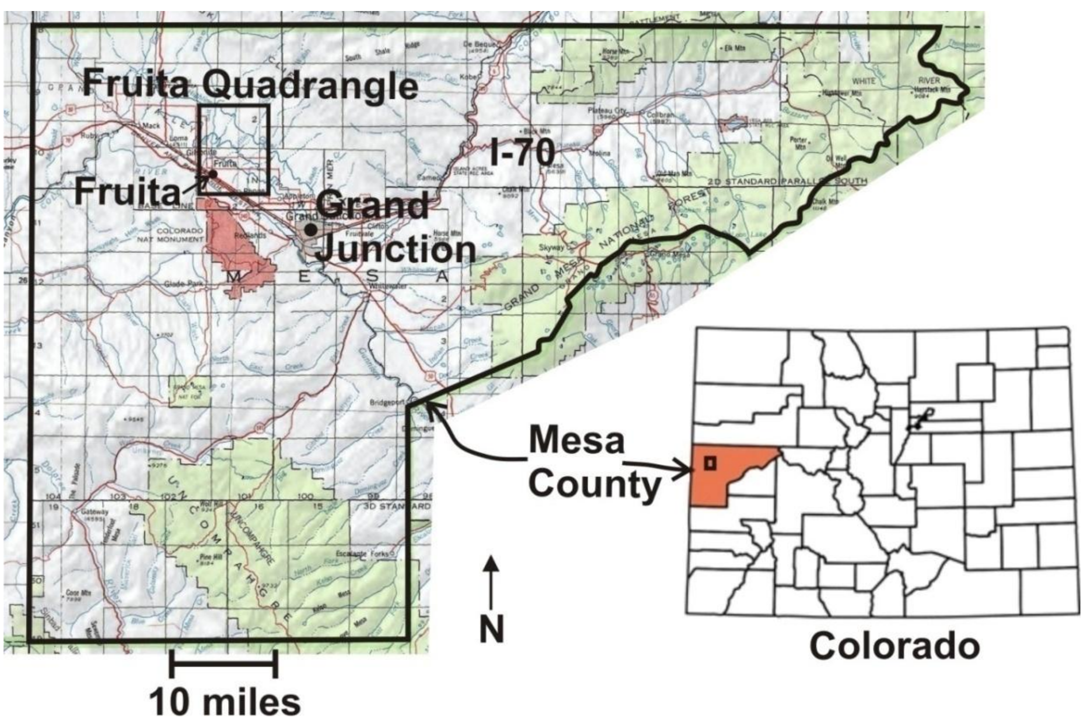

Figure 1. Location map showing of the cities Fruita and Grand Junction and the Fruita 7.5-minute quadrangle in western Colorado.

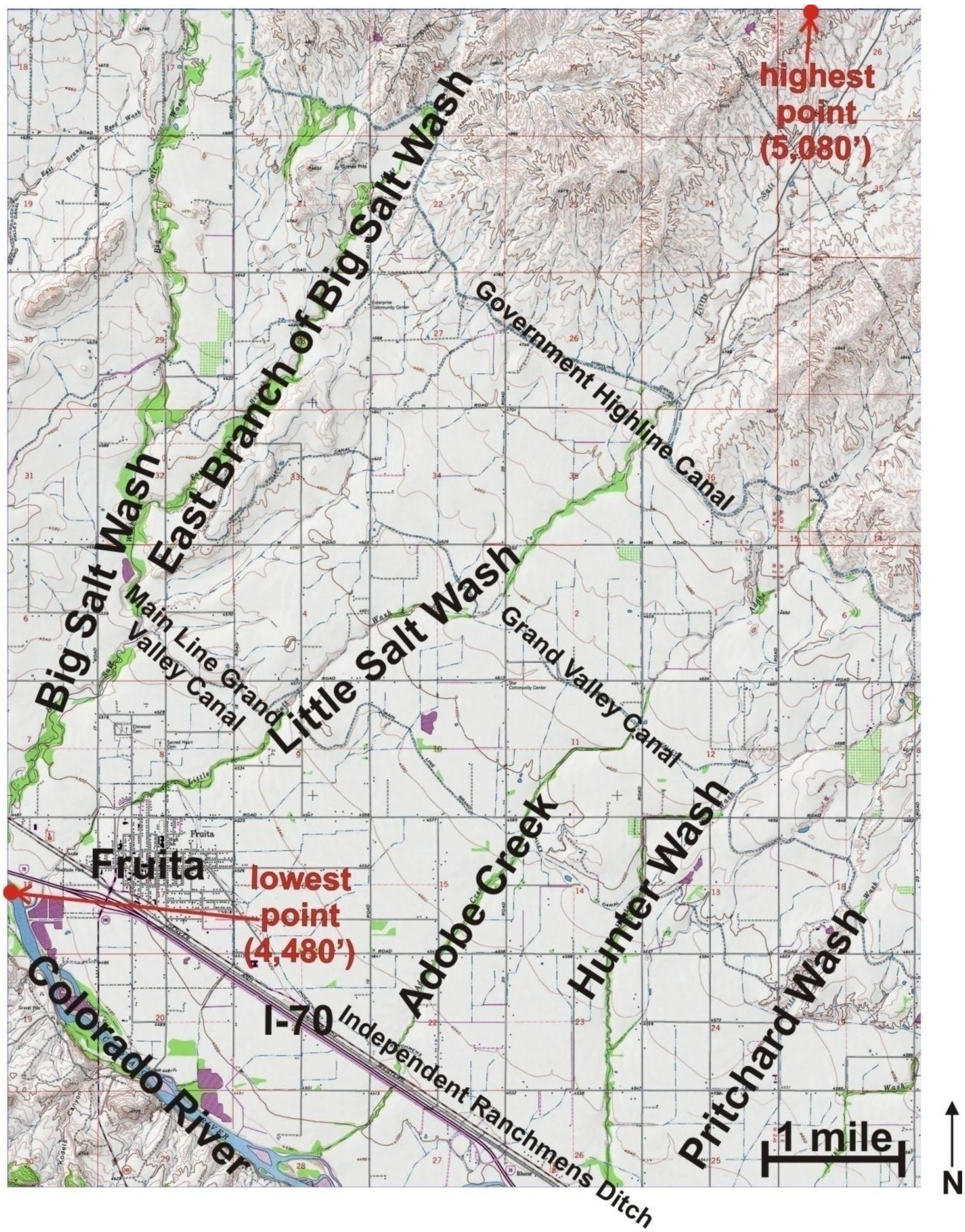

Figure 2. USGS Fruita 7.5-minute quadrangle illustrating the location of major physiographic and geomorphic features discussed in this text. The most important geomorphic feature is the Colorado River. The major southwestward-flowing tributaries of the Colorado River include Big Salt Wash, East Branch of Big Salt Wash, Little Salt Wash, Adobe Creek, Hunter Wash, and Pritchard Wash. Also illustrated are the topographically highest and lowest points.

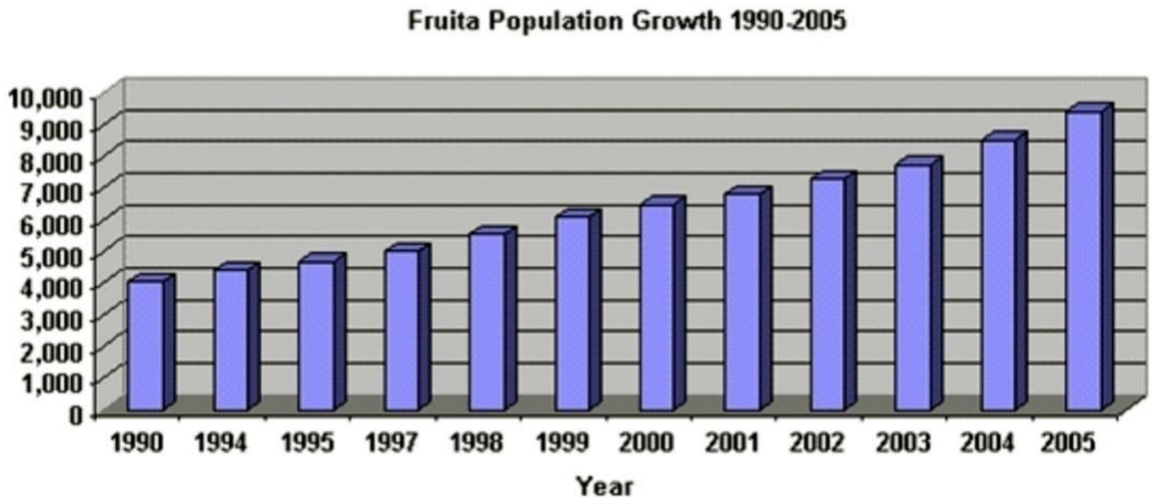

Figure 3. City of Fruita population growth. Note that the population of Fruita has more than doubled between 1990 and 2005. Data from: http://www.fruita.org/cityhome.htm; accessed October of 2008.

(5) interpretation of the USGS 1962 1:24,000 scale topographic map; (6) interpretation of the Mesa County contour map with a 2 ft contour interval (http://gis.mesacounty.us/interactive.aspx; 'egrab' hotlink; accessed in 2008); and (7) interpretation of the 2001 Mesa County flood plain map (http://gis.mesacounty.us/interactive.aspx; 'Contours, Drainage Basins & Flood Maps' hotlink, accessed in 2008). Bedrock geology and surficial deposits were mapped in the field on mylar overlays of aerial photographs. These data were visually plotted on the same airphoto base in ESRI ArcGIS 9.2 as shapefiles. The projection used was Universal Transverse Mercator (UTM; North American Datum 1983, Zone 12 North, meters). Coordinates are provided for key geologic areas and images in Zone 12. The maps were converted from Zone 12 to Zone 13 in ArcGIS.

PREVIOUS WORK

The Fruita quadrangle had not previously been mapped at 1:24,000-scale (Figure 4). Small-scale (1:250,000) geologic mapping of the Fruita area was done by Cashion (1973). Sinnock (1978) mapped the geomorphology and landforms of the quadrangle as part of a regional dissertation study, at a scale of 1:84,210. Scott and others (2001) mapped the geology of the Colorado National Monument quadrangle, located immediately south of the Fruita quadrangle, at a scale of 1:24,000 (Figure 4).

OVERVIEW OF GEOLOGIC SETTING AND FINDINGS

A map showing major, named physiographic, geomorphic, and geologic features in the Fruita quadrangle is shown in Figure 2. A page-size version of the Plate 1 geological map of the Fruita quadrangle is shown in Figure 5. The Fruita quadrangle is located on the Colorado Plateau structural province, just north of the Uncompahgre Plateau (Hunt, 1956). The Uncompahgre Plateau is one of a series of Colorado Plateau monoclinal structures that formed during the Late Cretaceous – Early Tertiary Laramide Orogeny (e.g., Davis, 1999; Miller and others, 1992). Laramide structures of the northern part of the Uncompahgre Plateau are characterized by a series of northwest-southeast striking monoclines and reverse faults (Hunt, 1956; Lohman, 1965, 1981; Stone, 1977; Tweto, 1977; Heyman, 1983; Scott and others, 2001). The Colorado National Monument quadrangle, found just to the south of the Fruita quadrangle, displays classic monocline and basement reverse fault structures (Scott and others, 2001). Two of these monoclinal structures are found in the southwest corner of the Fruita quadrangle. These structures are referred to as the Redlands monocline and an unnamed monocline (Heyman, 1983). The structure of the remainder of the Fruita quadrangle consists of a very gently, northeast dipping (2-3^{o}) homocline.

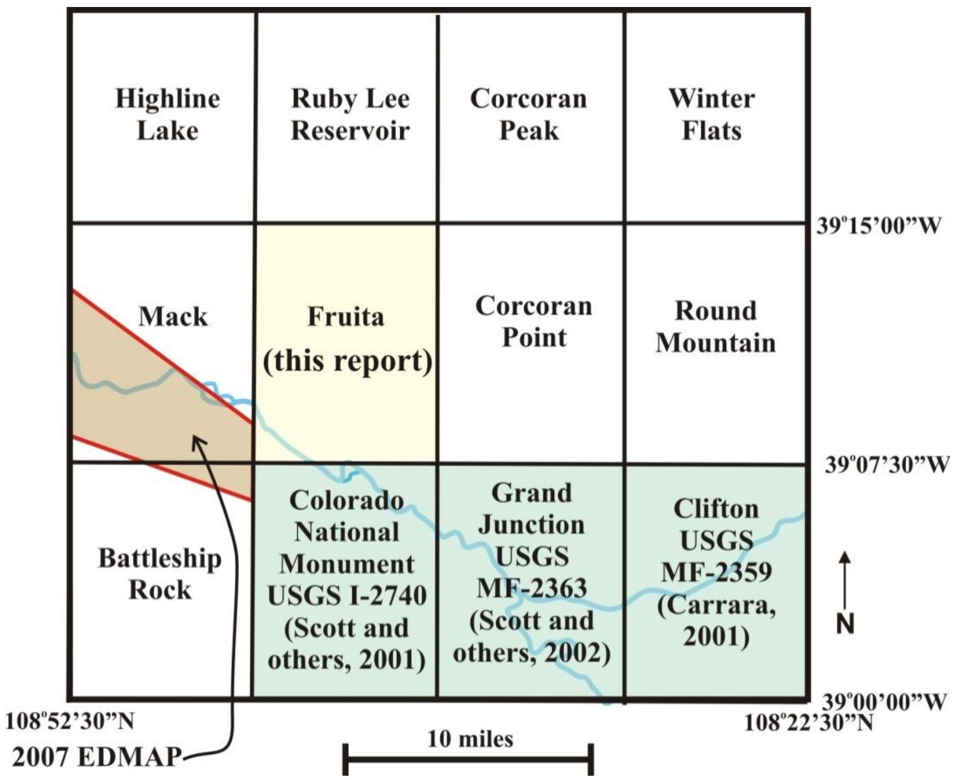

Figure 4. Index of published USGS 1:24,000-scale geologic maps and an unpublished USGS EDMAP (Nelson and others, 2007) located near the Fruita 7.5-minute quadrangle.

Jurassic to Cretaceous age bedrock is exposed in the Fruita quadrangle. These rocks record a protracted geological history of terrestrial to marine environments. Outcrops of Jurassic age bedrock are found in the southwest corner of the Fruita Quadrangle (Figure 5). The Upper Jurassic sandstones of the Kayenta Formation (Peterson, 1994) are the oldest exposed unit. These sandstones were deposited in high-energy braided rivers (Peterson, 1994). The overlying Middle Jurassic Entrada Formation consists of coastal eolian sand dunes (Kocurek and Dott, 1983, Peterson, 1988). The Entrada Formation is overlain by mudstones of the Wanakah Formation that were deposited in a nonmarine mudflat or a shallow lacustrine environment (Scott and others, 2001). These deposits are overlain by the 500 ft thick Upper Jurassic Morrison Formation. The Morrison Formation has been divided into three members in

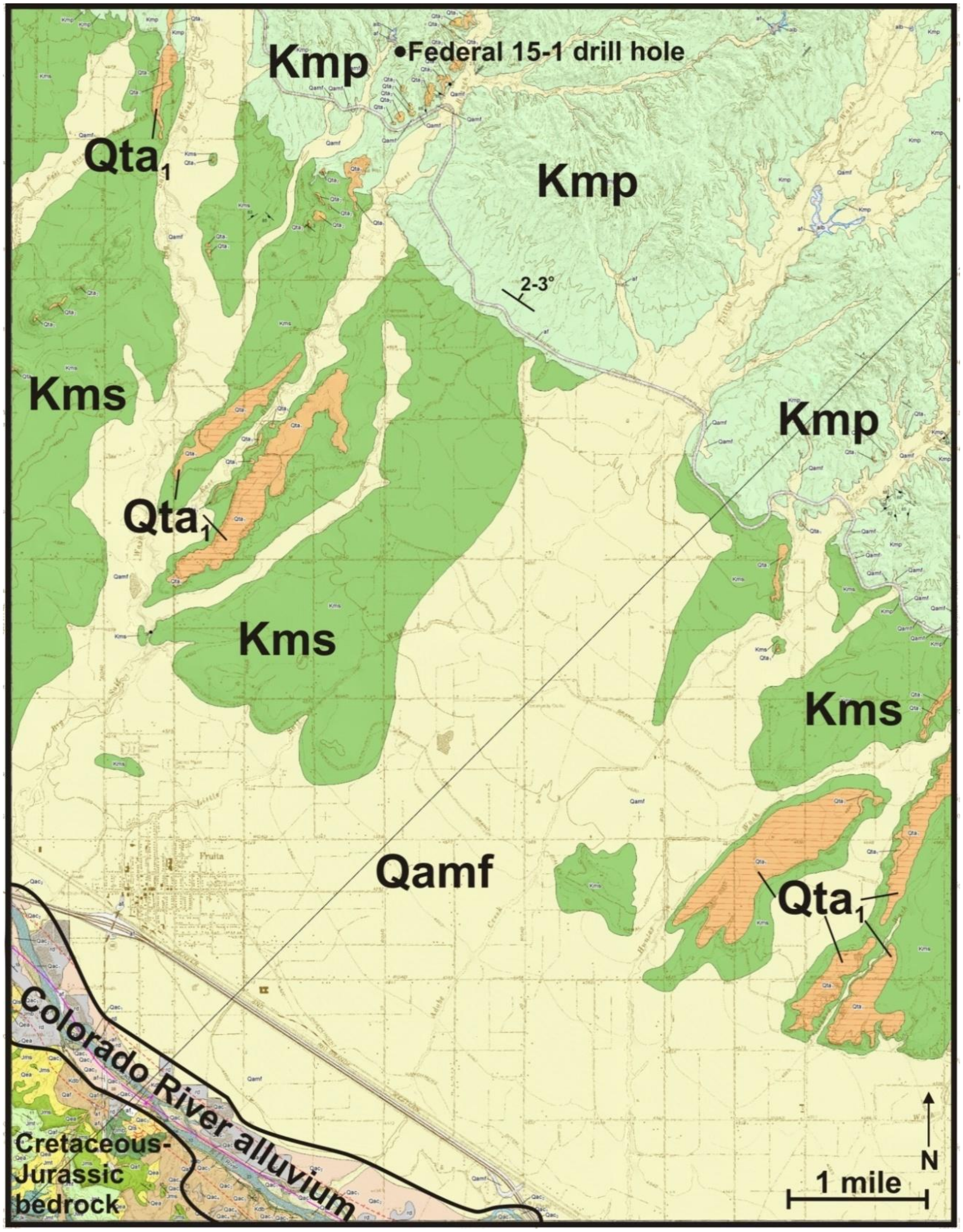

Figure 5. Page-size version of the Fruita quadrangle geologic map. The most widespread map units include the Prairie Canyon Member of the Cretaceous Mancos Shale (Kmp), the Smoky Hill Member of the Cretaceous Mancos Shale (Kms) and Quaternary-age 'alluvium and mudflow-and-fan valley-fill deposits' (Qamf). Cretaceous-Jurassic bedrock and alluvial terrace levels of the Colorado River are found in the southwest corner of the quadrangle. The Qta_1 unit represents remnant alluvial deposits of tributary streams. Also illustrated is the location of an abandoned gas well (Federal 15-1 drill hole).

this area: the lower Tidwell Member, Salt Wash Member, and upper Brushy Basin Member (Scott and others, 2001). The environment of deposition of the Morrison Formation was of fluvial channels in flood plains with saline to fresh water lacustrine lakes (Turner and Fishman, 1991). The Morrison Formation in the Fruita area is famous for the significant dinosaur bone discoveries that have been made in this formation (most notably at Dinosaur Hill). Shales and conglomeratic sandstones of the Lower Cretaceous Burro Canyon Formation overlie the Morrison Formation. The Burro Canyon Formation was deposited in a widespread fluvial system (Scott and others, 2001). These terrestrial deposits are overlain by the Dakota Formation, which represents the transition from marginal marine to marine conditions as the North American continent was flooded by the Late Cretaceous Western Interior Seaway. In the Fruita area, 4,600 ft of Mancos Shale was deposited above the Dakota Formation in this epicontinental seaway. The Mancos Shale represents muddy shallow-shelf deposits derived from deltas and shorelines that existed further to the west, in Utah (Armstrong, 1968; McGookey and others, 1972; Johnson, 2003).

Two members of the Mancos Shale, the Prairie Canyon Member (Kmp), and the underlying Smoky Hill Member (Kms) form the dominant outcrops in the Fruita quadrangle (Figure 5). These two members of the Mancos Shale are associated with two distinct topographic landforms. Incised badlands of the Prairie Canyon Member (Kmp) are found in the northern part of the quadrangle. Rounded low hills, knobs, and valleys of the Smoky Hill Member (Kms) are found in the central part of the quadrangle (Figure 5). The contact between these two members forms a distinctive topographic slope break.

Several terrace levels of Quaternary alluvial gravel deposits are found in the mapped area. Some were deposited by the modern and ancestral Colorado River as it migrated over the landscape. The Colorado River runs through the southwestern part of the mapped area and has four major geomorphic surfaces associated with it (including the modern flood plain). These terraces are found in a narrow band in the southwestern corner of the quadrangle adjacent to the current position of the Colorado River (Figure 5). These alluvial deposits and flood plains are labeled Qac_4, Qac_3, Qac_2, Qac_{1b} and Qac_{1a}. Qac_4 represents the oldest and highest terrace level and Qac_{1a} is the modern floodplain. Qac_2 is an inferred alluvial terrace level that may extend up to 1.5 miles north of the Colorado River.

North of the Colorado River, low-lying gravel-capped mesas form remnants of former tributary streams. Based on the height of terrace levels they are mapped as Qta_2 (oldest) and Qta_1 (youngest; Figure 5). Due to topographic inversion, these former channels now form mesa-capping, boulder-gravel veneers underlain by Mancos Shale.

Deposits of alluvial mudflow-and-fan valley-fill (Qamf) are the most extensive Quaternary unit. These deposits were derived from the Mancos Shale and blanket broad surfaces in the southern and central portions of the Fruita quadrangle (Figure 5).

Modern mass-wasting deposits, such as landslides, are common along the southern bank of the Colorado River. Here, Dakota and Burro Canyon Formations have formed the landslides into the Colorado River. The slip plane for these landslides is along the weathered and weakened Jurassic Morrison Formation. Other natural hazards include swelling and collapsible soils found throughout the Fruita quadrangle. These soils have caused damage to buildings and public infrastructure. The ground water table in the southwestern corner of the Fruita quadrangle is shallow (usually <5 ft). Alluvial aquifers are found close to the surface in this part of the quadrangle.

DESCRIPTION OF MAP UNITS

Geologic time divisions used in this report are shown in Appendix 1. Clast sizes are based on the modified Wentworth grain-size scale (Wentworth, 1922).

SURFICIAL DEPOSITS

Typically, all surficial deposits shown on the map are more than 5 ft thick, but may be thinner locally. For example, both the ‘alluvial mudflow-and-fan valley-fill deposits’ (Qamf) and ‘alluvium and eolian deposits’ (Qea) are, in places, shown on the map when they are only 1 ft thick. This was done because the thicknesses of Qamf and Qea are highly variable, with significant thickness changes of greater than 5 ft occurring over short distances of a few tens of feet. Additionally, the ‘tributary alluvium one’ (Qta_1) deposits are typically greater than 5 ft thick, but are also mapped when less than 5 ft thick. Qta_1 less than 5 ft thick is mapped in areas where the deposits have been artificially removed. In these areas, the artificially thinned Qta_1 deposits are represented by a different color scheme (a hachured pattern vs. a solid color pattern for deposits greater than 5 ft thick). Sheetwash, colluvium, and artificial fills of limited extent were not mapped (e.g., artificial fill in the parking area of Dinosaur Hill is not represented on the map).

Contacts between surficial units may be gradational and units shown on the map may locally include deposits of other types. Age divisions for the Holocene used in the Fruita quadrangle are arbitrary and informal. Relative age assignments for surficial deposits are based primarily on the degree of erosional modification of original surface morphology, height above modern stream levels, degree of dissection and slope degradation, soil development and stratigraphic relationships.

HUMAN-MADE DEPOSITS

af **Artificial fill (upper Holocene)** — Road fill and refuse placed during construction of roads, dams, and canals. Generally consists of unsorted silt, sand, clay, and rock fragments. Many of the canal embankments and irrigation ditches in the quadrangle were not mapped due to their limited areal extent. The average thickness of the unit is less than 10 ft.

rd **Reclaimed and Disturbed land (upper Holocene)** — Unsorted silt, sand, clay, and rock fragments. This unit may include areas of construction and quarrying operations where original deposits have been removed, replaced, or reworked.

alb **Artificial lake bed (upper Holocene)** – Light tan to brown, medium bedded mudstones found behind four artificial earthen dams in the northern portion of the map area. The following description is for the largest and best-exposed alb deposit. This deposit is found in the northeast portion of the map near 21 Road (Figure 6). The alb is a maximum of 9 ft thick. The entire alb sequence consists of about 14 to 15 individual mudstone beds with a typical thickness of 5 to 10 inches each (Figure 7). Each bed consists of an upward-fining sequence with a lower layer of silt and very fine-grained sand and upper layer of clay. The clay tops have the consistency of well-sorted modeling clay. The clay is mixed with fine wood fragments, typically elongate wood branches that more readily weather out leaving the clay with a pockmarked appearance. Clay bed tops are commonly mudcracked and sometimes have the appearance of long wavelength (5 – 7 inches) ripple marks. These long wavelength features may actually represent differential compaction structures. Soft sediment load structures are found between the beds. No variation in structure or lithology was noted between uppermost and lowermost beds. Internally, the beds are laminated as indicated by a tan to brown color change and some have epsilon cross-bedding with the cross-beds always dipping upstream. Each of the 14 to 15 individual beds is considered to represent a single hydrological flood event.

The uppermost 1 ft of deposits consists of more thinly bedded, laminated beds. These beds are considered to represent sheetwash deposits that flowed over the top of the dam after it backfilled and prior to gully incisement into the alb. The alb beds were deposited on gravel deposits of the 'alluvial mudflow-and-fan valley-fill' unit (Qamf). Locally, cut and fill channels of cobbles and sand incise the alb beds. All of the alb beds are flat lying, with small dip changes considered to be related to post-deposition compaction. The alb deposits have been incised by numerous 10 to 15 ft deep channels since the dam was backfilled and breached.

The alb deposits formed because of man-made damming of three minor tributary channels found east of Little Salt Wash. These channels drain basins composed of Mancos Shale and alluvial mudflow-and-fan valley-fill (Qamf) derived from Mancos Shale. The surface outcrop area of the artificial lake beds is ~667,000 ft^2. The drainage area of the basin that drained into the dam is about 2.7 $miles^2$, surprisingly small given the volume of the alb deposit. We have not been able to find any direct information regarding when this dam was built. We assume that the Civilian Conservation Corps (CCC), which was active in the area in the mid to late 1930's, built the dam. The 1962 USGS Fruita quadrangle map is based on airphotos taken in 1958. This map topographically shows this dam in its modern breached configuration. Based on this vague information, the dam is considered to have existed and accumulated artificial lake bed deposits between 1934-1941 and 1958. This is approximately 17 to 24 years. We interpret the alb as recording a brief (~20 years) history of flash flood events that affected this area. This would suggest an aggregation rate of approximately one individual 5 to 10 inch thick bed per year. Incisement of the 15 ft deep channels into the alb would have occurred over approximately the last 50 years (1958-2008). This yields a rapid incision rate of 3.6 in/yr. Incision would have been rapid because of upstream knickpoint migration from the dam breach into the soft lake beds.

EOLIAN DEPOSITS

Qea **Alluvium and Eolian deposits (Holocene to upper Pleistocene)** — Eolian sand and alluvial sheetwash deposits consisting chiefly of silty, very fine to fine sand that commonly contains coarse sand to granule-size fragments. The Qea mantles and blankets flat to gently sloping surfaces in the southwestern part of the Fruita quadrangle. This deposit locally includes coarser sandy material (Figure 8). Eolian sand consists of pale-brown to reddish brown, silty, very fine to fine sand that is poorly consolidated, moderately to very well sorted, subangular to subrounded sand grains. These deposits are 90% sand grains of quartz, 5% black lithic sand grains and 5% silt. The eolian deposits are commonly structureless to weakly bedded and lack eolian sedimentary structures, which may have been disrupted by bioturbation or

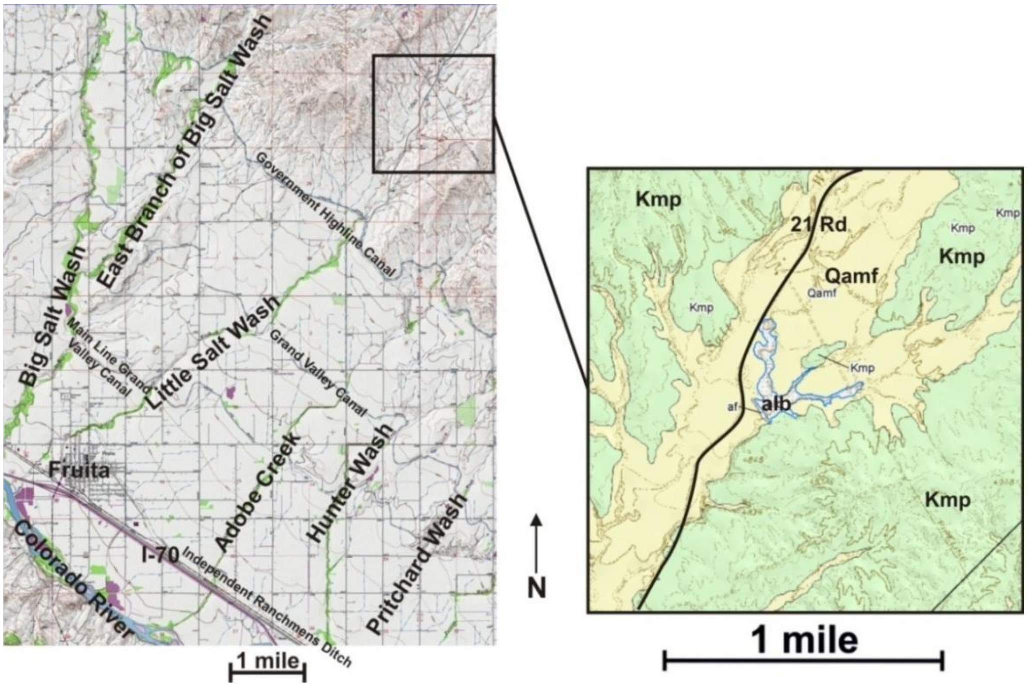

Figure 6. Location of the largest deposit of artificial lake beds in the northeast portion of the map near 21 Road. Image on right is an inset of the Geologic Map of Fruita Quadrangle (Plate 1). Artificial lake beds (alb) are shown in light purple. The southernmost 'af' unit is the actual dam. Map abbreviations: Qamf: Alluvial mudflow-and-fan valley-fill deposits; Kmp, Prairie Canyon Member of the Cretaceous Mancos Shale.

Figure 7. Stacked mudstone beds of alb that are consistently between 5 to 10 inches thick. Note upward fining character of individual beds, ripple marks or differential compaction structures on the tops of beds, and mudcracked clay tops of each bed. The entire alb deposit consists of 14 to 15 of these beds with a total thickness of 9 ft. [zone 12S UTMX: 703475, UTMY: 4344406]

vegetation roots. The sand is considered by Scott and others (2001) to be derived from erosion of nearby Jurassic sandstones. Eolian sand surfaces are commonly stabilized by vegetation such as grasses, sage, and rabbitbrush. Deposits within a few feet of the surface are more of a tan-white color due to calcite precipitation. Outcrops of this unit found proximal to the Uncompahgre Uplift (within a few 100 ft) tend to be more reddish in color.

Thin beds (0.5 to 2 inches thick) of fine eolian sand form a weak, discontinuous stratification (Figure 8). Coarse sand deposits found in the Qea contain discontinuous layers and lenses of poorly sorted coarse sand to granule-size clasts. These coarse sand deposits may represent alluvial sheetwash or eolian sheet sand deposits (Figure 8). Areas mapped as Qea may be prone to flooding, erosion, and sediment deposition. This unit may be 1 ft thick on hilltops to >5 ft thick on leeward slopes and in valleys.

Figure 8. Image of Holocene-age Qea deposits. Note weak stratification based on discontinuous layering of coarse to very fine-grained sand. The coarse sand deposits may represent alluvial sheetwash or eolian sheet sand deposits interbedded with fine to very fine sand of eolian origin. [12S UTMX: 695122, UTMY: 4334240]

ALLUVIAL DEPOSITS

Clastic sediments of clay, silt, sand, and gravel deposited in stream channels, on flood plains, and as alluvial fans and sheetwash along valley sides, and in tributary drainages. The approximate terrace heights reported for each unit are the elevation differences measured between the modern creek bed and the top of the original or remnant alluvial surface adjacent to the arroyo or river. Thickness reported is the maximum exposed thickness of the unit.

Alluvial Deposits of the Colorado River

The Colorado River flows through the southwestern part of the mapped area (Figure 5). It is characterized by three major terrace levels (Qac_4, Qac_3 and Qac_2) and a Holocene floodplain (Qac_{1a} and Qac_{1b}; Figures 9 and 10). All of these terrace levels, except Qac_2, are exposed in the southwestern part of the Fruita quadrangle flanking the Colorado River. The Qac_{1a} and Qac_{1b} represent the Holocene flood plain and, therefore, have little or no soil development. The modern river has incised and reworked older alluvial gravels. The gravel-clast compositions within these deposits are intermediate volcanics, granitoids, and metamorphic rocks and rare red sandstones (Figure 11). The intermediate volcanics are derived from the San Juan Mountains and Gunnison Uplift of southeastern Colorado (via the Gunnison River) and the metamorphic rocks, granitoids and red sandstones are derived from the Rocky Mountains found to the east of the Fruita quadrangle.

Qac_3 alluvial deposits in the Fruita quadrangle have been dated as 68.5$\pm$5.2 ka using the optically stimulated luminescence method (OSL, Andres Aslan and Paul Hanson, 2009, pers. comm.; sample at an elevation of 4520 ft, 50 ft above Colorado River at 12S, UTMX: 694614, UTMY: 4335090, see Figure 10). Using the age and elevation above the Colorado River for the Qac_3 alluvium yields an incision rate of 8.76 in/ky (or 222m/Ma). The age of Qac_4 alluvium can be estimated by using this incision rate and the height of the Qac_4 alluvium above the Colorado River (80 – 112 ft). This calculation yields a late Pleistocene age of 109.6 – 153.4 ka for Qac_4 alluvium. Colorado River terrace deposits near Palisade, Colorado, at a level above the Colorado River similar to our Qac_2 alluvium (25 – 35 ft above the river), have been dated as 13$\pm$5 to 24$\pm$5 ka (OSL datum, Andres Aslan and Paul Hanson, 2009, pers. comm.). The gravels that comprise the current floodplain (Qac_{1a} and Qac_{1b}) were originally deposited as upper Pleistocene alluvium at the end of the Pinedale glaciation. The modern Colorado River is a post-glaciation, underfit stream that is simply reworking older alluvium (Andres Aslan and Paul Hanson, 2009, pers. comm.). Evidence for this comes from the Gunnison River near Whitewater, Colorado. Here, OSL dating of alluvial gravels from a gravel pit at a depth *lower* than the modern Gunnison River yields late Pleistocene ages of about 15 Ka (Andres Aslan and Paul Hanson, 2009, pers. comm.). Holocene reworking of upper Pleistocene gravels qualifies the Qac_{1b} and Qac_{1a} as Holocene-age alluvial deposits.

Qac_{1a} **Lower alluvium one of the Colorado River (upper Holocene)** — Gravels and sandy to silty overbank deposits in the currently active stream channel, floodplain and low stream-terraces of the Colorado River valley. The gravels are brown to gray, poorly to moderately sorted and poorly consolidated. Gravel clasts consist of pebbles, cobbles, and boulders with subordinate clay, silt, and sand. Gravel clasts are subrounded to well rounded and the dominant sediment are pebbles and cobbles with a silty sand matrix. Some boulders reach 2 ft in diameter. The gravels are overlain with a 2 to 4 ft thick, brown to tan, medium to very fine sand to silt, poorly consolidated overbank deposits. The top surface of the overbank deposits forms the floodplain and low terraces that reach a maximum height of 4 to 5 ft above current stream level. These low terraces are densely to sparsely vegetated with some large cottonwood trees (>30 inch diameter trunks). Soil development, pedogenic carbonate, and rinds of $CaCO_3$ on gravel clasts are absent. Soil development is inhibited by the removal of soils and fine sediment by annual floods. Maximum exposed thickness of the unit locally exceeds 10 ft. This unit is a potential source of commercial sand and gravel.

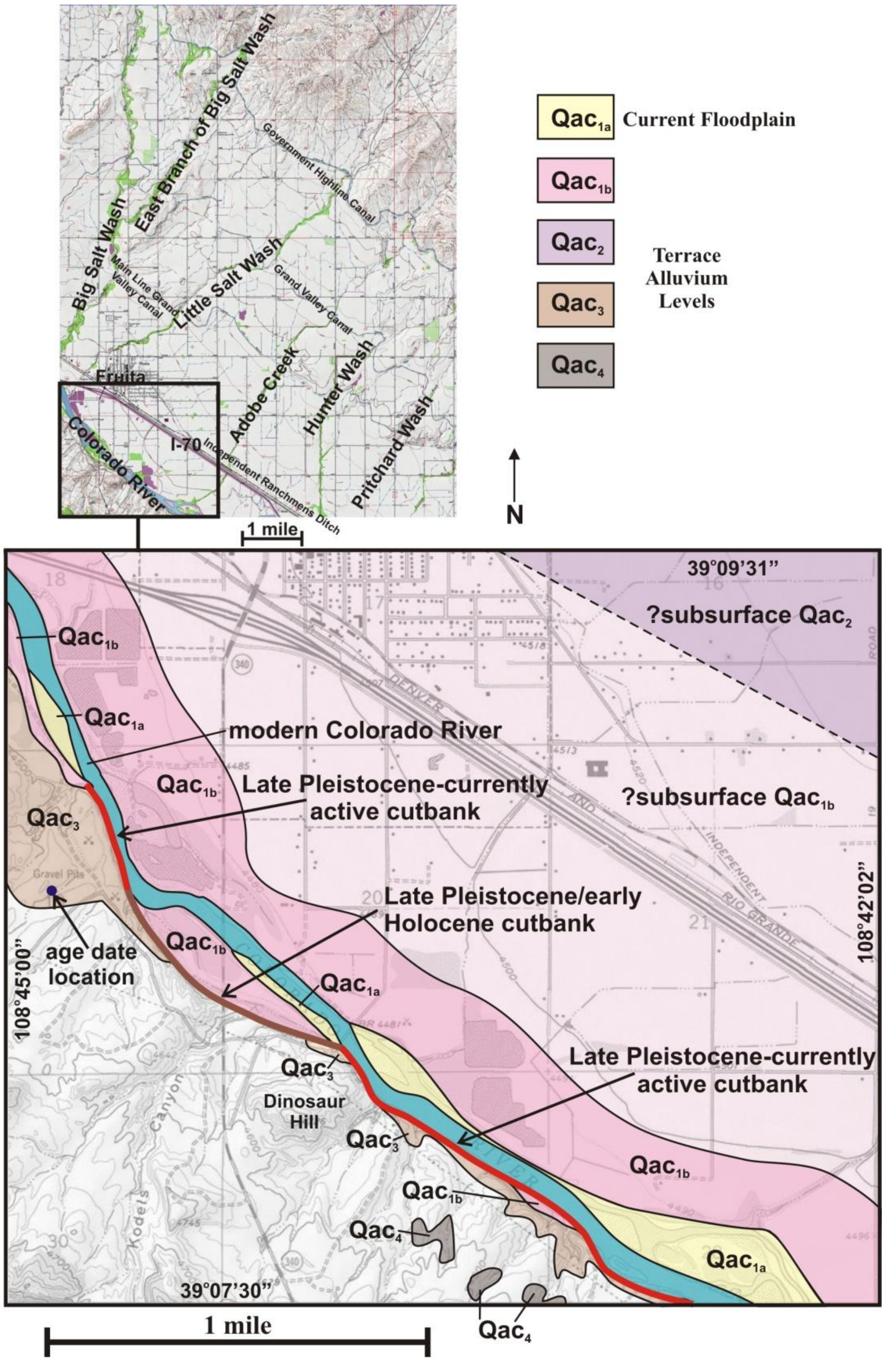

Figure 9. Map showing the generalized extent of alluvial terrace levels of the Colorado River in the Fruita quadrangle. These terrace levels are Qac_4 (oldest), Qac_3, Qac_2 (inferred), Qac_{1b} and Qac_{1a} (youngest and current floodplain). Location of Qac_{1b} and Qac_3 alluvium is extrapolated into areas where these gravels have been removed by quarrying operations (these areas are mapped as reclaimed and disturbed land or 'rd' on Plate 1). The Qac_3 age date location is also shown (gravel dated at 68.5$\pm$5.2 Ka, based on an Optically Stimulated Luminescence age date, Andres Aslan and Paul Hanson, 2009, pers. comm.).

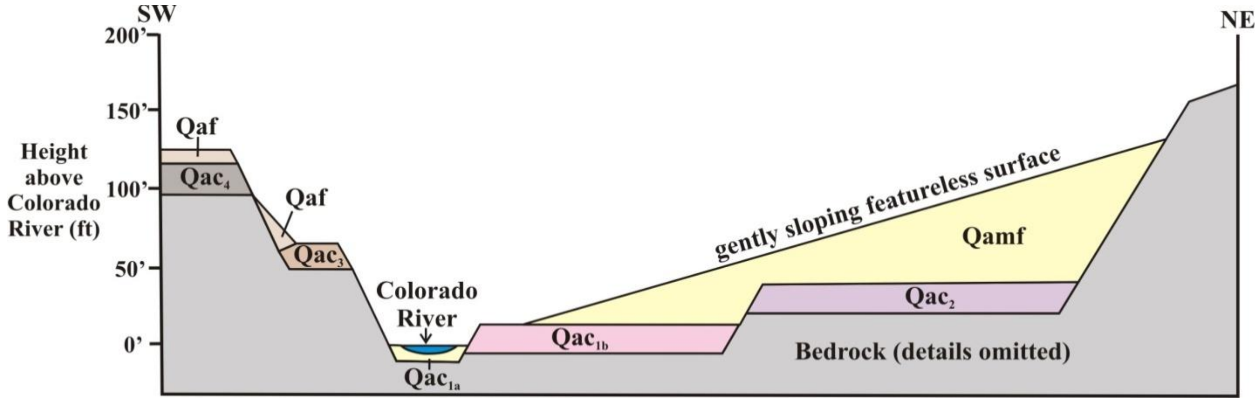

Figure 10. Diagrammatic cross-section illustrating the relative positions and extent of alluvial terrace levels of the Colorado River in the Fruita quadrangle. These terrace levels are Qac_4 (oldest), Qac_3, Qac_2 (inferred), Qac_{1b} and Qac_{1a} (youngest and current floodplain). Qamf represents Holocene-age 'alluvium and mudflow-and-fan valley-fill deposits'. The Qaf unit represents Holocene-age alluvial fan deposits. Note that Qac_{1b} is partially covered and the Qac_2 is completely covered by the Qamf. (19x vertical exaggeration)

Qac_{1b} **Upper alluvium one of the Colorado River (Holocene)** — Gravels overlain by sandy to silty overbank deposits (Figure 11). The gravels are brown to gray, poorly to moderately sorted and moderately consolidated. Gravel clasts consist of subrounded to rounded, prolate to oblate pebbles, cobbles, and boulders (up to 4 ft across) with subordinate clay, silt, and sand. The gravels are also bedded in 1 to 2 ft thick beds (Figure 11). This bedding is defined by planar horizons of finer, pebble-rich gravels (<1 ft thick) found between cobble-dominated layers. Clasts in the gravels display a well-developed imbrication. The gravels are overlain by a 2 to 3 ft thick, brown to tan, very poorly to poorly consolidated, medium to very fine sand to silt overbank deposits (Figure 12). The overbank deposits are planar bedded with some trough cross-bedding. The planar bedding is defined by changes in grain size, which varies from medium sand to silt. These deposits are found in stream terrace deposits at a height of 10 to 25 ft above the modern flood plain of the Colorado River. The alluvium commonly forms continuous and steep-sided, cut-bank walls where it has been dissected by the modern river. No pedogenic carbonate or clasts coated by rinds of $CaCO_3$ were recognized in this deposit. Maximum exposed thickness of the Qac_{1b} is 25 ft. The width of this unit cannot be determined. This is because the northeastern extent of this unit is completely buried by late Pleistocene to Holocene-age 'alluvium and mudflow-and-fan valley-fill deposits' of Qamf (Figure 10). Qac_{1b} is known to extend about 1 mile northeast of the Colorado River based on information provided by construction workers installing a sewer line within the city of Fruita (Figure 9; along Coulson Street between Pabor and Ottley Streets, the Qac_{1b} is 10 ft below the surface, the top of the Qac_1 at this location is then 20 ft above the Colorado River).

The unit generally forms a stable building surface, but there may be localized pockets of collapse-prone sediment along the outermost edges where fine-grained overbank deposits are found. The unit is a source of commercial sand and gravel and is currently being worked in several gravel pits just north of the Colorado River.

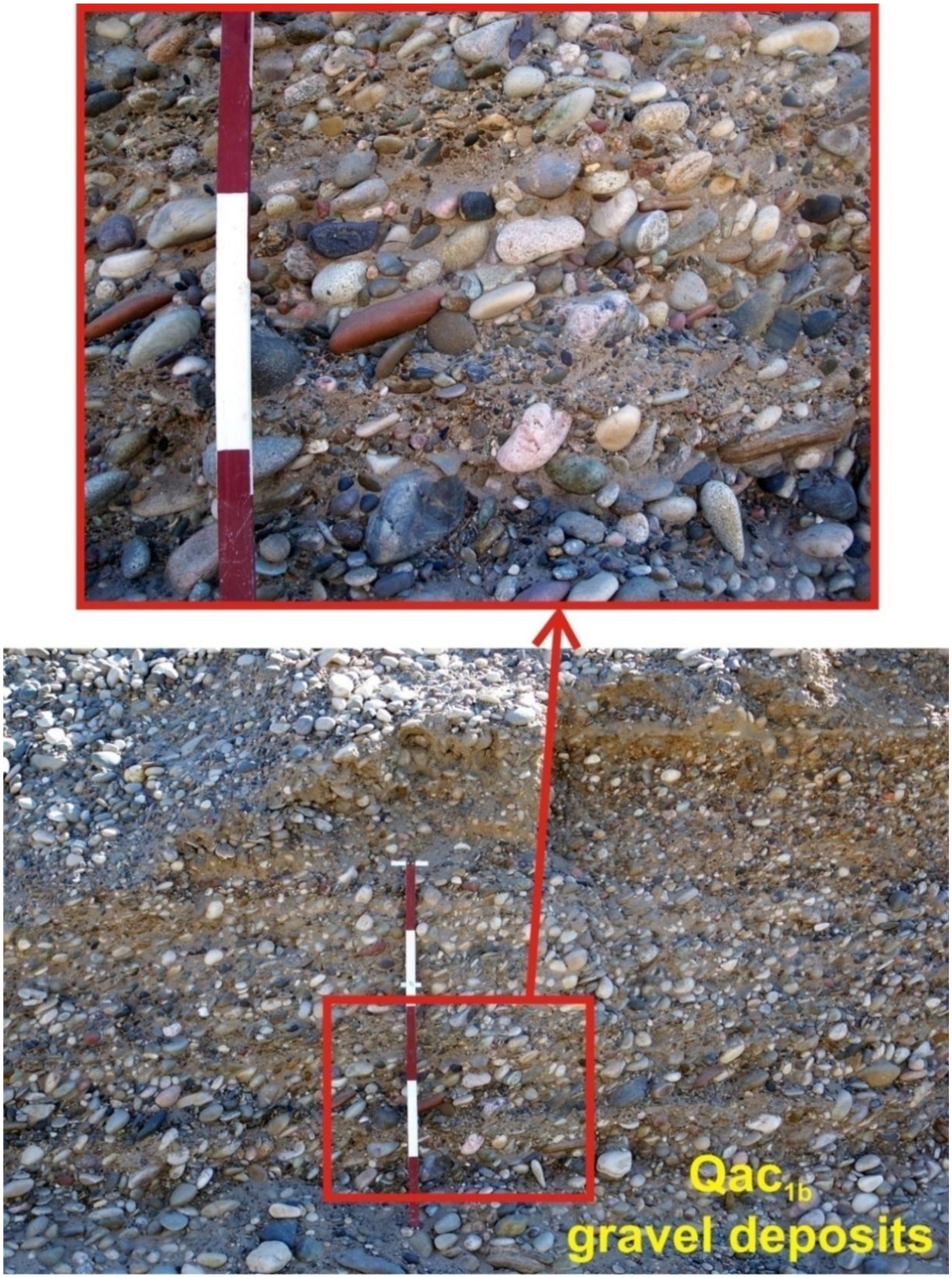

Figure 11. Holocene Qac_{1b} alluvial deposits in the United Companies of Mesa County Kiewit Lake/18 Road pit located a quarter mile north of the Colorado River. Note the bedding in the gravels as seen by planar horizons of pebble-rich gravel (<1 ft thick) that define a continuous planar bedding (upper image). Clasts in the gravels display a well-developed imbrication (upper image). Also, note the absence of clasts coated by rinds of $CaCO_3$. Jacob staff gradations are in feet (5 ft total). [12S UTMX: 696078, UTMY: 4334481]

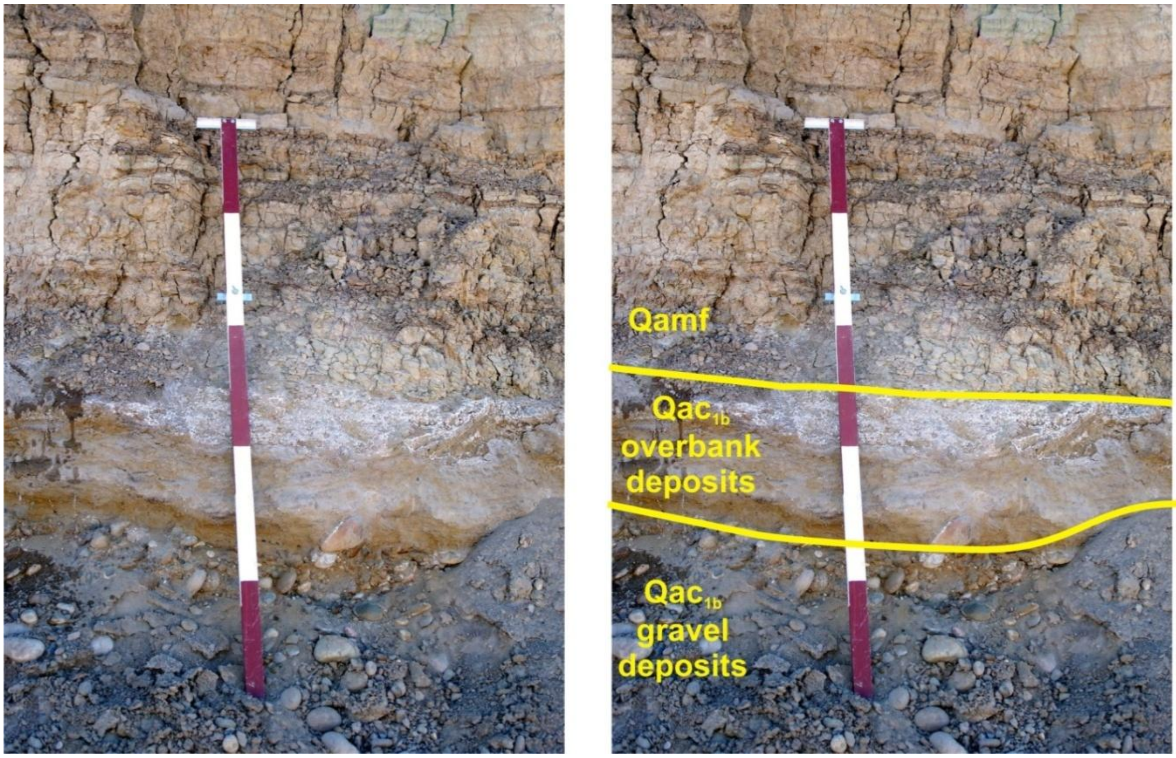

Figure 12. Holocene Qac_{1b} gravel and overbank deposits overlain by >5 ft thickness of distal Qamf fine-grained alluvial fan deposits. The Qamf deposits at this location are >9 ft thick. The overbank deposits are relatively thin (<1 ft thick) and may have been subjected to erosion prior to being covered with Qamf. This image was taken in the United Companies of Mesa County Kiewit Lake/18 Road pit. Jacob staff gradations are in feet (5 ft total). [12S UTMX: 696101, UTMY: 4334406]

Qac_2 **Inferred alluvium two of the Colorado River (upper Pleistocene)** — Gravel deposits inferred to exist in the subsurface beneath gently southwest-sloping Qamf deposits found north of the Colorado River. These gravels are inferred to occur at a level between Qac_{1b} and Qac_3 (25 to 35 ft above the Colorado River). The Qac_2 may underlie a one-mile wide belt north of the Colorado River (Figures 10 and 13). This inference is based on the topographic form of a, gently southwest-sloping geomorphic surface found north of the Colorado River and south of a topographic step that interrupts this surface. This topographic step strikes northwest-southeast and has a modest topographic relief up to 46 ft, but typically <20 ft (Figures 10 and 13). Sinnock (1978) first recognized this surface and mapped it as 'TApp'. Sinnock's (1978) 'TApp' refers to an "active transportational slope that is a panplain". This is a featureless, gently sloping surface that is similar to a floodplain because it parallels the river, but it occurs above the Colorado River floodplain and below the lowest pediment along the Book Cliffs (Sinnock, 1978). Sinnock (1981) described this Grand Valley feature as: "a 2.5 mile wide, very flat, undissected slip-off plain [that] slopes gradually toward the river." According to Sinnock (1978), this surface formed because of the late Pleistocene oscillation of the Colorado River. Terrace gravels related to the Colorado River are not found on the northern side of this broad, sloping surface or exposed

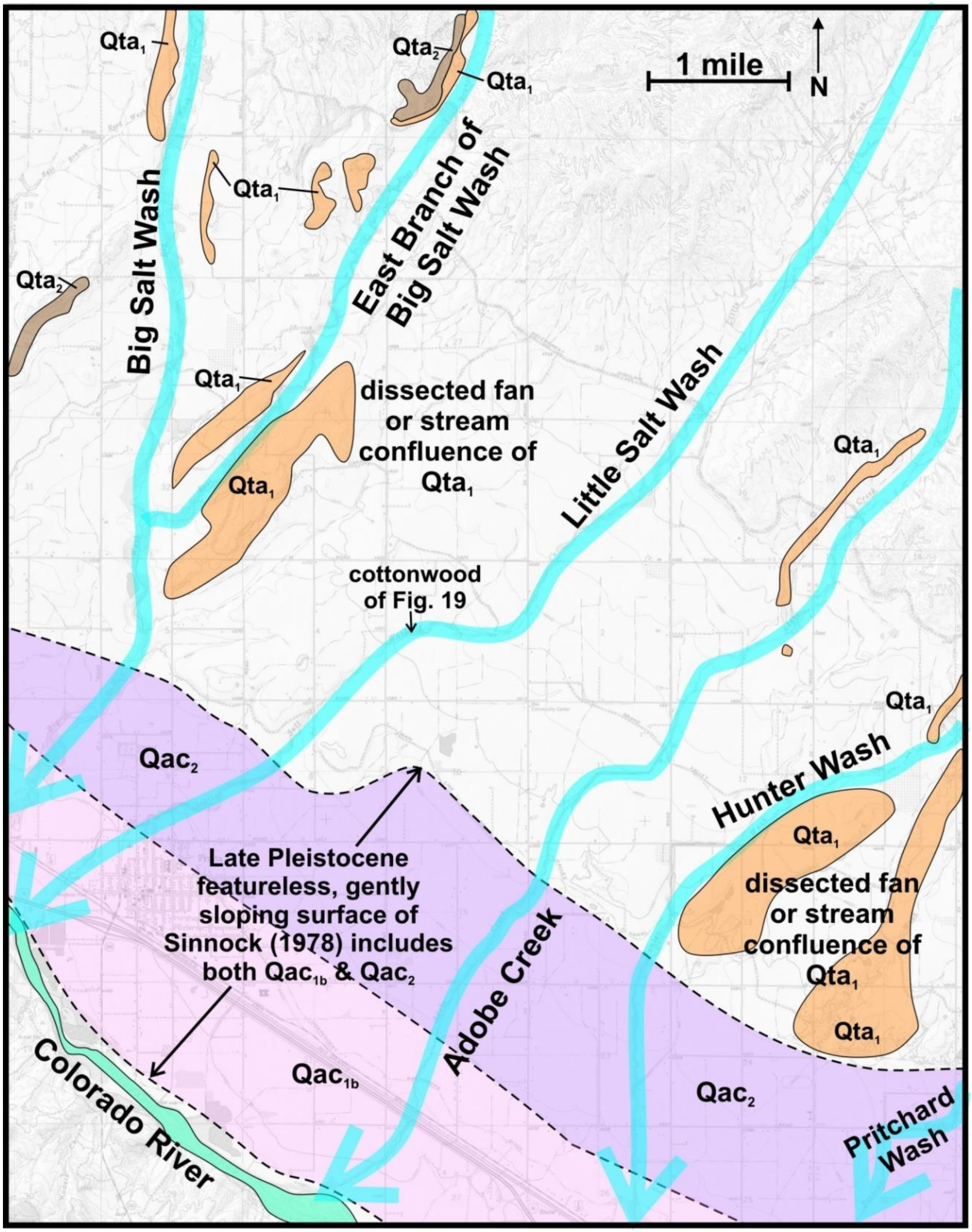

Figure 13. Map of Fruita quadrangle showing the generalized locations of major tributary streams and upper Pleistocene tributary alluvial deposits Qta_1 and Qta_2. The larger lobes of Qta_1 gravels may represent either gravel fans or former confluences that have been dissected by Holocene-age erosion and incisement. The southern extent of the Qta_1 deposits found near Hunter Wash are truncated by a late Pleistocene surface of Sinnock (1978). This suggests a late Pleistocene age for the Qta_1 alluvial deposits. It also suggests that Qac_2 deposits are younger than the Qta_1 deposits.

anywhere along it. Sinnock (1978) argued that: "[this gently sloping surface] rather than the terraces occupy the broadest expanse of upper Pleistocene drainage ways in the Grand Junction area." Our inference is that alluvial gravels related to this surface are completely covered by the widespread 'alluvial mudflow-and-fan valley-fill deposits' (Qamf) of Holocene age.

Qac_3 **Alluvium three of the Colorado River (upper Pleistocene)** — Medium to dark gray to light brown, poorly sorted, moderately consolidated silt, sand, pebble, and cobble gravel in stream terrace deposits above the modern flood plain of the Colorado River (Figures 10 and 14). The alluvium is poorly exposed and found in a limited number of outcrops along small valleys in unnamed broken hills south of the Colorado River. Holocene alluvial fan deposits (Qaf) typically cover and intertongue with the top of Qac_3 (Figure 15). Clasts are subrounded to well rounded and the dominant sediment is a bouldery, pebble-cobble gravel with a coarse sand matrix. $CaCO_3$ coats bottoms of clasts in this unit. The unit forms terraces that reach a height of 35 to 50 ft above current river level. The maximum exposed thickness of the unit is 15 ft. The base of this deposit sits on a strath of moderately northeast-dipping Cretaceous-age bedrock (Dakota and Burro Canyon Formations; Figure 14). This unit and the overlying Qaf generally form a stable building surface, although there may be very thick, localized pockets of fine-grained, collapse-prone gravel and Qaf sediment. The Qac_3 unit is a source of commercial sand and gravel. There are reclaimed commercial gravel extraction pits in the Qac_3 south of the Colorado River.

Qac_4 **Alluvium four of the Colorado River (upper Pleistocene)** — Medium to dark gray to light brown, poorly sorted, moderately consolidated silt, sand, and pebble, cobble, and boulder gravel in stream terrace deposits above the modern flood plain of the Colorado River valley. The alluvium is found along valley sides and quarries in the unnamed broken hills south of the Colorado River (Figure 10). The top of Qac_4 is typically covered with late Pleistocene to Holocene-age alluvial fan deposits (Qaf; Figure 16). Clasts are subrounded to well rounded and the dominant sediment is a bouldery, pebble-cobble gravel with a coarse sand matrix. Some boulders reach 2 feet in diameter. $CaCO_3$ coats bottoms of clasts in the lower and uppermost part of this unit. The unit forms terraces at a height of 80 to 112 ft above current river level. The maximum exposed thickness of the unit is 32 ft. The base of this deposit sits on a strath of moderately northeast dipping Jurassic Morrison Formation. This unit and the overlying Qaf generally form a stable building surface, although there may be very thick, localized pockets of fine-grained, collapse-prone gravel and Qaf sediment.

Tributary Alluvial Deposits

The most important geomorphic feature of the Fruita quadrangle is the Colorado River. The Colorado River flows in the low area found to the south of a gentle southwest dipping surface that contains five major southwestward-flowing tributary streams (Figure 13). These streams include: Big Salt Wash, East Branch of the Big Salt Wash, Little Salt Wash, Adobe Creek, and Hunter Wash (Figures 4 and 13). Two different alluvial deposit levels are recognized along these tributary streams (Qta_1 and Qta_2; Figure 13). Sinnock (1978) mapped tributary gravels Qta_2 and Qta_1 as P_3 and P_2, respectively (P refers to pediment). Our mapped locations of Qta_2 and Qta_1 are more aerially restricted and more precisely located than the P_3

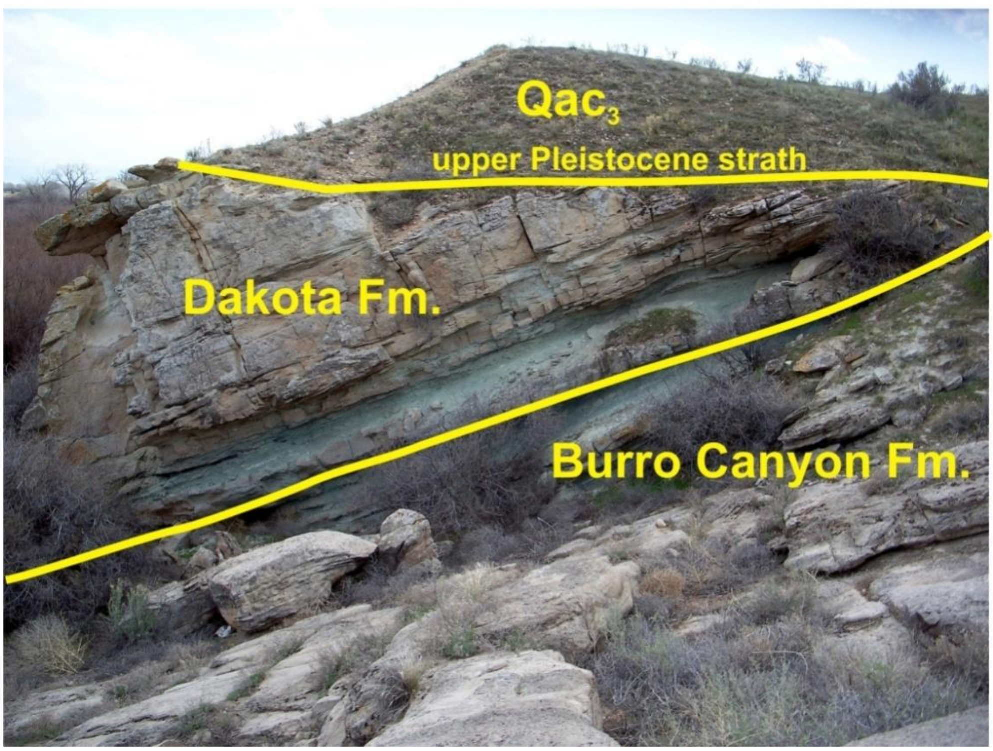

Figure 14. Image looking east at an outcrop of Burro Canyon and Dakota Formations covered by alluvium three of the Colorado River (Qac$_3$). The strath at the base of Qac$_3$ is considered as late Pleistocene in age. Note the low-amplitude, undulating cut-and-fill base of the sandstone that forms the contact between the Burro Canyon and Dakota Formations. [12S UTMX: 695290, UTMY: 4334461]

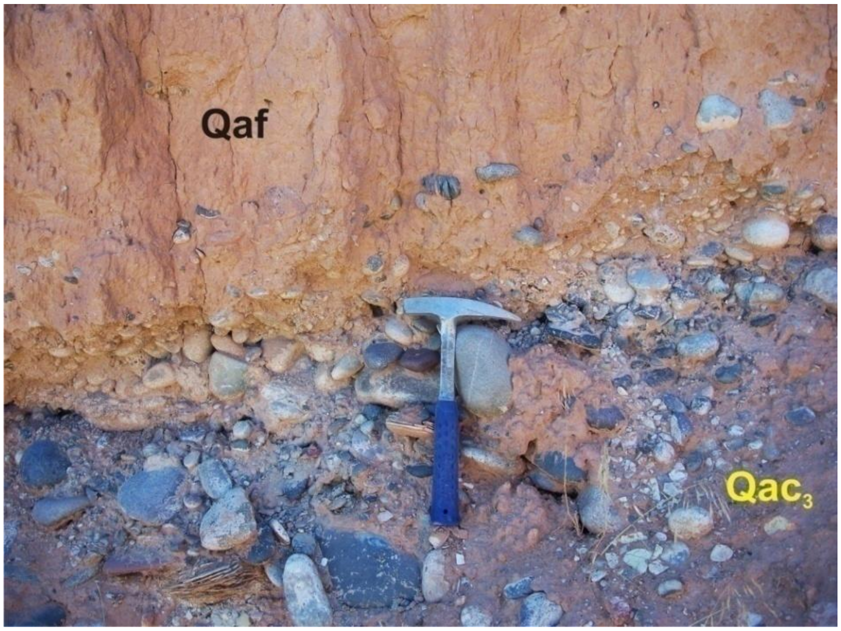

Figure 15. Image of Qac_3 gravels overlain by, and intertonguing with, alluvial fan deposits (Qaf). Note reworking and intermingling of upper gravels by younger alluvial fan deposits and partially developed carbonate rinds on gravel pebbles and cobbles of Qac_3. [12S UTMX: 697715, UTMY: 4332901]

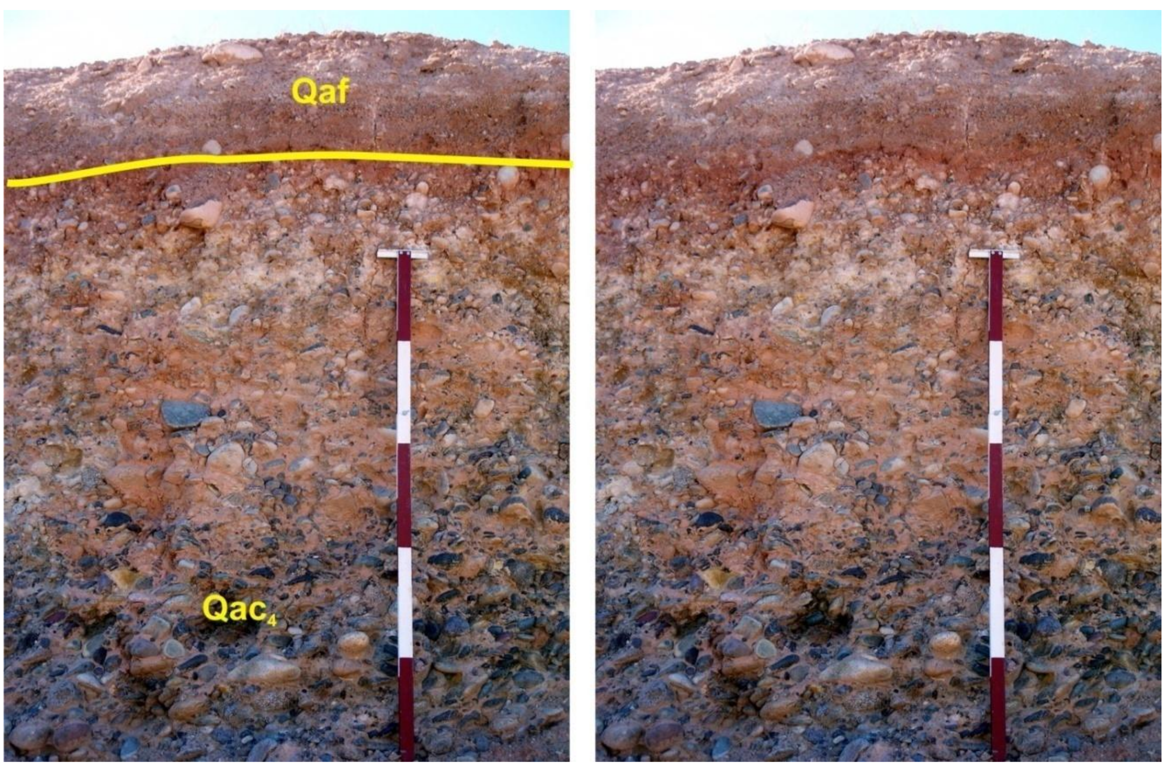

Figure 16. Image of the Qac_4 alluvial deposits of the Colorado River in a quarry located a quarter mile south of the Colorado River. Note thin (about 1 ft) veneer of alluvial deposits (Qaf) covering the top of the Qac_4 gravels and lack of soil development. Jacob staff gradations are in feet (5 ft total). [12S UTMX: 697173, UTMY: 4332838]

and P_2 levels shown by Sinnock (1978). Sinnock (1978) also mapped a lower tributary gravel as P_1. We did not recognize this P_1 level as being different from Qta_1.

The tributary alluvium was derived from southward transportation of Cretaceous and Early Tertiary bedrock formations from the Book Cliffs region. Source-area lithologies differentiate this tributary alluvium from the alluvial deposits of the Colorado River. The alluvial gravel and cobbles are dominantly composed of subangular, buff-colored sandstone from the Cretaceous Mesaverde Group. Also rarely found are oolitic, shaly carbonates from the Lower Tertiary Green River Formation and chert from the Lower Tertiary Wasatch Formation. All of these formations are exposed north of the mapped area in the Book Cliffs (Figure 17).

All tributary streams, except for Little Salt Wash and the lower (southern) portion of Adobe Creek are associated with or located near Qta_1 or Qta_2 deposits (Figures 13 and 17). Little Salt Wash, Big Salt Wash and Adobe Creek also extend far northward into the Book Cliffs. Little Salt Wash extends into the deeply incised Hunter Canyon of the Book Cliffs and Adobe Creek extends into an unnamed canyon just east of Hunter Canyon (Figure 17). The lack of tributary gravels associated with Little Salt Wash or the lower portion of Adobe Creek is, therefore, seemingly implausible. We infer that this is related to a series of stream capture events. These events would have occurred during the wetter climate of the late Pleistocene, when streams were flowing along the current exposures of Qta_1 and Qta_2 gravels (Figure 17). The rate of headward erosion and incision of potential pirating streams through the Mancos Shale would have been greater than the rate of incision and headward erosion of ancestral streams lined with erosionally more resistant Qta_1 and Qta_2 gravels. The earliest recorded event in the map area is the capture of the Qta_2 stream (ancestral Little Salt Wash and Big Salt Wash) by the lower East Branch of Big Salt Wash in the late Pleistocene (Event 2 of Figure 17). The modern Little Salt Wash and the lower portion of Adobe Creek began as small drainages that were incising northward (or headward) through Mancos Shale in the late Pleistocene. Little Salt Wash and the lower portion of Adobe Creek eventually captured Qta_1 streams. This likely would have occurred in the late Pleistocene when the wetter climate period of glacial runoff was ending. During the drier Holocene time, less gravel was transported southward from the Book Cliffs.

All of the tributary streams are currently incised into relatively deep (up to 30 ft) channels (Figure 18). Incisement of tributary streams is considered to be a modern phenomenon. Historic arroyo incisement, especially from 1880 and 1920, occurred throughout the southwestern United States (Hereford, 1984, 2002; Graf and others, 1987). These historic incisement events are related to climate variations or changes in land-use activities (grazing, agriculture), biological changes (tamarisk invasion), or unidentified causes (Graf and others, 1987).

Another possible cause of incisement of Grand Valley tributaries may be changes in stream hydrology due to modern irrigation practices. Since 1900, irrigation canals have provided ample and inexpensive water from the Colorado River for agriculture in the Grand Valley (canals labeled in Figure 2; Mayo, 2008). Flow in tributary streams down gradient from irrigated areas is perennial (flow year-round). This suggests that this flow is not natural, rather it is derived from irrigation seepage and seepage from unlined canals (Leib, 2008). Without irrigation, the tributary streams in the Grand Valley would be ephemeral and would flow only during periods of moderate to intense rainfall or snowmelt (Leib, 2008). Perennial irrigation outflow keeps the streambeds in the Fruita area perpetually wet, making it more vulnerable to erosion.

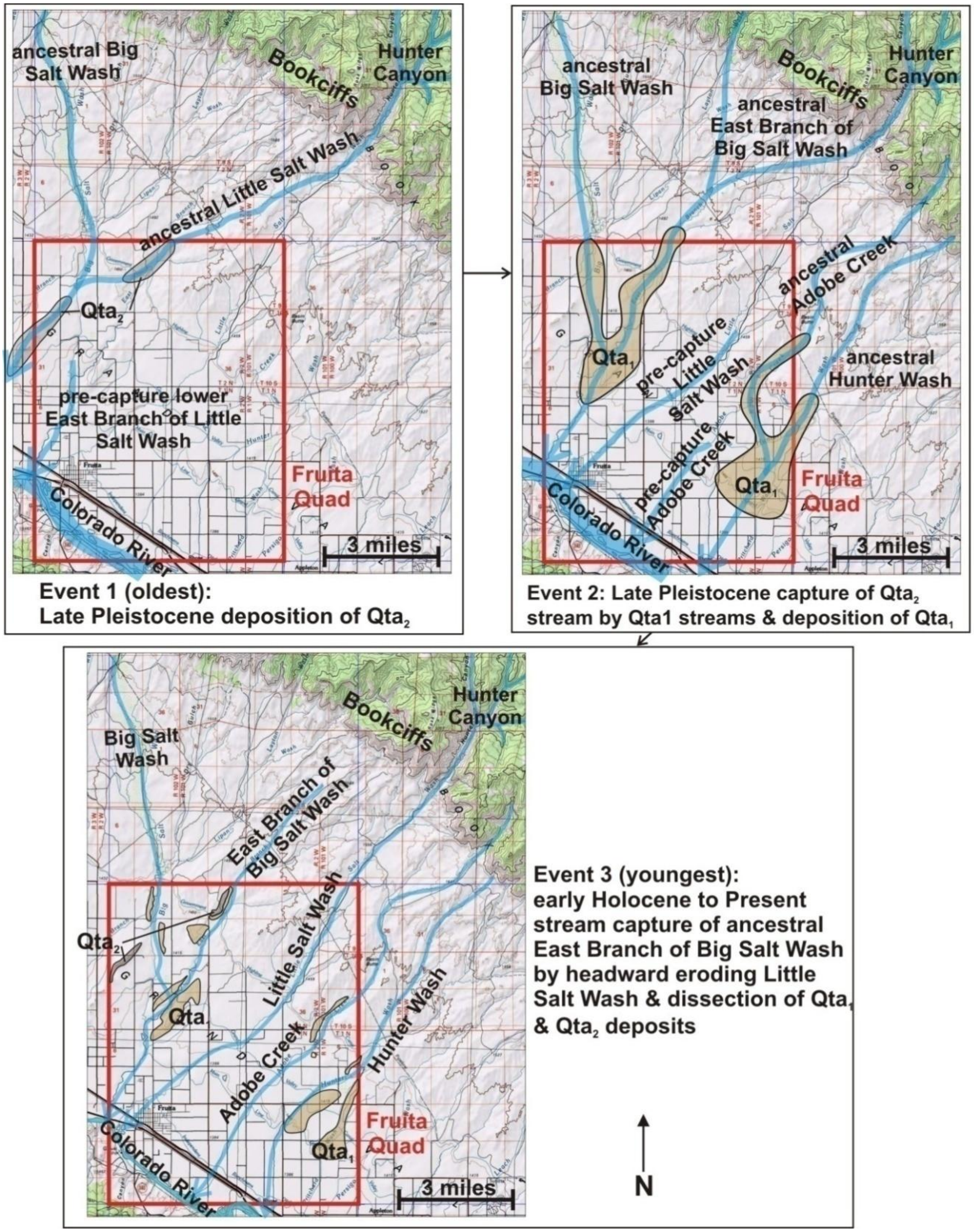

Figure 17. Time-slice sequence illustrating the deposition of Qta_2 and Qta_1 tributary stream gravels. We infer that these streams experienced a series of capture events. Capture occurred because the rate of headward erosion and incision of potential pirating streams through the Mancos Shale would have been faster than the rate of incision and headward erosion of ancestral streams lined with Qta_1 and Qta_2 gravels. This explains why Little Salt Wash and lower Adobe Creek are not associated with any older Qta_2 or Qta_1 gravel deposits. Because of a Holocene climate change, less gravel is being transported southward from the Book Cliffs.

Figure 18. Image of deep incision (28 ft) along Little Salt Wash just west of where this wash passes under 19 Road. The 30 ft high vertical wall is composed of the Smoky Hill Member of the Mancos Shale is controlled by northeast-southwest striking, vertical joints. Note that the stream flow in Little Salt Wash is all from agricultural irrigation runoff (image taken in October of 2008).

The local rate of incisement into Little Salt Wash was calculated using a large cottonwood that is rooted in the side of this incised tributary channel (Figure 19). This cottonwood is found just east of the intersection of Little Salt Wash and 19 Road ('cottonwood' of Figure 13). The cottonwood is rooted along the top of the old Little Salt Wash channel, that was subsequently filled in by local farmers ('artificial fill', Figure 19). Based on tree height and local tree-growing potential, this tree is estimated to be 50-75 years old (Christina Bishop of the USDA, 2008, pers. comm., following the work of Broadfoot, 1960). The base of the tree root is currently 11 ft above the incised channel base. Using the maximum age of 75 yrs for the cottonwood tree, yields a rapid incision rate of 1.8 in/yr (132in/75yrs) along Little Salt Wash.

Qta$_1$ **Tributary alluvium one (upper Pleistocene)** — Light brown to buff colored, poorly to moderately sorted, poorly consolidated gravels of angular to subangular pebbles, cobbles, and boulders in a matrix of fine sand and silt (Figure 20). The dominant sediment type is clast- to matrix-supported sandy pebble gravel in a fine sand to silt matrix. Some clasts are up to 2 ft in diameter. There is a crude bedding defined by 1 to 3 foot thick alternating lenticular layers of clast-supported pebble gravels and matrix-supported pebble gravels. These layers exhibit a poorly developed upward fining character. Pebbles and cobbles vary from well imbricated to non-imbricated. Clasts are dominantly buff-colored sandstones derived from the Upper

Figure 19. Image of a large, 50 to 75 year old cottonwood that is rooted in the side of the incised channel of Little Salt Wash. Note that the cottonwood is rooted along the Kms-artificial fill contact and is currently 11 ft about the base of the channel. [12S UTMX: 698904, UTMY: 4339716].

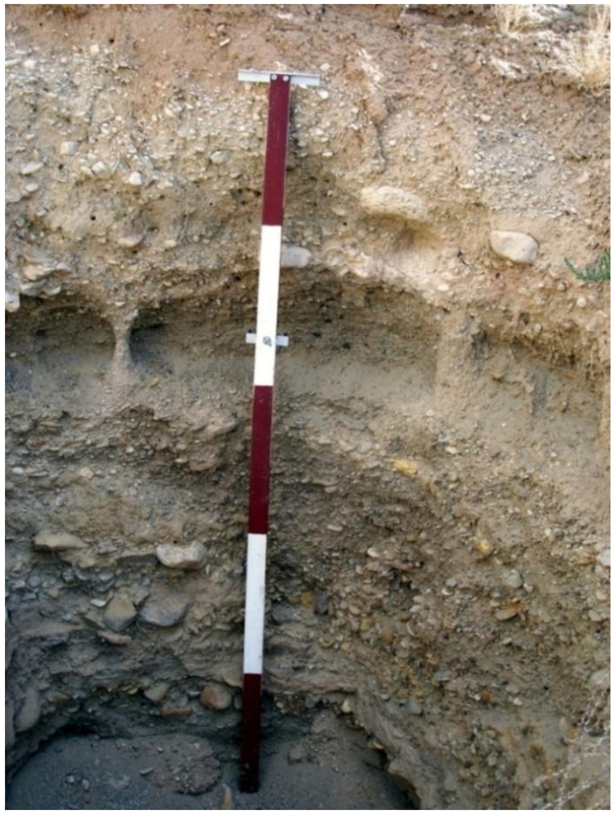

Figure 20. Image of the Qta_1 tributary alluvial deposits found 800 ft east of the East Branch of Big Salt Wash near 18.50 Road. Note poorly sorted nature of matrix-supported gravels with a moderate amount of imbrication and a crude bedding due to grain size variations. Jacob staff gradations are in feet (5 ft total). [12S UTMX: 697286, UTMY: 4341989].

Cretaceous Mesaverde Group with lesser amounts of buff to tan-colored carbonates from the Lower Tertiary Green River Formation.

These deposits are found in stream-terrace deposits above the current tributary stream channels. The alluvium commonly forms flat-topped hills adjacent to modern tributary stream channels. These Qta_1-covered hills overlie Mancos Shale bedrock and often have a discernable slope break along the contact with the Mancos Shale. Qta_1 fans have been dissected and modified by younger alluvial deposits of Qamf. Dissected fan-shaped landforms Qta_1 are recognizable in the southeastern and west-central part of the mapped area (Figure 13). This alluvium has a minimum exposed thickness of 13 ft and in places where it has been artificially removed it is <5 ft thick (symbolized with hachures on the map).There is very little, if any soil development along the top of this deposit. Using the gradient of the Qta_1 gravels to extrapolate their elevation downslope suggests that they were deposited when the base level was the Qac_3 terrace level of the Colorado River.

Qta_2 **Tributary alluvium two (upper Pleistocene)** — Light brown to buff colored, poorly to moderately sorted, poorly consolidated gravels of angular to subangular pebbles, cobbles, and boulders in a matrix of fine sand and silt (Figure 21). The dominant sediment type is clast-supported sandy pebble gravel in a fine sand to silt matrix. Some clasts are up to 3 ft in diameter. There is a crude bedding defined by 1 to 3 foot thick alternating lenticular, layers of clast-supported pebble-dominated gravels and matrix supported pebble gravels. These layers do not have an upward fining character. Pebbles and cobbles vary from well imbricated to non-imbricated. Clasts are dominantly buff-colored sandstones derived from the Upper Cretaceous Mesaverde Group with lesser amounts of buff to tan-colored carbonates from the Lower Tertiary Green River Formation.

These deposits are found in stream-terrace deposits above the current tributary stream channels in the west-central part of the map (Figure 13). The alluvium commonly forms flat-topped hills adjacent to modern tributary stream channels. These Qta_2-covered hills overlie Mancos Shale bedrock and often have a discernable slope break along the contact with the Mancos Shale. This alluvium has a minimum exposed thickness of 15 feet. It is commonly capped by a thin (<1 foot) layer of eolian sand or carbonate cemented gravels with very little, if any soil development.

Figure 21. Image of the Qta_2 tributary alluvial deposits found adjacent to the East Branch of Big Salt Wash. Note poorly sorted nature of clast-supported gravels with a moderate amount of imbrication. Alluvial pebbles and cobbles are dominantly composed of buff-colored sandstone and gray carbonate from the Upper Cretaceous Mesaverde Group (exposed north of the mapped area in the Book Cliffs). [12S UTMX: 698954, UTMY: 4345747]

Other Alluvial Deposits

Qaf **Alluvial Fan deposits, undifferentiated (upper Pleistocene to Holocene)** — Heterogeneous deposits of reddish brown to light brown, unsorted, and unstratified to weakly stratified clay, silt, and sand, and cobble- and boulder gravels. These deposits are ephemeral to intermittent stream-channel, valley-fill and flood deposits found in canyons and as sheetwash and flood plain gravel covering the tops of hills south of the Colorado River (Figure 5, labeled as 'Cretaceous-Jurassic Bedrock'). The deposits consist chiefly of sand and silt of stream-terrace alluvium and gravel deposits found along valley floors of ephemeral and intermittent streams to sandy-bouldery debris-flow deposits (Figure 22). Some of the cobbles in boulders in these gravels are reworked clasts derived from older Colorado River alluvium (Qac_3 and Qac_4). The uppermost parts of these deposits are slightly calcareous. The Qaf are also interbedded to interfingered with minor deposits of eolian sand (Qea; Figure 23).

Areas mapped as Qaf are prone to flash flooding, erosion, and sediment deposition. Similar valley-fill alluvial deposits mapped in the Colorado National Monument quadrangle were dated as 1,180 to 10,360 years old (based on calibrated ^{14}C ages; Stuiver and others, 1998; Scott and others, 2001). A mastodon tooth in similar deposits was found in No Thoroughfare Canyon of the Colorado National Monument quadrangle (about 2 miles south of the Fruita quadrangle). This tooth was considered to have eroded from the lowest part of this map unit and is consistent with a late Pleistocene age for the oldest part of the unit (Scott and others, 2001). This unit forms small terraces that reach a maximum height of 12 feet above modern stream level. Total thickness of the deposit may exceed 15 feet.

Figure 22. Local sandy to bouldery debris-flow deposits in Qaf overlying bedrock of the Jurassic Entrada Formation (Jwe). Note the total thickness of the Qaf is about 12 ft at this location. [12S UTMX: 695020, UTMY: 4332988]

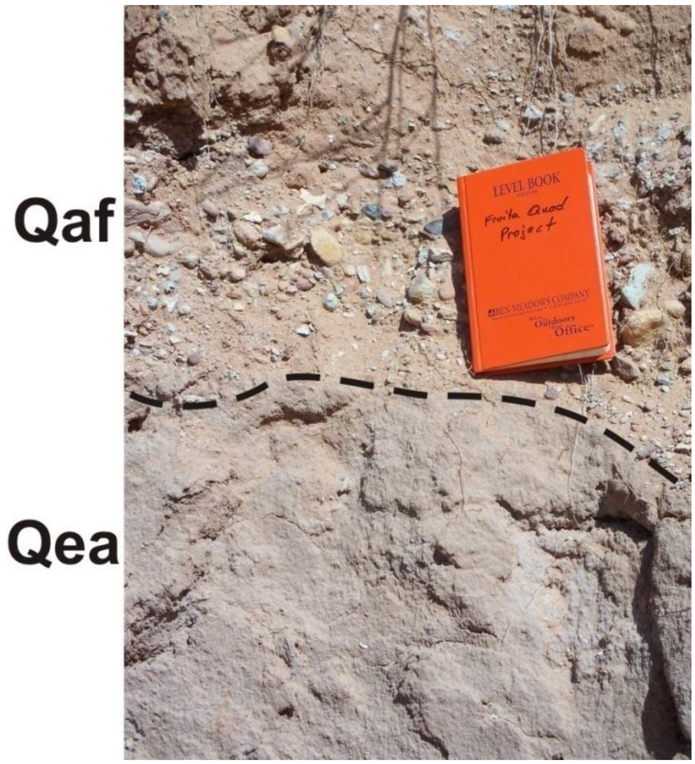

Figure 23. Qaf alluvial fan deposit in southwestern corner of the Fruita quadrangle. Note the Qaf gravel horizon overlies structureless fine-grained eolian sands (Qea). This interfingering and interbedding of Qaf and Qea is common. [12S UTMX: 695135, UTMY: 4332964]

Qamf Alluvial mudflow-and-fan valley-fill deposits (Holocene) — Light-tan to brown, well to occasionally poorly sorted, poorly consolidated, structureless to laminated, clayey to sandy silt (Figures 24 and 25). The Qamf consists chiefly of mudflow, sheetwash, flood plain and alluvial fan deposits covering broad surfaces of the Fruita quadrangle (Figure 5). Portions of the silty sand may be of eolian origin, but much of it is reworked by water. These flood plains represent a complex system of coalescing sheetwash and alluvial fan deposits related to repeated episodes of incision and backfilling. Alluvial lag gravels are found along the undulating cut and fill base of this deposit in some incised tributary streams (Figure 25). These gravels are identical to the older Qta_2 and Qta_1 gravels. They are brown to buff colored, poorly sorted, and poorly consolidated gravels of angular to subangular pebbles and cobbles in a matrix of fine sand and silt with the largest clasts up to 3 ft across.

Widespread agricultural and housing developments in the map area have significantly modified and obscured contacts between this unit and adjacent units. Dated samples of ^{14}C from base of Qamf deposit in the Olathe quadrangle yielded a conventional age of 9,810±60 Ka (Morgan and others, 2007). The presence of desiccation cracks on undisturbed surfaces suggests that the map unit contains expansive clays that may cause stability problems for roads and buildings.

Figure 24. Outcrop of light tan, poorly consolidated, massive to laminated, alluvial mudflow deposit of Qamf. These deposits cover extensive areas of the Fruita quadrangle and are composed of thin layers of clay and sandy silt. Shovel is 2 ft long. [12S UTMX: 696561, UTMY: 4344370]

Thickness of the Qamf deposits is variable and is typically 8 to 15 ft in thick valley sides (Figures 24 and 25) and may be greater than 20 ft in thick in terminal basins between hills of Mancos Shale. The filling of the basins has resulted in the burial of low hills and ridges of Mancos Shale. Many of the tributary stream mudflow deposits and fans are deeply dissected by latest Holocene stream erosion (within the last 130 years). This has resulted in narrow, steep-walled arroyos that can be 5 to 20 feet deep along the valley bottoms. Areas mapped as Qamf can be prone to flash flood and debris flow events. These catastrophic events are most likely to occur in non-incised valley-head and valley-side areas and along the deeply dissected modern arroyo channels. The deposits may be prone to collapse from hydrocompaction, or slope failure when wetted or loaded (Morgan and others, 2007; Morgan and White, 2007). Qamf deposits are extensively irrigated for use as agriculture cropland and pasture.

Figure 25. Outcrop of light tan, silty to bouldery alluvial mudflow deposit of Qamf along a cutbank of Adobe Wash. Note the lag gravels along the undulating, cut-and-fill base of Qamf deposit and arroyo incisement into the Prairie Canyon Member of the Mancos Shale. The rock hammer is for scale. Kmp refers to the Prairie Canyon Member of the Mancos Shale [12S UTMX: 704896, UTMY: 4342256]

MASS-WASTING DEPOSITS

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

Qls **Landslide deposits (upper Pleistocene to Holocene)** — Unsorted, unstratified, angular pebble, cobble, and boulder-size rock debris. These deposits are characterized by hummocky topography and formed by complex earthflow mass movements. The sizes, lithologies, and colors of the clasts of these deposits reflect those of the displaced bedrock units. Landslides are found in the southwestern part of the map area (Figure 26) where they formed on unstable slopes along the top of the Brushy Basin Member of the Morrison Formation (Jmb). These slopes are unstable because the Brushy Basin Member contains abundant expansive smectitic clays (Scott and others, 2001). When wet, these expansive clays reduce the shear strength of the Brushy Basin Member resulting in landslides that displace the Brushy Basin Member and overlying Burro Canyon and Dakota Formations (Kdb).

The most widespread landslide deposits in the Fruita quadrangle are found on the north side of Dinosaur Hill (Figure 26). Here, multiple, crescent-shaped headwall scarps are associated with landslide deposits derived from the Brushy Basin Member of the Morrison Formation and the overlying the Burro Canyon and the Dakota Formations. Evidence for the presence of expansive clays that contribute to slope instability is indicated by the abundance of desiccation cracks found on the surface of Dinosaur Hill. The youngest landslide scarps cannibalize preexisting landslide material.

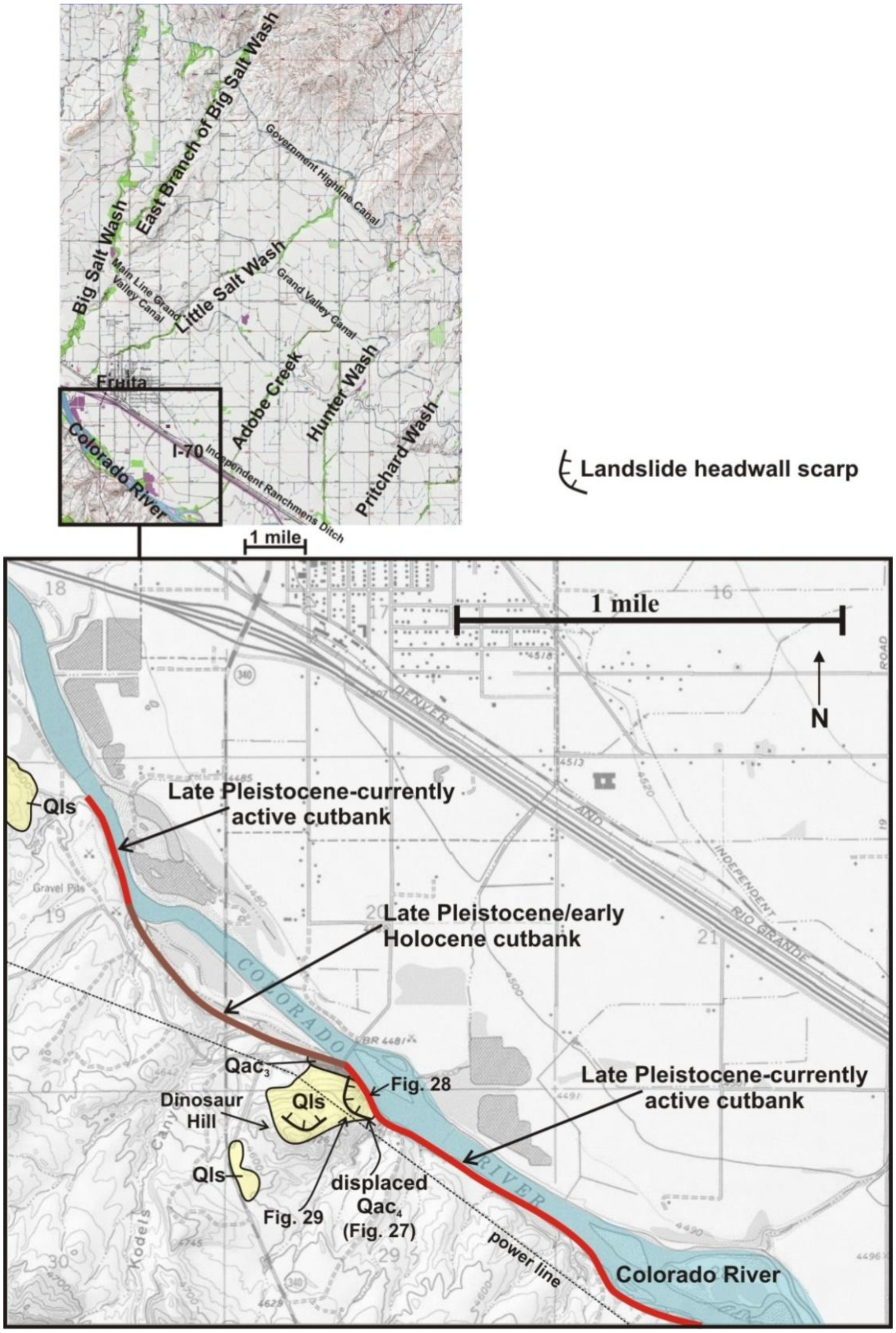

Figure 26. Map showing the location of major landslide deposits in the Fruita quadrangle. The most widespread landslide deposits in the Fruita quadrangle are found on Dinosaur Hill. All of the headwall breakaway scarps on Dinosaur Hill are roughly parallel with the Colorado River. This implies that landsliding was toward the river and down structural dip of the bedrock strata. These slides are, therefore, considered to have been caused by undercutting along this cutbank. Continued undercutting by the Colorado River may rejuvenate landsliding in this area.

The Dinosaur Hill landslide overlies the late Pleistocene-age Qac_3 alluvial gravels of the Colorado River (Figure 26). Upper Pleistocene Colorado River alluvial gravels of Qac_4 were displaced and incorporated into the landslide deposits on the eastern side of Dinosaur Hill. In this area, rounded Qac_4 alluvial gravel clasts are intermingled with angular landslide-related clasts (Figure 27). Therefore, landsliding is considered to have begun in the late Pleistocene.

Figure 27. Image taken on the southeastern side of Dinosaur Hill showing angular clasts of landslide deposits intermingled with rounded clasts of upper Pleistocene Colorado River alluvial gravels of Qac_4. [12S UTMX: 696238, UTMY: 4333890]

Very young, late Holocene-age headwall scarps are found along the northernmost part of Dinosaur Hill and just south of the Colorado River along the currently active cutbank (Figure 28). Power line support poles built on Dinosaur Hill near the youngest Holocene-age scarp shows signs of distortion related to continued instability of this slope. The power line poles are surrounded by soft, unconsolidated landslide deposits with ground cracks that are up to 1 ft long and several inches deep (Figures 26 and 29). The power line poles exhibit top-to-the north simple shear as indicated by distortion of wire cross-cable supports linking the two vertical poles (Figure 29). This implies that this slope is unstable and that landsliding toward the Colorado River continues today.

Figure 28. Very young, late Holocene-age landslide headwall scarp found on the north side of Dinosaur Hill along the currently active Colorado River cutbank. The associated landslide deposits were derived from the Brushy Basin Member of the Morrison Formation (Jmb) and the overlying the Burro Canyon and the Dakota Formations (Kdb). [12S UTMX: 696168, UTMY: 4334062]

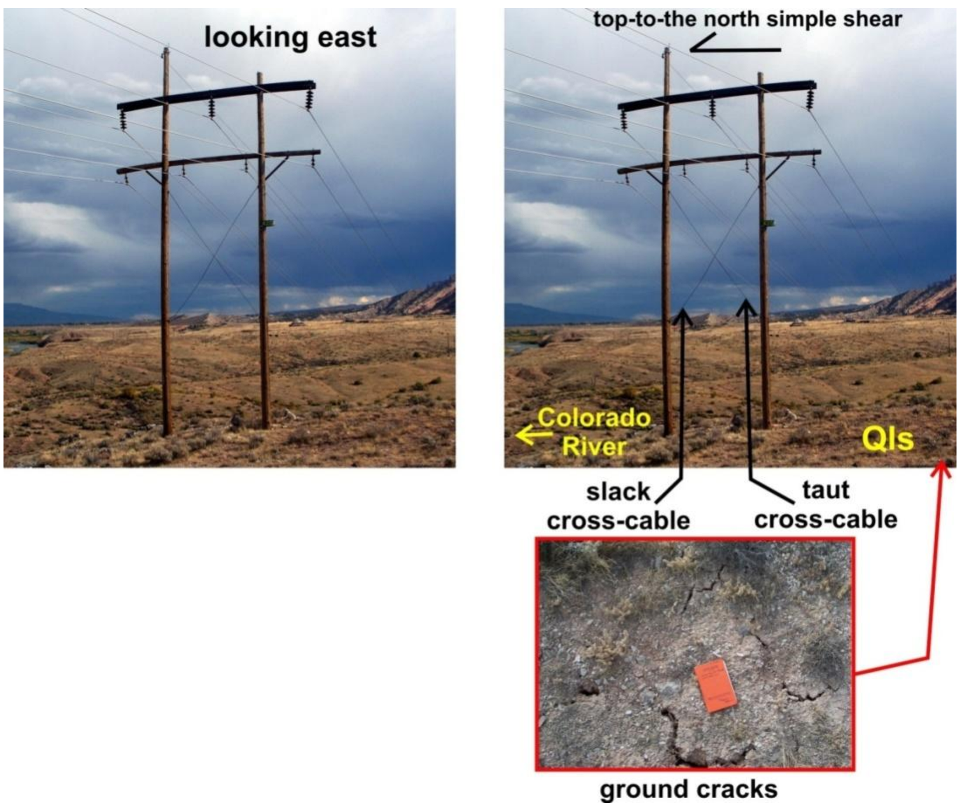

Figure 29. Power line support poles built on the south side of Dinosaur Hill near the youngest Holocene-age landslide scarp. The power line support poles show signs of distortion related to continued instability of this slope. The power line poles are surrounded by soft, unconsolidated landslide deposits with ground cracks that are up to 1 ft long and several inches deep. These ground cracks have formed in expansive clays that contribute to slope instability. The power line poles exhibit top-to-the north simple shear as indicated by distortion of wire cross-cable supports linking the two vertical poles. This implies that this slope is unstable and that landsliding toward the Colorado River continues today. [12S UTMX: 696084, UTMY: 4333946]

All of the headwall scarps on Dinosaur Hill are roughly parallel with the Colorado River. This implies that landsliding is toward the river and down structural dip of the bedrock strata. Modern landsliding is occurring in the downslope direction of a drainage on the top of the slide. These slides are considered to have been caused by undercutting along the late Pleistocene to currently active Colorado River cutbank (Figures 26). The lobate toes of these Dinosaur Hill landslides have been removed by erosion along this cutbank. Continued undercutting by the Colorado River has repeatedly rejuvenated landsliding in this area. This process continues today as indicated by distortion of the power poles. Thickness of landslide deposits is up to 30 ft.

BEDROCK UNITS

The exposed bedrock throughout the central and northern Fruita quadrangle is the Upper Cretaceous Mancos Shale. Cretaceous and Jurassic-age sedimentary formations underlying the Mancos Shale outcrop in the southwest corner of the map area (Figure 5). These formations include the Jurassic Kayenta, Entrada, Wanakah and Morrison Formations and the Cretaceous Burro Canyon and Dakota Formations.

Mancos Shale (Upper Cretaceous)

The Mancos Shale was deposited within a shallow marine seaway (Western Interior Seaway) that inundated the central part of North American Continent during Late Cretaceous time. The age range of the Mancos Shale in the Grand Valley area is considered to be Campanian to Cenomanian (Young, 1959).

The Colorado Geological Survey’s (CGS) approach to mapping the Mancos shale is to import nomenclature of stratigraphic members from other areas where the individual members are well exposed (Noe and others, 2007, 2008; Morgan and others; 2008). This includes the central Front Range Piedmont near Pueblo (Scott and Cobban, 1964, 1986; Cobban and Scott, 1972), the Mesa Verde area in southwestern Colorado (Leckie and others, 1997) and the nearby Book Cliffs of Grand Valley (Cole and others, 1997; Hettinger and Kirschbaum, 2002). Following the work of CGS geologists, we have recognized two members of the Mancos Shale in the Fruita quadrangle. These are the Prairie Canyon and Smoky Hill Members.

There is a subtle color contrast between the Smoky Hill (blackish-gray to orange-gray) and Prairie Canyon (gray to tan-gray) Members that is recognizable in the field. The most distinctive difference between Smoky Hill and Prairie Canyon is the topographic expression of these members (Figure 30). The Prairie Canyon member forms incised badlands of slightly angular, highly rilled hills, whereas the Smoky Hill Member forms rounded, low hills, knobs and valleys. The contact between these two members forms a distinct topographic slope break.

A key problem for drawing the cross-section for the Fruita quadrangle is estimating the thickness of the Mancos Shale. Data from a drill hole found in the north-central portion of the Fruita quadrangle (Federal 15-1 drill hole of Figure 5; Table 1; Appendix 2) resolves this problem. This drill hole provides precise data for the thickness of the Mancos Shale as well as the Dakota, Burro Canyon and Morrison Formations. The Federal 15-1 drill hole was spudded in the Prairie Canyon Member of the Mancos Shale

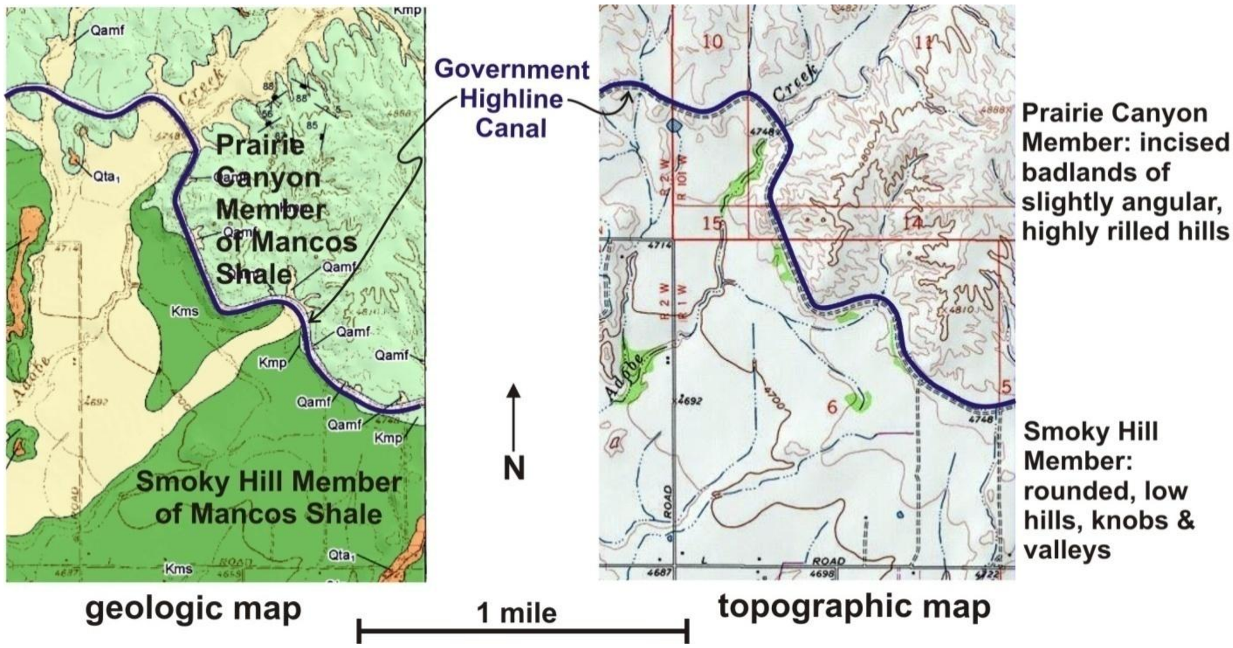

Figure 30. Cutouts of the same east-central portion of the Fruita quadrangle geologic map (Plate 1 and Figure 5) and topographic map (Figure 2). Note the distinct difference in topographic expression between Smoky Hill and Prairie Canyon Members of the Mancos Shale. Also, note the close correlation of Government Highline Canal with the contact between these two members. We infer that the Government Highline Canal was built in this location because: (a) it is along a line that corresponds with the abrupt change in elevation caused by difference in weathering morphology between the two members of the Mancos Shale and (b) most arable land is found at lower elevations, south of this contact on the topographically subdued Smoky Hill Member.

(Kmp), roughly 50 ft above the contact with the underlying Smoky Hill Member of the Mancos Shale (Kms). This gives a thickness of 2,050 ft for the Kms and Kml (undivided lower members of Mancos Shale). Thickness data for this drill hole was projected into our A-A' cross-section (a minor adjustment was made for the surface elevation difference).

Kmp **Prairie Canyon Member** — Gray to tan-gray, noncalcareous, fissile, sandy marine shale (Figure 31). Shales are interbedded with thin, rounded lenses of bioturbated sandstone (typically <2 to 4 inches in diameter) and thin (<1 ft thick) laterally continuous beds of much less bioturbated sandstone. These sandstones tend to be more resistant to surface weathering than the shales. Weathered horizons are typically covered with small sandstone lenses and chips. This unit is exposed in the northeastern portion of the mapped area. The basal contact with the underlying Smoky Hill Member is gradational over a 10 to 15 ft interval and conformable.

The type locality for the Prairie Canyon Member is found in the Book Cliffs, approximately 20 miles northwest of the Fruita quadrangle area (Cole and others, 1997). Cole and others (1997) and Morgan and others, 2008 argue that this member is actually regionally developed and

Table 1. Well log data from geology report of abandoned gas well Federal 15-1. Complete geology report for this well is found in Appendix 2. Data from Colorado Oil and Gas Conservation Commission website at http://oil-gas.state.co.us (well location is in section 15, T2N, R2W).

Formation	Log top	Thickness	Notes
Mancos Shale	0 ft	2,050 ft	Well spudded in lower Kmp
Dakota Fm.	2,050 ft	150 ft	Depth to Dakota – Burro Canyon Fm contact based on reinterpretation of well log as top of first sandstone beneath the black shale
Burro Canyon Fm.	2,200 ft	79 ft	Total Dakota-Burro Canyon Fms thickness = 229 ft
Brushy Basin Member of Morrison Fm.	2,279 ft	246 ft	
Salt Wash Member of Morrison Fm.	2,525 ft	158 ft	
Tidwell Member of Morrison Fm.	2,683 ft		Gray limestone encountered, well total depth = 2,715 ft

Figure 31. Gray to tan-gray, noncalcareous, fissile, sandy marine shale of the Prairie Canyon Member of the Mancos Shale (Kmp). [12S UTMX: 698966, UTMY: 4345704]

equivalent to the sandy Mancos "B" interval (Kellogg, 1977) and the Cortez Member (Leckie and others, 1997) found in southwestern Colorado. Fossil assemblages collected from this unit in other areas, indicate an Early Campanian age (82 Ma) for the Prairie Canyon Member (Noe and others, 2007; Cobban and others, 2006). These fossils include *Cataceramus balticus* (inoceramid) and *Baculites sp.* (*haresi*?). We have identified similar inoceramid fossils in this unit in the Fruita quadrangle. Kellogg (1977) and Johnson (2003) interpreted the unit to be a northward prograding shelf-slope deposit. More recently, Anderson (2007) suggested that the Prairie Canyon Member may be offlobe, mud-rich, delta-front turbidite deposits.

Only the lower 280 ft of the Prairie Canyon Member is exposed in the Fruita quadrangle. The Prairie Canyon Member has been recognized in the Book Cliffs area (northwest of the Fruita quadrangle) as being about 1,100 ft thick (Hettinger and Kirschbaum, 2002).

When exposed on steep slopes and in areas having ground-water discharge and seepage, the Prairie Canyon Member is prone to failure (landsliding and debris flows). This unit has moderate swelling potential due to the presence of expansive clays (Table 1; Scott and others, 2002; Morgan and others, 2008). Unimproved roads are impassable when wet.

Kms **Smoky Hill Member** — Blackish-gray to orange-gray, calcareous to silty, gypsiferous, marine shale (Figure 32). The shale is slightly calcareous and contains plant debris, shell fragments, and fish scales. These fossils are found in moderate amounts and are typically concentrated along bedding planes. Thin veins and seams of secondary gypsum, are present throughout the unit (Figure 32; Morgan and others, 2008). The gypsum occurs as fibrous or crystalline (selenite) forms and is found along bedding planes or in discontinuous joints at a high angle to bedding planes. Grayish orange marly limestone beds (~1 ft thick) are interbedded with the shales near the top of this member (Figure 33). These marly limestone beds form prominent benches with the upper part of the Smoky Hill Member.

The Smoky Hill Member is regionally developed. It is equivalent to the Smoky Hill Member at Mesa Verde in southwestern Colorado (Leckie and others, 1997) and to the Smoky Hill Shale Member of the Niobrara Formation near Pueblo (Scott and Cobban, 1964). It is also correlative with the lower Blue Gate Member of the Mancos Shale in eastern Utah (Johnson, 2003). The Smoky Hill Member is also prone to failure (landsliding and debris flows) where exposed on steep slopes. The main problem areas are incised channels of tributary streams that experience ground-water discharge, agricultural runoff and seepage. The Smoky Hill Member has moderate swelling potential due to the presence of expansive clays in bentonite beds (Table 2;Scott and others, 2002; Morgan and others, 2008). It also contains sulfate minerals (gypsum and thenardite) that are highly corrosive to concrete and metal pipes (Figure 32; Table 2; Scott and others, 2002). Unimproved roads are impassable when wet.

The upper contact of the Smoky Hill Member is gradational over a distance of 10 to 15ft and is conformable with the Prairie Canyon Member. The lower contact of the Smoky Hill Member is covered by Quaternary units (Qac_2 and Qamf) and not exposed in the Fruita quadrangle. Therefore, we assumed the thickness of the Smoky Hill Member to be 380 ft. This thickness is from the work of Morgan and others (2008) in the Delta quadrangle found to the south of the Fruita quadrangle.

Figure 32. Blackish-gray, slightly calcareous to silty, gypsiferous, marine shale of the Smoky Hill Member of the Mancos Shale. Note the thin veins and seams of gypsum, which form under near surface weathering conditions. The gypsum occurs as fibrous or crystalline (selenite) and is found along bedding planes or in discontinuous joints at a high angle to bedding planes. [12S UTMX: 697635, UTMY: 4344266]

Figure 33. Grayish-orange, marly limestone beds interbedded with the orange-gray shales near the top of Smoky Hill Member of the Mancos Shale. This prominent marly limestone is ~1 ft thick found about 30 ft beneath the Prairie Canyon/Smoky Hill contact. [12S UTMX: 697635, UTMY: 4344271]

Kmu **Lower members of the Mancos Shale, undivided** — Shown only in cross-section. This unit is assumed to consist of the lower members of the Mancos Shale that are not exposed on the surface.

Dakota and Burro Canyon Formations

Kdb **Dakota and Burro Canyon Formations (Upper and Lower Cretaceous) —** Due to their limited aerial extent, the Dakota Sandstone and Burro Canyon Formation are shown as undivided on the map (Kdb). They are described as individual formations below. Regionally, the base of the Dakota is characterized by braided fluvial facies that is incised as much as 60 ft into the underlying Burro Canyon Formation (e.g., Currie, 1997, note that the Burro Canyon is referred to as the Cedar Mountain Formation by Currie). This surface is commonly referred to as the K-2 or LK-2 unconformity (‘L’ referring to ‘lower’, e.g., Currie, 1997; Currie and others, 2008). Based on drill hole data from Federal 15-1 (Table 1), the combined thickness of the Dakota and Burro Canyon Formations is 229 ft.

Dakota Formation (Upper Cretaceous) — Dominantly sandstone, with subordinate conglomerate, mudstone and carbonaceous shales that, along with the underlying Burro Canyon Formation, form resistant ledges and cliffs along the southern side of the Colorado River. The basal contact of the Dakota Formation with the Burro Canyon Formation is well exposed (Figure 14). The upper contact with the Cretaceous Mancos Shale, however, is covered by alluvial deposits of the Colorado River (Qac_1 and Qac_2) and is not exposed in the map area. Therefore, our description is of the lower part of the Dakota Formation with a discussion of the upper part of the Dakota Formation based on the work of Scott and others (2001).

The lower part of the Dakota Formation is composed of channel-form sandstones and conglomeratic sandstones or carbonaceous shales. The channels were deposited by slightly to moderately sinuous streams flowing across broad, well defined flood plains that were densely vegetated and contained numerous abandoned channels that formed oxbow lakes (Scott and others, 2001). Outcrops in the Fruita quad indicate that, locally, the Dakota streams were incising into soft green-gray mudstones of the underlying Burro Canyon Formation. This is indicated by the cut-and-fill scour structure along the basal sandstone of the Dakota Formation (Figure 14).

The basal Dakota sandstone has a concave-upward relief of up to 1 ft along the contact of the Burro Canyon gray-green mudstone. These sandstones are brown to pale yellowish orange in color and silica-cemented. They also consist of subangular, moderately well-sorted, coarse-grained quartz sand (95%) with 2% lithic fragments and 3% clay rip up clasts derived from the underlying Burro Canyon mudstones. The cut-and-fill beds have trough cross-bedding to epsilon cross-bedding. The epsilon cross-beds dip both northward and southward indicating complex migration of laterally accreting meandering streams on a coastal plain during a Cretaceous marine regression (Weimer, 1970).

It has also been suggested that the northward and southward, low-angle (<15°), dipping epsilon cross-beds may indicate alternating currents in a marine tide-dominated estuary (Dave Noe, CGS, pers. comm., 2008). The cut-and-fill scour bases of these beds, however, seem more suggestive of laterally accreting meandering streams. The presence of interbedded conglomerates further suggests a fluvial origin of the basal sandstones. The conglomerates are interbedded with the sandstones in 1 to 2 ft thick, upward fining, lenticular beds with concave upward scour bases. They are also buff to light brown color, silica cemented, clast-supported, moderately well rounded, chert-pebble conglomerate. The Dakota Sandstone is interbedded with pale green mudstone and carbonaceous shale (Figure 34). The pale green mudstones may represent overbank flood deposits or reworking of the underlying Burro Canyon Formation. The carbonaceous shale is black and fissile with some pale brown limonite staining. This shale was deposited in freshwater swamp and marsh environments associated with the streams (Scott and others, 2001). Based on data from the Federal 15-1 drill hole (Table 1), the Dakota Formation is 150 ft thick. This is identical with the thickness of this formation measured in the Colorado National Monument quadrangle (Cole and others, 1999).

Figure 34. Carbonaceous black shale locally found at the base of the Dakota Formation. [12S UTMX: 695541, UTMY: 4334340]

Burro Canyon Formation (Lower Cretaceous) — Pale-olive to yellowish-green mudstone and interbedded buff to light tan sandstones and conglomerates. Typically, the upper, mudstone-dominated portion of this formation is exposed in the Fruita quadrangle. These mudstones consists of pale-olive to yellowish-green siltstone to claystone that is medium to thinly laminated (platy to fissile weathering), slightly calcareous, and commonly bioturbated. The mudstones are interbedded with thin (<1 ft thick), channel-form sandstone bodies to thicker sand bodies (about 20 ft thick). Thin (<1 to 3 ft thick) paleosol horizons composed of white to light-gray, earthy carbonate nodules are interbedded with mudstones (Figure 35). According to Scott and others (2001), these mudstones are also slightly bentonitic to non-bentonitic. The Burro Canyon Formation was deposited by a widespread fluvial system (Scott and others, 2001). Mudstones of the Burro Canyon Formation form slopes and the sandstone beds form steep cliffs along the south bank of the Colorado River.

The sandstone- and conglomerate-dominated lower part of this formation and the contact with the underlying Brushy Basin Member of the Morrison formation is poorly exposed and typically covered by colluvium (Qc) and alluvial fan material (Qaf). This basal contact is the K-1 (basal Cretaceous) unconformity (Peterson, 1994; Peterson and Turner, 1998) and has been arbitrarily defined as the lowest thick sandstone or conglomerate bed above the mudstone of the Brushy Basin Member (Aubrey, 1998). The thick mudstone sequence at the top of the unit represents flood plain and lacustrine deposition (Scott and others, 2001). Based on data from the Federal 15-1 drill hole (Table 1), the Burro Canyon Formation is 79 ft thick. This is close to the 88 ft thickness measured in the Colorado National Monument quadrangle found just to the south of Fruita quadrangle (Cole and others, 1999). The contact between the Burro Canyon Formation and underlying Brushy Basin Member of the Morrison Formation is termed the K-1 or LK-1 unconformity (Peterson, 1994; Peterson and Turner, 1998).

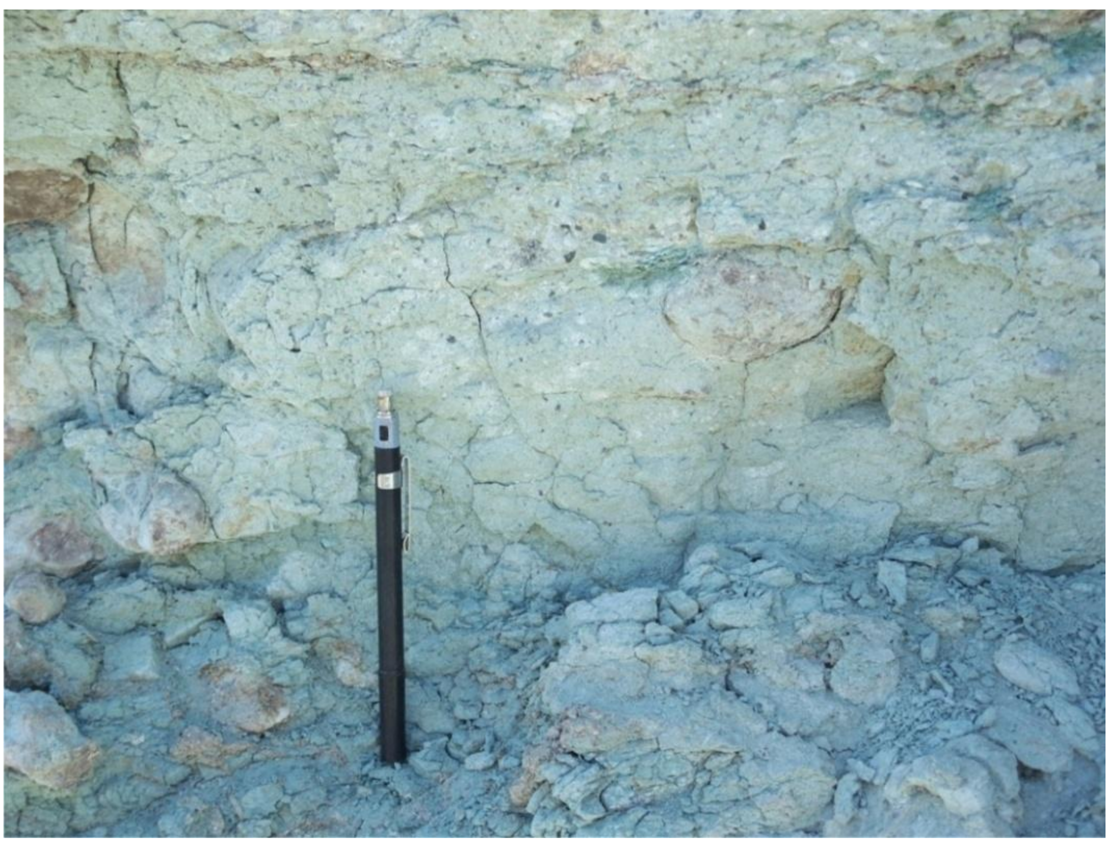

Figure 35. Paleosol horizons composed of white to light-gray, earthy carbonate nodules, that weather brown, interbedded with pale green mudstones of the Burro Canyon Formation. [12S UTMX: 695041, UTMY: 4334810]

Morrison Formation (Upper Jurassic)

The Morrison Formation (Upper Jurassic) is divided into three members, the lower Tidwell Member, middle Salt Wash Member and the upper Brushy Basin Member (Scott and others, 2001). The Morrison Formation is a total of 532 ft thick within and just south of the Colorado National Monument quadrangle (Cole and others, 1999). Individual members, however, do not have laterally consistent thicknesses (Cole and others, 1999). We estimated the Morrison Formation to be a total of 541 ft thick in the Fruita quadrangle.

Jmb **Brushy Basin Member** — Chiefly multicolored mudstone with some interbedded lenticular sandstones. The mudstone is variegated grayish-red to greenish-gray, medium to thinly laminated, mottled, slightly calcareous, clay-rich to silt-rich (Figure 36). The silty mudstone contains thin interbeds of very fine-grained, well sorted, bioturbated, lenticular sandstone. According to Scott and others (2001), 75% of the mudstone is very bentonitic. Bentonite is a rock that originates as volcanic ash. Diagenetic alteration transforms this ash into swelling, mixed-layer, smectitic clay minerals (Scott and others, 2001). The bentonitic nature of this mudstone causes it to expand and dry to form a distinctive, popcorn-like, weathered surface. The interbedded sandstone is yellowish gray, fine to medium-grained, moderately sorted, slightly calcareous, and friable. The sandstone occurs as lenticular channel-form beds that are up to 20 ft thick. The Brushy Basin Member forms gentle rounded slopes. The Brushy Basin Member was deposited in a mud flat to saline lacustrine environment with local fluvial channels (Turner and Fishman, 1991).

Paleontologist E.S. Riggs of the Chicago Field Museum of Natural History made significant dinosaur bone discoveries in the Brushy Basin Member in the Dinosaur Hill area in the early 1900's (Foster, 2007). In 1901, Riggs and his crew excavated the back two-thirds of an *Apatosaurus* skeleton from the southern part of Dinosaur Hill. This *Apatosaurus* specimen is still on display at the Field Museum of Natural History in Chicago (Foster, 2007). A commemorative plaque was established on this quarry site in 1938.

The upper contact between the Brushy Basin Member of the Morrison Formation and the overlying Burro Canyon Formation is covered and not exposed in the map area. Based on data from the Federal 15-1 drill hole (Table 1), the Brushy Basin Member is 246 ft thick.

Jms **Salt Wash Member —** Dominantly cliff-forming sandstones interbedded with mudstones. The sandstones are pale orange, yellowish gray, and light gray, fine to medium-grained, moderately sorted, slightly calcareous, and friable. The sandstone occurs as lenticular channel-form beds that range from 3 to 15 ft thick. Sandstone beds are typically cross-bedded in trough to epsilon cross bedding. The scour surfaces typically have pebble-size lag gravels composed of green mudstone, quartz, and chert. Burrows are common near the tops of the thicker sand bodies (Scott and others, 2001). The interbedded mudstone is pale-brown to greenish-gray, sandy siltstone to mudstone. The Salt Wash Member is a fluvial channel deposit with associated floodplains and shallow ponds (Turner and Fishman, 1991). Based on data from the Federal 15-1 drill hole (Table 1), the Salt Wash Member is 158 ft thick.

Figure 36. Image looking north of Dinosaur Hill. Dinosaur Hill is composed of the Brushy Basin Member of the Morrison Formation. The Brushy Basin member is partly covered with large blocks of sandstone that are remnants of landslide deposits derived from the overlying Burro Canyon Formation. [UTM83 12S UTMX: 695913, UTMY: 4333509]

Jmt **Tidwell Member —** Dominantly slope-forming mudstone interbedded with relatively thin ledges of sandstone and limestone. The mudstone, sandstone, and limestone all form laterally discontinuous beds. The mudstone is grayish-red to grayish-green, can sometimes be sandy, and occurs in beds up to 10 or 15 ft thick. Mudstone beds are massive (due to bioturbation) to thinly laminated. The limestone is light gray micrite or carbonate mudstone in beds up to 3 ft thick. Fossils are rare and consist of ostracodes, charophytes, and small gastropods (Scott and others, 2001). Some oncolite structures are also found. Sandstone is light gray to light brown, fine to medium-grained and moderately to well sorted and calcite-cemented. The sandstone is laminated to trough cross-bedded and occurs in beds that are up to 5 ft thick. The base of the Tidwell is defined as the 'A' sandstone bed (a 3 ft thick, coarser grained sandstone) that overlies on the Wanakah Formation along the J-5 unconformity (Pipiringos and O'Sullivan, 1978; Peterson, 1994). The green mudstone and the limestone were deposited in a fresh to brackish-water lacustrine deposits (Peterson, 1994, Scott and others 2001). Sandstone beds were deposited by fluvial and distributary channel systems (Peterson, 1994, Scott and others 2001). The Tidwell Member is about 134 ft thick in the Colorado National Monument quadrangle found just to the south (Cole and others, 1999). In the Fruita quadrangle, this member was measured at 137 ft. The contact between the Tidwell Member of the Morrison Formation and underlying Wanaka Formation is the J-5 unconformity (Pipiringos and O'Sullivan, 1978). This disconformity has very little erosional relief.

Wanakah and Entrada Formations undivided

Jwe **Wanakah and Entrada Formations undivided (Middle Jurassic) —** Due to their limited aerial extent, the Jurassic Wanakah and Entrada Formations were combined into a single undivided map unit (Jwe). They are described as individual formations below. The combined thickness of the Wanakah and Entrada Formations is about 187 ft.

Wanakah Formation — A slope-forming unit composed dominantly, reddish-brown, reddish-purple to greenish-gray mudstones with minor yellowish-brown sandstone and rare limestone and volcanic ash (Scott and others, 2001). Mudstones are medium to thinly laminated with a nodular to mottled weathering pattern. The sandstone occurs as thin interbeds of very fine to fine-grained, moderately to well sorted, silty sand. The Wanakah Formation was deposited in a nonmarine mudflat or shallow lacustrine environment (Scott and others, 2001). The Wanakah Formation is exposed in the southwestern-most corner of the map area. The top of the Wanakah Formation is truncated by the J-5 unconformity (Pipiringos and O'Sullivan, 1978) and overlain by the Tidwell Member of the Morrison Formation. The base of the Wanakah Formation is defined at the base of the red mudstone that rests on the pale orange sandstone beds of the upper informal "board beds" unit of the Entrada Sandstone. The Wanakah Formation is about 32 ft thick in the Colorado National Monument Quadrangle (Cole and others, 1999). This thickness is laterally very continuous and remains about 30 ft in the Fruita Quadrangle.

This formation was previously called the Summerville Formation in Colorado National Monument (Lohman, 1963, 1981). O'Sullivan (1980, 1992) suggested that the Summerville did not exist in western Colorado, whereas Anderson and Lucas (1998) proposed that the name Summerville Formation is appropriate for strata below the Salt Wash Member south and west of the map area. We have retained the term Wanakah following the work of Scott and others (2001) in Colorado National Monument quadrangle found just south of the Fruita quadrangle. The Wanakah is assigned to the Callovian age (O'Sullivan, 1992; Peterson, 1994).

Entrada Formation — Consists of two parts, an upper informal unit locally referred to as the "board beds" and the lower Slick Rock Member (O'Sullivan and Pipiringos, 1983; Scott and others, 2001). The "board beds" unit consists of dominantly sandstone interbedded with subordinate amounts of mudstone. Sandstone is very pale orange to very light gray, white, and pinkish gray, thin to thick bedded, slabby to blocky weathering, very fine to fine-grained, moderately to well sorted, intensely mottled by bioturbation, and calcareous. Mudstone consists of reddish-brown to grayish-red, thickly to thinly laminated, flaggy to fissile weathering, siltstone, and sandy siltstone, which is typically bioturbated. The environment of deposition of the "board beds" is considered to be a wet sand-flat environment in a coastal setting (Scott and others, 2001). The base of the unit is defined at the top of the orange-pink, cross-bedded Slick Rock Member of the Entrada. The thickness of the "board beds" unit is about 55 ft.

The Slick Rock Member is entirely pink to pale reddish orange sandstone. This sandstone is orange, very thinly to very thickly bedded, slabby to blocky weathering, very fine to fine-grained, moderately to well sorted, commonly mottled by bioturbation, calcareous, and weakly cemented. Small- to large-scale sets of trough, tabular-tangential, tabular-planar, and wedge-planar cross stratification is common. Cross-bed sets are mainly composed of wind-ripple lamination; grain-flow lamination is rare.

The Slick Rock Member was deposited as moderate-sized dunes (<65 ft) in coastal eolian setting with sand transportation to the south (Scott and others, 2001). The Slick Rock member forms rounded cliffs and overlies reddish-orange sandstone of the Kayenta Formation along the J-2 unconformity (Pipiringos and O'Sullivan, 1978; O'Sullivan and Pipiringos, 1983). The Slick Rock Member is Callovian Age (Peterson, 1988). The thickness of the Slick Rock Member is about 100 ft. The contact between the Slick Rock Member of the Entrada Formation and underlying Kayenta Formation is the J-2 unconformity (Pipiringos and O'Sullivan, 1978; O'Sullivan and Pipiringos, 1983). This disconformity can have up to 10 ft of erosional relief (Scott and others, 2001).

Jk **Kayenta Formation (Lower Jurassic) —** Consists dominantly of sandstone, with subordinate conglomerate and mudstone found mainly in the upper half. Sandstone is typically reddish orange, grayish orange pink, light greenish gray, or white, fine to medium-grained, moderately to well sorted, and quartz-cemented. The Kayenta forms thin to very thin beds and slabby beds. Sandstone sequences in the Kayenta contain numerous amalgamated scour surfaces that commonly have lag gravels consisting of mudstone clasts. Conglomerate is pebble to cobble-size clasts of reddish-orange mudstone in a matrix of medium-grained, moderately sorted, greenish-gray sandstone. The mudstone consists of reddish-brown to grayish-red, thinly laminated, moderately to well-sorted siltstone and sandy siltstone (Scott and others, 2001).

Stratification is well developed in the Kayenta Formation and consists of small- to medium-scale sets of laminations, with trough cross bedding and streaming lineations. These sandstones were deposited in high-energy braided rivers (Scott and others, 2001). The Kayenta commonly forms resistant ledges. The base of the Kayenta is not exposed in the map area. The Kayenta is Lower Jurassic or Pliensbachian in age (Peterson, 1994). The Kayenta Formation is 76 ft thick in Monument Canyon of the Colorado National Monument quadrangle (Cole and others, 1999).

Jwg **Wingate Sandstone (Lower Jurassic)** — Not exposed, shown only in the cross-section. This formation is 329 ft thick in the adjacent Colorado National Monument quadrangle (Cole and others, 1999).

Trc **Chinle Formation (Upper Triassic)** — Not exposed, shown only in the cross-section. This formation is 88 ft thick in the adjacent Colorado National Monument quadrangle (Cole and others, 1999).

Proterozoic Crystalline Rocks

Xu **Crystalline Rocks (Lower Proterozoic) —** Not exposed, shown only in the cross-section. These rocks are exposed in the adjacent Colorado National Monument quadrangle where they consist of migmatites and meta-igneous gneisses (Scott and others, 2001).

STRUCTURAL GEOLOGY

The Fruita quadrangle is located on the Colorado Plateau structural province, just north of the Uncompahgre Plateau (Hunt, 1956). The Uncompahgre uplift of western Colorado originated as a Pennsylvanian-Permian-age Ancestral Rockies uplift (e.g., Ye and others, 1996; Dickinson and Lawton, 2003). The Uncompahgre Plateau is one of a series of Colorado Plateau monoclinal structures that formed during the Late Cretaceous – Early Tertiary Laramide Orogeny (about 70 to 50 Ma; Lohman, 1965, 1981; Stone, 1977; Tweto, 1977; Heyman, 1983; Miller and others, 1992; Davis, 1999). The magnitude of the deformation on these Colorado Plateau monoclines is not as great as those Laramide structures found just to the east in the Rocky Mountains (e.g., Miller and others, 1992). The modern geomorphic expression of this structure is referred to as the Uncompahgre Plateau (White and Jacobson, 1983). Unfortunately, no direct evidence is found in the Colorado National Monument quadrangle (Scott and others, 2001) or Fruita quadrangle to determine the exact age of deformation of the Uncompahgre uplift.

Laramide-age structures of the northern part of the Uncompahgre Plateau are characterized by a series of northwest-southeast striking monoclines and reverse faults (Figure 37; Hunt, 1956; Lohman, 1965, 1981; Stone, 1977; Tweto, 1977; Heyman, 1983; Scott and others, 2001). The Colorado National Monument quadrangle, found just to the south of the Fruita quadrangle displays classic monocline and basement reverse fault structures (Figures 37; Scott and others, 2001). These monoclinal structures are found in the southwest corner of the Fruita quadrangle (Figures 38 and 39). Here, sedimentary strata are folded above inferred deep-seated, high-angle reverse faults to form a series of three monoclinal hingelines. These hingelines are related to two northeast-facing monoclines (Figures 38 and 39). The reverse faults that control the monoclines are inferred to be high-angle structures similar in dip to those found in the Colorado National Monument (Heyman, 1983; Scott and others, 2001).

The monocline hingeline locations are based on changes in dip of the strata (Figures 38 and 39). The limb of an unnamed monocline dips about 23^{o} to the northeast, whereas the limb of the Redlands monocline dips more steeply at 22^{o} to 45^{o} to the northeast. The unnamed monocline strikes northwest-southeast (Figure 37). The Redlands monocline strikes northwest-southeast and represents a continuation of a monoclinal structure found to the south in the Colorado National Monument quadrangle (Heyman, 1983; Scott and others, 2001). The Redlands monocline is a large structure with about 2,500 ft of structural relief. This is impressive considering that the main monocline found along the northeast front of the Colorado National Monument has only 1,600 ft structural relief (see cross-section B-B' of Scott and others, 2001). We hypothesize that the Redlands monocline is breached by a series of inferred reverse faults that propagate upward from a master basement reverse fault (the Colorado River reverse fault; Figures 38 and 39). The structure of the remainder of the Fruita quadrangle consists of a very gently, northeast dipping (1 to 2^{o}) homocline.

Additional important structures found in the Fruita quadrangle are a series of joints found in the Mancos Shale (Figure 18). The dominate strike of these joints is 55^{o}, which is roughly orthogonal to the average strike of all Mesozoic strata (305^{o}). We infer that the joints formed as near-surface, low confining pressure failures in response to a N55E-directed stress that formed the Laramide structures of the Uncompahgre Plateau (Wawrzyniec and others, 2002; Livaccari, 2007). Joints also partially control the course of tributary streams (Figure 18).

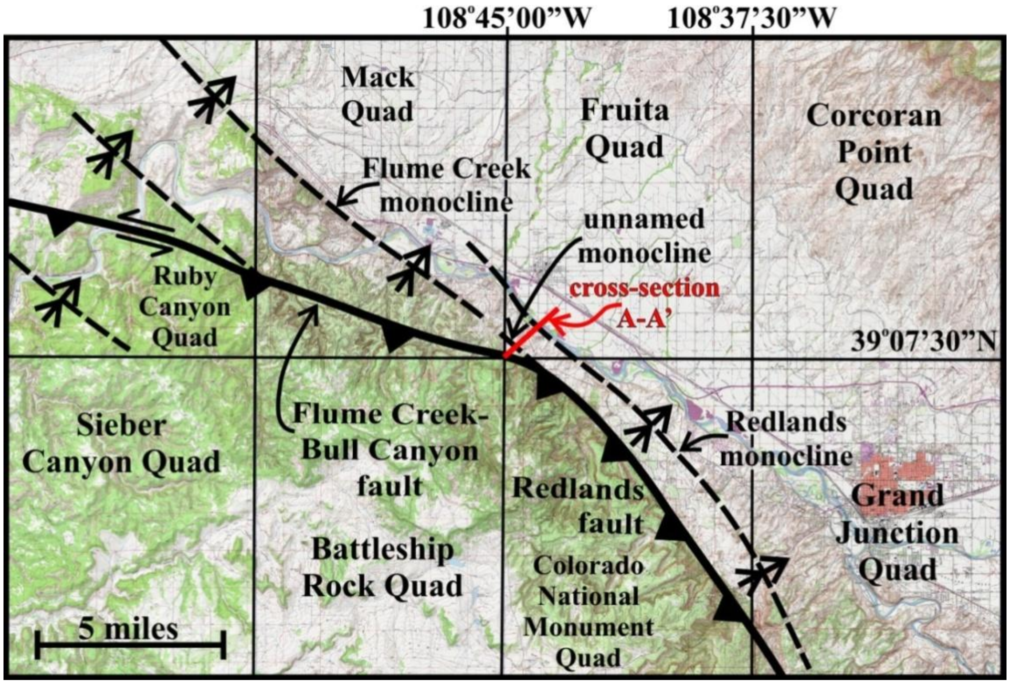

Figure 37. Map illustrating the regional Laramide structures of the northern Uncompahgre Plateau. This structure is characterized by a series of northwest-southeast striking monoclines and reverse faults. Also shown is the location of cross-section A-A' of Figure 38. Data compiled from Heyman, (1983), Scott and others (2001), and Nelson and others (2007).

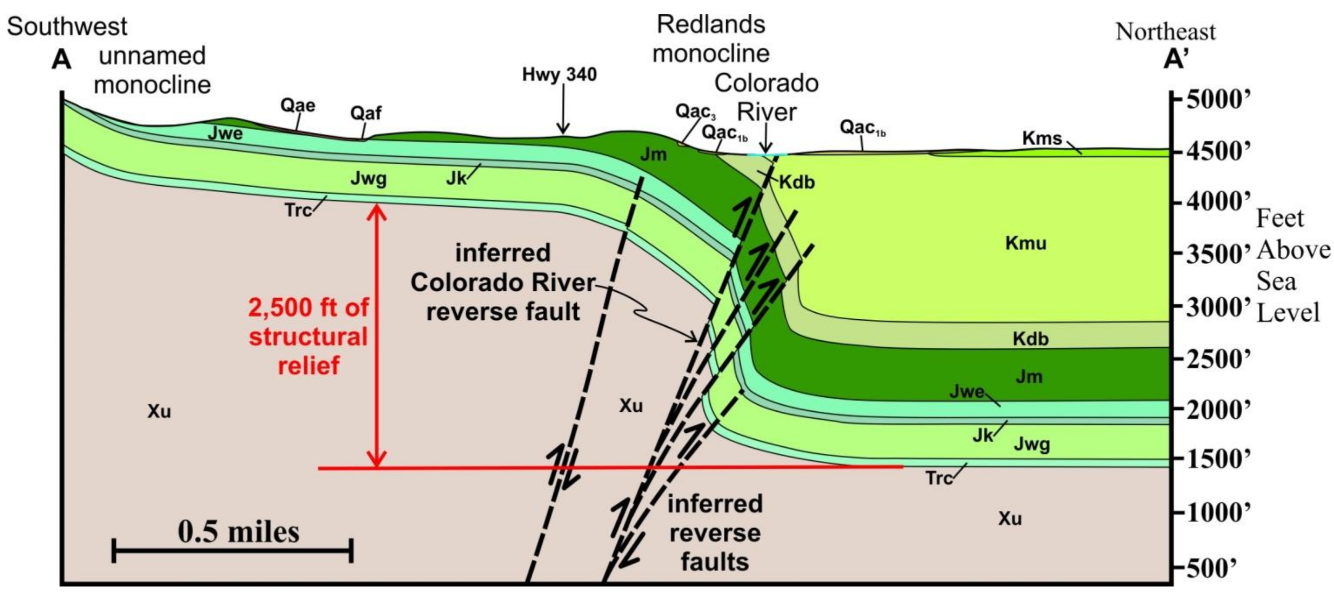

Figure 38. Northeast-southwest striking cross-section A-A' of Figures 37 and 38 showing the Redlands monocline and an unnamed monocline. Reverse faults shown controlling the monoclines are inferred structures. These inferred reverse faults are in attitude similar to exposed monocline-reverse fault structures found just to the south in the Colorado National Monument quadrangle (Scott and others, 2001). See 'Description of the Map Units' portion of this report for an explanation of the map unit symbols.

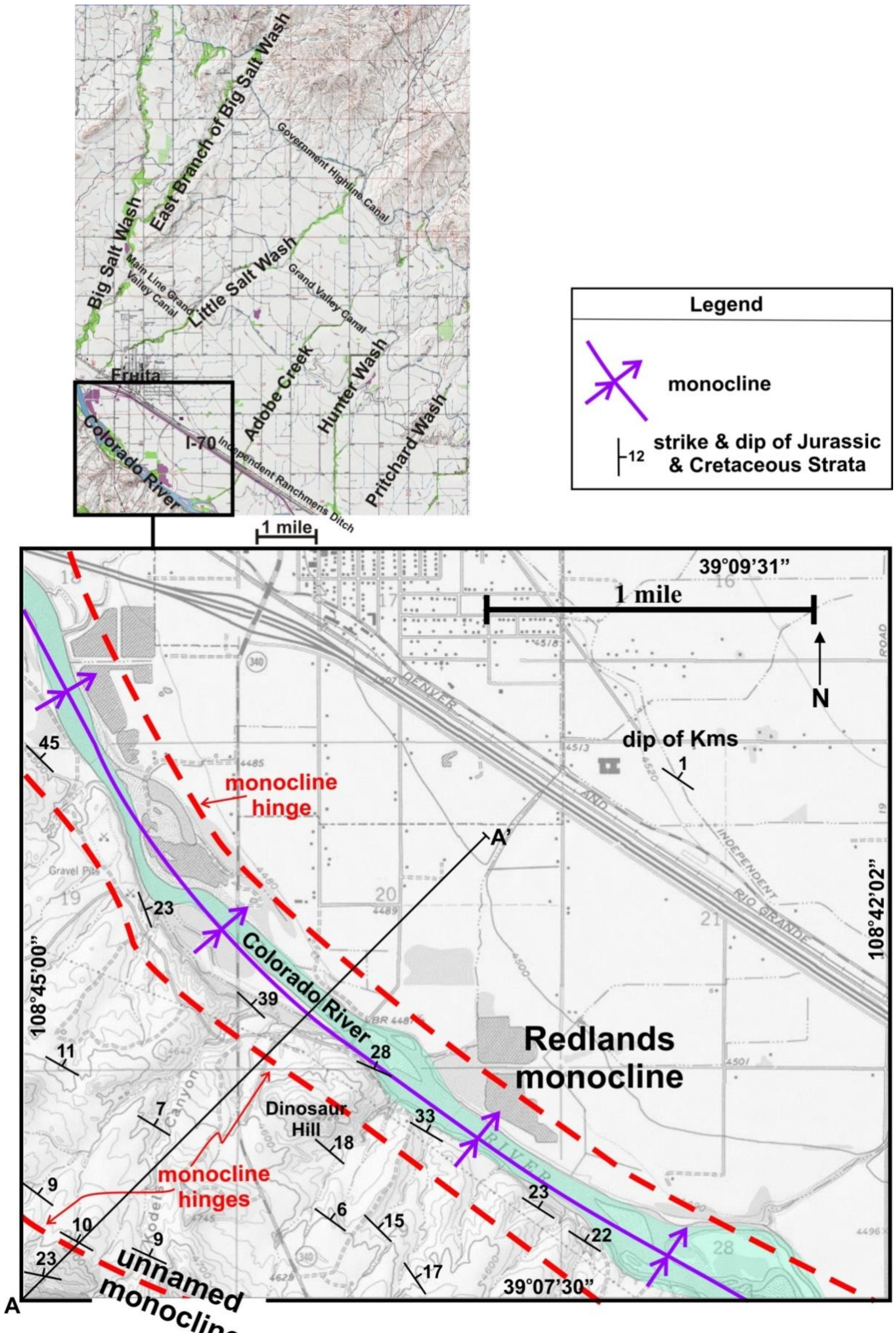

Figure 39. Map showing the two northeast-facing monoclines in the Fruita quadrangle. Monocline hingelines represent the zones of maximum curvature of structurally tilted strata. The A-A' line on the map is the cross section of figure 38.

GEOLOGIC HAZARDS

Bedrock structure, bedrock lithology, topography, and incisement of both tributary streams and the Colorado River control the development of geological hazardous areas in the Fruita quadrangle. Landslides in the Fruita quadrangle are most prevalent in the area south of the Colorado River (Figure 26). Problems related to swelling and shrinking (hydrocompactive) soils and the potential for mudflows due to cloudburst flash flooding impact the entire Fruita area. Additionally, potentially damaging corrosive and erodible soils are found in the Fruita area and there is the potential for earthquakes.

Landslides

The most widespread landslide deposits in the Fruita quadrangle are found on Dinosaur Hill where there are outcrops of the Brushy Basin Member of the Morrison Formation (Figure 26). As discussed earlier, mudstones of the Brushy Basin Member of the Morrison Formation contain significant amounts of expansive, smectitic clays (Scott and others, 2001). When wet, these expansive clays reduce the shear strength of the Brushy Basin Member (Jmb) resulting in landslides that displace the Brushy Basin Member and overlying Burro Canyon and Dakota Formations (Kdb). The older of these landslides probably formed in the late Pleistocene when the climate was wetter (Scott and others, 2001). Very young, late Holocene-age headwall scarps are found along the northern part of Dinosaur Hill. These scarps are found just south of the Colorado River along the currently active cutbank (Figure 26). Landsliding along the southern bank of the Colorado River should be considered as an active and ongoing process. Building of homes or any other structures should be prohibited in areas immediately south of these cutbanks.

Landslides may also occur in alluvial mudflow-and-fan valley-fill deposits (Qamf) and the Mancos Shale along tributary streams. All tributary streams incise the Qamf. Landsliding of Qamf has resulted in gullies with scalloped edges and moderate-angle stream bank walls. Unstable, vertical cut banks are also incised into the Qamf (Figure 25). For example, where Little Salt Wash incises into the Smoky Hill Member of the Mancos Shale, gully walls are vertical and 10 to 30 ft high (Figures 18 and 19). The shale in this area is structurally weakened by a series of systematic northeast-southwest striking joints. Landslides of vertical walls of Qamf or Mancos Shale could result in larger and potentially catastrophic events that could cause temporary damming and stream avulsion. This may cause widespread flooding of local homes and buildings.

Landslides may be accelerated by agricultural and residential building practices in this area. For example, watering of lawns by homeowners living in the southwest corner of the Fruita quadrangle can locally activate movement of expansive soils and clays in the Brushy Basin Member of the Morrison (Jmb). This has occurred in a similar geological setting in the Redlands area of the Colorado National Monument and Grand Junction quadrangles, causing damage to homes (Scott and others, 2001, 2002). Additionally, runoff and infiltration from farmland irrigation can lubricate fractures. This increases the pore pressure of the overburden alluvium and weathered bedrock found along incised tributary streams. This will reduce slope stabilities and enhance the potential for slope failures.

Debris Flows (Mudflows) and Flash Floods

The Colorado National Monument is found south of the Fruita quadrangle, and the Book Cliffs are located to the north of the Fruita quadrangle. Both of these areas are characterized by steep canyons, bare rock, and a semi-arid climate. These conditions are ideal for the generation of flash floods (Richard, 2004, 2007). Intense summer monsoonal thunderstorms are common on the Colorado National Monument and the Book Cliffs. These thunderstorms can rapidly funnel water into the tributary drainages of the Fruita quadrangle creating fast-moving, powerful floods (Richard, 2004, 2007). These kinds of flash floods could also generate mudflows and debris flows. Debris flows are dense, heterogeneous mixtures of mud, rock fragments, and plant materials that follow preexisting drainages (Varnes, 1978). They are the result of torrential rainfall or very rapid snowmelt runoff, where sediment supply is abundant and easily mobilized (Selby, 1993). The size and power increase as debris flows move down valleys and incorporate additional materials into the flow. When the flow reaches an area of lower gradient, the flow drops its load and the suspended sediment is deposited at the mouth of the drainage (Varnes, 1978). Debris flows can form at any point along a drainage including on the sides of valleys.

Between 1948 and 2003, eleven flash floods occurred that caused damage and flooding in the community bordering the Colorado National Monument (Richard, 2004, 2007). This is one event every five years. Our investigation of the artificial lake beds (alb) in the northern Fruita quadrangle suggests that mudflow events from the Book Cliffs occur at a rate of approximately one per year.

Much of the Fruita quadrangle area consists of mud-dominated alluvium and alluvial fan deposits deposited as sheetflows, mudflows and debris flows (Qamf and Qaf; Figure 5). Unfortunately, much of the area in the Fruita quadrangle covered by these deposits has also undergone urban and agricultural development. These areas, especially those areas close to tributary streams, are at a serious risk for flash floods, mudflows and debris flows. During the half-year course of this mapping project, we witnessed the construction of several new homes in the southwest corner of the Fruita quadrangle in areas proximal to canyons and alluvial fans originating in the Colorado National Monument. Residents living within or in close proximity to tributary streams or on Qamf or Qaf deposits and their associated drainage ways should be aware of the possibility that monsoonal-type precipitation events can trigger flash floods, mud flows or debris flows that may inundate these areas with dangerous amounts of water and sediment.

Rockfall

Rockfall deposits are included in the landslide (Qls) deposits in the Fruita quadrangle. Much of the rockfall hazard occurs along the active cutbanks of the Colorado River (Figure 26) or along mesa edges where loose cobbles and boulders of Qta_2 and Qta_1 overlie unconsolidated Mancos Shale (Figure 13). Areas mapped as Qls, especially the northeast side of Dinosaur Hill or near the active cutbank of the Colorado River (Figure 26), are susceptible to future rockfall events. Developers and homeowners should be cautious when building in proximity to these areas.

Earthquakes

Historically, Mesa County has experienced few earthquakes. The U.S. Geological Survey has rated Mesa County as having a low to moderate earthquake hazard (4%-16% g, USGS database of historic earthquakes *http://earthquake.usgs.gov/regional/states/colorado/history.php*). Minor seismic activity, however, has been recorded in the Fruita area (Figure 40). A moderate earthquake occurred on January

30, 1975 in an area just north of the Fruita quadrangle (Figure 40; magnitude 4.4 according to the USGS database of historic earthquakes and magnitude 3.7 according to the Mesa County Colorado Pre-Disaster Mitigation Plan, 2004). According to the USGS, this earthquake was felt throughout the Fruita area, including Grand Junction and is attributed to an unknown fault.

The USGS also warns that earthquakes have a broad range of damage beyond their epicenters. Therefore, earthquakes having epicenters outside of Mesa County should also be considered. For example, in 1994 a magnitude 5.9 earthquake occurred near Afton, Wyoming, almost 300 miles from Fruita. Despite the distance to the epicenter, it was widely felt across the Grand Valley, and for many hours a local radio station reported the epicenter was near Grand Junction. The USGS argues that unconsolidated sediments underlying the Grand Valley (Qamf and the Mancos Shale) contributed to greater ground motion than would be expected for an earthquake of that size and at that distance.

Additional information on faulting and earthquakes in this area is described in the CGS Colorado Earthquake Map Server (Widmann and others, 2002; Kirkham and others, 2004).

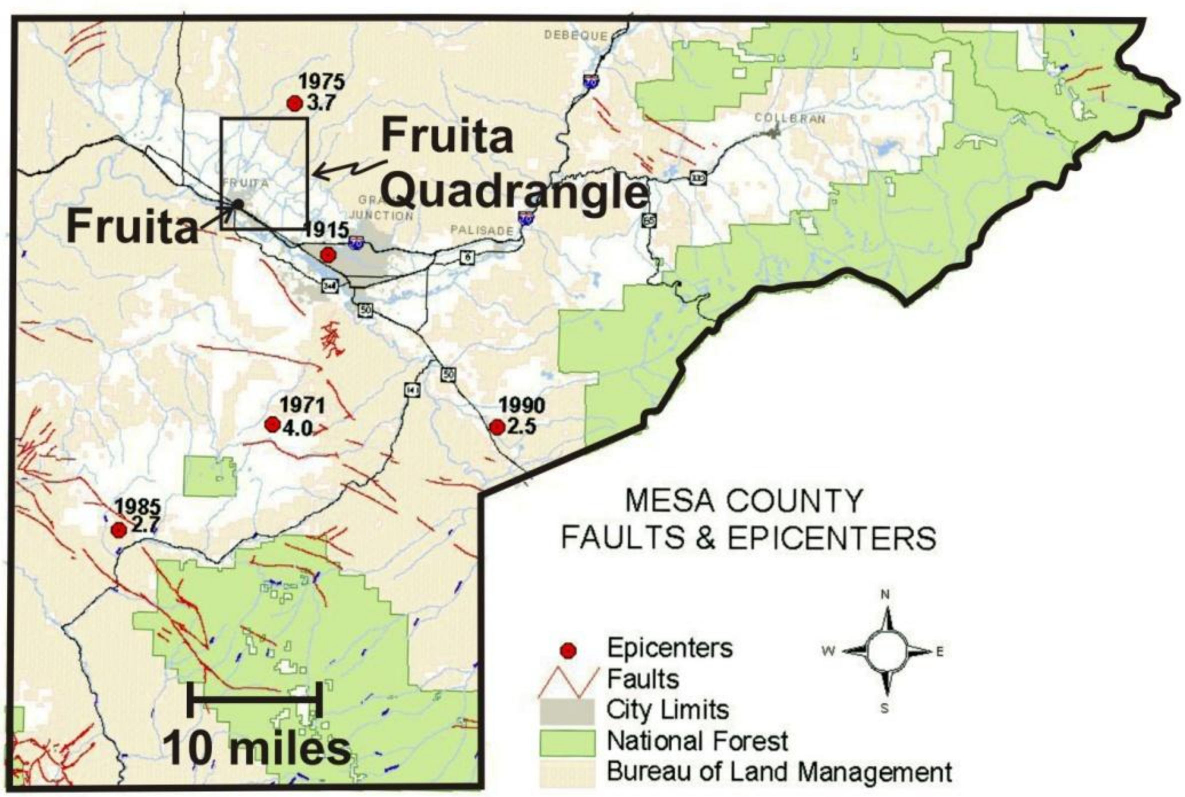

Figure 40. Location of large earthquakes, their magnitude, and date recorded in Mesa County Colorado (Mesa County Colorado Pre-Disaster Mitigation Plan, 2004). Note the 3.7 magnitude event recorded just north of the Fruita quadrangle in 1975.

Swelling Soils and Bedrock

The Mancos Shale, surficial units derived from the Mancos Shale (Qamf), the Morrison Formation and surficial units derived from the Morrison Formation (Qaf), may undergo volumetric swelling when wetted due to the presence of bentonite, smectite and expansive clay minerals (Morgan and others, 2007, 2008; Scott and others, 2001). Bentonite is a soft, plastic, light-colored rock derived from volcanic ash. Devitrification and chemical alteration causes bentonite to break down to a swelling clay know as montmorillonite or smectite (Klein and Dutrow, 2007). Expansive clay minerals remain dry under natural climate conditions. Upon wetting, they absorb water into their crystalline structure and expand (Noe, 2007). High swell pressures may result from this process of hydration and expansion of clay. The expansion of clays results in ground heaving and potential damage to residential, private, and public buildings, retaining walls, paved roads, concrete flatwork, and underground utility pipes (Noe, 2007).

The Natural Resources Conservation Service (NRCS) Soil Survey maps of the Fruita area give the linear extensibility of surface deposits in the Fruita quadrangle (Figure 41 and Table 2). Linear extensibility is a measure of a soils shrink-swell behavior; "low" linear extensibility (<3) refers to <18% mixed or smectitic clays; "moderate" linear extensibility (3-6) refers to 18-35% mixed or smectitic clays and "high" linear extensibility (>6) refers to >35% mixed or smectitic clays (Morgan and others, 2007; NRCS, 2008). When the linear extensibility is >3, shrinking and swelling can cause damage to buildings, roads, and other structures (NRCS, 2008).

Because of variations in clay mineralogy within the Fruita quadrangle, there are also variations in linear extensibility of surface deposits (Figure 41 and Table 2). Because of this, detailed assessment of soil conditions is best accomplished on a site-specific basis to properly design foundations and other civil works. This involves the drilling or excavating test holes, recovering samples from critical strata and depths, and testing the properties of those samples (see Noe, 2007 for further discussion).

Soils engineers in the Fruita area have noted significant variations in the presence or absence of swelling soils. For example, a house was constructed near the west-central edge of the Fruita quadrangle, with a non-engineered, slab-type concrete foundation poured directly on Mancos Shale with no adverse affects (Martin Chenoweth, pers. comm., 2008). This worked because the local near-surface Mancos Shale contained very little swelling clay material. This situation, however, is considered unusual for the Fruita quadrangle area (Martin Chenoweth, pers. comm., 2008).

Collapsible Soils and Bedrock

The Mancos Shale and surficial units derived from the Mancos Shale (Qamf) are also prone to collapse and settlement. Gypsum crystals typically grow in near-surface, weathered Mancos Shale along bedding planes and fractures (Figure 32). Volume increase due to the crystallization of gypsum can create pressures that force or wedge apart bedding planes and fractures (Morgan and others, 2007). Conversely, dissolution of the gypsum can cause collapse when loaded.

The alluvial mudflow-and-fan valley-fill, Qamf deposits are derived from the Mancos Shale. These deposits are very prone to hydrocompaction (Morgan and others, 2008). This occurs when water is added to dry Qamf deposits causing the soil-binding agents to weaken, resulting in collapse of the loose soil skeletal fabric. This allows the soil particles to reorient into a more compact structure, resulting in ground settlement. Collapse typically occurs in matrix-supported deposits such as Qamf, where clay-, silt-, and

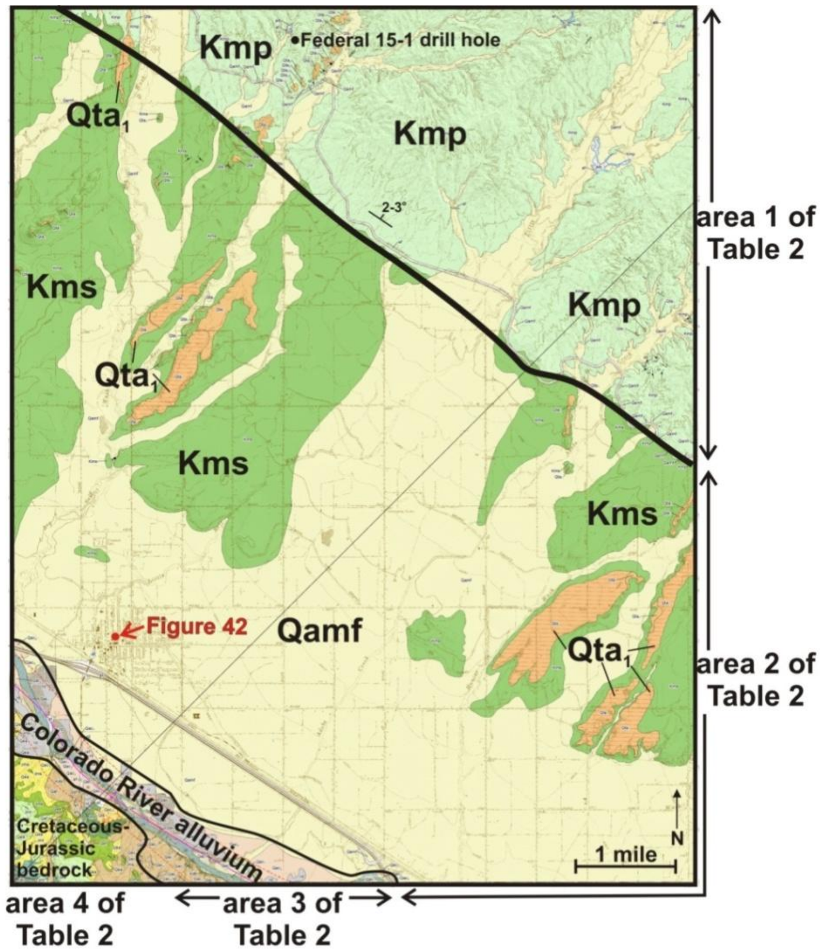

Figure 41. Location of areas 1–4 used in the soils report of Table 2 and of image in Figure 42. Abbreviations of map units given in caption of Figure 5.

Table 2. Soils report for the Fruita quadrangle (NRCS, 2008). Location of areas 1-4 is given in Figure 41. Note that in area 2 the Qamf is derived from the both the Smoky Hill and Prairie Canyon Members of the Mancos Shale.

Area	Surface outcrop	Linear extensibility (0 to 3 ft depth)	Plasticity Index (PI, 0 to 3 ft depth)	Risk of corrosion to concrete	Risk of corrosion to steel	Wind erodibility group	Water erodibility (Kw factor, 0 to 1 ft depth)	Gravel source
1	Qamf & Kmp	3.1 to 4.5 (moderate) for Kmp; 1.5 (low) for Qamf	4 – 23 low to high	high for Kmp, low for Qamf	high for Kmp, moderate for Qamf	3-4 (moderate)	0.17-0.37 (moderate)	poor
2	Qamf & Kms	1.5 to 4.5, low to moderate	12.5 – 26 moderate to high	low to high	moderate to high	3-6 (moderate)	0.24-0.37 (moderate)	poor
3	Qac_1 - Qac_4	1.5 (low)	0 – 12.5 low to moderate	low to high	moderate to high	3-8 (low to moderate)	0.02-0.37 (low to moderate)	fair
4	Qaf & Jurassic bedrock	1.5 to 3.7, low to moderate	9 – 12 moderate	low	moderate to high	3-8 (low to moderate)	0.28-0.32; moderate	poor

fine-sand-sized particles dominate the matrix. Additionally, dissolution of gypsum within these deposits can contribute to settlement and collapse (Morgan and others, 2008).

The process of dispersion may occur in deposits with specific mineralogy and soil chemistry (Morgan and others, 2008). Dispersion is a form of piping erosion in collapse-prone units. Clay particles with high sodium ion content will mobilize and disperse in presence of fresh water (Morgan and others, 2008). The result is the formation of pseudokarst land features, such as sinkholes, pipes, soil bridges and other subsurface voids. Some of these voids grow large enough to engulf people, cattle, and farm implements (Morgan and others, 2008). Deposits at risk for hydrocompaction and dispersion-collapse may exist in areas mapped as alluvial fans (Qaf) and Qamf.

Damage such as cracking of foundations and other structural problems can be caused by ground settlement, sinkholes, subsurface voids, and heaving, usually as a result of adverse wetting and structural loading. Dry density, moisture content, and swell-consolidation tests are usually performed to determine the degree of potential hydrocompaction. Crumb tests, pinhole tests, double hydrometer tests, and measurement of soluble salts and calculation of the Sodium Absorption Ratio (SAR) are more specialized tests to determine the potential of soil dispersion (Morgan and others, 2008). Because of the frequency of subsurface voids and potential for long-term settlement, residents should be cautious when building upon or traversing the units mapped as Qaf and Qamf.

Some of the bedrock zones and soil deposits may have both collapse and swelling properties (Morgan and others, 2008). The response of bedrock to introduced water depends on its clay mineralogy, natural moisture content, presence and abundance of gypsum, and applied external load (weight of a structure; Morgan and others, 2008). The reaction of surficial deposits such as Qamf to wetting depend on its porosity and internal skeletal fabric, clay mineralogy, moisture content, and applied load. It is possible for certain deposits to slightly swell upon wetting but quickly settle or collapse upon incremental loading. Such conditions need to be assessed by professional engineering geologists or geotechnical engineers and taken into account during the design of structure foundations, concrete slabs, and road pavements (Morgan and others, 2007).

Swelling and collapsible soils, referred to as 'adverse' soils by local engineers, are a well-known problem in the Fruita area (Table 2). Many buildings have experienced minor damage due to adverse soils (Martin Chenoweth, pers. comm., 2008). For example, the Fruita Civic Center building is a large two-story structure in downtown Fruita (325 E. Aspen; Figure 42). This building was constructed in 1912 and has experienced minor damage from ground settlement. The evidence for this is the one-story high, east-west striking, subvertical, extensional crack found in the center of this building (Figure 42). This crack emanates upward from a cracked foundation. This failure facilitated differential settling of the building. Public infrastructure such as streets, curb/gutters, sidewalks, and bridges may also be affected by swelling and collapsible soils.

Erodible Soils

Wind and water runoff are the biggest causes of erosion. These processes of erosion are amplified by development and grazing of vegetated lands where the soil is exposed and easily eroded (Morgan and others, 2008).

A wind erodibility group consists of soils that have similar properties affecting their susceptibility to wind erosion in cultivated areas such as the Fruita quadrangle (NRCS, 2008). Soils assigned to group 1

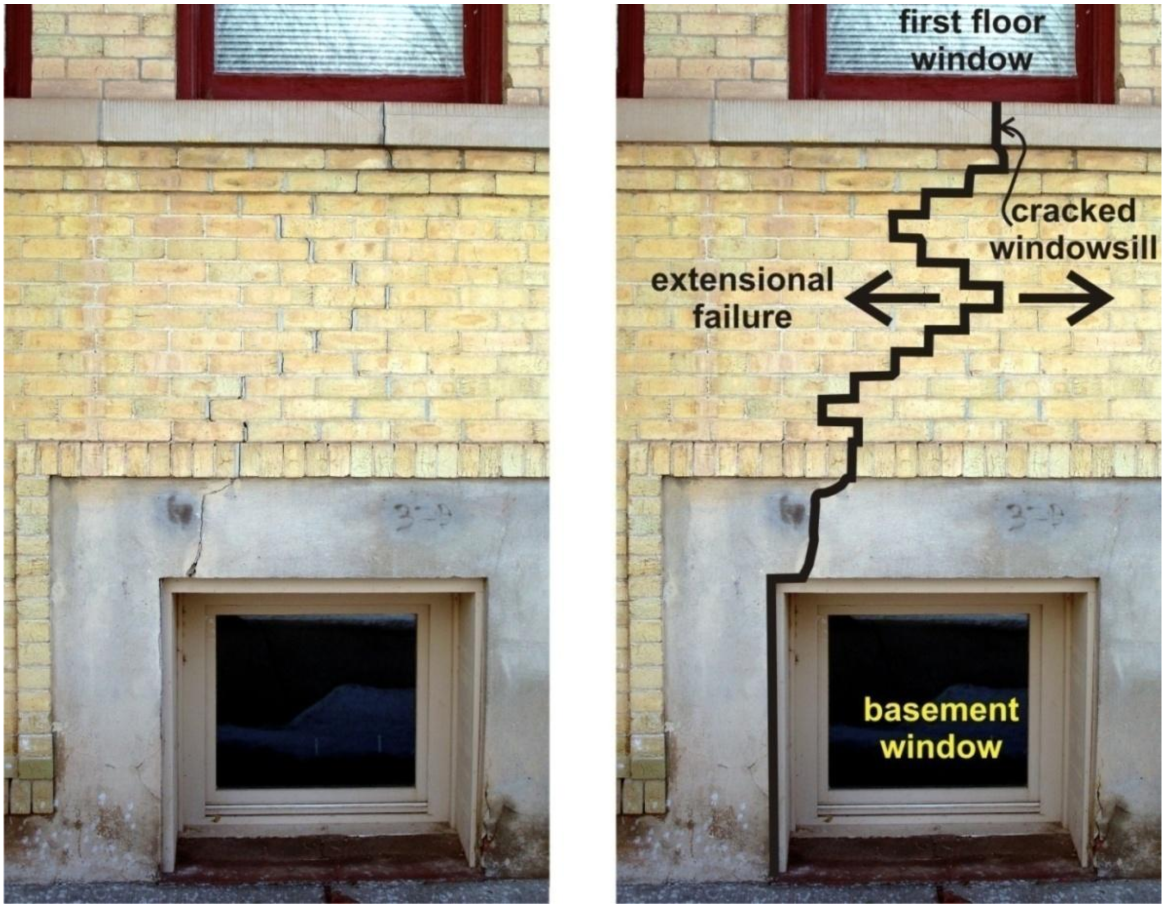

Figure 42. Image of the east-facing, outside wall Fruita Civic Center building. This large, two-story structure is located in downtown Fruita and was constructed in 1912 (Figure 41). This building has experienced minor damage from collapsible soils due to loading by this building. The one-story high, east-west striking, subvertical crack found in the center of this building shows down-to-the south displacement. [UTM83 12S UTMX: 696084, UTMY: 4336928]

are the most susceptible to wind erosion, and those assigned to group 8 are the least susceptible (NRCS, 2008). Areas of exposed Mancos Shale bedrock and the Qamf deposits (areas 1 and 2 of Figure 41) have moderate wind erodibility, especially where vegetation is naturally absent or has been removed (Table 2; NRCS, 2008). The NRCS 'Wind Erodibility Index' estimates that 56 to 86 tons per acre per year of soil erosion is possible from the Mancos Shale and Qamf. Areas with exposed Colorado River alluvial deposits and Jurassic bedrock (areas 3 and 4 of Figure 41) have low to moderate wind erodibility (Table 2). The NRCS 'Wind Erodibility Index' estimates that up to 86 tons per acre per year of soil erosion is possible from the Jurassic bedrock and surficial deposits that cover them (Qaf and Qea).

Erosion factor K is an indicator of susceptibility of a soil to sheet and rill erosion by water (Table 2; NRCS, 2008). Factor K can be used to predict the average annual rate of soil loss by sheet and rill erosion in tons per acre per year. K values range from 0.02 to 0.69, the higher the value, the more susceptible the soil is to sheet and rill erosion by water. Kw factor indicates the erodibility of the whole soil (Table 2). The Kw factor for most of the Fruita quadrangle, except for Colorado River alluvium, is between 0.17-0.37, or moderate. Along the Colorado River, the Kw values range from low to moderate (Table 1).

Airborne dust created by wind erosion can adversely affect the respiratory functions of humans and livestock by reducing air quality. Soil erosion also increases the risk of pollution to surface and ground waters from the use of pesticides from agricultural and residential treatment of vegetation (Morgan and others, 2008). Selenium is found in the Mancos Shale and deposits derived from the Mancos Shale. It can be mobilized by windstorm events and inhaled by humans and livestock. Adverse health effects may be caused by chronically breathing selenium laden dust (selenium poisoning and selenosis; MedicineNet.com, 2008). Ironically, elevated levels of selenium in the blood can also have a beneficial anti-carcinogenic effect (MedicineNet.com, 2008). We do not have enough information available to us to determine how widespread a problem this may or may not be.

Corrosive Soils

The Mancos Shale and surficial deposits derived from the Mancos Shale may have high salt and sulfate content and should be considered a potentially corrosive soil. Corrosive soils may damage typical concrete and buried metal (Morgan and others, 2008). Based on the NRCS soils report (Table 2), the risk of corrosion to concrete varies from low to high in areas with surface outcrops of Mancos Shale, Qamf and Colorado River alluvial deposits. Only those areas in the southwest corner of the Fruita quadrangle where Jurassic bedrock is found, is the risk of corrosion to concrete low.

Risk of corrosion to steel is rated as moderate to high for the entire Fruita quadrangle (Table 2). Soils engineers in the Fruita area can specify special corrosion-resistant concrete mixes for foundations and other concrete installations and protective coatings for buried metal works. The use of PVC pipes and plastic tanks, cathodic protection, or corrosion-resistant coatings is highly recommended for the Fruita area. Tests for corrosive soils include sulfate and chloride levels, pH, and electroconductivity measurements (Morgan and others, 2007).

MINERAL RESOURCES

Sand and gravel pits and natural gas wells are located within the Fruita quadrangle. Figure 43 shows the locations of some of the currently active and abandoned sand and gravel pits and abandoned gas wells found within the quadrangle.

Sand and gravel are currently the most economically significant mineral resources in the Fruita quadrangle. Five active sand and gravel quarries are located in the mapped area (Figure 43). All of these quarries are located in Colorado River gravels (area 3 of Figure 41; quarries are located in Qac_{1b} north of the river and Qac_3 south of the river). The United Companies of Mesa County Kiewit Lake/18 Road pit produces 200,000 tons of aggregate per year (Guilinger and Keller, 2004). The Grand Junction Concrete Pipe Company produced 250,000 tons of aggregate from their Fruita pit in 2008 (Ed Settle, 2008, pers. comm.). No production data for the other mines in the area could be found. During the course of this mapping project, we observed continuing sand and gravel mining in both the United Companies of Mesa County Kiewit Lake/18 Road pit and the Lafarge West Fruita Ready Mix pit. Also of interest is the fact that 600-700 gallons/minute of water need to be pumped out of the pits to keep them dry during quarrying

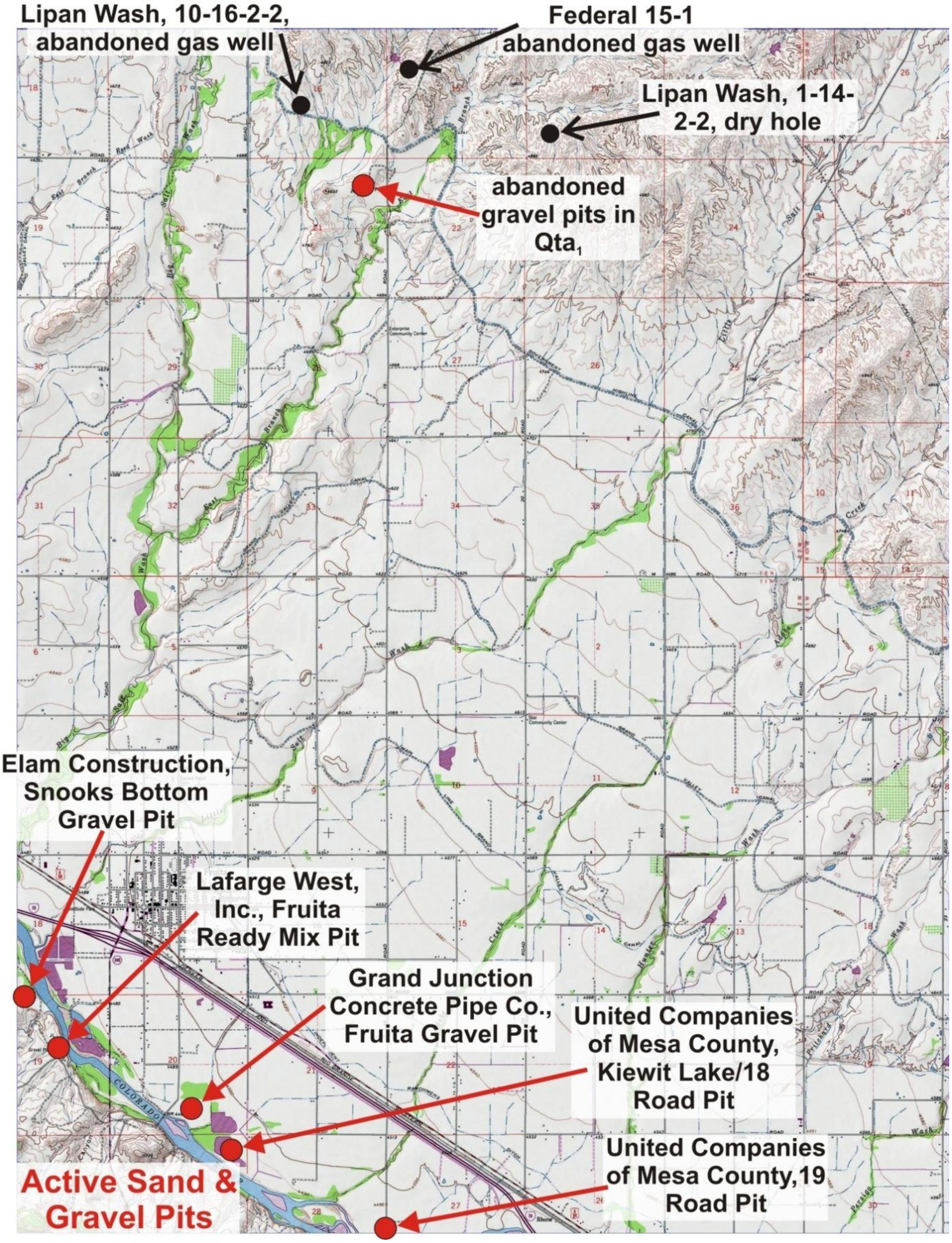

Figure 43. Map of the Fruita quadrangle showing the locations of some active and abandoned sand and gravel pits and abandoned gas wells.

operations. When quarrying ceases and the pumps are turned off, the pits completely fill with water in about 4 months (Ed Settle, 2008, pers. comm.). Some abandoned gravel pits are found in the tributary stream gravels in the northern part of the Fruita quadrangle (Figure 43). These pits are located in tributary alluvium one (Qta_1).

The Natural Resources Conservation Service (NRCS) Soil Survey maps of the Fruita area rated the area along the Colorado River (area 3 of Figure 41) as fair gravel potential. A rating of good or fair means that the source material is likely to be in or below the soil. Potential exists for the development of additional sand and gravel operations in the alluvial deposits in this portion of the mapped area.

Three abandoned gas wells are found in the north-central part of the Fruita quadrangle. These wells were originally drilled by the now defunct Mitchell Energy in the early 1970's (Schwochow, 1978; COGCC or Colorado Oil and Gas Conservation Commission website at http://oil-gas.state.co.us). Mitchell Energy produced gas from some of these wells (see Federal 15-1 on the map of Schwochow, 1978). No production data, however, was available from the COGCC website or Schwochow (1978) regarding this early production. Operation of these wells was transferred to Maralex Resources in 1997. Between 1999 and 2004, Maralex Resources produced nearly 30,000 MCF of gas from Federal 15-1 and 25,000 MCF of gas from Lipan Wash 10-16-2-2 (COGCC website; Figure 43). All of these wells are now abandoned.

The producing zone is referred to in the geology report as a sandstone in the middle of the Dakota Formation. We reinterpret this sandstone to be the lowest sandstone in the Dakota Formation. We make this assertion because this sandstone is found just above the carbonaceous black shale/coal layer that defines the base of this formation (Appendix 2; Scott and others, 2001).

SURFACE and GROUND-WATER RESOURCES

The City of Fruita receives its drinking water from the Ute Water Conservancy District (Leib, 2008). The Ute Water Conservancy District derives its drinking water from surface runoff reservoirs on the Grand Mesa. No potable domestic drinking water is derived from wells in the Fruita quadrangle (Colorado Division of Water Resources or CDWR database; Martin Chenoweth, pers. comm., 2008; Leib, 2008). This is due to ground water contamination by salts and trace elements such as selenium and uranium (Levinson 1980; Leib, 2008).

Two wells drilled within the city of Fruita reported water table depths of 4 ft (CDWR database). The water table remains high (within 4 ft of surface) south of the city of Fruita, towards the Colorado River (area 3 of Figure 41; Martin Chenoweth, pers. comm., 2008). In this area, gravels of Colorado River alluvial deposits (Qac_{1b}) are the main aquifer (Topper and others, 2003).

The presence of a perched water table and swelling clays found in the Qamf deposits that blanket much of the Qac_{1b} is locally causing significant problems to new housing developments built in this area (Martin Chenoweth, pers. comm., 2008). The source of some of the water in this perched Qamf water table is landscaping and septic systems associated with residential houses.

Another substantial problem in the Fruita area is excessive salt and selenium in ground water and surface runoff (Leib, 2008; Topper and others, 2003). Since 1900, canals have provided ample and inexpensive water from the Colorado River for agricultural irrigation (Figure 2; Mayo, 2008). Elevated levels of these two constituents are directly related to the location and amount of irrigation in the Fruita area. This problem is common to the entire Grand Valley. The reach of the Colorado River from the Gunnison River confluence (in Grand Junction, see Figure 1) to the Utah Border, and tributaries in the Grand Valley, are on the State of Colorado 303(d) list of impaired water bodies (Leib, 2008). This is because concentrations of selenium in these waterways exceed the State of Colorado chronic standard for aquatic life of 4.6 micrograms per liter (μg/L; Leib, 2008). Upstream from the irrigated area of the Grand Valley, selenium concentrations are well below the chronic standard (1 μg/L; Butler and others, 1996).

Adobe Creek, found in the Fruita quadrangle, is one of the streams chosen by the USGS to study the input of salt and selenium from tributary streams of the Grand Valley (Figure 44; Leib, 2008). Along Adobe Creek, the concentration of selenium is significant and it increases downstream. The selenium concentration measured near the mouth of Adobe Creek is 38.5 μg/L (Leib, 2008; Figure 44). This is 8.4 times higher than the State of Colorado chronic standard for aquatic life. The greatest increases in salt and selenium along the entire course of Adobe Creek occurs where the creek incises through highly irrigated agricultural areas (Figure 44; Leib, 2008). The highest concentration of selenium recorded anywhere along Adobe Creek was 120 μg/L (measured just south of an unnamed tributary, this is 26x higher than the Colorado chronic standard for aquatic life, see Figure 44 for location; Leib, 2008).

Holocene alluvial mudflow-and-fan valley fill deposits (Qamf derived from Mancos Shale) and the Smoky Hill Member of the Mancos Shale are found in the area where a majority of the selenium load is acquired (Figure 44). Therefore, the major source of the selenium must be these two units. It should be noted that except for a short segment of the Main Line Grand Valley Canal (between 17.5 and 18.5 Roads), that all three of the major irrigation canals in the Fruita quadrangle are unlined (Figure 44). Deep percolation of irrigation water and seepage of irrigation water from unlined canals leaches and mobilizes considerable amounts of salt and selenium from near-surface units (Butler and others, 1996; Mayo, 2008; Leib, 2008). Previous workers have attributed the source of selenium to the Mancos Shale (undivided) and alluvial mudflow-and-fan valley-fill deposits (e.g., Butler and others, 1996). Our claim is that the Smoky Hill Member of the Mancos Shale is highly seleniferous and the major contributor to selenium loading in the Fruita area. The Smoky Hill Member of the Mancos Shale underlies much of the arable land in the Fruita quadrangle resulting in the widespread selenium-loading problem.

Natural ground water in shallow aquifers seeping into tributary streams may also be a nonpoint source of salt and selenium contamination (Mayo, 2008; Leib, 2008). Grand Valley, however, has a semiarid climate, so natural ground water seepage cannot be significant source of water found in the tributary streams (Leib, 2008). Flow in tributary streams down gradient from irrigated areas is perennial, suggesting that this flow is derived from irrigation seepage (Leib, 2008). Without irrigation, the tributary streams in the Grand Valley would be ephemeral and would flow only during periods of moderate to intense rainfall or snowmelt (Leib, 2008). Therefore, irrigation water, if not totally consumed, returns to the Colorado River as ground or surface water.

The Grand Valley Selenium Task Force (GVSTF; http://www.seleniumtaskforce.org/), established in 2002, is a watershed initiative to address the selenium problem in the Grand Valley (Leib, 2008). This group involves members from local, State and Federal agencies. Their goal is to examine remediation and management practices to address the selenium issue in the Grand Valley. The transition from agricultural land use to residential and urban land use is occurring throughout the Grand Valley. How this transition will affect selenium levels in rivers and streams of the Grand Valley is one of the issues that needs to be studied (Leib, 2008).

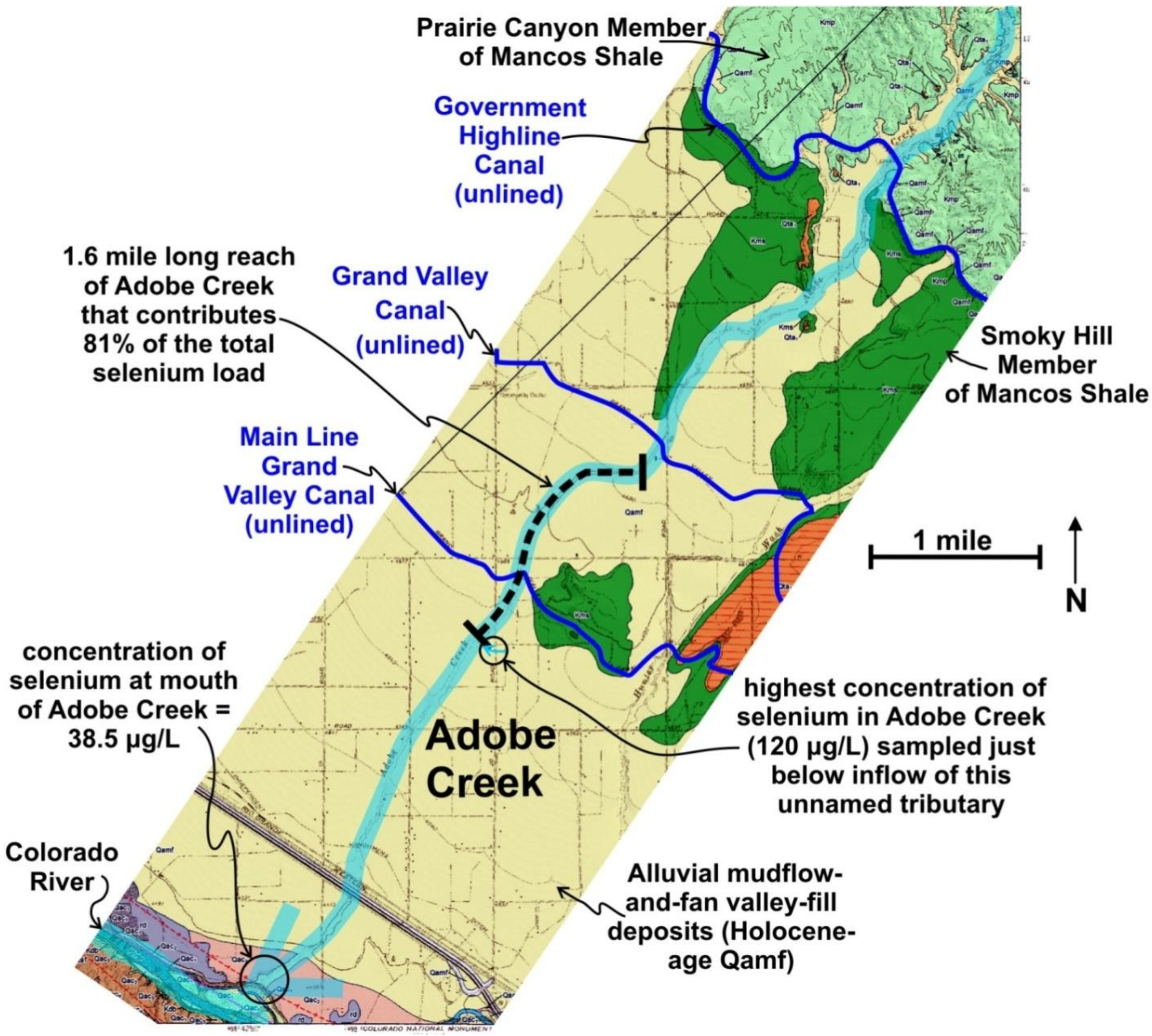

Figure 44. Cutout of the portion of the Fruita quadrangle geologic map (Plate 1 and Figure 5) along the Adobe Creek drainage (Figure 2). Data on the selenium concentrations along Adobe Creek are from the work of Leib (2008). The selenium concentration measured near the mouth of Adobe Creek (38.5 µg/L) is 8.4 times higher than the State of Colorado chronic standard for aquatic life. Note that a majority of the selenium concentration in Adobe Creek is acquired south of the Grand Valley Canal. Surface geology in this area consists of both the Holocene alluvial mudflow-and-fan valley fill deposits (Qamf derived from Mancos Shale) and the Smoky Hill Member of the Mancos Shale. Therefore, these two units must be the source of the selenium. Deep percolation of irrigation water and seepage of irrigation water from unlined canals leaches and mobilizes considerable amounts of selenium from these units.

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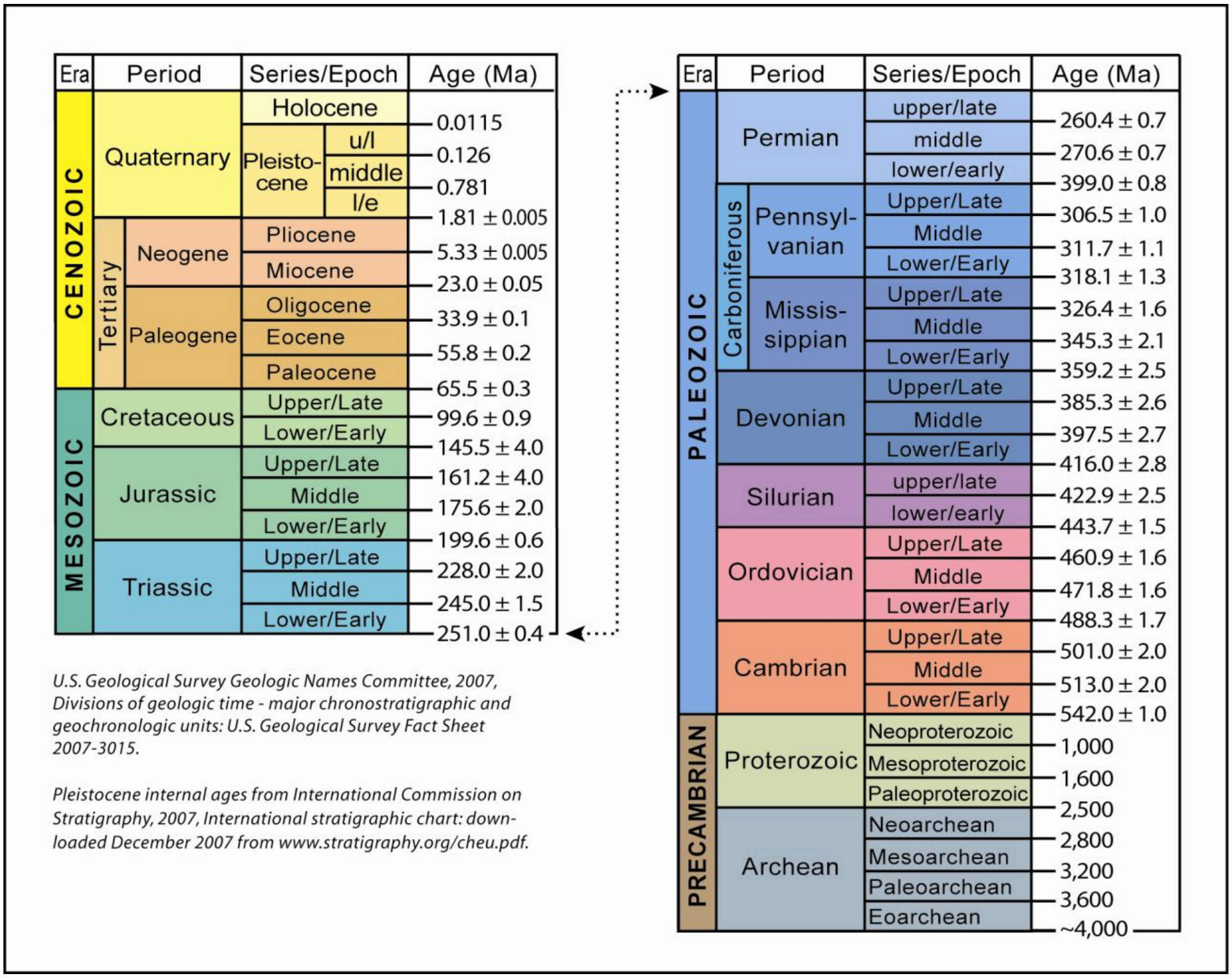
APPENDIX 1

Appendix 1. Geologic time chart adopted by the Colorado Geological Survey



APPENDIX 2

Appendix 2 (on following two pages). Geology report for drill hole Federal 15-1, drilled in 1973. From COGCC website at http://oil-gas.state.co.us

GEOLOGICAL REPORT

Mitchell Energy and Development Corp.

#15-1 Federal

SW NW Section 15, T 2 N, R 2 W

Mesa County, Colorado

by

JOE KIRN

Consulting Geologist

555 – 17th Street

Denver, Colorado 80202

(303) 255-2556

WELL DATA

WELL NAME:	Mitchell Energy & Development Corp. #15-1 Federal
LOCATION:	990' FWL, 1980' FNL (approximate SW NW) Section 15 – T 2 N, R 2W
ELEVATION:	4817' Ground, 4827' K.B.
SPUD:	June 13, 1973
CASING:	8 5/8", 20 lb. casing set at 220' with 150 sxs. cement, 3% calcium
CONTRACTOR:	Carmack Drilling Company, Grand Junction, Colorado
HOLE SIZE:	12¼" to 230', 7 7/8" to 2715'
DRILLING FLUID:	Air drilled to 2047' Air-Mist to 2270' Mud drilled, gel and chemicals, 2270' to 2715'
LOGS:	Schlumberger Dual-Induction Laterlog, 224' – 2715' Schlumberger Compensated Formation Density Log, 1950' – 2715' Schlumberger Compensated Neutron Formation Density, 1950' – 2715'
TOTAL DEPTH:	2715' Driller, 2715' Schlumberger
COMPLETED:	Ran production casing June 18, 1973

CHRONOLOGICAL RECORD

Date:	Activity as of 8:00 A.M.
6-13-73	Spud, drilled to 230' ran and cemented surface casing, nippled up, drilled to 615'
6-14-73	Drilled to 2096'; trip for bit #2, shut down at 2096' to test gas flow, did not get a gauge
6-15-73	Drilled to 2383'; down hole fire at 2270', trip for bit, mudded up, drilled to 2382'

CHRONOLOGICAL RECORD (cont.)

6-16-73	Drilled to 2658', trip for drill collars at 2388'
6-17-73	Drilled to 2715', conditioned hole for logs, ran logs, prepared to run casing
6-18-73	Ran and cemented production casing

BIT RECORD

Bit No.	Size	Make	Type	Serial	Depth Out	Ft.	Hrs.	Dev.
1	12 1/4"	Reed	YS1-J	Rerun	230			
2	7 7/8"	Reed	YS4G-J	96576	2,047	1,817	23½	
3	7 7/8"	Reed	F-62	Rerun	2,271	224	5¼	
4	7 7/8"	Reed	F-62	506692	2,715	444	22	

LOG TOPS

Mancos Shale	Surface
Dakota	2,050
Upper Dakota sand	2,073 – 2,111
Middle Dakota sand	2,123 – 2,147
Buckhorn	2,241
Morrison	2,279
1st Brushy Basin sand	2,329
2nd Brushy Basin sand	2,409
Salt Wash, 1st sand	2,525
2nd Salt Wash sand	2,643
3rd Salt Wash sand	2,664
Grey Limestone	2,683

LOG CALCULATIONS

Interval	Rw	Porosity	Water Saturation
2073-2111	.09	11%	35%
2123-2147	.09	10%	42%
2241-2243	.09	24%	68%
2243-2266	.09	22%	100%
2273-2279	.09	3-4%	100%
2329-2335	.09	6%	90%
2409-2417	.09	9%	76%
2525-2530	.09	6%	98%
2643-2658	.09	16%	65%
2664-2673	.09	6%	95%

SAMPLE DESCRIPTION

30' samples to 2040', 10' samples from 2040' to 2715'

230-1070	Shale dark grey to black, fissil, slightly micaceous and silty
1070-1530	Shale as above with streaks siltstone buff, grey
1530-1720	Shale black as above
1720-2000	Shale as above with streaks siltstone grey-brown
2000-2030	Shale as above with white bentonite
2040-2050	No Sample

DAKOTA 2050

2050-2073	Sandstone grey-brown, buff, vfg, slightly calcareous, hard, tite, white clay cement, sub-angular to sub-round, trace pyrite, partly white, quartzitic interbedded with shale black, fissil, hard, very sandy

UPPER DAKOTA SAND 2073

2073-2080	Sandstone white, vf-cg, unconsolidated probably porous, sub-angular to sub-round, poorly sorted, few vf black and brown grains, trace bentonite, few clusters grey, buff, very hard, quartzitic, slightly glauconitic, white clay filled slightly pyritic, one cluster dark grey, filled with black hydrocarbon residue (?), most clusters spotty bright yellow fluorescence, fast, light cut
2080-2090	Sandstone buff, m-cg, sub-angular to sub-round, hard, some clay filling, tite, abundant dark grey and brown grains, gew inclusions coal or black carbonaceous material, scattered fluorescence with cut as above
2090-2100	Sandstone as above and sandstone dark grey, vf-fg, very hard, tite, white clay filled, very pyritic in part, few black carbonaceous inclusions, fluorescence and cut as above
2100-2111	Sandstone as above and sandstone buff, cg, conglomeratic, hard, tite, angular to sub-round, grey and brown grains, few carbonaceous inclusions, fluorescence and cut as above. Gas show on connection at 2084', shut down at 2096' to test gas flow. Shut off air, gas burned with 10'-12' flare, did not get a guage on flow. The flare did not seem to diminish after drilling resumed.

2111-2123	Shale black, hard, silty, macaceous with siltstone dark grey, black, orgillaceous, carbonaceous, hard

2nd DAKOTA SAND 2123

2123-2147	Sandstone dark grey, f-mg, angular, shaly in part, hard, tite with abundant black carbonaceous or hydrocarbon residue, trace pyrite and sandstone buff, m-cg, partly conglomeratic, abundant grey and brown grains, spotty bright yellow fluorescence with slight cut.
2147-2200	Shale black, silty with siltstone black, very shaly, partly quartzitic, slightly glauconitic, hard
2200-2241	Sandstone white, buff, f-cg, quartzitic, angular to sub-angular, hard, tite, few black and dark grey grains, partly unconsolidated, no show with claystone green, grey-green, waxy

BUCKHORN 2241

2241-2270	Poor samples, mostly black shale with loose sand grains, f-cg, clear, sub-angular to sub-round, no show
	Downhole fire at 2270', mudded up at 2270'
2270-2279	Sandstone white, green-white, glassy, quartzitic, hard to distinguish grains, m-cg, angular to sub-angular, conglomeratic, green, red, black and brown chert pebbles, slightly calcareous, trace spotty bright yellow fluorescence, fair cut

MORRISON 2279

2279-2329	Claystone green, waxy sandy with shale red, brown-red, sandy and streaks sandstone white, green-white, f-cg, conglomeratic, limey, hard, tite, trace limestone grey-green, mic-xln

1st BRUSHY BASIN SAND 2329

2329-2334	Sandstone white, f-mg, quartzitic, angular, white clay cement, slightly calcareous, hard, tite, no show
2335-2409	Shale variegated, mostly red, waxy, slightly sandy with shale green, grey-green, waxy, sandy with streaks sandstone variegated, red, white, green, f-mg, hard, tite, trace pyrite

2nd BRUSHY BASIN SAND 2409

2409-2418	Sandstone white, f-mg, hard, white clay filled, slightly calcareous, sub-angular to sub-round, tite, few black, metallic looking grains, trace black carbonaceous or hydrocarbon residue, no show
2418-2460	Shale variegated as above with streaks sandstone variegated as above
2460-2525	As above with trace limestone red, pink, hard, tite, mic-xln, partly chalky

1st SALT WASH SAND 2525

2525-2530	Sandstone white, green-white, vf-mg, poorly sorted, sub-angular to sub-round, calcareous, quartzitic in part, hard, tite, no show
2530-2605	Shale variegated as above with streaks green, red and white sandstone as above. Some white bentonite
2605-2610	Sandstone white, f-mg, friable, angular to sub-angular, tite, very calcareous
2610-2643	Variegated shale and sandstone as above

2nd SALT WASH SAND 2643

2643-2659	Sandstone white, f-mg, friable, sub-angular to sub-round, probably good porosity and permeability, calcareous, few black, xln, metallic grains, no stain, fluorescence or cut
2659-2664	Variegated shale as above

3rd SALT WASH SAND 2664

2664-2673	Sandstone white, fg, fair to good sorting, friable, calcareous, tite, sub-angular to sub-round, few black grains, no show, trace limestone brown, dense
2673-2683	Shale variegated as above with sandstone as above

GREY LIMESTONE 2683

2683-2715	Limestone brown, grey, buff, green-grey, mic-xln to dense, sandy in part with streaks red and green, variegated shale. Trace sandstone grey, white, fg, limey, some white clay filled, tite, trace black carbonaceous residue.