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Cover

Midwest Exploration and Utah Southern No. 1 Shafer well, drilled in 1924. Left photograph is the view if the rig across the Colorado River. The cable-tool rig was floated down the river from the town of Moab. Right photograph of the well blowing out after encountering gas at 2028 feet (618 m) in the Cane Creek shale. The rig caught on fire and was destroyed. Courtesy of the Utah Division of State History and the Utah State Historical Society.

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Potential Drilling Hazards for Wells Targeting the Cane Creek Shale, Pennsylvanian Paradox Formation, Paradox Fold and Fault Belt, Southeastern Utah and Southwestern Colorado

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ABSTRACT

The Cane Creek shale of the Pennsylvanian Paradox Formation represents a major target for oil and gas in the Paradox fold and fault belt of the northern Paradox Basin of southeastern Utah and southwestern Colorado. Early exploration and development attempts resulted in blowouts due to unexpected gas-bearing intervals and casing collapses caused by salt flowage in the Paradox Formation. These problems represent some of the types of drilling hazards that could be expected when planning Cane Creek wells. Horizontal drilling first used in the early 1990s changed the Cane Creek shale play from one of mostly drilling failures to a more successful commercial play.

Depending on the location, exploratory Cane Creek wells may penetrate a section that ranges in age from Cretaceous through Pennsylvanian. Drilling in the region often encounters a wide variety of lithologies (carbonates, shale, mudstone, sandstone, and evaporites) and associated potential hazards that may include: (1) swelling clays, (2) high porosity-permeability or fractured zones resulting in lost circulation or excessive mudcake buildup, (3) "kicks" due to the influx of reservoir fluid (oil, water, or gas) into the wellbore, (4) uranium-rich zones, (5) washouts, (6) hole deviation, sticking, and other well-integrity problems, (7) chert, and (8) overpressured intervals. In addition, natural carbon dioxide, which flows from the partially human-made Crystal Geyser near some Cane Creek wellsites, represents an unusual drilling hazard if encountered in the northernmost part of the fold and fault belt.

Using the lessons learned from the recently completed research well, State 16-2 (renamed the State 16-2LN-CC, API No. 43-019-50089, after the horizontal leg was drilled), and other wells in the region, drilling engineers and operators can better plan for potential hazards when exploring for hydrocarbons in the Cane Creek shale or deeper targets (Mississippian Leadville Limestone and Devonian Elbert Formation) in the fairly remote, relatively sparsely explored Paradox fold and fault belt. The goal is to de-risk wells, lower expenses, and mitigate problems before they occur. The expected results are safer and more successful drilling of wells to the Cane Creek shale and deeper reservoirs ultimately leading to additional commercial hydrocarbon discoveries in the region.

INTRODUCTION

Exploration for oil in the Paradox fold and fault belt of the northern Paradox Basin in southeastern Utah and southwestern Colorado has been ongoing for over 100 years. Early wells mainly targeted surface structures. In 1924, the Midwest Exploration and Utah Southern No. 1 Shafer well was drilled on the large, northwest-southeast-trending Cane Creek anticline (figures 1A and 2). The cable-tool rig was floated 20 miles (32 km) down

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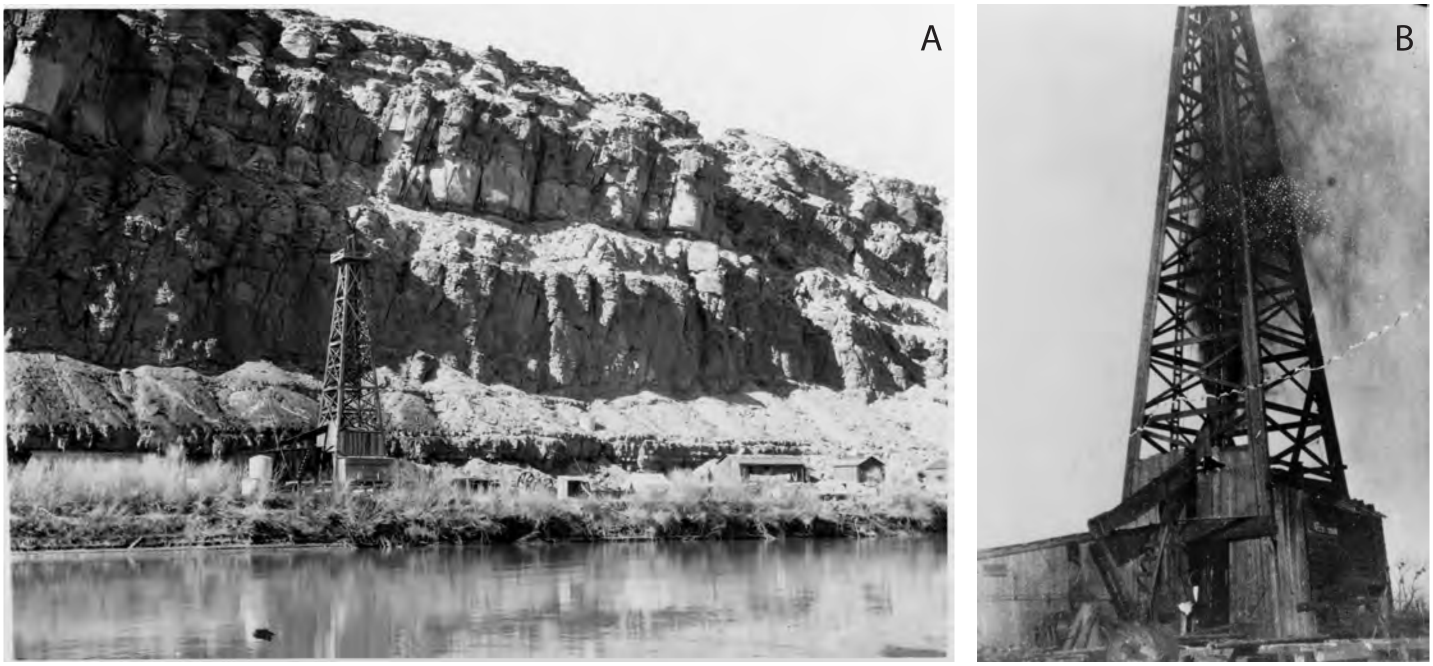

Figure 1. Midwest Exploration and Utah Southern No. 1 Shafer well, drilled in 1924. (A) View across the Colorado River. The cable-tool rig was floated down the river from the town of Moab. (B) The well blew out after encountering gas at 2028 feet (618 m) in the Cane Creek shale and the rig caught on fire and was destroyed. Courtesy of the Utah Division of State History and the Utah State Historical Society.

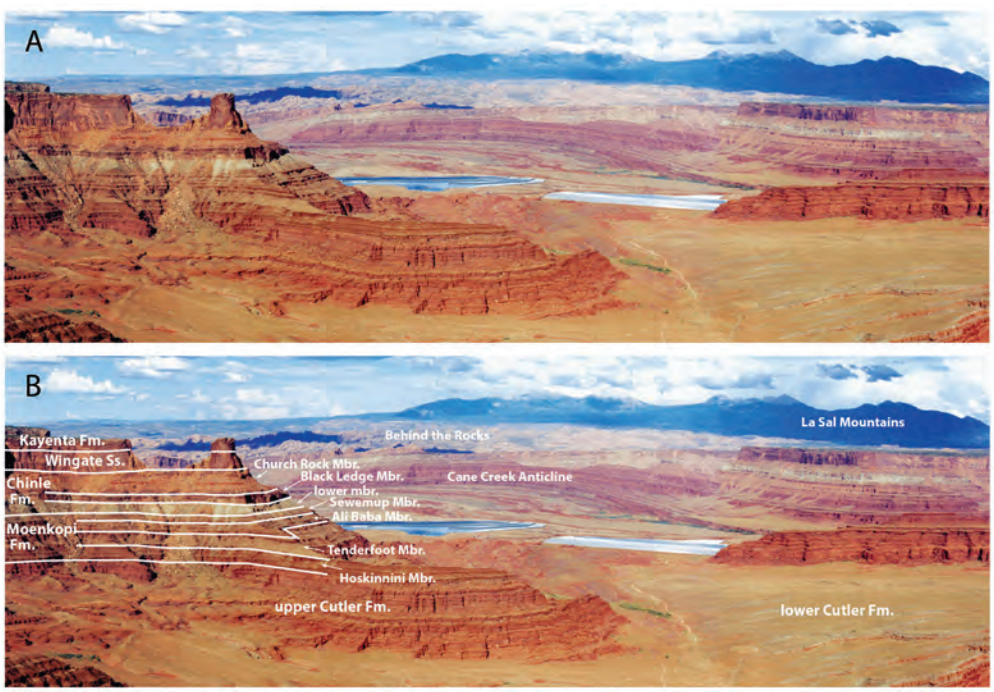

Figure 2. Panorama of the Cane Creek anticline (middle ground); view east from Dead Horse Point State Park overlook; un-annotated (A) and annotated (B). Note solar evaporation ponds in front of the fold and the jointed Jurassic Navajo outcrops of the Behind the Rocks area in front of the La Sal Mountains in the distance. The Lower Jurassic Kayenta Formation forms the rim of the overlook at the Point followed down section by the Wingate, Chinle, Moenkopi, and Cutler Formations at the base. Modified from Doelling and others (2010).

the Colorado River from the town of Moab, Utah. However, after encountering oil and gas in the Cane Creek shale of the Pennsylvanian (Desmoinesian) Paradox Formation, the well blew out at 2028 feet (618 m), and the rig caught fire and was destroyed (figure 1B) (Smith, 1978). Cumulative production was 1887 barrels of oil (BO) and 25,000 thousand cubic feet of gas (MCFG) before abandonment of what was called the Cane Creek oil field (Stowe, 1972). Drilling activity targeted subsidiary structures along the Cane Creek anticline again from the mid-1950s through the early 1960s leading to the discoveries in 1962 of Long Canyon and Bartlett Flat fields, with wells also targeting the Cane Creek shale (figure 3). Bartlett Flat produced 26,000 BO before salt flowage in the Paradox Formation caused the production casing to collapse around the tubing. All subsequent drilling and completion attempts similarly failed and the field was abandoned (Smith, 1983). It was not until the advent of horizontal drilling techniques and their application to Bartlett Flat field area (now called Big Flat, figure 3) in the early 1990s that the Cane Creek shale became a commercially viable drilling target and emerging unconventional oil play in the region. Total production from the Cane Creek shale is over 10 million BO from 18 fields in the Utah part of the Paradox Basin, with some wells having initial flowing potentials up to 1500 BO per day (Vanden Berg, 2021; Utah Division of Oil, Gas and Mining, 2023a).

The problems that occurred during the early drilling and completion attempts described above represented an indication that due diligence would be required if operators were to successfully find and produce oil and gas from the Cane Creek shale in the Paradox fold and fault belt. Drilling may encounter both common and unusual hazards that can significantly add to rig time and well costs: swelling clays, high porosity-permeability or fractured zones resulting in lost circulation or excessive mudcake buildup, a wide variety of lithologies (carbonates, shale, sandstone, and evaporites), and overpressured intervals (summarized in table 1).

Beginning in 2020 and into 2021, the Utah Geological Survey (UGS), Energy & Geoscience Institute of the University of Utah, and Zephyr Petroleum Company (formerly Rose Petroleum) drilled the State 16-2 research well (renamed the State 16-2LN-CC, API No. 43-019-50089, after the horizontal leg was drilled; section 16, T. 22 S., R. 17 E., Salt Lake Base Line & Meridian [SLBL&M]) (figure 3) to take core from the Cane Creek shale as part of a project to better characterize the petrographic and petrophysical properties of the reservoir, and extend the play farther north (Vanden Berg, 2021; Paronish and others, 2022; Vanden Berg and others, 2022). The State 16-2 research well, and several dry holes nearby that penetrate the stratigraphic section into the Paradox Formation, provide a wealth of drilling information about the rocks encountered and any associated hazards common to the region. In addition, drill cuttings and cores from several wells are publicly available at the UGS's Utah Core Research Center in Salt Lake City, and can be used as a further stratigraphic guide along with mudlogs, and caliper and geophysical logs (figure 4). Close-up photographs of representative cuttings of the Cretaceous Mancos Shale through the Cane Creek are included in the appendix.

As with any exploratory well targeting hydrocarbons in the Cane Creek shale, or deeper potential reservoirs (Mississippian Leadville Limestone and Devonian Elbert Formation), the wellsite geologist and mudlogger need to pay close attention to (1) the rate of penetration (ROP), (2) mud weight, (3) bit wear and number of times they have to be replaced, (4) loss of circulation, (5) unexpected and unwanted influx of reservoir fluid (oil, water, or gas) into the wellbore (referred to as a "kick") due to an underbalanced condition in which pressure inside the wellbore or bottom-hole pressure is less than formation pressure, (6) hole integrity (e.g., washouts, borehole breakouts, rugosity, deviation, excessive mudcake buildup, sticking problems), (7) increases in chloride content, (8) changes in background and trip gas, and (9) characteristics of cuttings (e.g., size and shape, lithology, hydrocarbon shows).

The goal of this paper is to de-risk wells, lower expenses, and mitigate problems before they occur by providing drilling engineers and operators the information they need to help plan for potential drilling hazards when exploring for additional commercial hydrocarbons in the Cane Creek shale and deeper targets in the fairly remote, relatively sparsely explored Paradox fold

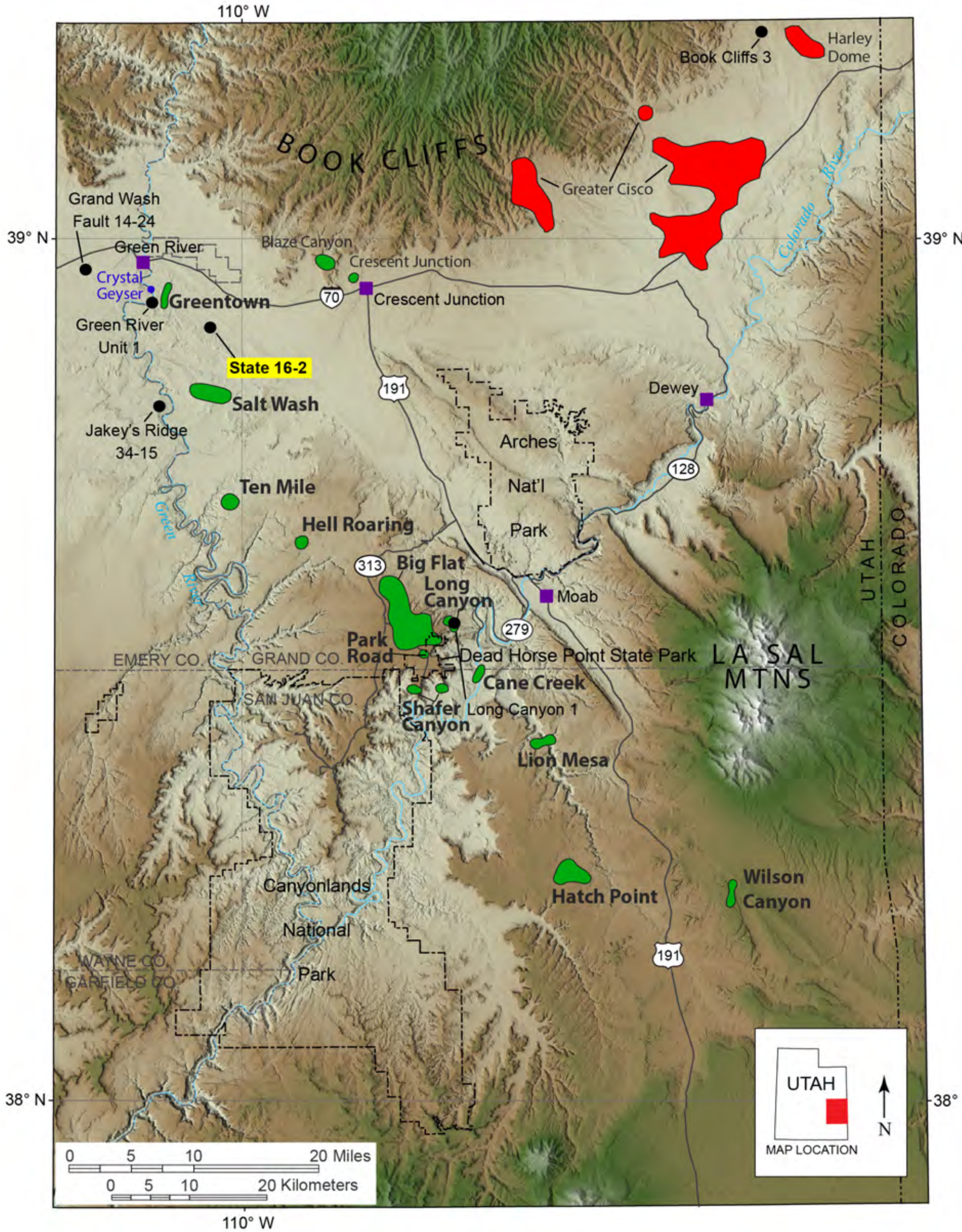

Figure 3. Location of the State 16-2 research well (section 16, T. 22 S., R. 17 E., SLBL&M, Grand County), as well as oil and gas fields in green and red, respectively (Cane Creek field names in bold), surrounding parks, towns, and highways, southeastern Utah. Black dots indicate locations of the wells from which cuttings were obtained and photographed for the appendix.

Table 1. Potential drilling hazards while targeting the Cane Creek shale in the Paradox fold and fault belt.

Formation	Thickness (ft)	Dominant Lithologies	Potential Drilling Hazards
Mancos Shale	±3800	shale	sticking & bit balling due to swelling clays, washouts
Naturita Formation	0–200	sandstone	possible gas in lenticular sandstone beds, water flow in porous sandstone
Cedar Mountain Fm.	80–300	mudstone, conglomerate	possible gas in lenticular sandstone beds, water flow in porous sandstone, sticking in mudstones, washouts
Morrison Formation	400–1000	mudstone, sandstone	possible gas in lenticular sandstone beds, sticking in mudstones, bit balls, washouts, sloughing, water flow in porous sandstone, radioactive zones
Summerville Fm.	5–400	siltstone, mudstone	washouts
Curtis Formation	0–230	sandstone	loss of circulation in porous units
Entrada Sandstone	60–500	sandstone	well deviation due to jointing & contorted bedding, loss of circulation or water flow in porous units
Carmel Formation	20–300	sandstone, siltstone, mudstone	washouts
Navajo Sandstone	0–510	sandstone	loss of circulation or water flow in porous units, thin limestone beds, possible carbon dioxide
Kayenta Formation	60–360	sandstone	loss of circulation in porous units
Wingate Sandstone	70–450	sandstone	loss of circulation or water flow in porous units & jointing & fracture zones
Chinle Formation	150–630	mudstone, shale	sticking and bit balling due to swelling clays, washouts, drilling problems due to contorted bedding, radioactive zones
Moenkopi Formation	240–910	sandstone, siltstone, mudstone	washouts, well deviation issues
Black Box Dolomite	60–160	dolomite, limestone	loss of circulation in fractured zones
White Rim Ss.	0–500	sandstone	loss of circulation & sticking due to mudcake buildup in porous units, water flow in porous units
Organ Rock Fm.	0–300	sandstone, shale	washouts
Elephant Canyon Fm.	1000–1200	sandstone, limestone	loss of circulation in porous & fractured zones, excessive bit wear due to chert
Cutler Formation	900–1200	arkosic sandstone, siltstone, limestone	loss of circulation or water flow in porous & fractured zones
Honaker Trail Fm.	1600–5000	sandstone, limestone, siltstone	loss of circulation or water flow in porous & fractured zones, excessive bit wear due to chert, possible gas-bearing zones
Paradox Formation	±14,000	sandstone, siltstone, limestone & dolomite mudstone, shale, anhydrite, halite	washouts, sticking, salt flowage, gas kicks, overpressure, loss of circulation due to hydrofracturing by weighted drilling fluid, difficulties drilling horizontally in complex geology

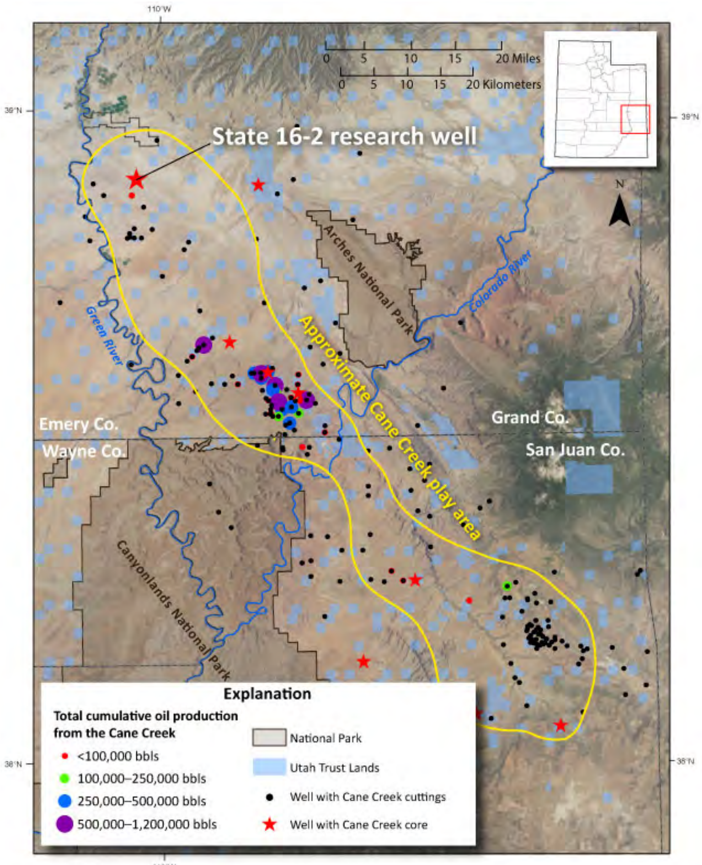

Figure 4. Map of the Cane Creek shale play area showing locations of wells with drill cuttings and cores from the Cane Creek publicly available at the Utah Geological Survey's Utah Core Research Center. Cumulative Cane Creek oil production in barrels (bbls) also shown. After Vanden Berg (2021).

and fault belt. Using this report, and the lessons learned from drilling the State 16-2 research well, will hopefully result in future wells successfully reaching the objective Cane Creek shale reservoirs with minimal unexpected cost and downtime while creating the safest work environment possible for the rig crew and other wellsite personnel.

OVERVIEW OF THE CANE CREEK SHALE PLAY

Paradox Basin

The Paradox Basin is an elongate, northwest-southeast-trending, evaporite-rich basin that developed predominately during the Pennsylvanian, about 323 to 299 million years ago (Ma). The dominant structural features in the basin are surface anticlines that extend for miles in the northwesterly trending fold and fault belt (figure 5). During Cambrian through Mississippian time, this region, as well as most of eastern Utah, was the site of typical marine deposition represented by a relatively thin stratigraphic section on a craton with thicker deposits in a miogeocline to the west (Hintze and Kowallis, 2021). However, major changes began in the Pennsylvanian when a pattern of basins and fault-bounded uplifts developed from Utah to Oklahoma. One result of this tectonism was the uplift of the Ancestral Rockies in the western United States, including the Uncompahgre Highlands (uplift) in eastern Utah and western Colorado.

The Uncompahgre Highlands are bounded along their southwestern flank by a stack of large, basement-involved, high-angle, reverse faults identified from seismic surveys and exploration drilling (Frahme and Vaughn, 1983; Kluth and DuChene, 2009). As the highlands rose, an accompanying depression, or foreland basin, formed to the southwest—the Paradox Basin. Rapid basin subsidence, particularly during the Pennsylvanian and continuing into the Permian, accommodated large volumes of evaporitic and marine sediments that intertongue with non-marine arkosic material shed from the highland area to the northeast (Hintze and Kowallis, 2021). Deposition in the basin produced the thick cyclical sequence of carbonates, evaporites, and organic-rich shale that compose the Paradox Formation.

The Paradox Basin can generally be divided into three areas: the Paradox fold and fault belt in the north, the Blanding sub-basin in the south-southwest, and the Aneth platform in the southernmost part in Utah (figure 5). The area now occupied by the Paradox fold and fault belt was also the site of greatest Pennsylvanian-Permian subsidence and salt deposition. The area was created during the Late Cretaceous through Quaternary by a combination of (1) reactivation of basement normal faults, (2) additional salt flowage followed by dissolution and collapse, and (3) regional uplift (Trudgill and Paz, 2009; Doelling, 2010).

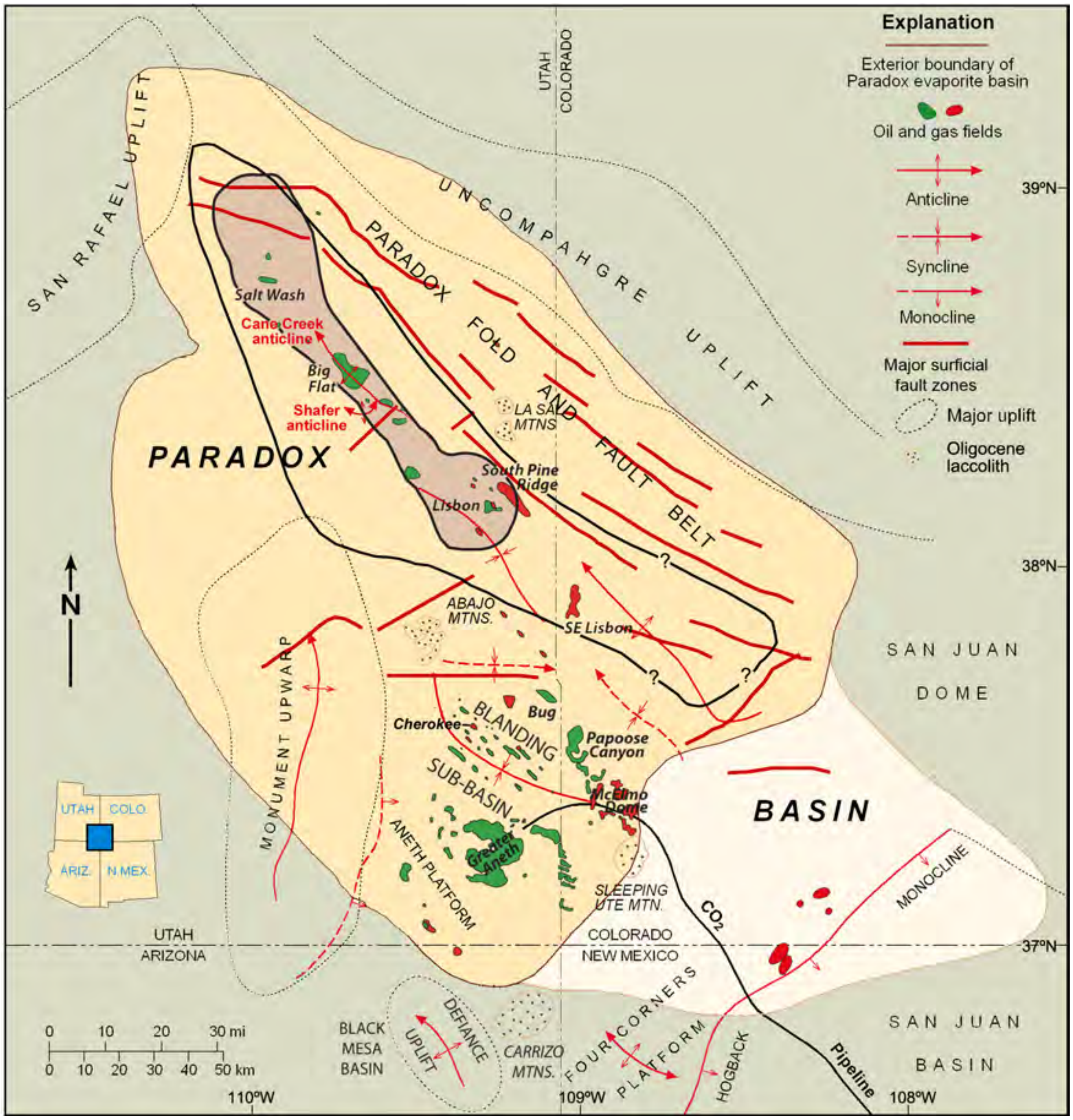

Figure 5. Oil and gas fields in the Paradox Basin of Utah, Colorado, Arizona, and New Mexico. Modified from Harr (1996) and Wood and Chidsey (2015). The extent of the Pennsylvanian Paradox Formation is shown in light orange; the Cane Creek shale play area within is light brown. From Chidsey and Eby (2017).

Stratigraphy and Thickness

The Paradox Formation is part of the Pennsylvanian Hermosa Group (figures 6 and 7). The 500- to 5000-foot-thick (150–1500 m) Paradox Formation is overlain by the Honaker Trail Formation and underlain by the Pinkerton Trail Formation (Hintze and Kowallis, 2021). The Cane Creek shale generally ranges from 0 to about 200 feet (0–60 m) thick in the region. Within the main Cane Creek play "fairway" (figures 4 and 5), the thickness is 60 to 170+ feet (18–52+ m) (figure 8). The depositional strike of the Cane Creek is north-northwest to east-southeast with a thinner section through the central part of the trend that thickens to the northeast and southwest (figure 8). However, farther to the southwest it thins where it laps onto the lower Paradox member or the Pinkerton Trail Formation (Carney and others, 2014; Morgan and others, 2014). Thickness variations are the results of diapiric salt movement, depositional thickening on the downthrown side of faults, or depositional thinning on the upthrown side of faults or over subtle, early structural highs (Morgan, 1992).

Depositional Environment

Throughout the Pennsylvanian, the Paradox Ba-

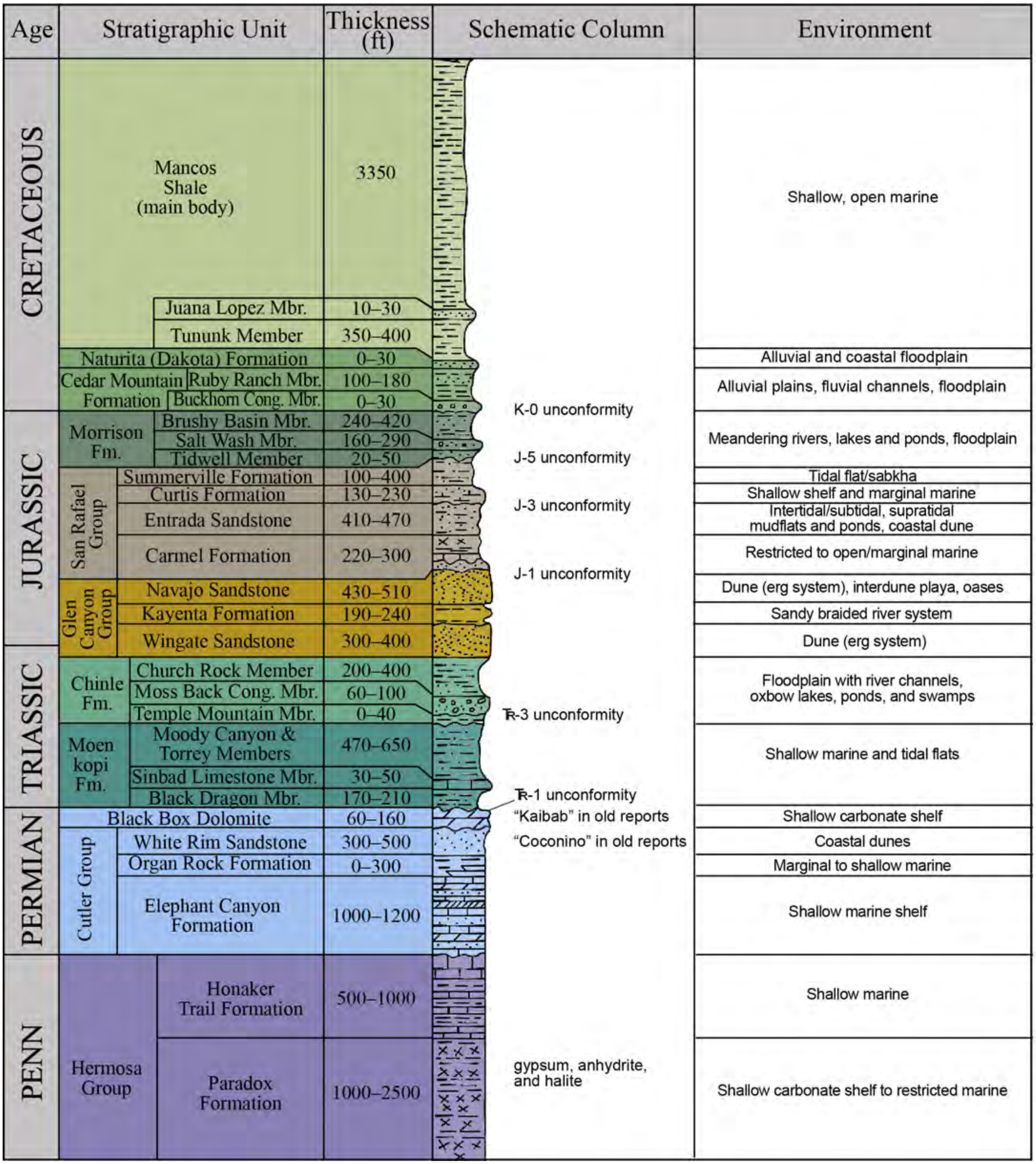

Figure 6. Stratigraphic column in the northern part of the Paradox fold and fault belt of Utah. Modified from Hintze and Kowallis (2009).

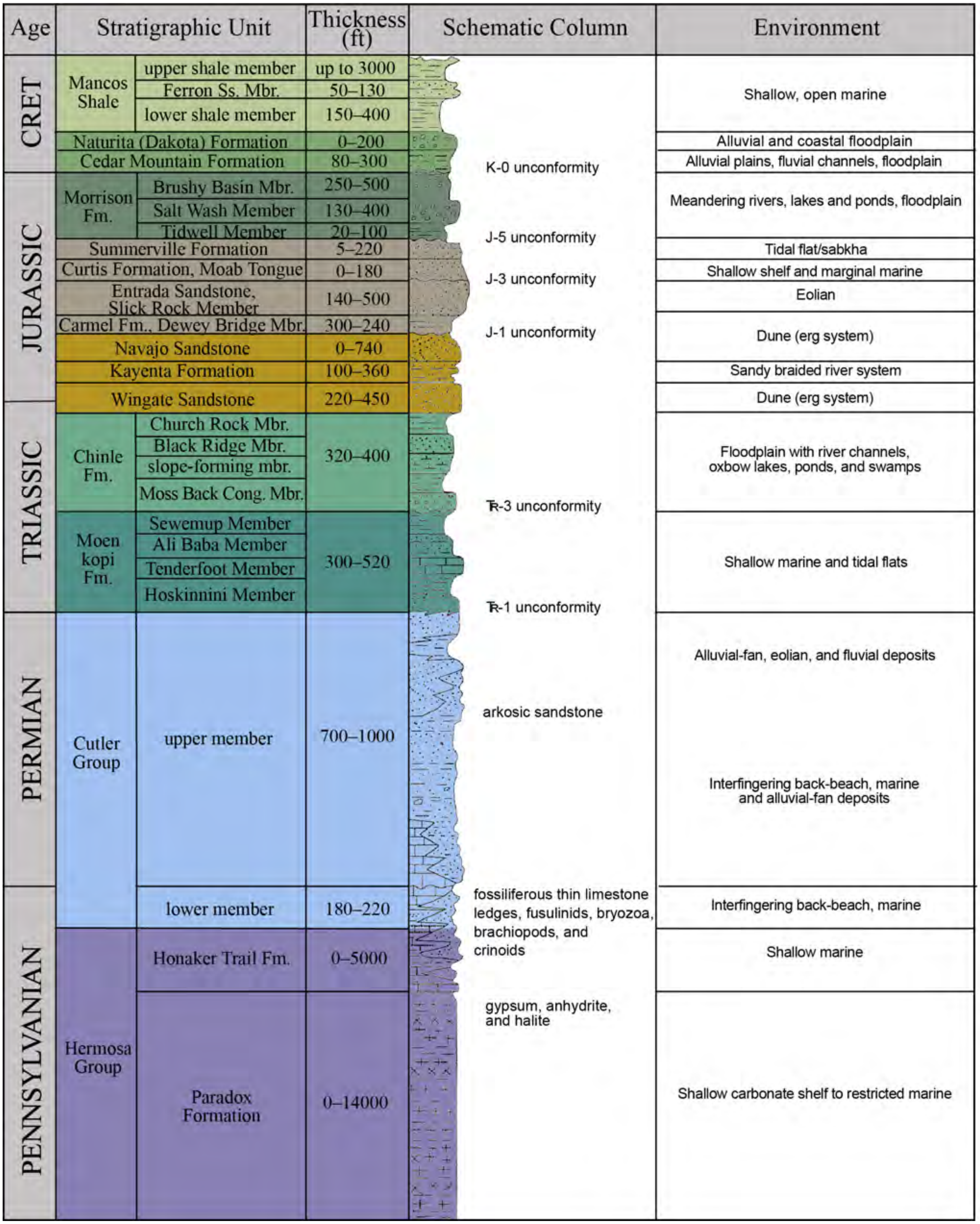

Figure 7. Stratigraphic column in the central part of the Paradox fold and fault belt of Utah near Big Flat field, and Canyonlands and Arches National Parks. Modified from Hintze and Kowallis (2009) and Doelling and others (2010).

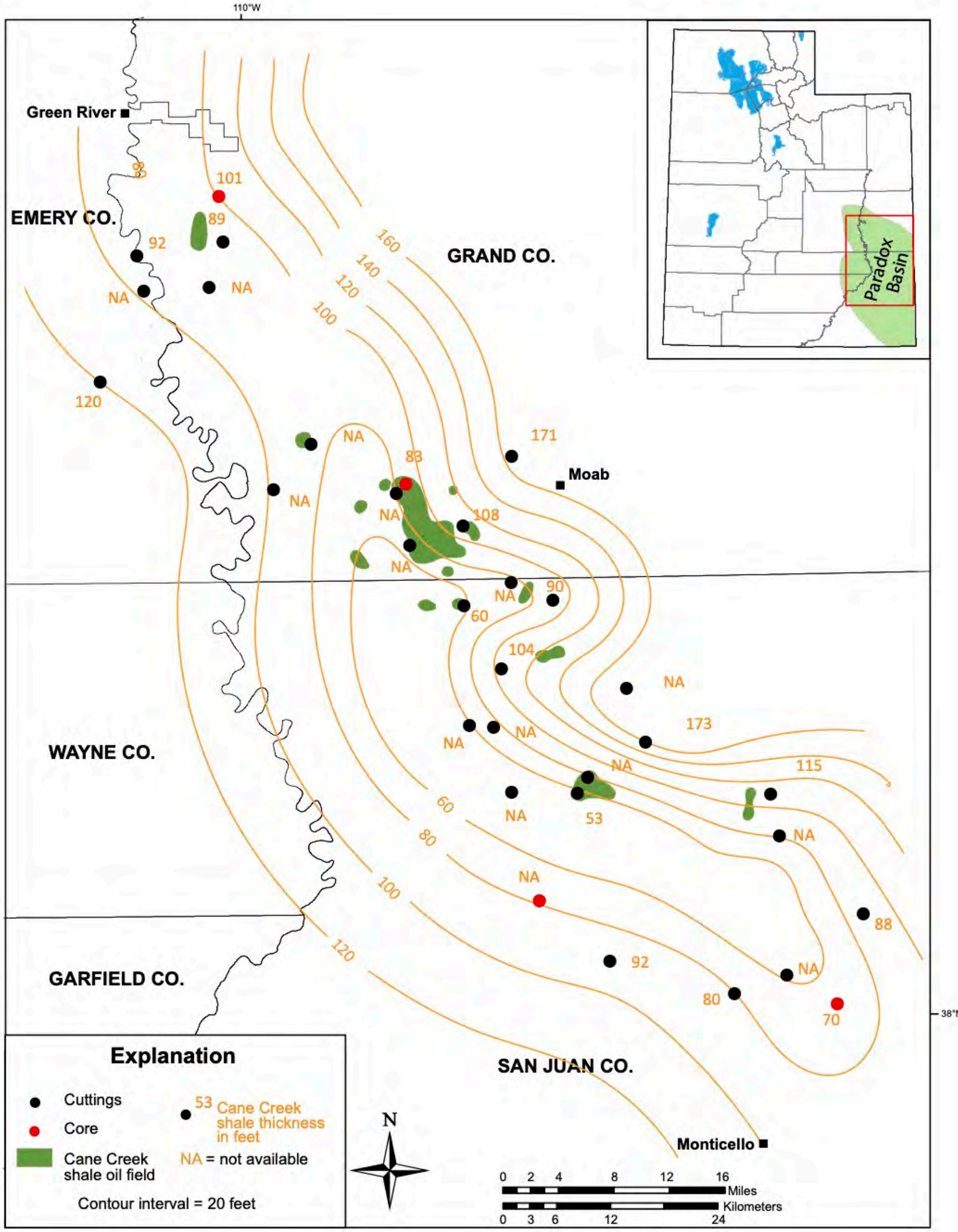

Figure 8. General thickness of the Cane Creek shale using selected wells with cuttings (black dots) and cores (red dots). Other wells not shown are scattered throughout the region or concentrated in the producing oil fields, and if used as data points would likely result in a map showing additional thick and thin areas related to salt flowage, faulting, or depositional thinning over minor early structural highs. After Chidsey and Eby (2017).

sin had subtropical, dry climatic conditions (Peterson and Hite, 1969; Heckel, 1977; Parrish, 1982; Blakey and Ranney, 2008). During transgressions, open-marine waters flowed across a shallow cratonic shelf into the basin through up to four postulated marine access ways (Fetzner, 1960; Ohlen and McIntyre, 1965; Hite, 1970). Periodic decreased water circulation resulted in deposition of thick salts (halite with sporadic thinner beds of potash and magnesium salts) and anhydrite in the northern and northeastern part of the basin.

Cyclicity during Paradox Basin deposition was primarily controlled by glacio-eustatic sea-level fluctuations. These sea-level cycles were also influenced by (1) regional tectonic activity and basin subsidence (Baars, 1966; Baars and Stevenson, 1982), (2) proximity to basin margin (Hite, 1960; Hite and Buckner, 1981), (3) climatic variation and episodic blockage of open marine-water access ways (Fetzner, 1960; Ohlen and McIntyre, 1965; Hite, 1970), and (4) fluctuations in water depth and water energy (Peterson and Ohlen, 1963; Peterson, 1966; Hite and Buckner, 1981; Heckel, 1983).

The Cane Creek shale generally records a low-energy environment varying between aerobic to dysaerobic and occasionally anoxic conditions (for thin, organic-rich black shale intervals). Water depths were probably variable, ranging from below fair-weather and storm wave base for organic shales to relatively shallow to near exposure for the siltstones, sandstones, limestones, finely crystalline primary or very early diagenetic dolomites, and nodular anhydrites and other evaporites (Chidsey and Eby, 2017).

Petroleum Geology

Structure and Trapping Mechanisms

Structurally the Cane Creek shale is deepest in the northern part of the play area, -2400 to -4000 feet (-730 to -1200 m) below sea level (figure 9). The Cane Creek shallows near the southwestern edge/shelf of the basin. Petroleum is usually trapped in fractured sandstones and dolomites on subtle, seismically defined subsidiary structural noses and fault closures along major southeast-northwest-trending, salt-cored regional anticlines, or on the crests of other smaller, local anticlinal closures (Smith, 1978; Morgan, 1992; Grove and others, 1993; Chidsey and others, 2016; Chidsey and Eby, 2017). Salt movement along zones of weakness or areas of low confining pressure formed large folds such as the Cane Creek and Shafer anticlines (figure 2). Second-order folds caused by salt flowage are aligned directly over local bulges or pillows of Paradox salt and the overlying rocks are fractured (Lorenz and Cooper, 2009). Fracture data from oriented cores in the Cane Creek show regional, northwest to southeast and northeast to southwest, near-vertical, open, extensional fracture systems that are not significantly affected by orientations of localized folds (Morgan and others, 1991, 2014; Grove and Rawlins, 1997). Hydrocarbon production from the Cane Creek is not limited to the crests of anticlines but also from structurally high positions on upthrown fault blocks and on the downthrown side of faults. Plunging noses without apparent four-way closure produce from the Cane Creek as well as where extensive fracturing exists.

Hydrocarbon Source and Seals

Hydrocarbons in Paradox Formation reservoirs are thought to be generated from source rocks within the formation itself. Organic-rich sapropelic shale in the Cane Creek and other organic-rich shales are well-established source rocks for hydrocarbon production in the Paradox Basin (Hite and others, 1984; Nuccio and Condon, 1996). The average total organic content of the black shale in the Cane Creek is 15% with some samples containing up to 28% (Grummon, 1993; Morgan and others, 2014). Kerogens are oil-prone types I and II; maturity (based on T_{max}) and production indices from three cores place the Cane Creek in mostly the oil window (Morgan and others, 2014; Chidsey and Eby, 2017). The Cane Creek shale began to generate hydrocarbons within the Paradox fold and fault belt from 270 to 239 Ma (Middle Permian–Middle Triassic) (Rasmussen and Rasmussen, 2009). Expulsed hydrocarbons migrated through dolomite, sandstone, and other porous lithologies along regional northwest-trending folds, faults, and fracture zones.

The upper and lower seals for the reservoir units in the Cane Creek shale are provided by anhydrite and

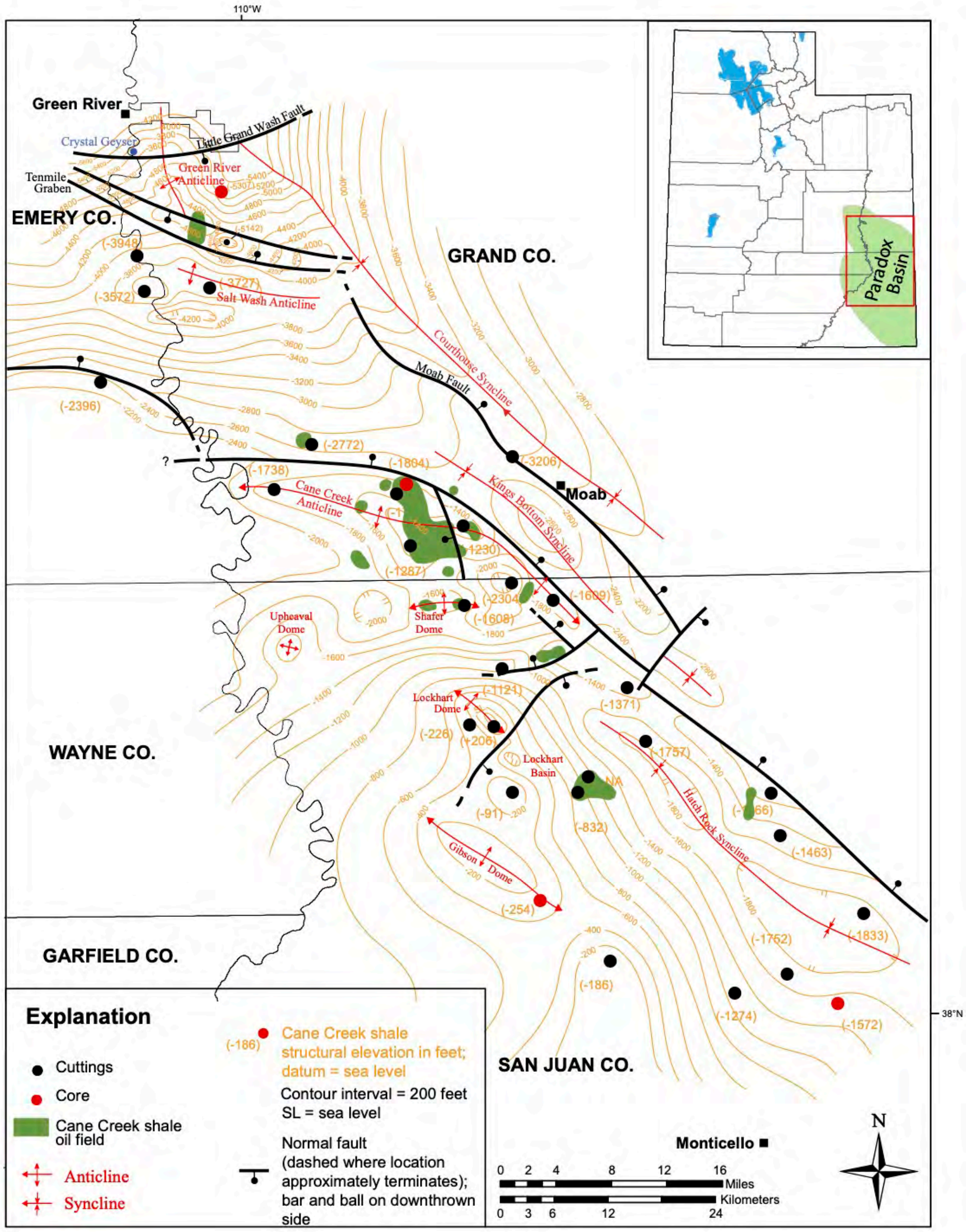

Figure 9. Generalized structural map on top of the Cane Creek shale. The map was created by combining published oil field reservoir maps (Peterson, 1973; Quigley, 1983; Grove and others, 1993; Morgan, 1994) and regional geologic maps and cross sections (Gualtier, 1988; Doelling, 2002, 2004; Doelling and others, 2015) without the benefit of seismic data. Major folds and faults projected from surface expressions may die out in Paradox salt zones above the Cane Creek, whereas basement-involved structures may be present at the Cane Creek level where they can best be detected by seismic. The map also shows selected wells with cuttings (black dots) and cores (red dots). Other wells not shown are scattered throughout the region or concentrated in the producing oil fields, and if used as data points would likely result in a map with greater structural complexity. Additional faults and folds are present but are not shown given the small scale of the map. After Chidsey and Eby (2017).

halite beds. Lateral seals are permeability barriers in unfractured rock. Thus, the Cane Creek serves as the source and seal, as well as the oil reservoir rock.

Reservoir Properties

The Cane Creek shale in the Big Flat field area (figure 3) exhibits a net-pay thickness of 25 to 30 feet (7–9 m). Dolomites and sandstones have been the main targets of horizontal drilling. Productive zones have porosity (matrix and fractures) up to 15% (Grove and others, 1993; Morgan and others, 2014). Pore types in dolomite beds are predominantly intercrystalline and microbial constructional pores, microporosity, and minor interparticle porosity (Chidsey and Eby, 2017). Sandstones and siltstones exhibit intergranular porosity. These lithologies can also contain significant microporosity and fracture porosity, including microfractures (Gathogo and others, 2022). Microfractures resulted from internal hydrocarbon generation (Fritz, 1991). Potential oil-prone areas in the Cane Creek play were identified based on hydrocarbon shows in porous lithologies recognized using epifluorescence microscope techniques on cuttings, core chips, and uncovered thin sections (Chidsey and Eby, 2017).

Matrix permeability in the Big Flat area (figure 3) from Horner plots is less the 0.1 millidarcies (mD), but ranges from 39 to 400 mD with fractures (Grove and others, 1993). The larger tectonic fractures may account for most of the permeability, but the microfractures probably provide most of the fracture porosity in the reservoir. Core analysis from the productive interval in the Cane Creek No. 26-3 well (section 26, T. 25 S., R. 19 E., SLBL&M) in Big Flat field (figure 3), Grand County, Utah, showed sandstones, argillaceous sandstones, and dolomitic argillaceous siltstones contain 5% to 12% porosity, and permeability ranging from 0.002 to 36 mD; porosity and permeability in silty dolomite was 7% and 0.004 mD, respectively (Core Laboratories, Inc., 2013; Morgan and Stimpson, 2017).

Initial water saturations are estimated at 10% for the fractured Cane Creek shale. The reservoir temperatures range from 119° to 132°F (48°–56°C) and the reservoir drive mechanism is solution gas (Grove and others, 1993). The Cane Creek is highly overpressured in the Big Flat area (but not everywhere in the Cane Creek play area), which is probably the result of hydrocarbon generation between very impermeable upper and lower anhydrite and halite seals. The sedimentary sequence above the salt is lower pressure due to exposure along the canyons of the Colorado River (Morgan and Stimpson, 2017). Fluid gradients exceed 0.85 to 0.94 pounds per square inch (psi)/foot (19.23–21.27 kPa/m); the initial reservoir pressures average 6650 psi (45,850 kPa) (Grove and others, 1993; Morgan and Stimpson, 2017).

Horizontal Drilling

Natural fractures and the need to drill through them, organic-rich shale beds, overpressure, low permeability, thin intervals, and the widespread stratigraphic presence of the Cane Creek shale are characteristics ideal for horizontal drilling, which is required for commercial hydrocarbon production. Fracture orientation, critical for determining horizontal drilling directions, are often difficult to predict. Once identified, vertical to near-vertical natural fractures in the Cane Creek can allow economic oil production without the need for hydraulic fracturing unlike the unconventional oil plays in the Permian Basin of West Texas and Williston Basin of North Dakota (Vanden Berg, 2021). The relatively thin Cane Creek shale zone, averaging about 100 feet (30 m) thick or less, is bounded by salt. Fractures created by hydraulic fracturing in the Cane Creek would likely penetrate the salt beds above and below, possibly mobilizing the salt that could plug up the existing and new fractures, thus preventing fluid flow from the reservoir into the wellbore (Vanden Berg, 2021).

Drilling horizontally greatly increases the probably of intersecting vertical to near-vertical open fractures in the Cane Creek shale. The direction of the horizontal wellbore is based on the dip of the structure being tested, predicted fracture orientation, the available surface location, and lease and reservoir drainage models (Morgan and Stimpson, 2017). The orientation and length of each Cane Creek horizontal well are different and can result in varying amounts of oil production. Some short-radius laterals (100 to 800 feet [30–250 m]) parallel to the regional fracture trends have produced more oil than long-reach laterals (greater than 2000 feet

[600 m]) drilled in a similar direction or perpendicular to the fracture trend (Morgan and Stimpson, 2017; Islam and Hossain, 2020).

Finally, horizontal drilling in the Cane Creek shale, or other Paradox clastic cycles, have presented additional hazards and problems over those occurring in vertical wells. These must be anticipated and overcome to achieve commercial Cane Creek oil production.

REGIONAL STRATIGRAPHY AND DRILLING HAZARDS

Wells, such as the State 16-2 research well, targeting the Cane Creek shale in the Paradox fold and fault belt may penetrate a stratigraphic section ranging from the Cretaceous Mancos Shale or older formations to the Pennsylvanian Paradox Formation (figures 6 and 7). Drilling hazards may occur before reaching or within the Cane Creek shale. This region is particularly unique in that all of the formations encountered during drilling, with the exception of the Paradox, are exposed at the surface within 50 miles (80 km) of any well (figure 10). This affords the opportunity to visit outcrop sites before and while drilling to better understand the stratigraphic section, the physical characteristics of the rocks, and problems that may occur.

Many drill sites in the region may have a relatively thin veneer of unconsolidated Quaternary deposits overlying the bedrock geology. These deposits typically include alluvium and colluvium, older alluvium, and eolian sands. Thick eolian sands could present initial drilling problems due to sloughing and require setting conductor pipe to protect the integrity of the shallow wellbore.

The bedrock stratigraphic section, from the Mancos Shale through the Paradox Formation, is described below based on geologic maps (Hintze, 1980; Gualtieri, 1988; Hintze and others, 2000; Doelling, 2002, 2004; Doelling and others, 2015) and research in the region published by various workers and analysis of core and well cuttings (Nielsen and others, 2013; Chidsey and Eby, 2017; Morgan and Stimpson, 2017; Jagniecki and others, 2021). These descriptions include the age, general lithology (with close-up photographs of typical well cuttings in the appendix), thickness ranges, and the nature of the contacts with overlying and underlying formations. The descriptions are followed by potential drilling hazards that may be encountered while drilling through the respective formations. However, it is important to note that there is always the possibility of new unforeseen problems, especially when drilling in the Paradox fold and fault belt where wells penetrating the Paradox Formation are relatively sparse.

Cretaceous Mancos Shale

Lithology, Thickness, and Contacts

The shallow open marine, Upper Cretaceous Mancos Shale is the youngest formation exposed in the Paradox fold and fault belt and is divided into the upper main body, Juana Lopez Member, and basal Tununk Member within the region (Birgenheier and others, 2015; Hintze and Kowallis, 2021) (figure 6). For the most part these members are soft and deeply weathered, forming slopes and low, rounded hills devoid of vegetation; the State 16-2 research well spudded in the Tununk Member of the Mancos. The Tununk and main body have very similar characteristics in outcrop and drill cuttings consisting of light to dark gray, medium to dark brown or black shale, shaley siltstone, and mudstone (appendix, figure A1). Shale is fissile, breaking into platy, angular fragments. Some shale beds are bentonitic, providing regional correlation markers. Bedding is indistinct or even, thin, and laminated with a few siliceous zones. The Juana Lopez is a light to dark gray, organic-rich, thin- to medium-bedded, heterolithic zone of shale and shaly siltstone.

The Mancos Shale is about 3800 feet (1160 m) thick; the amount of section that would be penetrated by most new wells in the northern part of the Paradox fold and fault belt is significantly less. The Juana Lopez and Tununk Members range in thickness from 10 to 30 feet (3–9 m) and 350 to 400 feet (107–120 m), respectively (Hintze and Kowallis, 2021).

Drilling Hazards

The Mancos Shale consists of beds composed of a

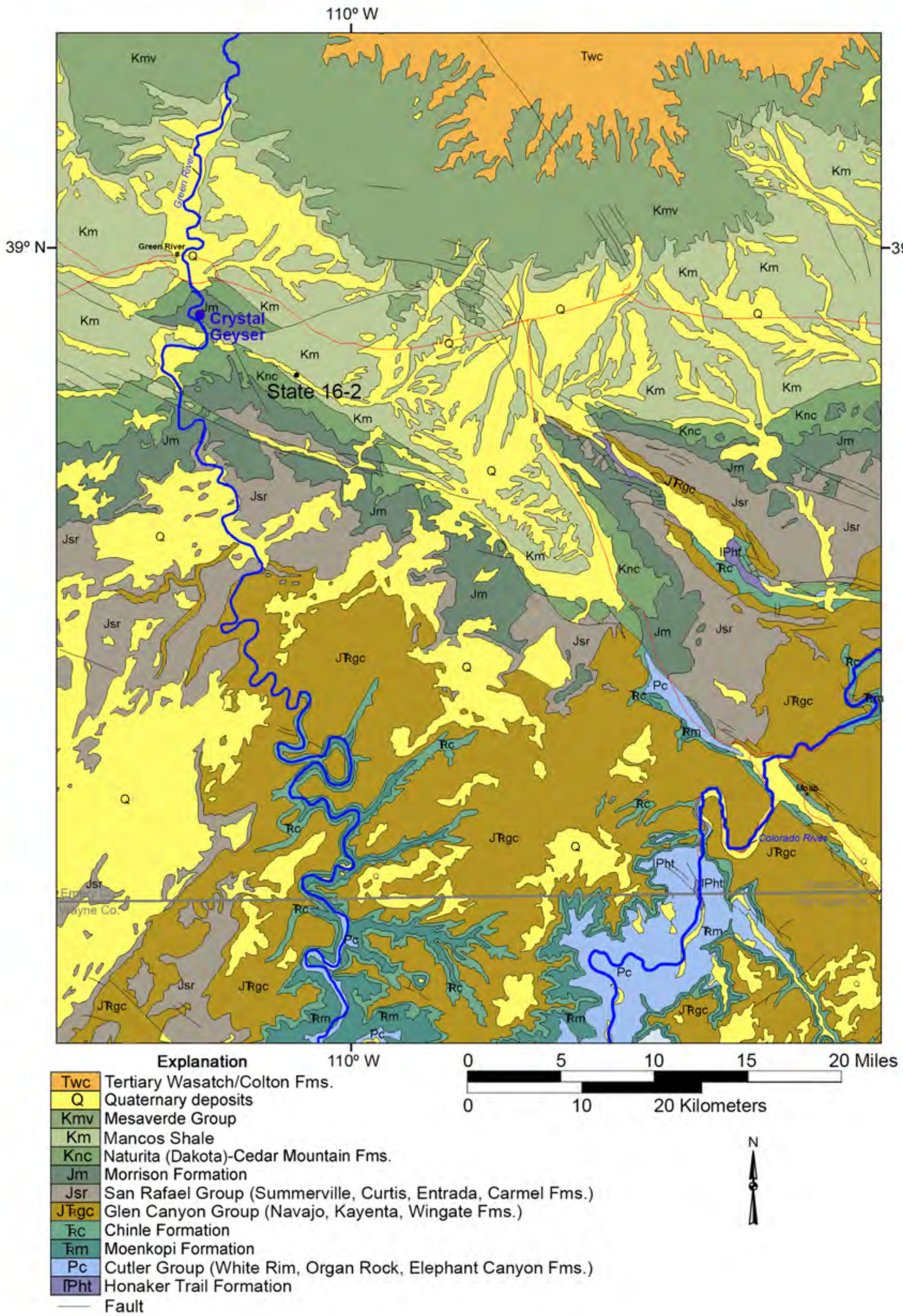

Figure 10. Geologic map of part of the Paradox fold and fault belt and surrounding region of east-central Utah. Note the locations of the State 16-2 research well and Crystal Geyser. Modified from Hintze and others (2000).

variety of clays and a number of bentonite beds that can swell causing sticking problems and bit balling while drilling. Bit balling is a condition that arises when clays stick to the drill bit and form a ball. A balled-up bit can reduce the ROP and torque on the bit (McCoremick, 2015). In addition, like all shale beds, washouts can be a major wellbore problem, especially when the hole size is large during the initial phase of drilling. Conductor pipe is often set in the underlying Naturita Formation.

Cretaceous Naturita (Dakota) Formation

Lithology, Thickness, and Contacts

The Upper Cretaceous Naturita Formation (formerly called the Dakota) unlike other formations is not widespread. The Naturita represents an alluvial and coastal floodplain environment and consists of light yellow, tan, yellow-brown, orange-gray, light tan-gray, or light brown sandstone (appendix, figure A2), conglomeratic sandstone, conglomerate, shale, and coal, particularly east of the San Rafael Swell (Doelling, 2002; Kirschbaum and Schenk, 2011; Doelling and others, 2015). Sandstones are friable, quartzitic, fine to coarse grained, and moderately to well sorted. Conglomerates contain rounded to sub-rounded pebbles of chert and quartzite. Sandstones and conglomerates are thin to thick bedded and cross-stratified; some ripple and convolute bedding is also present. The upper part of the Naturita contains lenticular sandstone beds, 5 to 12 feet (1.5–3.7 m) thick and encased in mudrock (Kirschbaum and Schenk, 2011). Shale beds are often the only rocks that represent the Naturita section.

The Naturita Formation is 0 to 200 feet (0–60 m) thick (Hintze and Kowallis, 2021) (figures 6 and 7). The contact with the conformable overlying Mancos Shale is defined by the first absence of deeper marine shale (Molenaar and Cobban, 1991).

Drilling Hazards

Low-permeability lenticular sandstone beds of the Naturita Formation produce gas in small combination stratigraphic/structural traps at Greater Cisco and other fields along the northwest-plunging Uncompahgre uplift (figure 3). Although gas in similar sandstone beds is not anticipated in wells drilled to the west in the northernmost part of the Paradox fold and fault belt, the possibility does exist for a gas kick. Water flows from the Naturita are unlikely in areas where it outcrops but are possible elsewhere. The water that is present in the formation may potentially be fresh depending on the hydrodynamics of the aquifer system.

Cretaceous Cedar Mountain Formation

Lithology, Thickness, and Contacts

The Lower Cretaceous Cedar Mountain Formation was deposited on alluvial plains, in meandering channels and floodplains. It is divided into two members along the western flank of the San Rafael Swell and to the east (figure 6): the Ruby Ranch and the basal Buckhorn Conglomerate (Kirkland and others, 2016). In outcrop and cuttings, the Ruby Ranch Member consists of subtle bands of dark gray to dark purplish-gray mudstone and tan to gray sandstone (appendix, figure A3) (Doelling, 2002; Doelling and others, 2015; Kirkland and others, 2016). Mudstone is clayey and silty with local lenticular sandstone beds. Sandstone is fine grained to pebbly, poorly sorted, trough cross-stratified, and discontinuous, and usually occurs in the upper half of the section. The Ruby Ranch is medium to thick bedded. The Buckhorn Conglomerate is discontinuous and consists of gray to dark brown conglomerate to conglomeratic sandstone having subordinate amounts of sandstone and mudstone. Pebbles and cobbles are composed of poorly to moderately sorted, sub-angular to well-rounded clasts of white quartzite, and black, brown, light brown, and light gray chert. Conglomerate beds are either clast supported or supported by a matrix of clay or medium- to coarse-grained sandstone. Bedding is lenticular, thick to massive, trough cross-stratified, and generally fines upward.

Regionally, the Cedar Mountain Formation ranges from 80 to 300 feet (24–90 m) thick (Hintze and Kowallis, 2021); in the northern Paradox fold and fault belt, the Ruby Ranch and Buckhorn Conglomerate Members range in thickness from 60 to 130 feet (18–40 m) and 0 to 80 feet (0–24 m), respectively (Kirkland and others, 2016). The contact between the Cedar Mountain and the underlying Upper Jurassic Morrison Formation is difficult to recognize when the Buckhorn Conglomerate Member is absent and thus the two formations are mapped together in the subsurface. In San Rafael Swell outcrops, this situation places the Ruby Ranch Member of the Cedar Mountain over the Brushy Basin Member of the Morrison Formation—both create colorfully banded steep slopes and badland topography. However, the Cedar Mountain has (1) a more drab, variegated color, (2) less smectite clay, (3) the presence of polished chert pebbles (gastroliths), (4) abundant carbonate nodules, and (5) a thick paleosol at the base (Kirkland and Madsen, 2007). The contact with the overlying Naturita Formation is an unconformity with about 2 feet (0.6 m) of relief in some areas (Doelling and others, 2009).

Drilling Hazards

Like the Naturita Formation, low-permeability lenticular sandstone beds are present in the Cedar Mountain Formation and also produce gas in small stratigraphic/structural traps in many fields along the Uncompahgre uplift (figure 3). The Naturita and Cedar Mountain are also often mapped together in the subsurface and the production is commingled. Again, gas in these sandstones is not anticipated in wells drilled in the northern part of the Paradox fold and fault belt, but the possibility does exist for a gas kick. In addition, much of the Cedar Mountain Formation consists of mudstone beds that can washout and/or cause sticking problems while drilling. Water flows from the Cedar Mountain Formation, like the overlying Naturita Formation, are unlikely in areas where it outcrops. The water that is present in the Cedar Mountain may also be fresh.

Jurassic Morrison Formation

Lithology, Thickness, and Contacts

The Upper Jurassic Morrison Formation, world famous for its dinosaur fossils, was deposited in meandering rivers, lakes and ponds, and floodplains. It is divided into three members within the region, which in descending order are the Brushy Basin, Salt Wash, and Tidwell (figures 6 and 7). The Brushy Basin Member consists of purple, green, red, yellow, maroon, bluish-gray, gray, and white-colored bands of mudstone, claystone (often bentonitic/smectitic), and siltstone interbedded with white, gray, and light brown sandstone with subordinate limestone and conglomerate (Gualtieri, 1988; Doelling, 2002; Doelling and others, 2015). The Salt Wash Member consists of red, gray, purple, or brown mudstone and siltstone with a few sandy limestone beds and light yellow-gray, light gray to gray sandstone (appendix, figure A4), conglomeritic sandstone, and conglomerate (Doelling and others, 2015). Sandstone beds are fine to coarse grained, sub-angular to well rounded, arkosic or quartzose, and contain well-displayed trough cross-stratification. Conglomerate is composed of poorly sorted, sub-angular to well-rounded chert and quartzite ranging in size from pebbles to cobbles in a matrix of coarse quartz sand. The Tidwell Member consists of lavender, maroon, red, red-brown, or light gray interbedded siltstone, shale, limestone (marl), sandstone, and gypsum. The Morrison was a major target and producer of uranium during the boom of the 1950s.

The Morrison Formation ranges in thickness from 400 to 1000 feet (120–300 m): the Brushy Basin Member is 240 to 500 feet (73–152 m), the Salt Wash Member is 130 to 400 feet (40–122 m), and the Tidwell Member is 20 to 100 feet (6–30 m) (Hintze and Kowallis, 2021). The Brushy Basin is separated from the overlying Lower Cretaceous Cedar Mountain Formation by the K-0 unconformity (Pipiringos and O'Sullivan, 1978; Hintze and Kowallis, 2021).

Drilling Hazards

The Morrison Formation, again similar to the overlying Cedar Mountain and Naturita Formations, contains lenticular sandstone beds. These produce oil in small stratigraphic/structural traps at Greater Cisco field (figure 3). Oil and gas (including helium and carbon dioxide at Harley Dome [figure 3] within the Greater Cisco field complex [Bon, 1999; Wiseman and Eckels, 2020]) in similar Morrison sandstones is also not anticipated in new wells in the northern part of the Paradox fold and fault belt, but like the gas in the formations above the possibility does exist for a kick.

Much of the Brushy Basin Member consists of bentonitic/smectitic claystone beds that can washout and/or swell causing sticking and bit balling problems while drilling. Sloughing while penetrating the Morrison has been reported in shallow wells in the Greater Cisco field and other areas. Water flows from the Morrison are unlikely in areas where it outcrops like the overlying Naturita and Cedar Mountain Formations. The water that is present in the Morrison may be fresh. Flowing water was encountered in the lower section of the Salt Wash Member in the State 16-2 research well. Finally, the Morrison may contain intervals rich in uranium-bearing ores that would need to be cased off as required by the Utah Division of Oil, Gas and Mining.

Jurassic Summerville Formation

Lithology, Thickness, and Contacts

The lower Upper Jurassic Summerville Formation, the uppermost unit of the San Rafael Group, represents a tidal flat/sabkha environment and consists of red-brown, light to medium brown siltstone, mudstone, sandstone, and white gypsum with subordinate claystone/shale and gray limestone (appendix, figure A5) (Stanton, 1976; Caputo and Pryor, 1991; Doelling, 2002). The Summerville becomes sandstone dominated to the southeast before pinching out. Siltstone is the most common lithotype in east-central Utah, present both as mottled regular bedded units or small lenses, and is composed of silt with abundant clay. Sandstone is very fine to fine grained, and silty; bedding is laminar to medium.

The Summerville Formation is 5 to 400 feet (1.5–120 m) thick (Hintze and Kowallis, 2021). The Summerville is separated from the overlying Morrison Formation by the regional J-5 unconformity of Pipiringos and O'Sullivan (1978); the contact is sharp.

Drilling Hazards

Siltstone, mudstone, and gypsum beds within the Summerville Formation will likely cause circulation problems, especially washouts. These beds are fairly consistent throughout the formation and the ROP will probably be slow.

Jurassic Curtis Formation

Lithology, Thickness, and Contacts

The shallow-shelf and marginal marine, lower Upper Jurassic Curtis Formation of the San Rafael Group consists of light gray-green, light gray, to light brown sandstone (sublitharenite, lithicarenite, and subarkose), siltstone, and claystone/shale (appendix, figure A6) with subordinate conglomerate and limestone (Smith, 1976; Caputo and Pryor, 1991; Doelling, 2002; Doelling and others, 2015). In the central part of the fold and fault belt, the Curtis consists of eolian sandstone of the Moab Tongue (Doelling, 2010). Sandstone is very fine to coarse grained, poorly to moderately sorted, sub-rounded to sub-angular, and quartzose. The green color in east-central Utah is attributed to the presence of glauconite in the matrix, although it may be iron-chlorite clay instead (written communication to Mario V. Caputo from Richard Pollastro, U.S. Geological Survey, October 1987). Bedding is finely laminated to medium.

The Curtis Formation is 0 to 230 feet (0–70 m) thick (Hintze and Kowallis, 2021). The contact with the overlying Summerville Formation is gradational and conformable.

Drilling Hazards

The relatively thin sandstone beds that comprise the Curtis Formation should drill relatively problem free. Some loss of circulation could occur in the more porous units.

Jurassic Entrada Sandstone

Lithology, Thickness, and Contacts

The Middle Jurassic Entrada Sandstone of the San Rafael Group represents a wide variety of depositional environments: intertidal/subtidal marine, supratidal mudflats and ponds, and coastal dunes. It consists of orange-brown, red-brown, or light brown sandstone (appendix, figure A7), siltstone, mudstone, and subordinate oolitic limestone in the northern to northwestern part of the Paradox fold and fault belt. Red siltstone and silty sandstone are dominant in the basal part of the Entrada (Gualtieri, 1988). In the central part of the fold and fault belt, the Entrada consists almost entirely of eolian sandstone and is the primary arch former in Arches National Park (Doelling, 2010). Sandstone beds are friable, porous, silty or very fine to fine grained with scattered coarse grains, poorly to moderately sorted, and cemented with calcite or iron oxide. A variety of sedimentary structures are found in the Entrada: ripple marks, mudcracks, rip-up clasts, trough cross-stratification, micro-cross-lamination, and soft-sediment deformation. Bedding is thin to massive, sometimes with deformation features in the basal section along the contact with the underlying Carmel Formation.

The Entrada Sandstone is 60 to 500 feet (18–152 m) thick (Hintze and Kowallis, 2021). The Entrada is separated from the overlying Curtis Formation by the regional J-3 unconformity of Pipiringos and O'Sullivan (1978).

Drilling Hazards

The Entrada Sandstone is a thick, relatively homogenous formation that generally presents few drilling problems. However, it is prone to jointing at the surface, as observed in Arches National Park to the southeast, which may cause possible well deviation issues. Porous zones may result in some loss of circulation or water flow whereas thin, impermeable units may slow the ROP when they are encountered. Contorted beds near the base of the Entrada may also cause some well deviation. Gas, including carbon dioxide and helium, is produced at Harley Dome within the Greater Cisco field complex to the east (Bon, 1999; Wiseman and Eckels, 2020) but is unlikely to be encountered in new wells in the northern part of the Paradox fold and fault belt due to lack of a trapping mechanism.

Jurassic Carmel Formation

Lithology, Thickness, and Contacts

The Middle Jurassic Carmel Formation, the lowermost unit of the San Rafael Group, was deposited in a restricted to open/marginal marine environment. It is divided into four members, which in descending order are the: Winsor, Paria River, Crystal Creek, and Judd Hollow (forming the dark flatirons along the steeply dipping east flank of the San Rafael Swell to the west) in the northern Paradox fold and fault belt (figure 6). However, all four members are not always present within the region; in the Arches-Canyonlands area, the Carmel consists only of shale and siltstone beds of the Dewey Bridge Member (Doelling, 2010; Hintze and Kowallis, 2021) (figure 7). The members of the Carmel and other Middle Jurassic formations in the region have been mapped, measured, and described by Sprinkel and others (in preparation). In general, the Carmel consists of interbedded light-brown to light-gray or yellow sandstone (appendix, figure A8), red to gray siltstone, dark-gray to green mudstone, and light- to medium-gray limestone with subordinate amounts of dolosiltite, doloarenite, calcarenite, and calcisiltite. Limestone may be laminated, micritic, or finely crystalline, with silty, argillaceous, and dolomitic zones. The Paria and Winsor Members also contain silty or white alabaster gypsum beds. These lithotypes are generally thin to medium bedded.

The Carmel Formation ranges in thickness from 20 to 300 feet (6–91 m) (Hintze and Kowallis, 2021). The Entrada Sandstone lies conformably above the Carmel Formation. However, at the contact with the overlying Entrada, bedding in the Carmel is irregular, contorted, and "bumpy" caused possibly by loading of thick Entrada sand onto non-lithified Carmel mudstone related to groundwater activity, gypsum dissolution or flowage, or paleoearthquakes.

Drilling Hazards

Drilling through siltstone, mudstone, and gypsum beds within the Carmel Formation may produce washouts. The heterogeneous distribution of these beds may make drilling the Carmel difficult as lithologies change rapidly as the formation is penetrated. Surface casing is often set in the Carmel because there is a potential for higher pressure in the underlying Navajo Sandstone.

Jurassic Navajo Sandstone

Lithology, Thickness, and Contacts

The Lower Jurassic Navajo Sandstone, the uppermost unit of the Glen Canyon Group (figures 6 and 7), was deposited in a vast erg (dune) system with interdune playas and oases. The Navajo is light brown to light gray, thick-bedded to massive sandstone that is cross-stratified in large trough sets. The sandstone beds are friable and composed of clean, fine- to medium-grained, frosted, sub-rounded to sub-angular, moderately to well-sorted quartz sand (appendix, figure A9) with minor amounts of feldspar and scattered heavy mineral grains. The Navajo locally contains thin, lenticular, light-gray limestone beds.

The Navajo Sandstone is 0 to 510 feet (0–160 m) thick (Hintze and Kowallis, 2021). The Navajo Sandstone is separated from the overlying Middle Jurassic Carmel Formation by the J-1 unconformity (Pipiringos and O'Sullivan, 1978) and the contact is sharp.

Drilling Hazards

The thick, porous Navajo Sandstone is a relatively homogenous formation deposited as great dunes in an erg system that may present a number of drilling problems. Dunal sandstone intervals have high porosity and permeability (greater than 20% and up to 700 mD based on outcrops in the San Rafael Swell to the west [Dalrymple and Morris, 2007]) that could result in significant loss of circulation and mudcake buildup causing drill string sticking problems. As with all high-porosity and -permeability sandstones, there is also the potential for water flow while drilling depending on regional hydrodynamic conditions. In addition, interdune intervals composed of limestone beds 6 to 8 feet (1.8–2.4 m) thick (Dalrymple and Morris, 2007; Doelling and Chidsey, 2012) may quickly slow the ROP and increase bit wear.

The Navajo produced 38,775 BO and 4556 MCFG from a small, faulted anticline at the shut-in Blaze Canyon field about 10 miles (16 km) northeast of the State 16-2 research well (figure 3) (Matheny, 1993; Utah Division of Oil, Gas and Mining, 2023a). Similar structural traps could exist but have not been identified in the northern part of the Paradox fold and fault belt area.

One of the more unusual geologic features in the area is Crystal Geyser along the Green River, 7.5 miles (12 km) northwest of the State 16-2 research well (figures 3, 10, and 11). The geyser is partially human-made; an exploration well drilled in 1936 encountered a pressurized groundwater system in the Navajo Sandstone (and possibly the Entrada Sandstone above) that was charged with carbon dioxide gas. The east-west-trending Little Grand Wash fault acted as a barrier to gas migration from depth and served as a conduit for upward flow into the Navajo, thus creating a structural trap (Baer and Rigby, 1978; Mayo and others, 1991; Shipton and others 2004; Heath and others, 2009; Weaver, 2018). Salt tectonics created the Little Grand Wash fault and the nearby Ten Mile graben (figures 9 and 10). The timing of the creation of these faults is post-Jurassic so the Navajo structure will be similar to the Paradox structure along these features (figure 9). Tufa deposits related to ancient (Pleistocene?) geysers and springs (Doelling, 2002; Doelling and others, 2015) are located on the highest part of the hanging wall near the Little Grand Wash fault cutoff. Geologic evaluations of new Cane Creek wells planned for the area should evaluate the shallower structural geology where carbon dioxide could be trapped and associated drilling hazards.

Jurassic Kayenta Formation

Lithology, Thickness, and Contacts

The Lower Jurassic Kayenta Formation, the middle unit of the Glen Canyon Group (figures 2, 6, and 7), was deposited in a sandy braided river system and consists mostly of sandstone lenses, with lesser amounts of eolian sandstone, intraformational conglomerate, siltstone, and shale. The unit is primarily red-brown sandstone (appendix, figure A10), but individual lenses and beds vary considerably in color; some are purple, lavender, tan, orange, or white. Sandstone in the Kayenta exhibits both high-angle and low-angle cross-bedding. The grain size is more variable than in the underlying Wingate and overlying Navajo Sandstones, ranging mostly from fine to medium. Siltstone, shale, and intraformational conglomerate appear as partings or are in-

Figure 11. Crystal Geyser, Grand County, Utah. Photograph by Lance Weaver, Utah Geological Survey.

terlayered with the sandstone. These softer constituents are rare in the lower half of the formation and become common in the upper part.

The Kayenta Formation is 60 to 360 feet (18–110 m) thick (Hintze and Kowallis, 2021). The upper contact is mostly sharp, but intertonguing between the Kayenta and the overlying Navajo Sandstone is common.

Drilling Hazards

The relatively thin sandstone lenses that comprise the sand-rich Kayenta Formation should drill relatively problem free. Some loss of circulation could occur in the more porous sandstone beds. There have been oil shows and minor, non-commercial production from the Kayenta in the northernmost part of the Paradox fold and fault belt, but there is no trapping mechanism to the south.

Triassic–Jurassic Wingate Sandstone

Lithology, Thickness, and Contacts

The eolian (dune erg system) Upper Triassic–Lower Jurassic Wingate Sandstone, the lowermost unit of the Glen Canyon Group (figures 2, 6, and 7), consists mostly of light-orange-brown, moderate-orange-pink, or pale-red-brown, fine-grained, well-sorted sandstone (appendix, figure A11). The rock is usually well cemented and well indurated, and cross-bedded in outcrop. The Wingate is ordinarily described as one massive unit because partings or bedding planes are rare except near the base of the formation where parallel sandstone beds occur.

The Wingate Sandstone is 70 to 450 feet (90–137 m) thick (Hintze and Kowallis, 2021). The contact of the Wingate with the overlying Kayenta Formation is generally sharp and conformable.

Drilling Hazards

The Wingate Sandstone, like the eolian Navajo Sandstone above is also a thick, porous, homogenous formation that may present some potential for drilling problems. High porosity and permeability zones could result in significant loss of circulation. However, there is also the potential for water flow while drilling. In outcrop, jointing is extensive due to the nature of the underlying Chinle Formation, discussed in the next section. Jointing and fractures at depth could be an additional cause of lost circulation.

Triassic Chinle Formation

Lithology, Thickness, and Contacts

The Upper Triassic Chinle Formation is famous for its petrified wood, uranium in red-brown lenticular channel sandstone beds, and multicolored mudstone and shale derived from altered volcanic ash. It was deposited in a floodplain with river channels, oxbow lakes, ponds, and swamps. The Chinle consists of complex interbedding and lensing arrangements of sandstone, pebble conglomerate, siltstone, mudstone, and rare limestone. The red-brown, tan, and gray-red sandstones are very fine to coarse grained, moderately to well sorted, quartzose, and slightly micaceous. Pebble and intraformational conglomerates occur as lenses and in scour channels concentrated in the lower parts of sandstone beds. Siltstone is interbedded with the sandstones and conglomerates, and displays low-angle cross-stratification and ripple lamination. Mudstone is gray-red to gray-green, and bentonitic. The Chinle Formation was a major target and producer of uranium during the 1950s along with the Morrison Formation described above. The Chinle is divided into as many as five members within the region, the two most widespread of which are the Church Rock and Moss Back Conglomerate/Sandstone Members at the top and base, respectively (Doelling and Chidsey, 2010; Hintze and Kowallis, 2021) (figures 6 and 7).

The Church Rock Member is mostly a red-brown sandstone and siltstone (figure 2; appendix, figure A12), but sandstone beds are more common in the lower part. Some beds include distinctive ripple-laminated sandstone, but the bedding in much of this unit is indistinct. Red-brown, fine-grained, well-sorted, thick-bedded sandstone is common in the upper 10 to 30 feet (3–9 m) of the section (Doelling and Chidsey, 2010).

The Moss Back Conglomerate/Sandstone is dominated by red-brown sandstone (appendix, figure A13) and conglomerate. In outcrop, the sandstones commonly contain scattered logs and branches of petrified wood. Lowermost lenses of sandstone are locally mineralized with uranium and copper minerals. The upper contact is gradational into the upper section.

The Chinle Formation ranges in thickness from 150 to 630 feet (45–190 m); Church Rock Member is 150 to 400 feet (45–120 m) and Moss Back Conglomerate is 0 to 100 feet (0–30 m) (Hintze and Kowallis, 2021). The contact of the Chinle Formation with the overlying Wingate Sandstone of the Glen Canyon Group is sharp and conformable, commonly being placed below the massive well-sorted sandstone typical of the Wingate. No regional channeling or angular unconformity is apparent, and the lowermost part of the Wingate includes thin, bedding-parallel sandstone and siltstone beds that suggest continuous deposition across the Chinle–Wingate contact.

Drilling Hazards

The thick Chinle Formation presents a number of drilling challenges. It contains volcanic ash composed of bentonite and other clay minerals that can swell causing sticking and bit balling problems. Mudstone and shale beds produce major washouts while drilling and wells in the Paradox Basin have had to case through them to maintain circulation. Contorted bedding may also lead to additional hole integrity problems. In addition, wells in the region have drilled straight until encountering the Chinle where some then drifted updip. Finally, as with the Morrison Formation up section, the Chinle may contain uranium-rich intervals that would also need to be cased off as required by the Utah Division of Oil, Gas and Mining.

Triassic Moenkopi Formation

Lithology, Thickness, and Contacts

The Lower Triassic Moenkopi Formation was deposited in a shallow marine to tidal flat environment. It is divided into four members in the northern part of the Paradox fold and fault belt, which in descending order are the Moody Canyon, Torrey, Sinbad Limestone, and Black Dragon (Hintze and Kowallis, 2021) (figure 6); in the Dead Horse Point–Arches National Park area they are the Sewemup, Ali Baba, Tenderfoot, and Hoskinnini Members (figures 2 and 7) (Doelling and others, 2010; Doelling and Chidsey, 2012). The classic outcrops of the Moenkopi in southern Utah and northern Arizona are chocolate brown, whereas those in the San Rafael Swell and the northern Paradox fold and fault belt have been bleached to various shades of yellow, possibly by migrating hydrocarbons and iron-reducing groundwater.

In outcrop and in cuttings, the slope-forming Moody Canyon/Sewemup Member consists of red-brown to chocolate-brown, interbedded very fine to fine-grained sandstone, siltstone, and mudstone (appendix, figure A14), having subordinate muddy limestone and calcisiltite. The ledgey to slope-forming Torrey/Ali Baba and Tenderfoot Members consist of sandstone and shaly siltstone with minor limestone, calcarenite, calcisiltite, and pebble conglomerate. These beds display a variety of colors, locally banded: altered green-gray, yellow-gray, red-brown, yellow, yellow-brown, or tan-gray. Sandstone beds are very fine to fine grained with some micaceous and calcareous units. The Sinbad Limestone Member represents a mixed carbonate-siliciclastic cyclic sequence consisting of medium gray and yellow-gray to light brown limestone, dolomitic limestone, and calcareous sandstone with a few shaly siltstone intervals in outcrops and cuttings (appendix, figure A15), (Doelling, 2002; Doelling and Kuehne, 2008; Doelling and Chidsey, 2010). Carbonate fabrics include mudstone (crystalline), or grainstone and packstone composed of ooids, peloids, intraclasts, and skeletal grains (Goodspeed and Lucas, 2007; Morris and others, 2007). The basal Black Dragon/Hoskininni Member consists of sandstone, siltstone, and mudstone that may be green-gray, yellow-gray, light gray, or light yellow-brown in color (appendix, figure A16). Sandstone beds are very fine to fine grained and composed of quartz sand. Bedding is thin to medium and most units are calcareous; some have argillaceous or gypsiferous beds. A few gray limestone and cherty pebble conglomerate beds are found at the top and base of the Black Dragon, respectively. Some zones appear saturated with hydrocarbons (Doelling, 2002; Doelling and Kuehne, 2008).

Regionally, the Moenkopi Formation ranges in thickness from 240 to 910 feet (73–277 m); the Moody Canyon and Torry Members are 470 to 650 feet (143–198 m), the Sinbad Member is 30 to 50 feet (9–15 m), and the Black Dragon Member is 170 to 210 feet (52–64 m) in the northern part of the Paradox fold and fault belt (Hintze and Kowallis, 2021). The contact with the overlying Chinle Formation is sharp and unconformable, but commonly poorly exposed. It is placed at the base of a distinctive white to mottled gritstone, or between the gray-red or gray-green mudstone and siltstone of the lower part of the Chinle and the orange-red siltstones of the upper part of the Moenkopi.

Drilling Hazards

The thick, mud-rich Moenkopi Formation also produces large washouts and openings during drilling like the overlying Chinle Formation as shown by caliper logs. Operators have had to steer back to vertical due to deviation while drilling through the Moenkopi and Chinle and case through it to maintain circulation. The ROP should be typically slow, consistent with a shale-dominated formation.

Permian Black Box Dolomite

Lithology, Thickness, and Contacts

The Lower Permian Black Box Dolomite is equivalent to the Kaibab Formation (listed as such in many publications and maps covering the region) and was deposited on a shallow carbonate shelf. It generally consists of light gray, light brown, brown, or cream-colored cherty dolomite (appendix, figure A17) and limestone overlying yellow-gray to gray sandstone. In outcrop, a zone of light brown, sandy thin-bedded limestone or calcareous sandstone is locally present at the base of the formation, representing reworking of the underlying Permian White Rim Sandstone (Doelling, 2002). Some limestone beds consist of oolitic grainstone whereas others are coarsely crystalline; sandstone beds are fine grained. Nodules and geodes (up to 6 inches [15 cm] in diameter) composed of chert, quartz, or calcite are diagnostic features within these beds (Doelling, 2002; Doelling and Kuehne, 2008). Doelling (2002) reports that some geodes contain oil. Carbonates range from thin to thick bedded whereas clastic beds are generally thin bedded.

The Black Box Dolomite, where present, ranges in thickness from 60 to 160 feet (18–49 m) (Hintze and Kowallis, 2021) (figure 6). To the east, the Black Box has been eroded off the Uncompahgre uplift and thins and is missing to the south of the northern part of the Paradox fold and fault belt where the Moenkopi lies directly on the Permian White Rim Sandstone or Cutler Formation. The erosional boundary between the Permian and Triassic is sharp, referred to as the TR-1 unconformity (Pipiringos and O'Sullivan, 1978).

Drilling Hazards

The relatively thin Black Box Dolomite should present few drilling problems. Possible loss of circulation could occur in any fractured zones encountered and the ROP should be typically slow, consistent with a carbonate-dominated formation.

Permian White Rim Sandstone

Lithology, Thickness, and Contacts

The White Rim Sandstone, the uppermost formation on the Lower Permian Cutler Group, was deposited as coastal dunes (figure 6). It is a fine- to medium-grained quartzose sandstone (appendix, figure A18), exhibiting both planar and cross-stratified beds. The upper section is a reworked marine unit whereas the lower unit is eolian-dominated having large-scale cross-stratification. The upper contact of the White Rim strata with the overlying Triassic beds is sharp, marked by local scouring and channeling and is unconformable. The White Rim is up to 300 to 500 feet (90–150 m) thick (Hintze and Kowallis, 2021). It pinches out to the east as observed from the view west from Dead Horse Point (Doelling and Chidsey, 2010).

Drilling Hazards

The chief drilling hazard associated with the White Rim Sandstone will be loss of circulation, especially when heavier drilling muds are required in the deeper Paradox Formation (Smith, 1983). The White Rim can have excellent porosity and permeability as seen in outcrops within the San Rafael Swell, but cores taken from wells farther to the west show it as almost a quartzite, which if encountered could damage drill bit cones. Fractures are common and can lead to greater loss of circulation when encountered. However, while drilling the State 16-42 (section 16, T. 22 S., R. 17 E., SLBL&M) in the same section as, but drilled previously to, the State 16-2 research well (figure 3), the drill string became stuck in the White Rim resulting in a fishing operation and required a sidetrack hole. Possible causes include (1) a decrease in hole size, as indicated by the caliper log due to excessive mudcake buildup in a highly porous and permeable section of the White Rim, or (2) differential pressure from an overbalanced mud system (Rose Petroleum, written communication, 2019). The State 16-2 research well encountered significant water flow in the White Rim and thus water flow could also be a major drilling problem when targeting the Cane Creek shale and deeper potential reservoirs.

Gas shows in the White Rim Sandstone have been observed in Salt Wash field (figure 3). Water flows from the White Rim in some wells on the hanging wall of the Little Grand Wash fault (figure 9) are charged with carbon dioxide. Finally, small amounts of hydrogen sulfide have also been reported in the White Rim.

Permian Organ Rock Formation

Lithology, Thickness, and Contacts

The Organ Rock Formation of the Cutler Group (figure 6) was deposited in a marginal to shallow marine environment and consists of reddish-brown, fine-grained to silty sandstone, sandy shale, and minor siltstone (appendix, figure A19); it is medium to thick bedded. The upper contact of the Organ Rock strata with the overlying White Rim Sandstone is sharp and conformable. The Organ Rock ranges in thickness from 0 to 300 feet (0–90 m) (Hintze and Kowallis, 2021).

Drilling Hazards

The mud-rich Organ Rock Formation also produces large washouts like the Moenkopi and Chinle Formations. The ROP should again be typically slow, consistent with a shale-dominated formation.

Permian Elephant Canyon Formation

Lithology, Thickness, and Contacts

The Elephant Canyon Formation, the basal formation of the Cutler Group in the region (referred to as the Pakoon Dolomite in a number of past publications) (figure 6), was deposited on a shallow marine shelf and consists of interbedded pink dolomite, light gray to light brown or red sandstone and limestone (appendix, figure A20), locally cherty. Sandstone is fine grained and commonly dolomitic; bedding is thin to thick (Doelling, 2002).

The Elephant Canyon Formation ranges in thickness from 1000 to 1200 feet (300–370 m) (Hintze and Kowallis, 2021). Regional analyses of fusulinid (Welsh and Bissell, 1979) and conodont (Ritter and others, 2007) zones indicate an unconformity between the Lower Permian and Upper Pennsylvanian.

Drilling Hazards

The Elephant Canyon Formation, although thick, should present few drilling problems. Possible loss of circulation could occur in any fractured zones or sandstone beds encountered. The ROP should be typically slow in carbonate-dominated sections and speed up in sandstone beds. The presence of chert within the carbonates can cause rapid and extensive wear on the bit as well as extremely slow drilling.

Permian Cutler Formation

Lithology, Thickness, and Contacts

Where the White Rim Sandstone is missing, as seen at its stratigraphic pinchout from Dead Horse Point, the Triassic Moenkopi Formation overlies the Permian Cutler Formation, which is divided into informal upper and lower members (Doelling and others, 2010) (figures 2 and 7). During the Permian, the Uncompahgre Highland to the northeast that began during the Pennsylvanian continued to rise, and erosion eventually exposed granitic and mafic (iron-manganese-rich) rocks that were very old (Proterozoic, 570 to 2000 Ma). The clastic erosional debris shed to the southwest into the Dead Horse Point area and near Arches National Park was deposited as a series of alluvial fans at the foot of the mountain range; the embayment was filled and the ocean shorelines retreated farther to the southwest. The iron content of the source rocks imparted a red coloration to the rocks deposited in this area. Granites, made up of quartz, feldspar, mica, and small percentages of dark iron-bearing minerals, were eroded and provided source material for sandstones rich in feldspar, or arkoses (Doelling and others, 2010).

The upper and lower members of the Cutler Formation are similar and were deposited in interfingering back beach, marine, fluvial, and alluvial-fan environments. They consist of interbedded arkosic sandstone, subarkosic sandstone, sandstone, conglomerate, micaceous siltstone, and limestone. In outcrop, many of the arkosic and subarkosic sandstone beds display trough cross-bedding and cut-and-fill structures. In the upper member of the Cutler, arkosic and quartzose sandstones are mostly fine grained, well sorted, and micaceous (appendix, figure A21). The fluvially deposited arkoses, subarkoses, and conglomerates are dark red to purple whereas the eolian rocks are mostly orange and red-orange. The lower member of the Cutler Formation contains numerous gray marine limestone beds (appendix, figure A22), laid down during short intervals when the sea was able to push shorelines northeastward. These beds form the basis for dividing the lower from the upper member; the Shafer Trail below Dead Horse Point is on a limestone bed representing the contact (Doelling and Chidsey, 2012). The number of limestone beds decreases northeastward. In outcrop, these are locally fossiliferous, containing brachiopods, bryozoans, gastropods, crinoid debris, and rare cephalopods and trilobites.

The Cutler Formation ranges in thickness from about 900 to 1200 feet (300–370 m); the upper member and lower members are 700 to 1000 feet (200–300 m) and 180 to 220 feet (55–67 m) thick, respectively (Doelling and others, 2010). The regional unconformity between the Lower Permian and Upper Pennsylvanian is found at the base of the Cutler (Welsh and Bissell, 1979; Ritter and others, 2007).

Drilling Hazards

The Cutler Formation, although thick, should present few drilling problems. Possible loss of circulation could occur in any units with good intergranular porosity or fractured zones, particularly limestone beds, or sandstone/arkosic beds encountered. Again, the ROP should be typically slow in carbonate-dominated sections and speed up in sandstone-dominated sections.

Pennsylvanian Honaker Trail Formation

Lithology, Thickness, and Contacts

The shallow marine Honaker Trail Formation, the uppermost formation of the Pennsylvanian Hermosa Group (figures 6 and 7), consists of interbedded sandstone, limestone, and siltstone in outcrop and cuttings (appendix, figure A23). The sandstone is very fine to fine grained, well to moderately sorted, micaceous, and calcareous; some beds are cross-bedded. Bedding is thick to massive. Limestone is gray to light gray, variably argillaceous (clayey), and 1 to 10 feet (0.3–3 m) thick. Many limestone beds are fossiliferous, containing a marine fauna of crinoid debris, brachiopods, bryozoans, gastropods, foraminifera, and rare trilobites. Chert nodules are common and many fossils have been silicified. The siltstone is micaceous, locally bioturbated, and cross-stratified.

The Honaker Trail Formation is 1600 to 5000 feet (490–1500 m) thick (Doelling and others, 2010; Hintze and Kowallis, 2021). The contact between the Pennsylvanian Honaker Trail Formation and the overlying Permian rocks of the Cutler Formation is a paraconformity, with beds of both formations parallel to one another.

Drilling Hazards

The Honaker Trail Formation, although generally thicker than the Elephant Canyon and Cutler Formations, should likewise present few drilling problems. Similarly, possible loss of circulation could occur in any fractured zones or porous sandstone beds encountered. The ROP should also slow in carbonate-dominated sections and speed up in sandstone beds. Chert is fairly common within the carbonates causing an extremely slow ROP and rapid wear on the bits.

Some sandstone beds in the Honaker Trail Formation produce gas in the Paradox Basin. Gas shows in the Honaker Trail occur in drilling mud systems and from drill-stem tests. There is a possibility of gas in sandstones that pinchout updip to the southwest in the region.

Pennsylvanian Paradox Formation

Lithology, Thickness, and Contacts

The targeted Cane Creek shale zone is within the Paradox Formation of the Hermosa Group (figures 6 and 7). The Paradox Formation was deposited on a shallow carbonate shelf to restricted marine environment in the Paradox Basin. The Paradox Formation is divided into (1) an upper member of interbedded dolomite (appendix, figure A24), dolomitic shale, and anhydrite, (2) a middle (saline) member consisting of thick halite interbedded with dolomite, dolomitic siltstone and shale, and anhydrite, and (3) a lower member consisting of interbedded black shale, siltstone, dolomite, and anhydrite. The thickness of the Paradox Formation is up to 14,000 feet (4270 m) in the interior of the basin where the Paradox fold and fault belt is located (Hintze and Kowallis, 2021). The contact between the Paradox Formation and the overlying Honaker Trail Formation is conformable and can be difficult to identify. Conodonts and other fossils are often used to define the contact in outcrops and cores, but generally the first encounter of evaporites (anhydrite) is used in well logs.

Hite (1960), Hite and Cater (1972), and Hite and Buckner (1981) divided the middle member of the Paradox Formation in the evaporite basin into 29 salt cycles that onlap onto the basin shelf to the west and southwest (figure 12); Rasmussen (2010) identified as many as 35 cycles. Each cycle consists of a clastic interval/salt couplet described in detail by Massoth and Tripp (2011) and Massoth (2012). The clastic intervals are typically interbedded dolomite, dolomitic siltstone, and organic-rich shale (appendix, figures A25, A27 through A32, and A36) generally overlain and underlain by anhydrite and halite (figure 13; appendix, figures A26 and A36). These intervals typically range in thickness from 10 to 200 feet (3–60 m) and are generally overlain and underlain by 200 to 400 feet (60–120 m) of halite beds. Within the interior of the basin, a typical cycle consists of a black shale lithofacies overlain almost entirely by salt, whereas on the shelf, a cycle consists of a black shale lithofacies overlain primarily by carbonates. The regionally extensive black shale lithofacies allows correlation of salt cycles in the interior of the basin with carbonate cycles on the shelf.

The Paradox Formation is divided into informal zones, in descending order: Ismay, Desert Creek, Akah, Barker Creek, and Alkali Gulch (figure 12) (Hite and Cater, 1972; Reid and Berghorn, 1981). This terminology is currently the most common in the literature, as well as in completion and production reports. The Cane Creek shale zone is the basal part of cycle 21 in the Alkali Gulch zone (figure 12) and the targeted shale generally ranges from 0 to about 200 feet (0–60 m) thick. The Cane Creek consists of thin dolomitic sandstones/siltstone and dolomite interbedded with anhydrite and organic-rich marine shale overlain and underlain by halite (Smith, 1983; Morgan, 1992; Grove and others, 1993). The Cane Creek is divided into three intervals in descending order: A, B, and C (figure 13). The thickness of the A interval averages 31 feet (10 m), ranging from 10 to 84 feet (3–26 m); it is generally thicker to the north. The average thickness of the B interval is 26 feet (8 m), ranging from 4 to 72 feet (1.2–22 m). It forms a thick band east to west across the region. The average thickness of the C interval is 36 feet (11 m), ranging from 10 to 81 feet (3–25 m); it is generally thicker to the north as more sandstone is included.

Lithologically, the A interval is composed of alternating thin beds (1 to 4 feet [0.3–1.2 m] thick) of silty and anhydritic dolomitic mudstone (appendix, figure A33), gray to black shale and mudstone of low to high percent TOC, and laminated to nodular anhydrite, with minor amounts of burrowed or bioturbated siltstone and fine-grained sandstone (Chidsey and others, 2016; Chidsey and Eby, 2017; Morgan and Stimpson, 2017; Jagniecki and others, 2021, 2022; Vanden Berg and others, 2022). Porosity and permeability are low. The A interval was deposited under anoxic-saline conditions (Jagniecki and others, 2021).

The B interval, the primary fractured oil reservoir unit, is composed of interbedded, thin-bedded gray and black shale and mudstone of low to high percent TOC, silty to sandy laminated dolomite, and abundant fine-grained sandstone and siltstone beds (figures 14 and 15; appendix, figure A34) (Chidsey and others, 2016; Morgan and Stimpson, 2017; Jagniecki and others, 2021, 2022; Vanden Berg and others, 2022). Bedded anhydrite

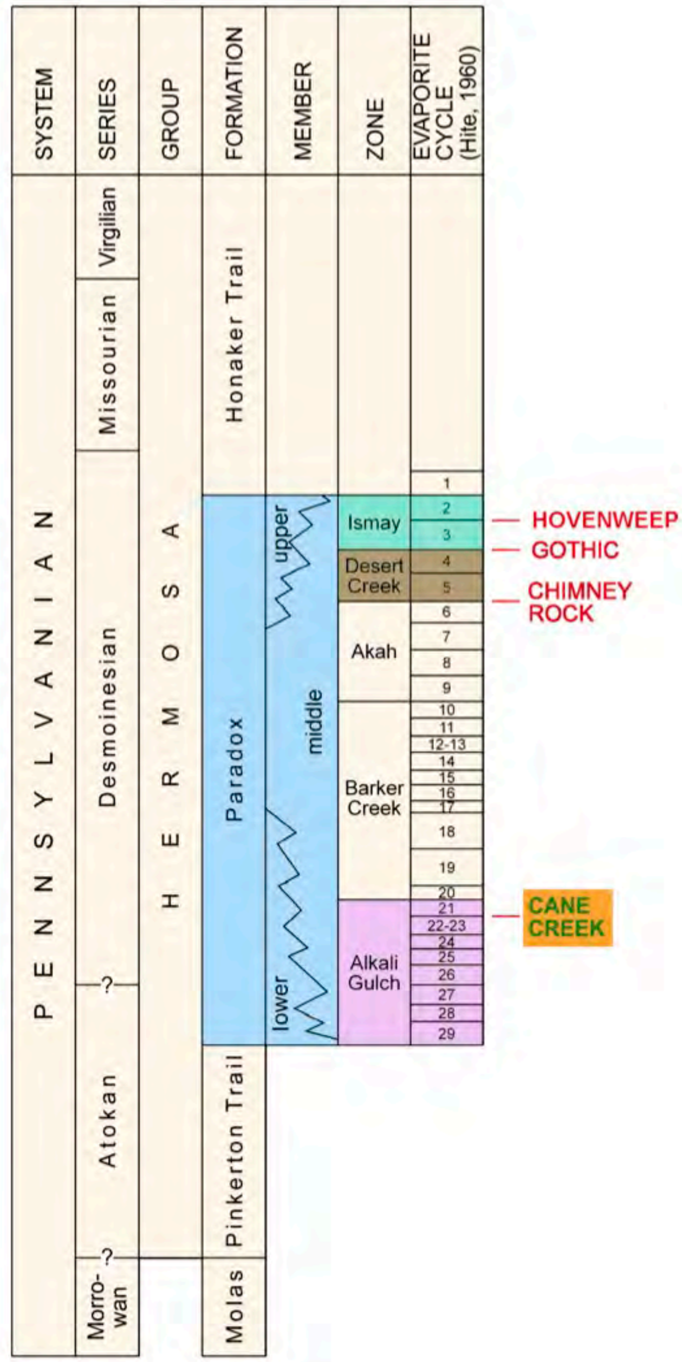

Figure 12. Stratigraphic column for the Paradox Basin; cycles and informal zones with significant production are highlighted with colors. Note the position of the Cane Creek shale, which occurs below the U.S. Geological Survey's Hovenweep, Gothic, and Chimney Rock Shale Oil and Gas Assessment Units (2012) in the Paradox Basin (also see Chidsey, 2016). Modified from Hite (1960), Hite and Cater (1972), and Reid and Berghorn (1981).

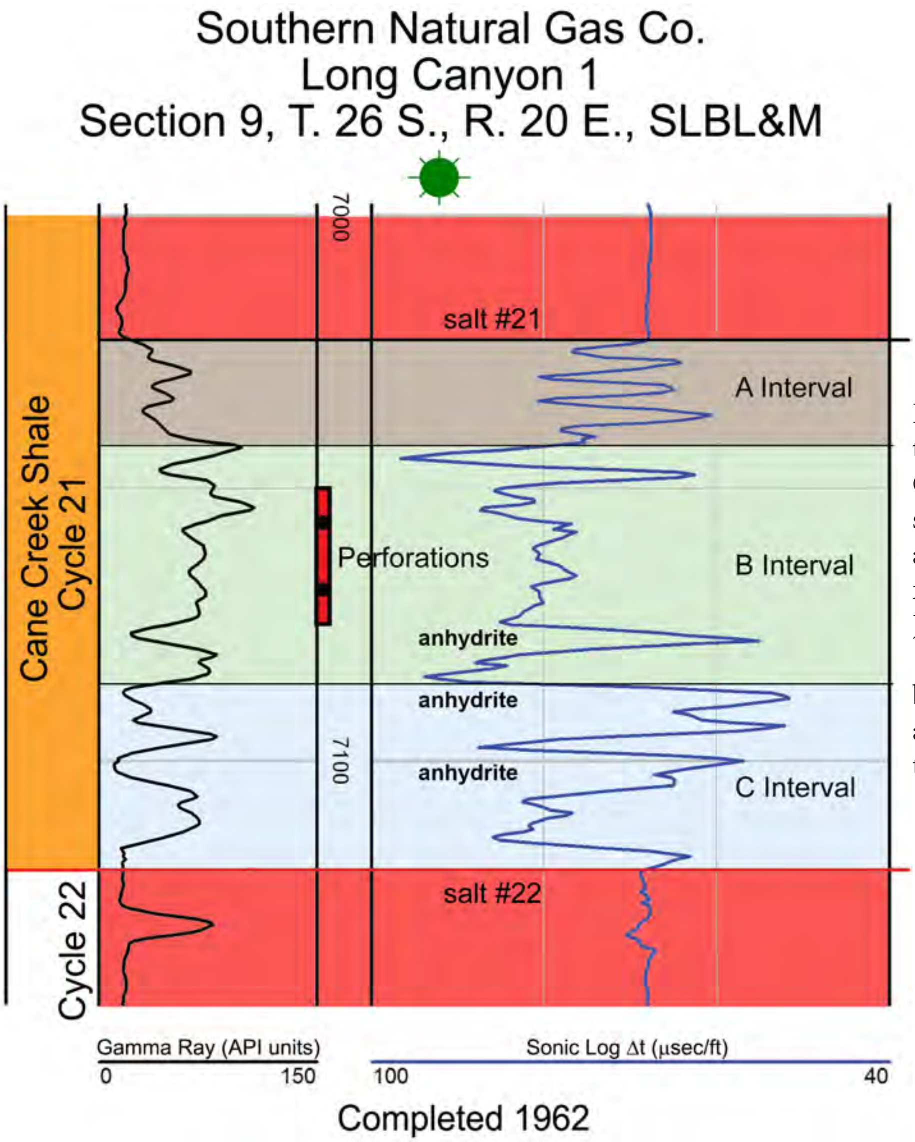

Figure 13. Typical gamma ray-sonic log of the Cane Creek shale, Long Canyon field, Grand County, Utah, showing the divisions of the Cane Creek shale into "A," "B," and "C" intervals. Cumulative production from a vertical wellbore in this well (to January 1, 2023) = 1,134,948 barrels of oil, 1.16 billion cubic feet of gas, and 610,423 barrels of water (Utah Division of Oil, Gas and Mining, 2023b). See figure 3 for location of Long Canyon field.

is absent although some beds contain minor mottled anhydrite. Wave ripples, burrows, and bioturbation are common in siltstone and sandstone. Sandstone is thicker in the central and northern parts of the play. Fractures and microfractures are commonly sealed with halite, anhydrite, clay, and calcite (Chidsey and others, 2016; Morgan and Stimpson, 2017; Jagniecki and others, 2021, 2022; Gathogo and others, 2022; Paronish and others, 2022). Porosity and permeability are low to high. The B interval was deposited under oxic-fresher water conditions (Jagniecki and others, 2021).

The C interval is composed of interbedded abundant fine-grained sandstone and siltstone, silty dolomite, and laminated anhydrite with shale and mudstone of low percent TOC in the lower part (appendix, figure A35) (Chidsey and others, 2016; Morgan and Stimpson, 2017; Jagniecki and others, 2021, 2022; Vanden Berg and others, 2022). Wave ripples, burrows, and bioturbation are common in siltstone and sandstone. Sandstone is thicker in the northern part of the play. Porosity and permeability are medium to high. The B interval was deposited under mixed oxic-anoxic conditions (Jagniecki and others, 2021).

Drilling Hazards

The targeted Paradox Formation poses the most drilling hazards and challenges for any well in the re-

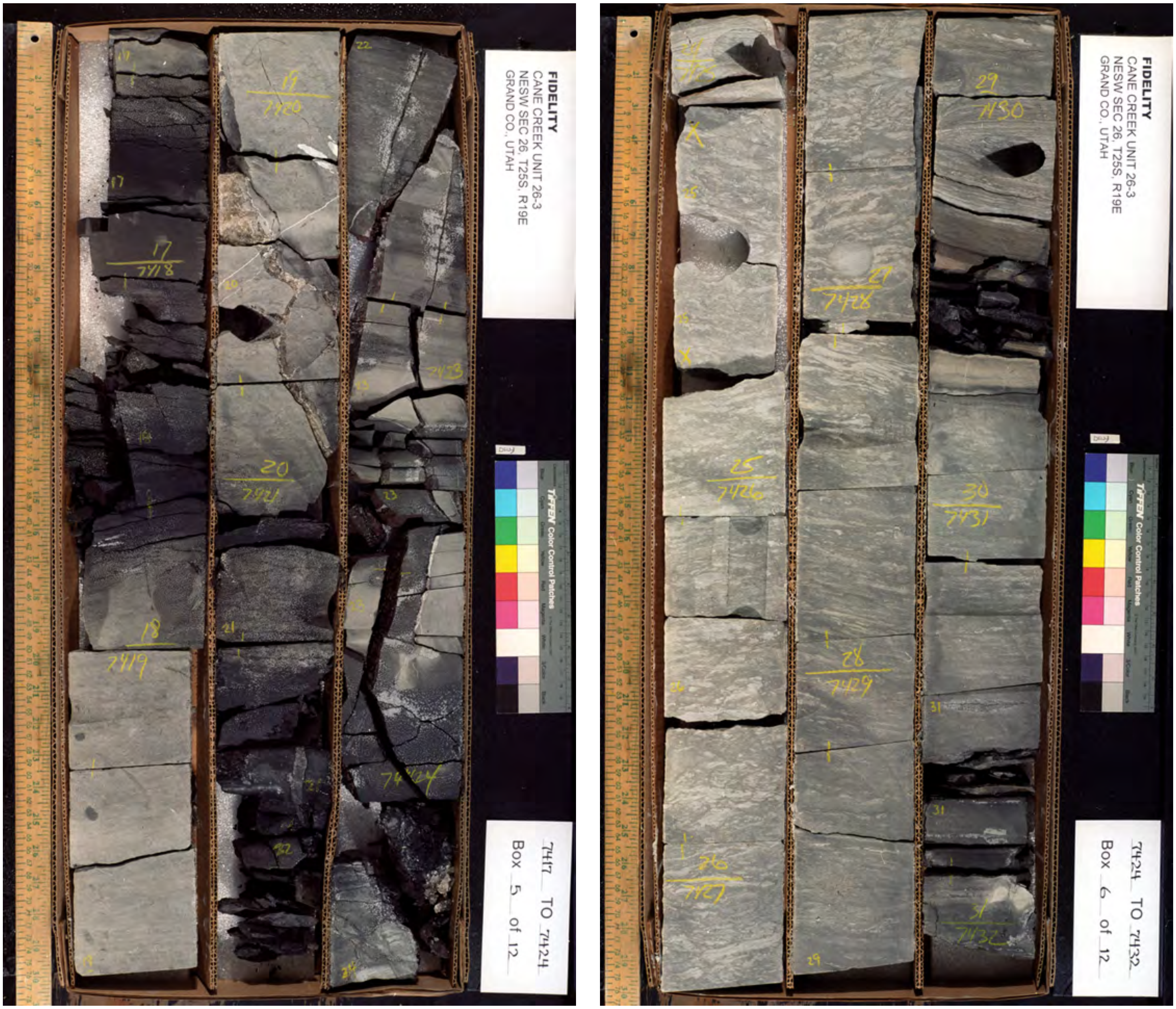

Figure 14. Typical fractured, silty to muddy dolomite with thin siltstone and black organic-rich shale beds (left box) and silty to very fine grained sandstone (right box) deposited in the deep water, open marine environment of unit B in the Cane Creek shale zone; Cane Creek Unit No. 26-3 well (section 26, T. 25 S., R. 19 E., SLBL&M), Big Flat field, Grand County, Utah, slabbed core from 7418 to 7432 feet (2261–2265 m). Core photography by Triple O Slabbing, Denver, Colorado, provided courtesy of Fidelity Exploration & Production Company.

gion. The loss of drilling fluids from the wellbore into fractured clastic beds is common. Weighted drilling fluid could hydrofracture the salt and adjacent clastics, creating possible pathways for fluid circulation into the formation. Gas shows or gas kicks can occur while drilling through Paradox salt. (In 1964, Texas Gulf Sulfur Inc., began underground room-and-pilar mining of potash [sylvite] from the Paradox cycle 5 along the Cane Creek anticline near Dead Horse Point State Park [figures 2 and 9]. Underground mining operations were difficult due to pockets of natural gas, high temperatures, and contorted beds [Phillips, 1975]. Before mine

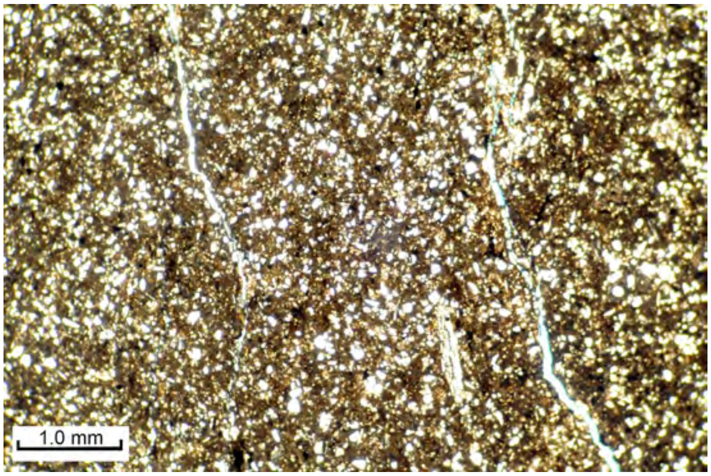

Figure 15. Fractured silty to very fine grained sandstone in unit B in the Cane Creek shale zone. Remington No. 21-1H wildcat well (section 21, T. 31 S., R. 23 E., SLBL&M), San Juan County, Utah, photomicrograph (plane light) from 7450 feet (2270 m). From Nielsen and others (2013).

operations began, 18 miners were killed in a gas explosion while constructing later shafts [Huntoon, 1986]). To eliminate the potential for large gas kicks in clastic zones, 10,000-pound blowout preventors are required by the Utah Division of Oil, Gas and Mining. Nevertheless in January 2023, Zephyr Energy reported a major gas kick in their State No. 36-2 LNW-CC well (section 36, T. 22 S., R. 17 E., SLBL&M, Grand County, Utah) when drilling encountered a major fracture network in the Cane Creek shale at 9598 feet (2925 m). The unexpected influx of gas was safely diverted at the surface and flared until the well was stabilized (press release, Zephyr Energy, January 19, 2023). Washouts due to dissolution of salt beds may also occur but can be prevented by switching to oil-based muds (Morgan and Stimpson, 2017) and using the natural supersaturated brine available in the area (Smith, 1983).

The geology can be unpredictable due to salt movement. Faults, folds, and vertical beds can be present that might jam drill bits. Bedding in salt may be highly contorted and slowly flow into the wellbore. Salt flow can result in sticking problems during drilling, coring, and logging operations, and later when setting casing, or completing or working over wells. Salt flow can cause the casing to collapse. For example, Bartlett Flat field (now part of Big Flat field, figure 3) was originally discovered with a vertical well in 1962; however, after producing 26,000 BO, the production casing collapsed around the tubing and the original completion was abandoned (Smith, 1983). Drilling rapidly through the salt before it begins to flow and subsequently using high-strength casing cemented completely across the salt section are practices that can be employed to avoid salt-flow problems (e.g., Greentown field [figure 3]). Conducting three-dimensional seismic surveys over prospective areas will reduce drilling risks and lead to a better understanding of the salt tectonics and structure as well as define drilling targets.

As mentioned earlier, the Cane Creek shale zone and other clastic cycles in the Paradox Formation are often overpressured and the water salinity is high. In Greentown field (figure 3), blowouts occurred related to clastic cycles 18 and 19. Overpressure in clastic cycle 1-A was encountered in three wells in the field requiring up to 12.8-pound mud to control; the wells likely penetrated an open fracture system due to salt tectonics. A blowout could result in potential flow of oil or brines into lower pressure zones in or around salts 21 or 22 (figure 13). Such a drill hole could be shut-in for days or weeks. As a well penetrates the Paradox, a number of overpressure indicators may be observed in the mud system: (1) an increase in background gas, (2) an increase in chlorides, and (3) the cuttings will increase in size and the shape will appear as if spalling has occurred. Best practices involve drilling to the top of the salt section and setting casing.

The objective of horizontal drilling in the Cane Creek shale is to penetrate the zone with the drill bit parallel to the bedding plane and perpendicular to open vertical or near-vertical natural fractures. The Cane Creek is not a flat-lying bed and is often folded due to salt tectonics so the trajectory of the wellbore can be very complex and sinusoidal as shown on figure 16 (Morgan and Stimpson, 2017). It is generally desirable to drill the bed at low dip (up or down) so the drill string can slide through the horizontal section. The Cane Creek has structural dip and secondary folding due to salt movement. These folds generally have a wave height of 300 feet (90 m) and distance of 1000 feet (300 m) (Grove and others,

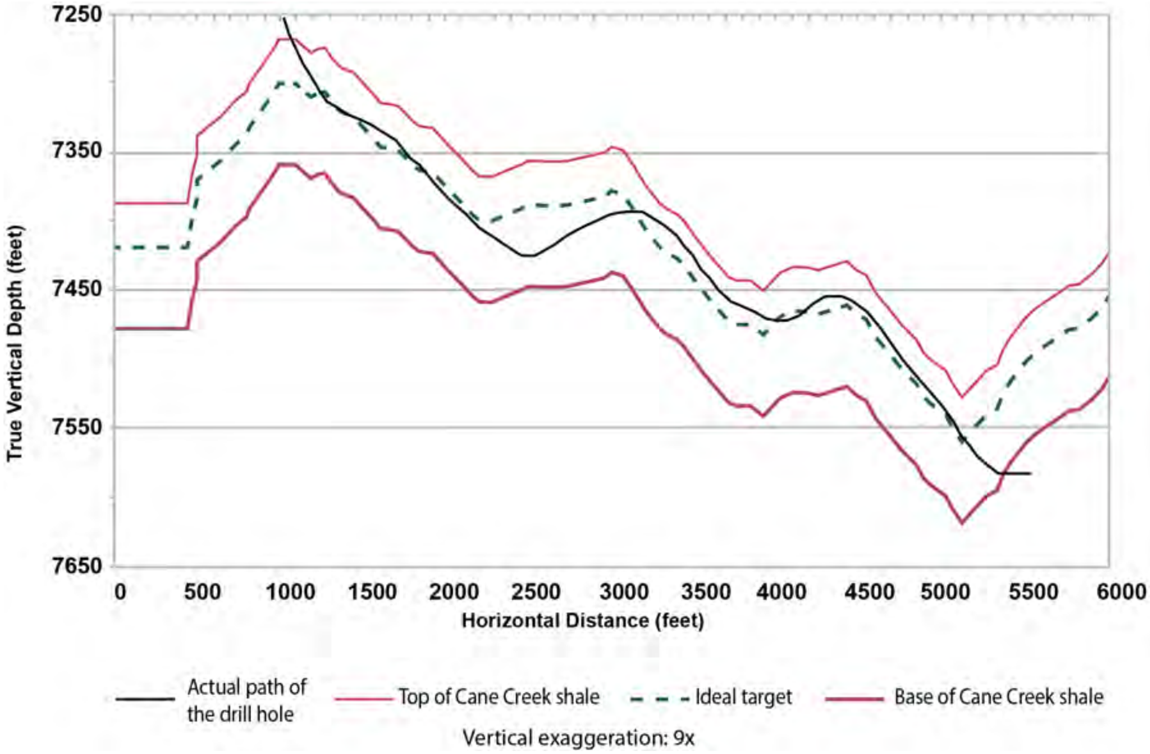

Figure 16. Horizontal profile of the lateral drilled in the Cane Creek Unit 26-3H well (NE1/4SW1/4 section 26, T. 25 S., R. 19 E., SLBL&M, Grand County; bottom-hole location – SW1/4NW1/4 section 25), Big Flat field. The lateral was drilled in a down-dip direction and encountered secondary salt folding that added to the difficulty of keeping the wellbore in the target zone of the Cane Creek shale. The well bottomed in the underlying salt after encountering an apparent dip reversal. Data from Utah Division of Oil, Gas and Mining well records. After Morgan and Stimpson (2017).

1993). As a result, a horizontal lateral in the Cane Creek can have a wavy pattern in a structural dip. In addition, drilling horizontally in the A interval is difficult because of the presence of relatively thick anhydrite beds interbedded with soft shales or mudstones (i.e., the bit tends to "bounce" off the anhydrite beds). Finally, the Cane Creek is challenging to core and prone to jamming (e.g., the anhydrite problem in the A interval or vertical/contorted), adding to the cost of the drilling operations through increased rig time and possible loss of the wellbore in the Cane Creek.

SUMMARY

The Cane Creek shale represents a major target for oil and gas in the Paradox fold and fault belt of the Paradox Basin. Exploratory wells may penetrate a section that ranges in age from Cretaceous through Pennsylvanian. Drilling will encounter a wide variety of lithologies (carbonates, shale, mudstone, sandstone, and evaporites) that may result in both common and unusual hazards that can significantly add to rig time and well costs. These hazards include: (1) swelling clays, (2) high porosity-permeability or fractured zones resulting in lost circulation or excessive mudcake buildup, (3) kicks due to the influx of reservoir fluid, oil, water, or gas into the wellbore, (4) uranium-rich zones, (5) washouts, (6) hole deviation, sticking, and other well-integrity problems, (7) chert, and (8) overpressured intervals. These potential difficulties demonstrate the need for operators to carefully monitor mud systems (cuttings, background and trip gas, chlorides, circulation, etc.), the rate of penetration, and wellbore location to successfully find and produce oil and gas from the Cane Creek shale, other clastic zones in the Paradox Formation, and deeper formations. Following these recommendations and the lessons learned from past drilling efforts, drilling engineers and operators can plan for potential hazards when exploring for hydrocarbons in the Cane Creek shale in the fairly remote, relatively sparsely explored Paradox fold and fault belt. The result should be de-risking wells by successfully and safely drilling to the Cane Creek shale reservoir or other targets with minimal unexpected cost and rig downtime, ultimately leading to additional commercial hydrocarbon discoveries in the region.

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APPENDIX

PHOTOGRAPHS OF SELECTED DRILL CUTTINGS FROM THE CRETACEOUS MANCOS SHALE THROUGH THE PENNSYLVANIAN PARADOX FORMATION, PARADOX FOLD AND FAULT BELT, PARADOX BASIN, UTAH

INTRODUCTION

This appendix contains close-up photographs of selected drill cuttings from wells in the Paradox fold and fault belt in the northern part of the Paradox Basin, Utah. These cuttings cover all formations that may be encountered when drilling a well in the region targeting the Cane Creek shale and other clastic cycles of the Pennsylvanian Paradox Formation: the Cretaceous Mancos Shale into the Pennsylvanian Paradox Formation (text figures 6 and 7). All cuttings are publicly available at the Utah Geological Survey's Utah Core Research Center in Salt Lake City. The photographs of the cuttings were taken dry, using a high-resolution digital camera. The scales are the same in all photographs. Refer to figure 3 in the text for the locations of the wells from which the cuttings were obtained. Each photograph includes the formation and/or member name; well name, location, and API number; and a brief general description from the mudlog or wellsite geologist's drilling report (well logs and mudlogs are publicly available at the Utah Division of Oil, Gas and Mining's website [https://oilgas.ogm.utah.gov/oilgasweb/index.xhtml] under Well Files and Well Logs); note, at the time of this paper, the confidentiality period for the State 16-2 research well was still in effect (renamed the State 16-2LN-CC, API No. 43-019-50089, after the horizontal leg was drilled; the operator is listed as Rose Petroleum).

The cuttings are meant to represent the typical characteristics, such as lithology, grain size, and color of the drilled formations. They were generally taken from the middle or well into the individual formations, so the material contains fewer grains sloughed off from formations above. Certain formations include members with distinct characteristics that differ from other members. In many of those cases, cuttings from specific members are included. In other instances, the depth ranges of the cuttings in the sample envelopes cover anywhere from 10 to as much as 50 feet (3–15 m) of section. Thus, intervals that cross formation/member boundaries were not used. Some members are relatively thin and identifying a specific set of cuttings was not always possible. Finally, the cuttings photographed were simply what were in the sample envelopes and thus, there was no hand picking of individual rock chips, which would not be representative of the section drilled.

The Paradox Formation consists of cycles of clastic interval/salt couplets, as described in more detail in the main report text. The clastic intervals are typically composed of significant amounts of fine-grained sandstone interbedded with dolomitic siltstone, dolomite, organic-rich shale and mudstone, and anhydrite generally overlain and underlain by halite. Because many of these clastic intervals look very similar, only nine examples, which show some variations from each other, are included in this appendix; one example of halite is also included. The Cane Creek shale is divided into three intervals in descending order: A, B, and C (text figure 13). Because the Cane Creek is the primary drilling objective, it is critical to identify these intervals even if the differences are very subtle. Therefore, examples of cuttings from each interval are included in this appendix. (Note: the core descriptions, reservoir data, and other information obtained from the Cane Creek shale in the State 16-2 research well was presented in Gathogo and others, 2022; Jagniecki and others, 2021, 2022; Paronish and others, 2022; Szymanski and Reiners, 2022;

Vanden Berg and others, 2022.)

The purpose of this appendix in providing photographs of drill cuttings from the formations possibly penetrated by wells targeting the Cane Creek shale is to serve as an additional guide, along with mudlogs and geophysical logs, for the mudlogger and wellsite geologist during drilling operations. The appendix can also help geologists in their mapping and exploration efforts by using the photographs as templates to evaluate wells where cuttings or cores are not available. It is certainly not all-inclusive because stratigraphic units and facies change throughout the region. Finally, the photographs and descriptions of these cuttings will help drilling engineers, and their geologic counterparts, in identifying potential drilling hazards that may be encountered when targeting the Cane Creek shale, other clastic cycles in the Paradox Formation, or deeper formations.

Mancos Shale

Book Cliff 3
Section 10, T. 18 S., R. 24 E., SLBL&M, Grand Co., Utah
API No.: 43-019-31366

330–360 feet

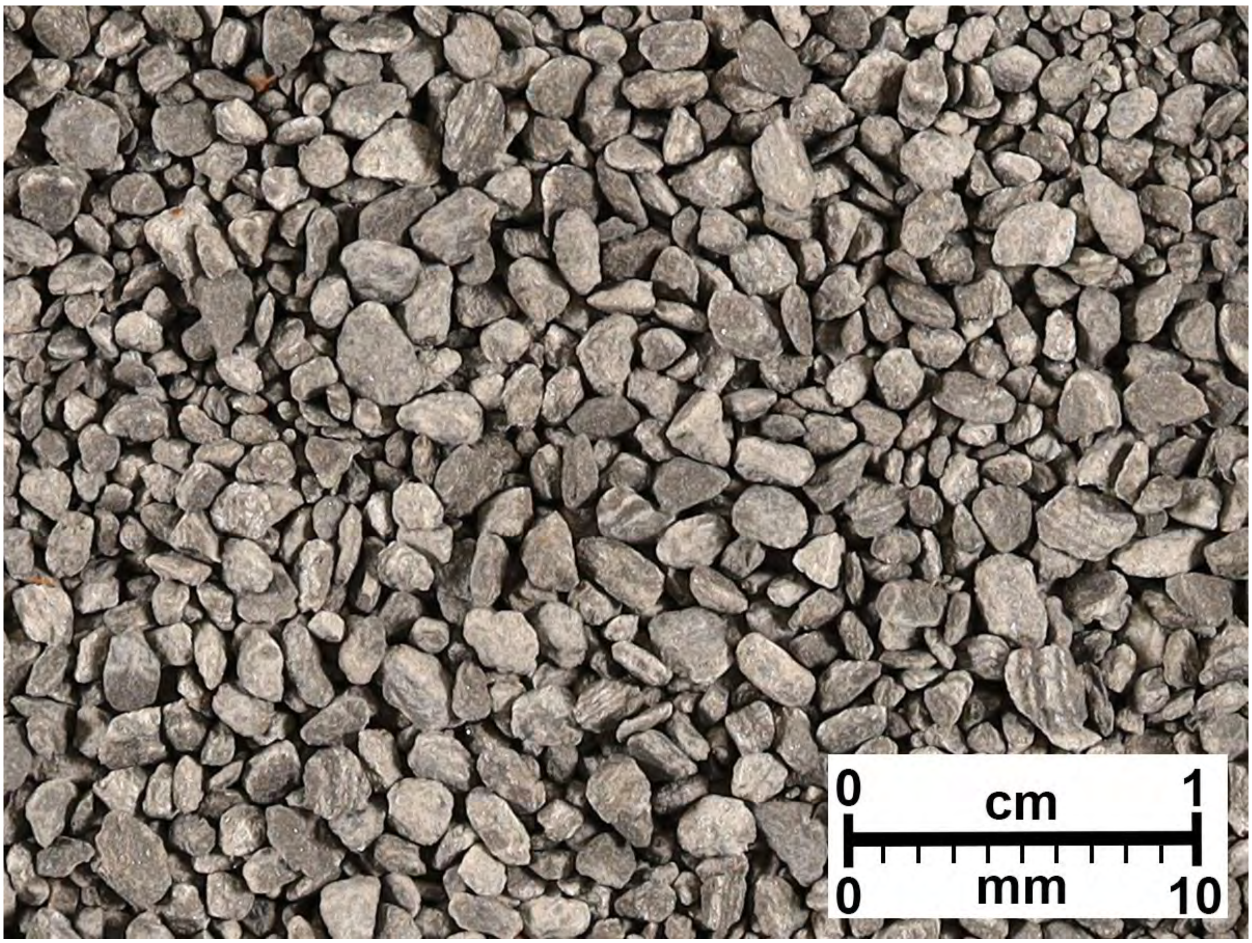

Figure A1. Shale, medium to dark gray to gray-brown, slightly silty in part, soft to medium firm, platy to blocky; relatively small-sized cuttings.

Naturita (Dakota) Formation

Grand Wash Fault Unit 14-24
Section 24, T. 21 S., R. 15 E., SLBL&M, Emery Co., Utah
API No.: 43-015-11182

610–620 feet

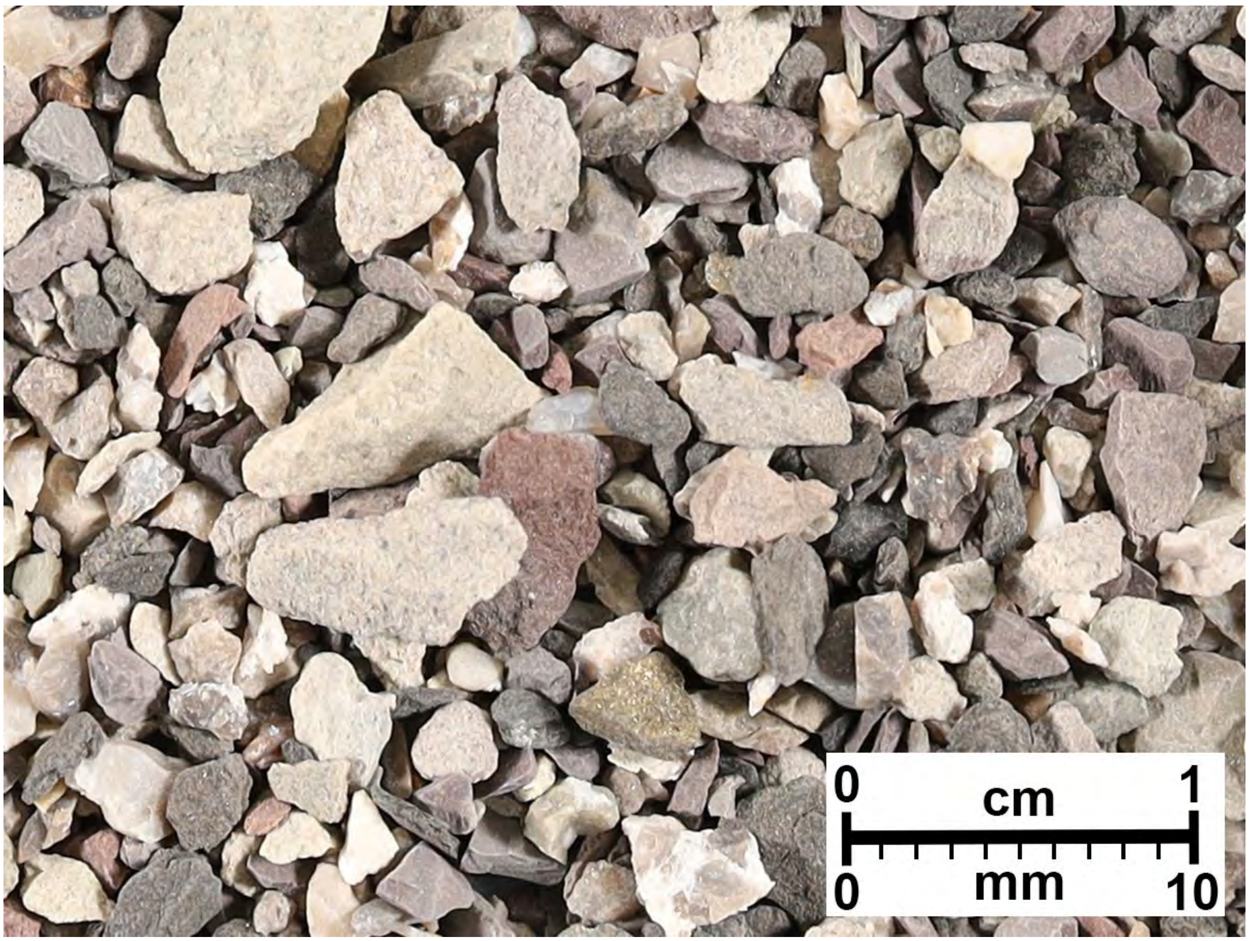

Figure A2. Sandstone, light to dark gray or tan to orange-gray or light purple, very fine to fine grained, friable, sub-angular to rounded, moderate to well sorted, occasional iron staining; shale, light to dark gray, platy, occasionally carbonaceous; distinctively larger and variable sized cuttings than the Mancos Shale above.

Cedar Mountain Formation, Ruby Ranch Member

Grand Wash Fault Unit 14-24
Section 24, T. 21 S., R. 15 E., SLBL&M, Emery Co., Utah
API No.: 43-015-11182

630–640 feet

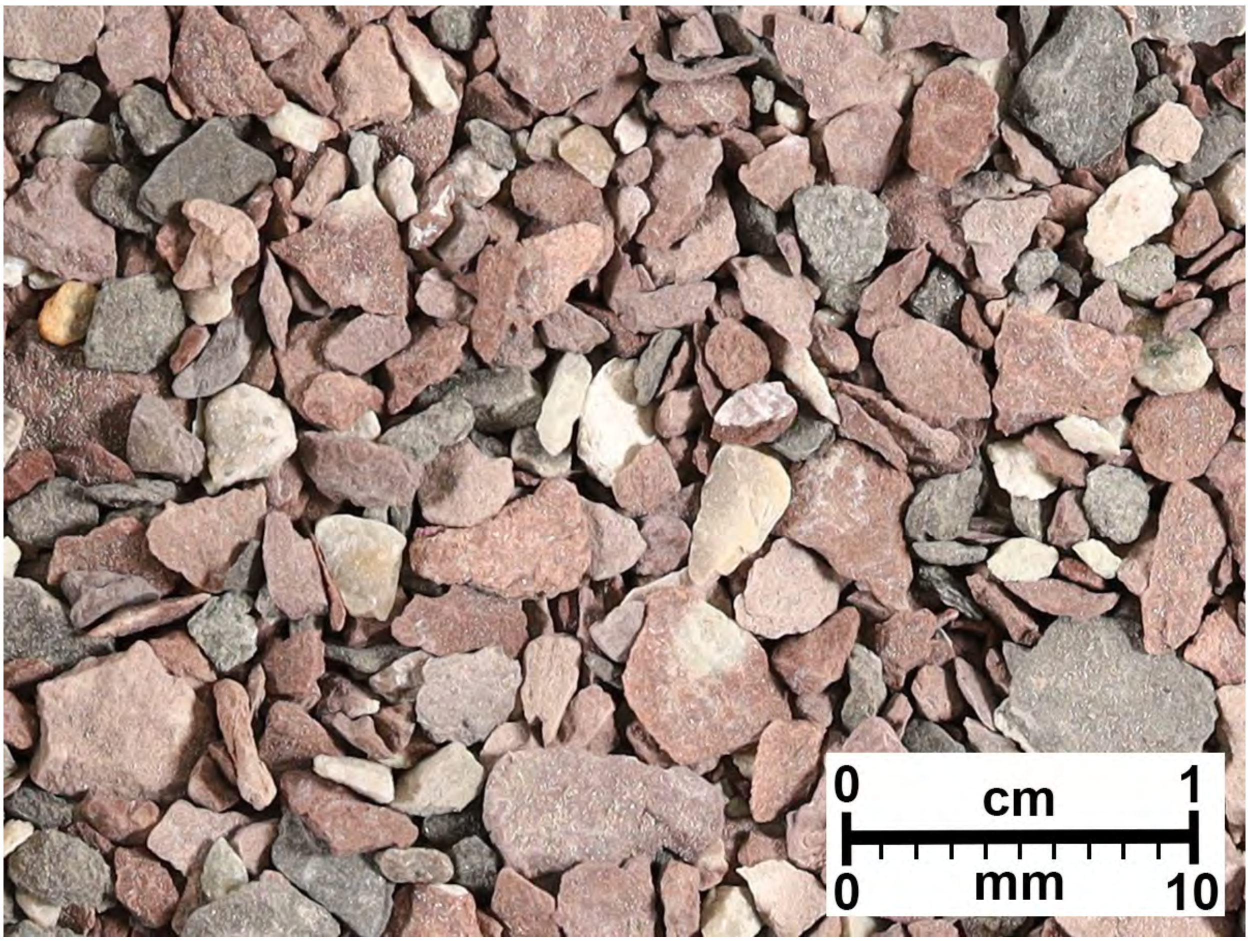

Figure A3. Mudstone/shale, dark red and reddish to purplish orange, soft, clayey to silty, platy; sandstone, tan to gray, very fine to fine grained, sub-angular to sub-rounded, poorly sorted; occasional limestone from limestone nodules; contact with underlying Brushy Basin Member of the Morrison Formation difficult to recognize with cuttings as well as in outcrop when the basal Buckhorn Conglomerate Member is absent because they have near-identical characteristics.

Morrison Formation, Salt Wash Member

Grand Wash Fault Unit 14-24
Section 24, T. 21 S., R. 15 E., SLBL&M, Emery Co., Utah
API No.: 43-015-11182

910–920 feet

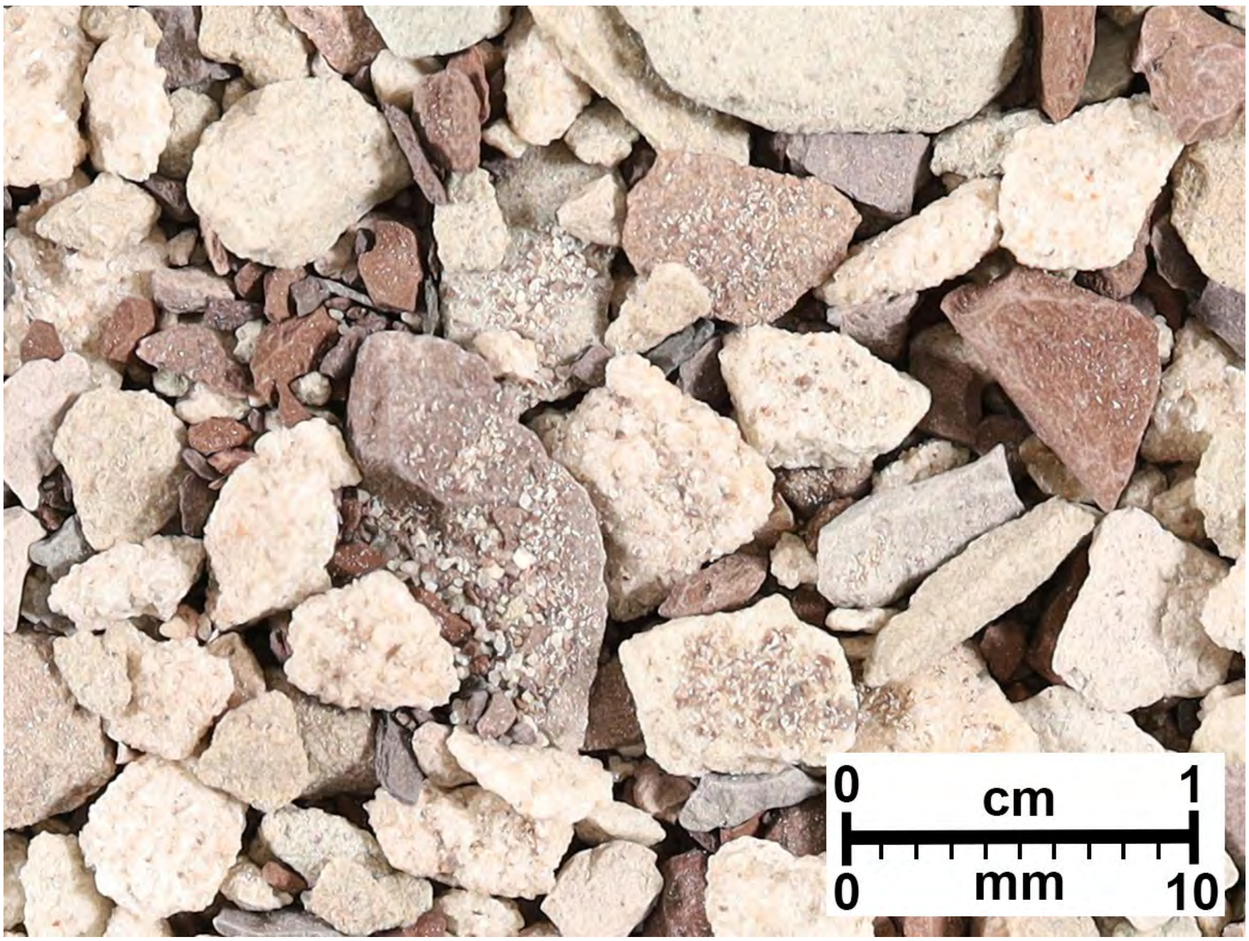

Figure A4. Sandstone, buff to white to light red, quartzose, very fine to coarse grained, friable to well cemented, sub-angular to well rounded, moderate to well sorted, calcareous cement.

Summerville Formation

Green River Unit 1
Section 2, T. 22 S., R. 16 E., SLBL&M, Grand Co., Utah
API No.: 43-019-10030

645–650 feet

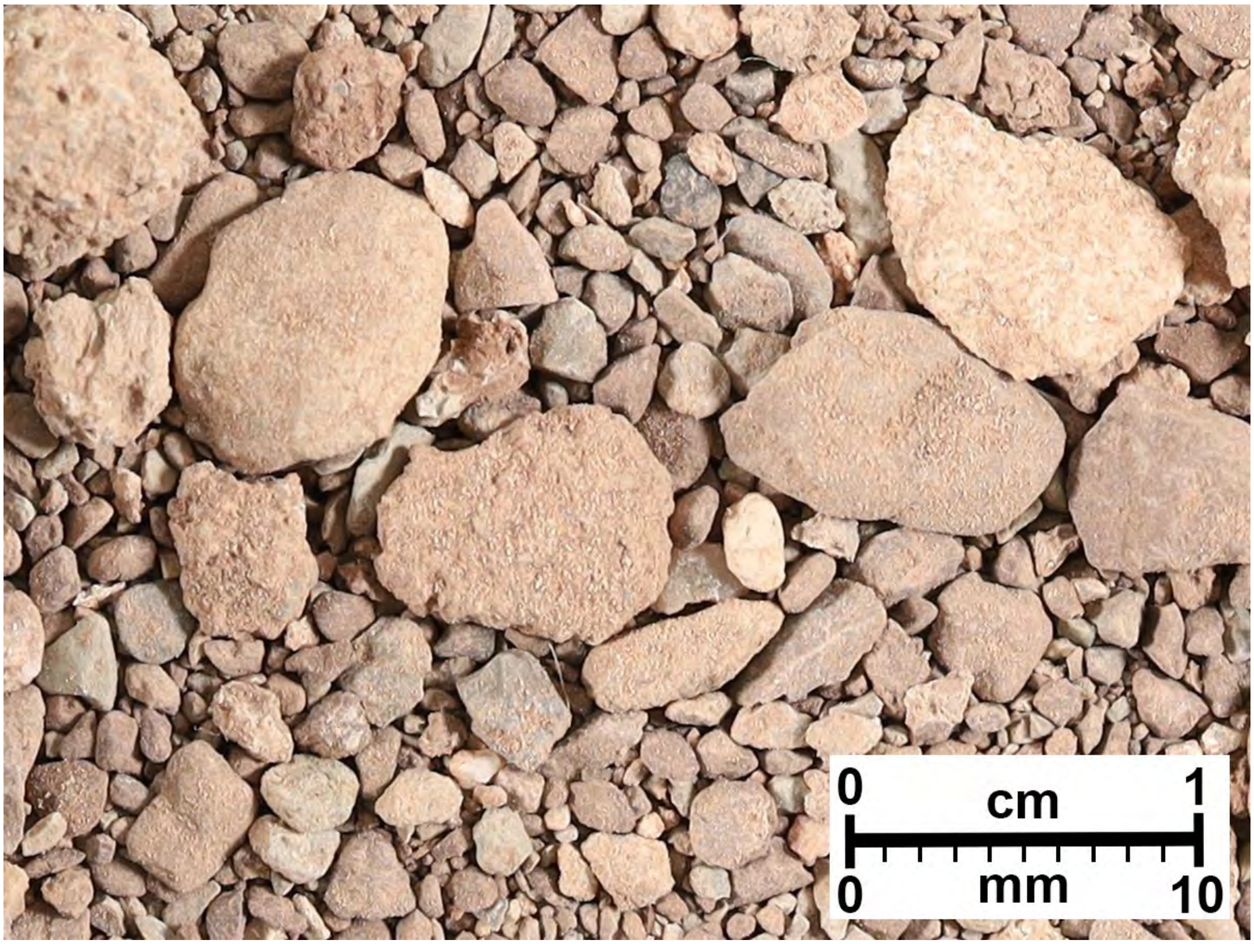

Figure A5. Mudstone/shale, light brown-red, sandy to clayey, platy to blocky; siltstone to sandstone, pale red, very fine to fine grained, granular, calcareous; some gray limestone.

Curtis Formation

Green River Unit 1
Section 2, T. 22 S., R. 16 E., SLBL&M, Grand Co., Utah
API No.: 43-019-10030

790–795 feet

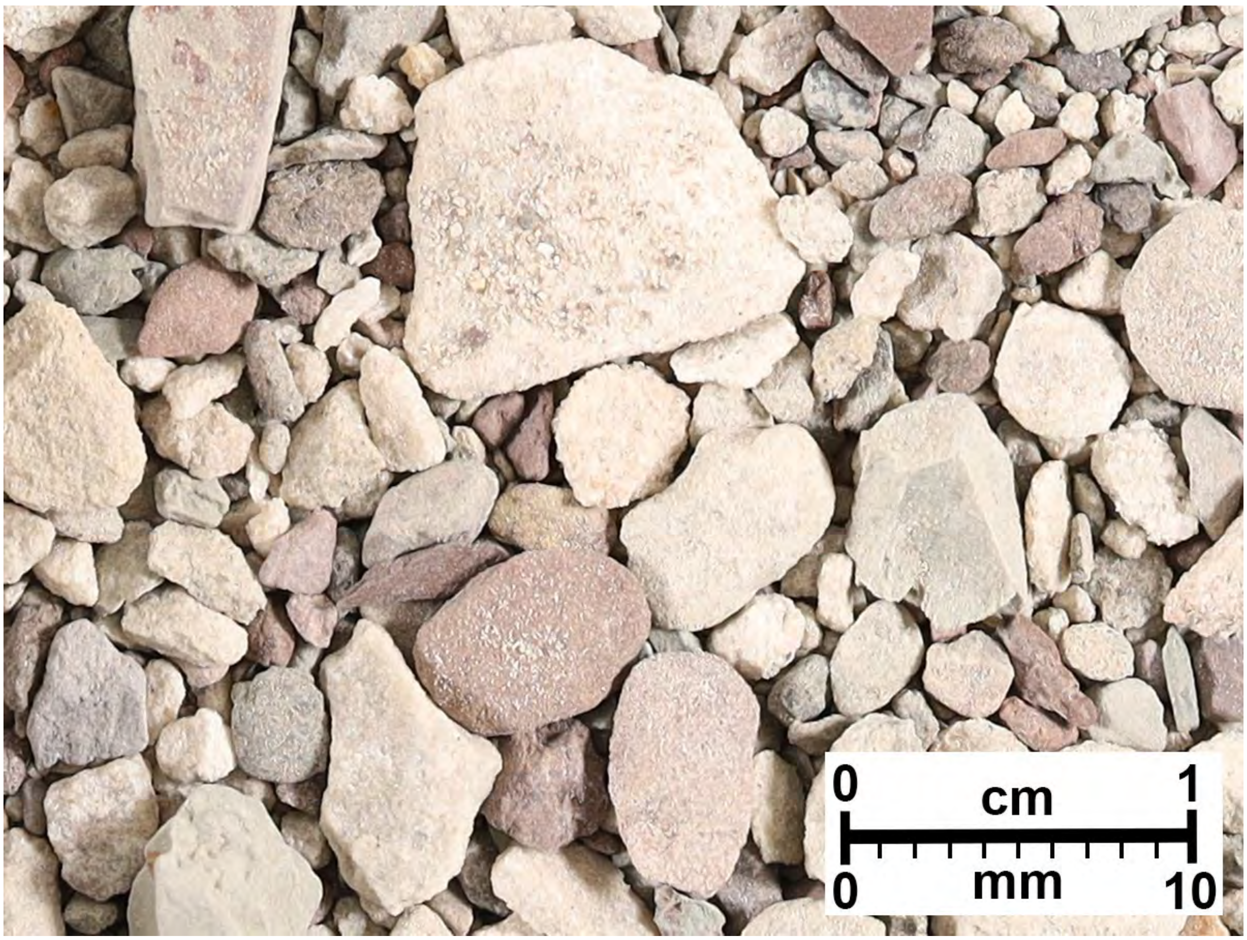

Figure A6. Sandstone, cream to pale red to greenish gray, quartzose, very fine to medium grained, poorly to moderately sorted, sub-rounded to sub-angular, calcite to dolomitic cement; claystone/shale, light gray to greenish gray.

Entrada Sandstone

Green River Unit 1
Section 2, T. 22 S., R. 16 E., SLBL&M, Grand Co., Utah
API No.: 43-019-10030

1000–1005 feet

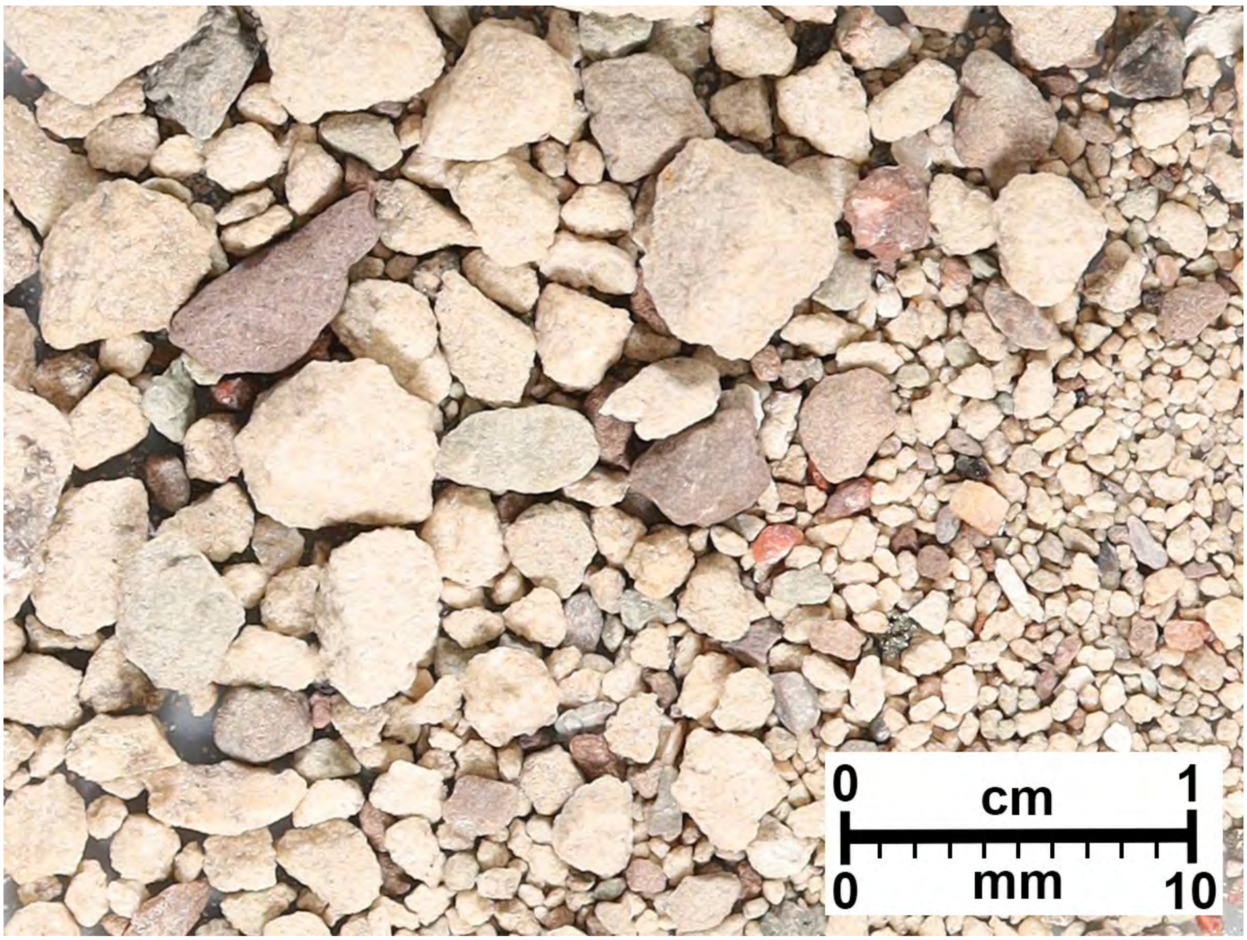

Figure A7. Sandstone, pinkish cream, quartzose, friable, silty, very fine to medium grained, poorly to moderately sorted, good porosity, sub-rounded to rounded; cuttings consist of variable sizes.

Carmel Formation

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

1620–1650 feet

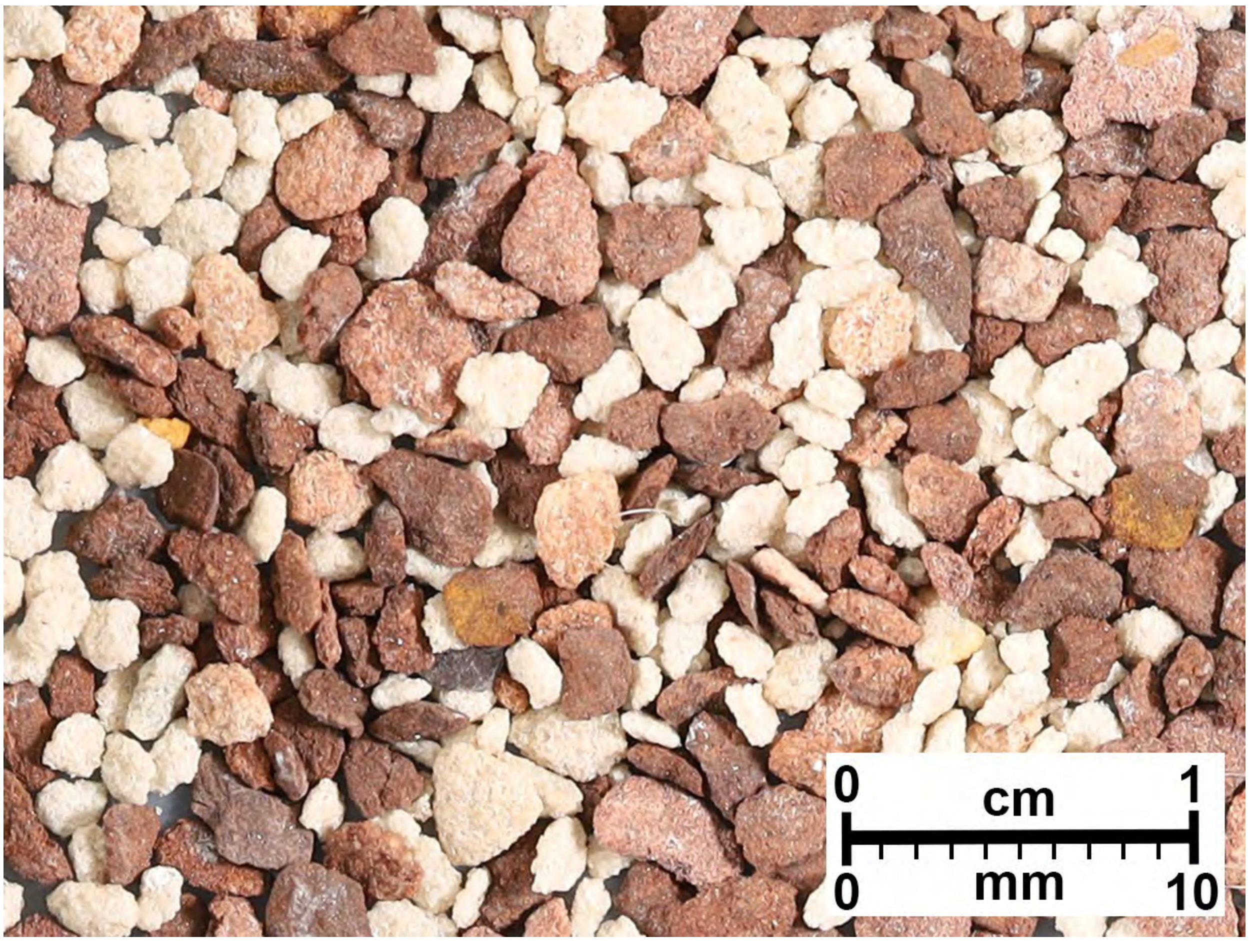

Figure A8. Sandstone (80%), translucent, light orange to pink, friable to firm in part, fine to medium grained, rounded to sub-angular, moderately to poorly sorted, calcareous cement; shale (20%), red-brown, firm, earthy to silty, sandy in part, slightly calcareous, grading to interbedded silts; probably represents the basal Judd Hollow Member of the Carmel Formation.

Navajo Sandstone

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

1650–1700 feet

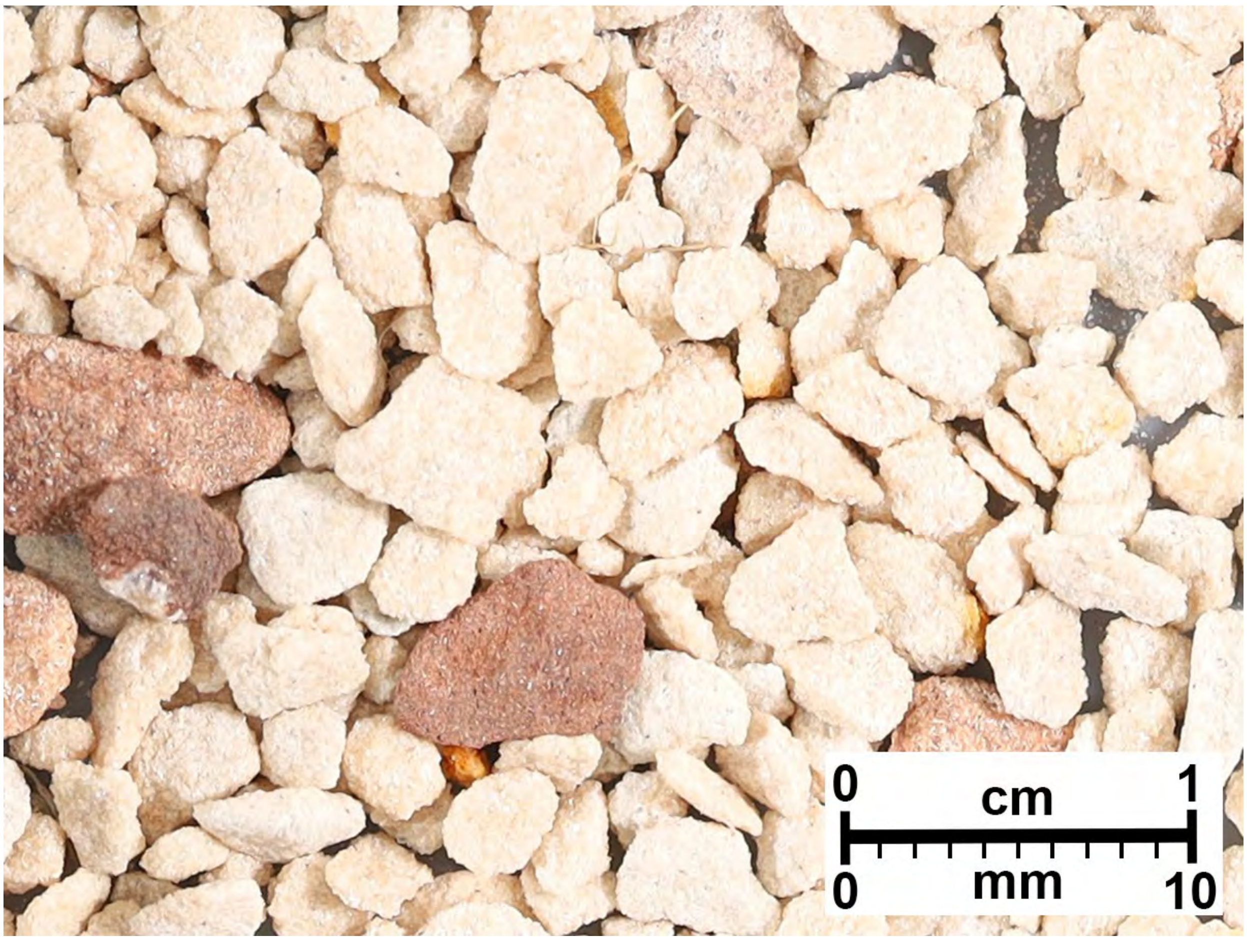

Figure A9. Sandstone, quartzose, translucent, white to light orange, firm to friable in part, fine to medium grained, frosted, rounded to sub-angular, well sorted, good intergranular porosity, calcareous cement.

Kayenta Formation

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

2050–2100 feet

Figure A10. Sandstone, quartzose, pale orange-brown colored, fine grained, friable, well sorted, moderate to good intergranular porosity, siliceous to slightly calcareous cement, occasional red-brown silty matrix.

Wingate Sandstone

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

2200–2250 feet

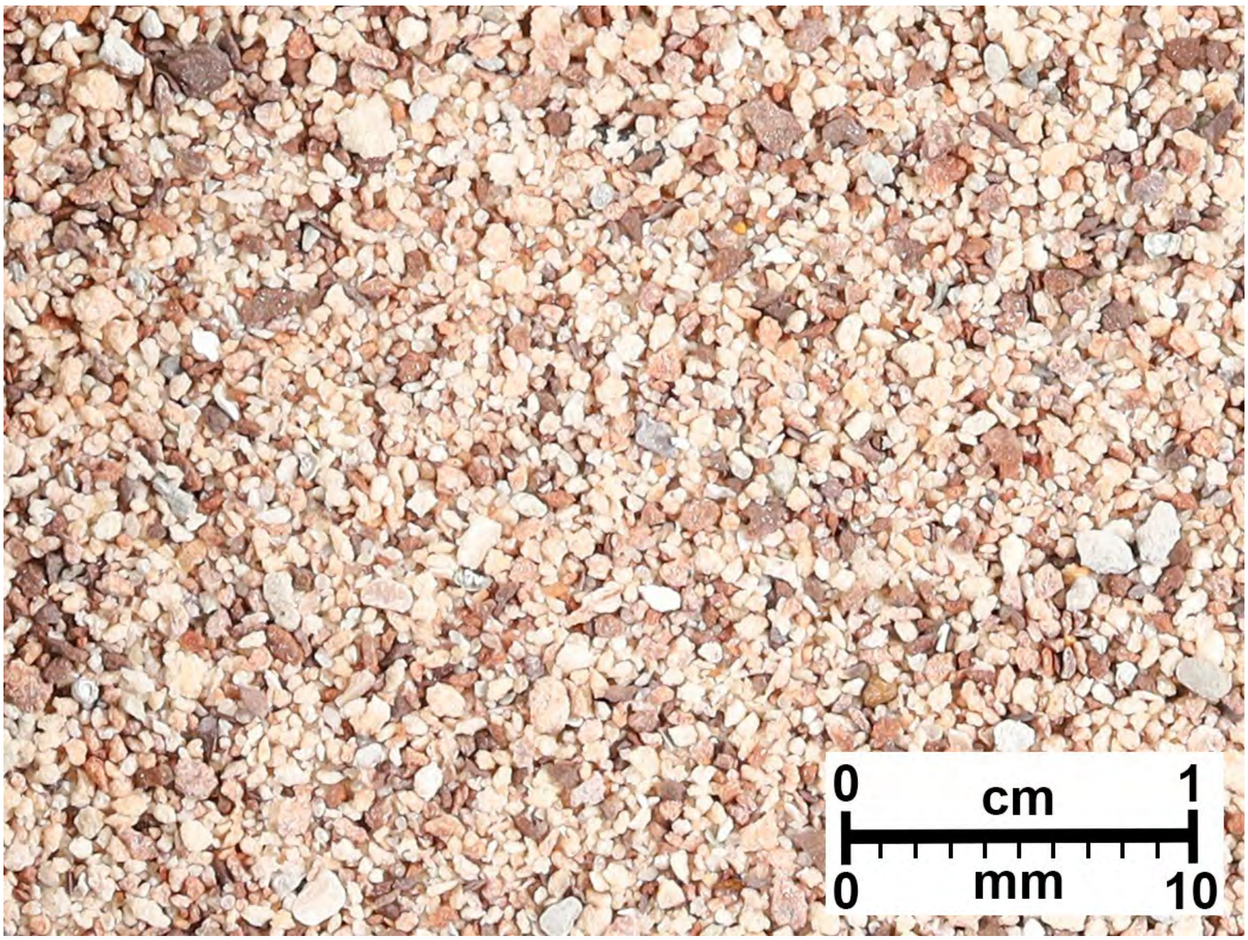

Figure A11. Sandstone, quartzose, light orange-brown to white, very fine to fine grained, sub-angular to rounded, distinctively smaller sized cuttings than the Navajo Sandstone or Kayenta Formation above.

Chinle Formation, Church Rock Member

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

2650–2700 feet

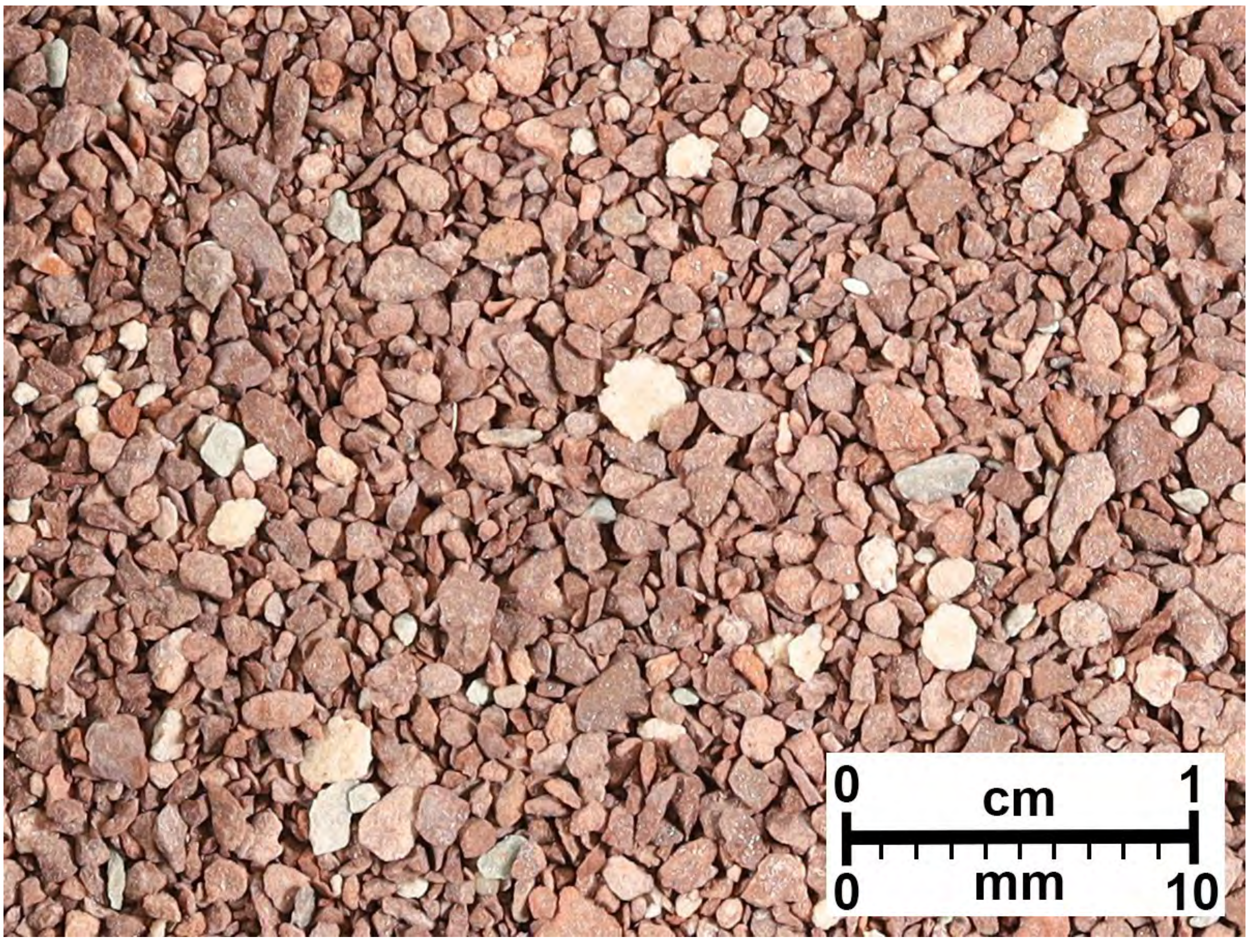

Figure A12. Shale, silty in part, red-brown, calcareous mottling, blocky, firm to brittle, grading to siltstone, possible rare fossil fragments; distinctively small-sized cuttings.

Chinle Formation, Moss Back Member

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

2850–2900 feet

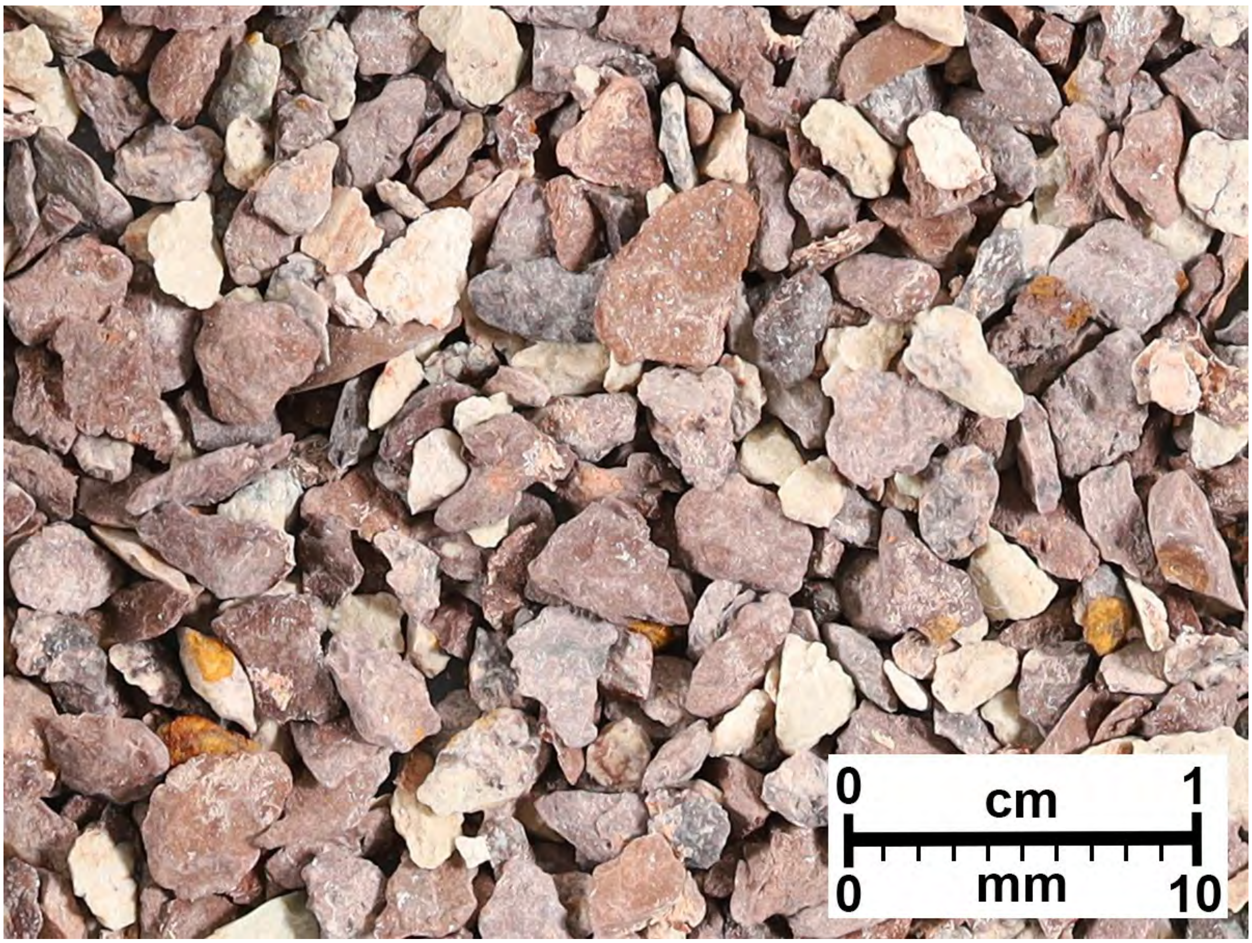

Figure A13. Sandstone, red-brown to purplish-brown to off white, fine grained, firm, sub-angular to sub-rounded, well sorted, argillaceous matrix in part, calcareous, trace of conglomerate; distinctively larger-sized cuttings than the Church Rock Member above.

Moenkopi Formation, Moody Canyon Member

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

2950–3000 feet

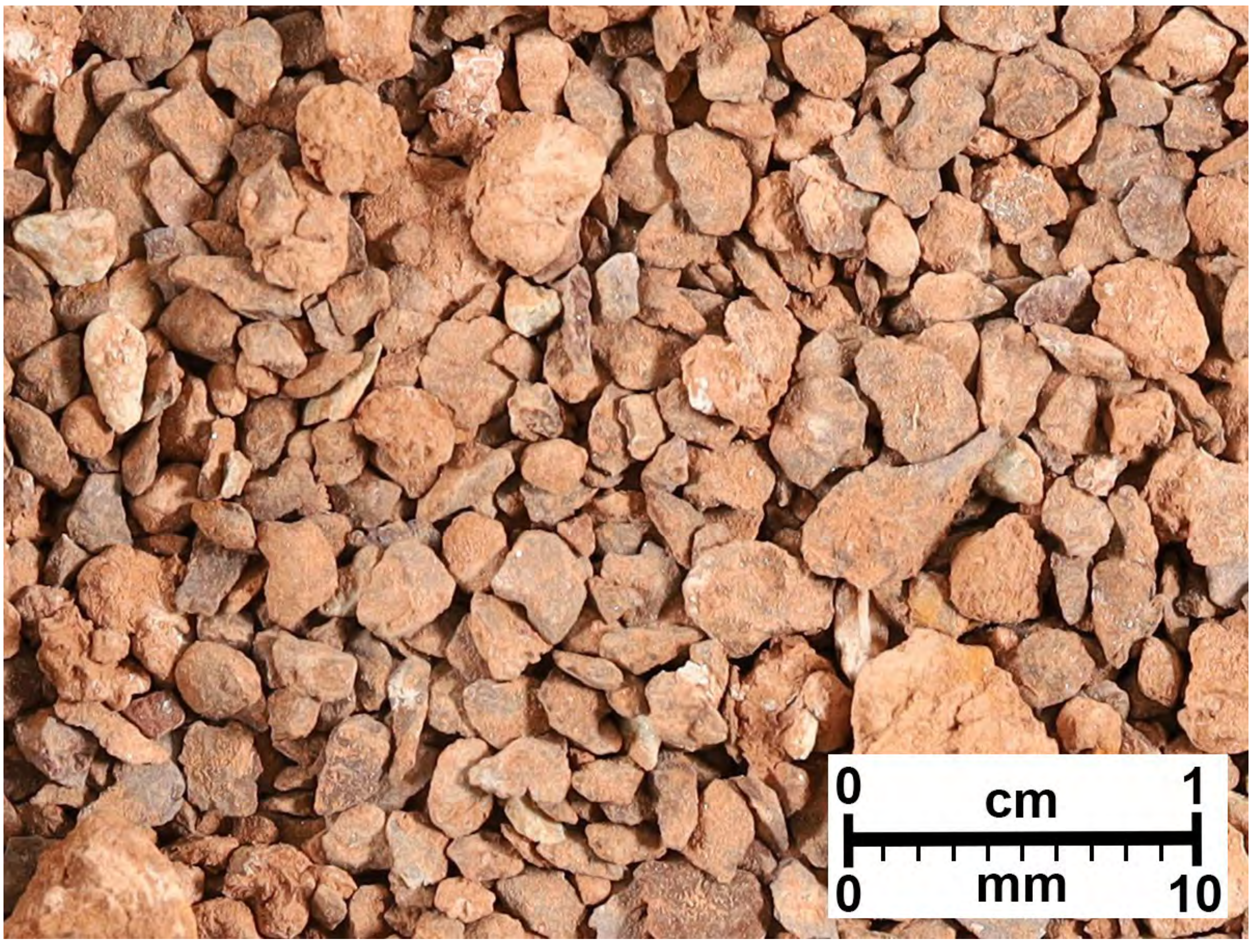

Figure A14. Sandstone, light orange-brown to light brown, firm to slightly hard, fine to very fine grained, sub-angular to sub-rounded, red-brown argillaceous matrix in part, calcareous.

Moenkopi Formation, Sinbad Limestone Member

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

3450–3500 feet

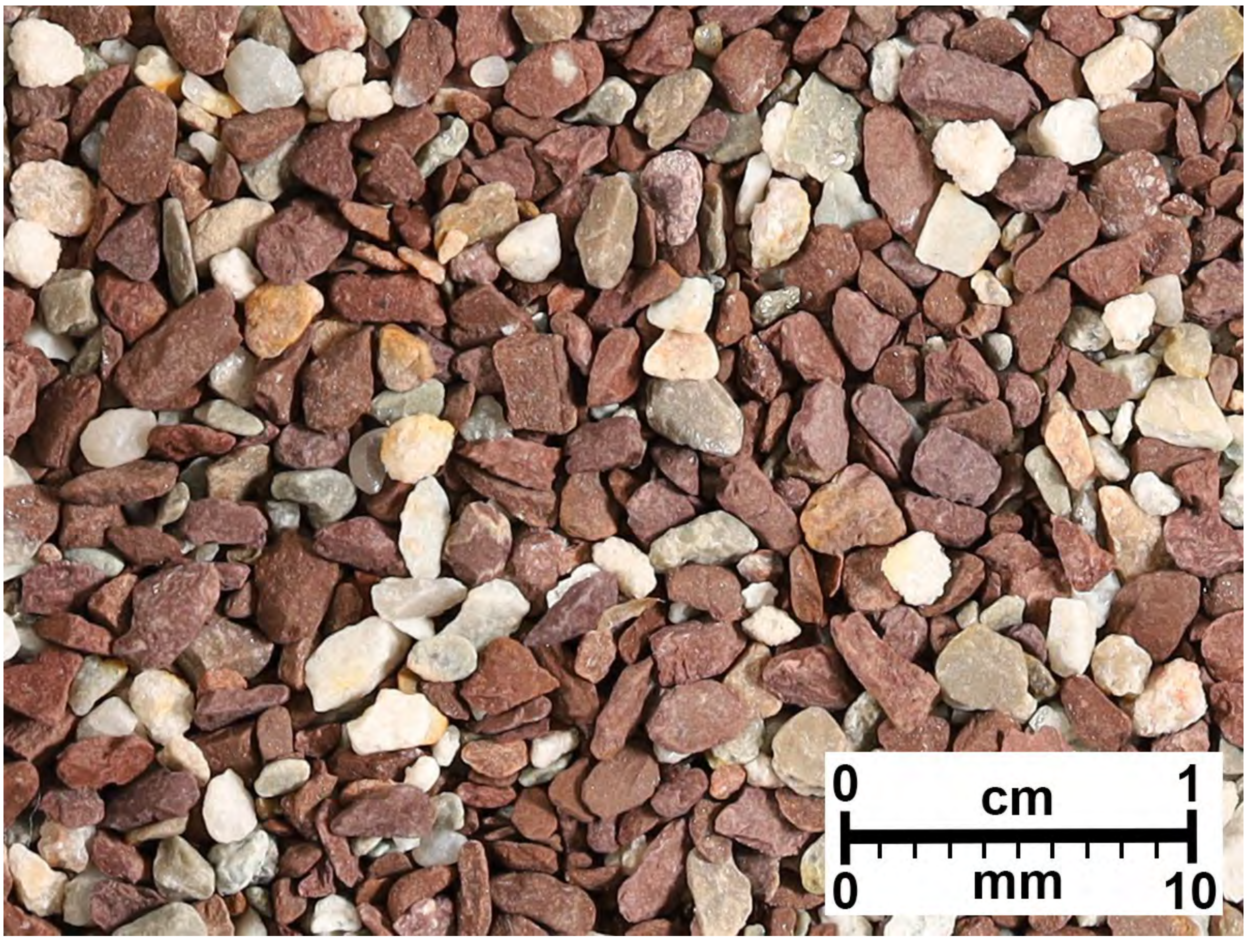

Figure A15. Shale, brown, blocky to platy, silty in part grading to siltstone; limestone, translucent to white, clean crystalline calcite, occasionally sandy.

Moenkopi Formation, Black Dragon Member

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

3500–3550 feet

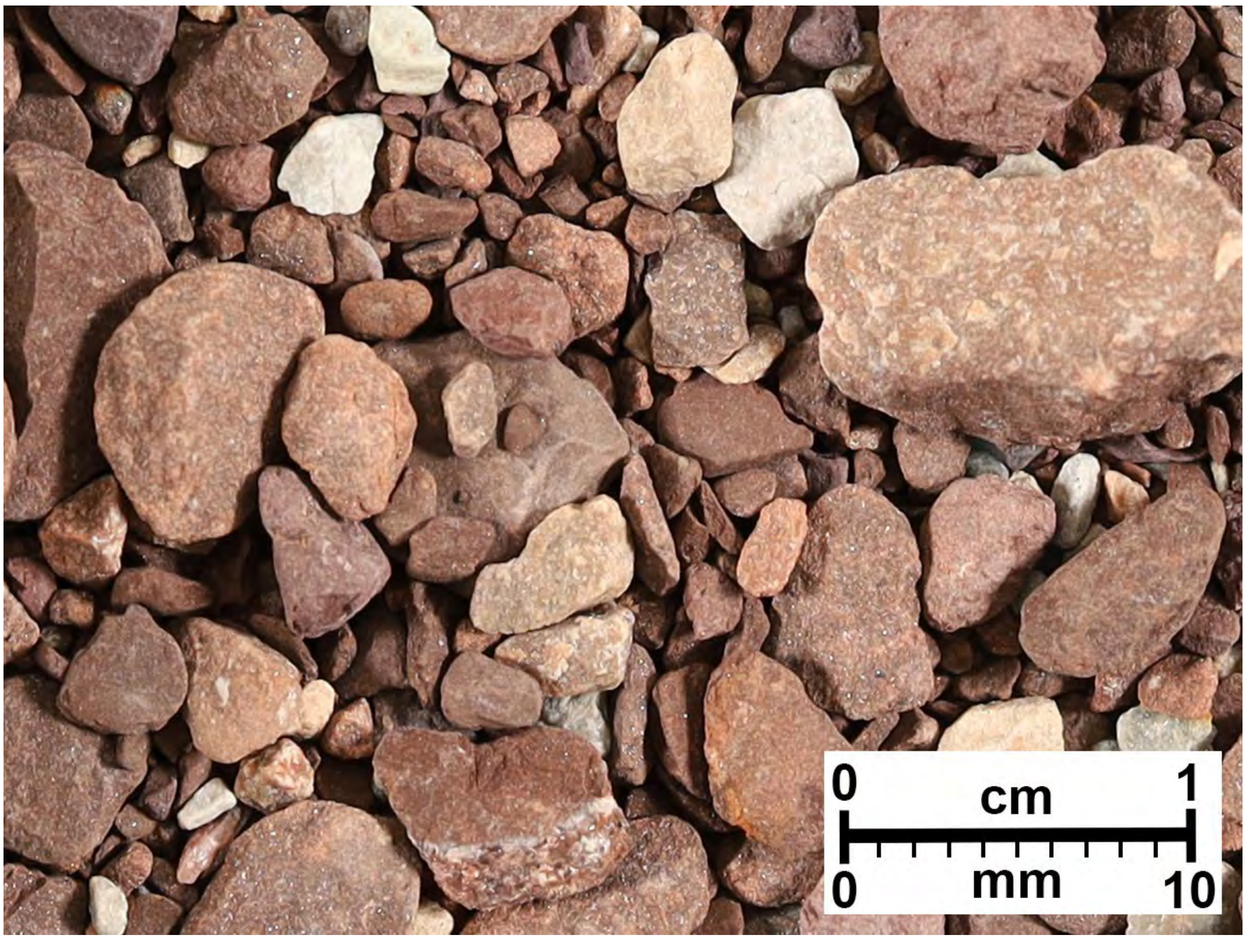

Figure A16. Sandstone, white to reddish-brown, quartzose, clean, medium to fine grained, poorly to moderately sorted, calcite and silica cement; distinctively larger-sized cuttings than the Sinbad Limestone above.

Black Box Dolomite

Jakey's Ridge 34-15
Section 15, T. 23 S., R. 16 E., SLBL&M, Emery Co., Utah
API No.: 43-015-10737

2440–2460 feet

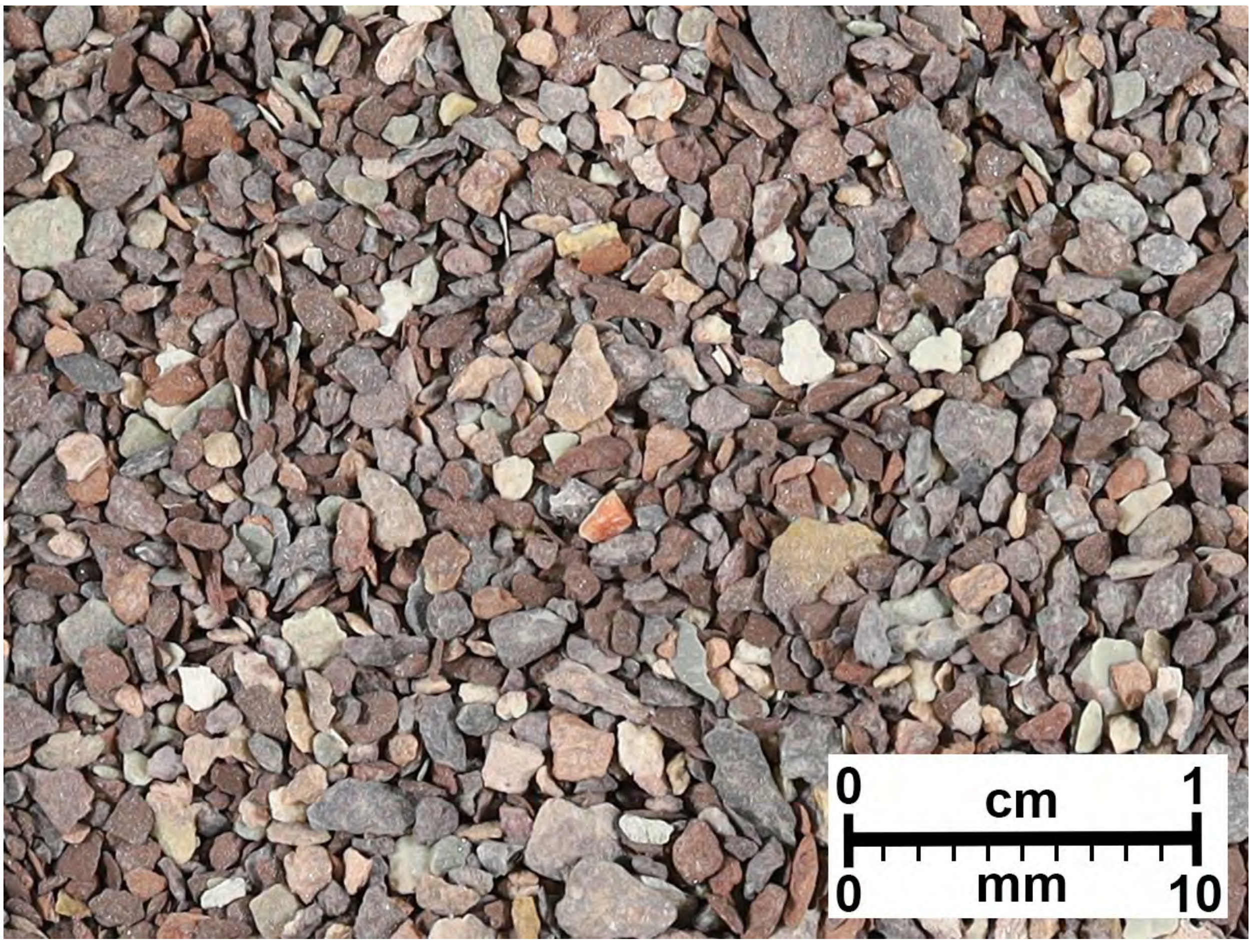

Figure A17. Dolomite, gray to light gray, platy, finely crystalline, noncalcareous (dolomite), no visible porosity, some possible chert; distinctively smaller-sized cuttings than the Black Dragon Member of the Moenkopi Formation above.

White Rim Sandstone

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

3600–3650 feet

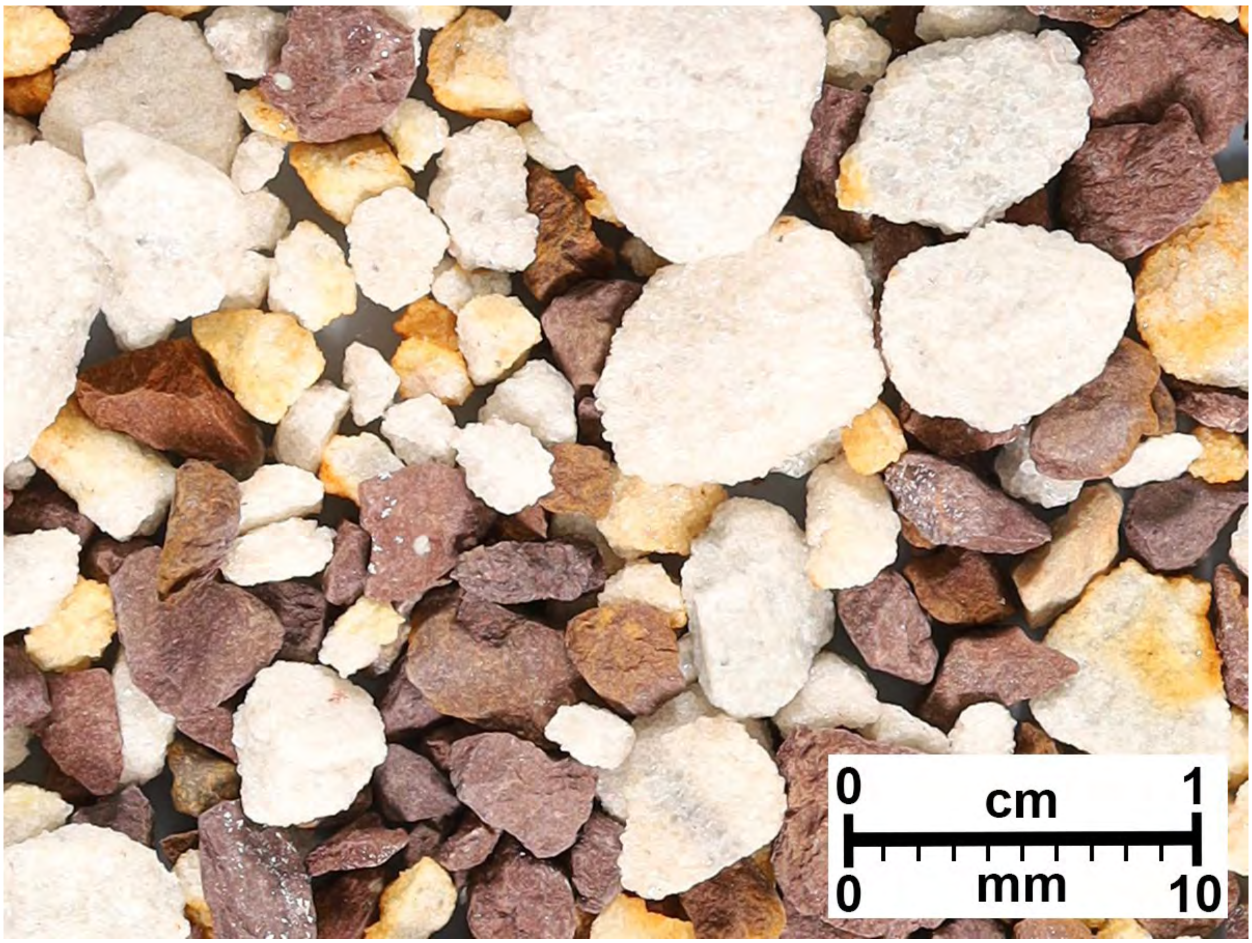

Figure A18. Sandstone, white to translucent, quartzose, fine to medium grained, frosted, hard to firm, sub-angular to sub-rounded, moderately to well sorted, calcareous cement, trace of very fine pyrite.

Organ Rock Formation

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

3900–3950 feet

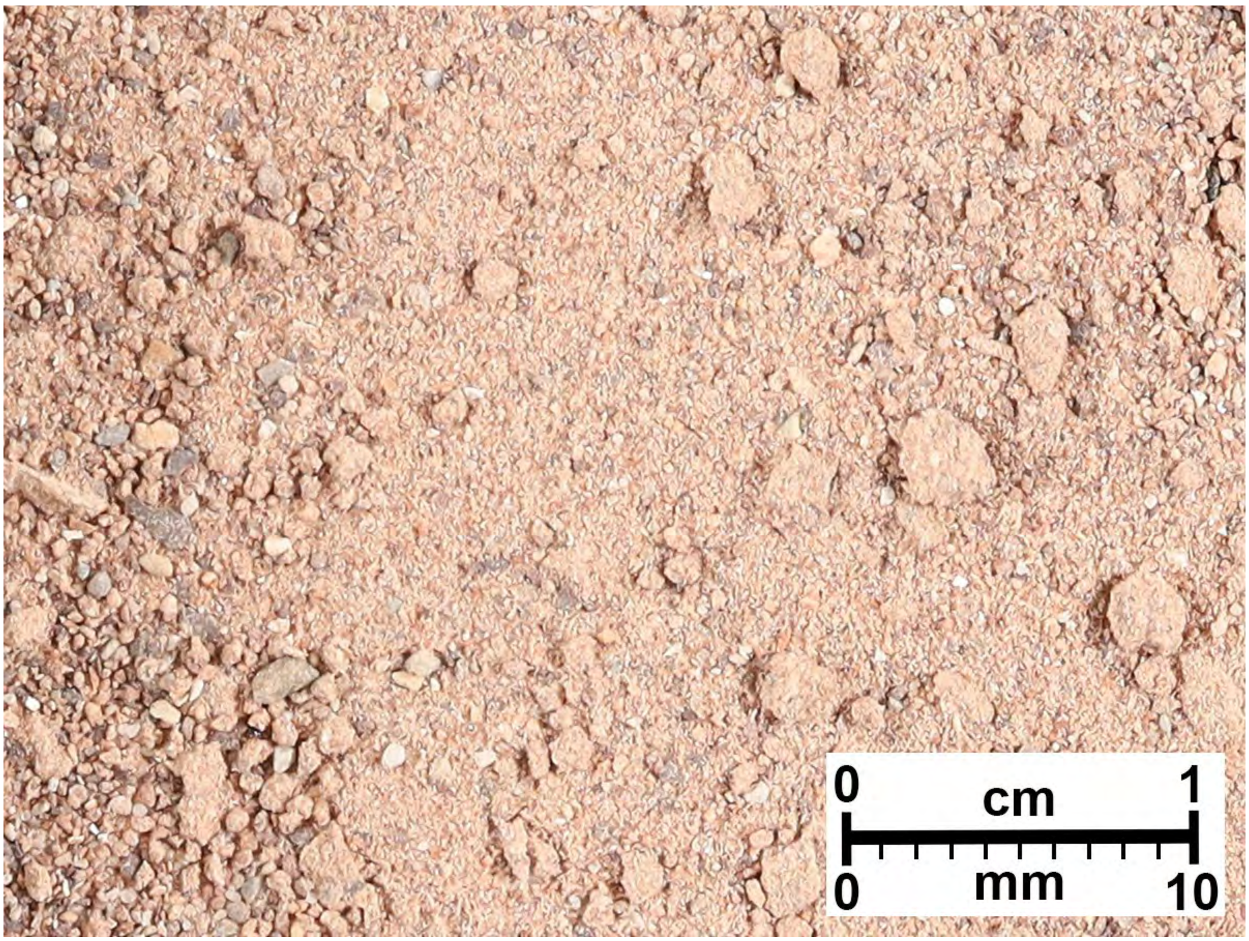

Figure A19. Sandstone, moderate to abundant orange-brown matrix, very fine to medium grained, rounded to sub-rounded, calcareous cement, occasional sandy limestone in part; siltstone grading to shale, orange brown to brown, slightly to very calcareous, abundant mica; distinctively very small sized cuttings.

Elephant Canyon Formation

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

4600–4650 feet

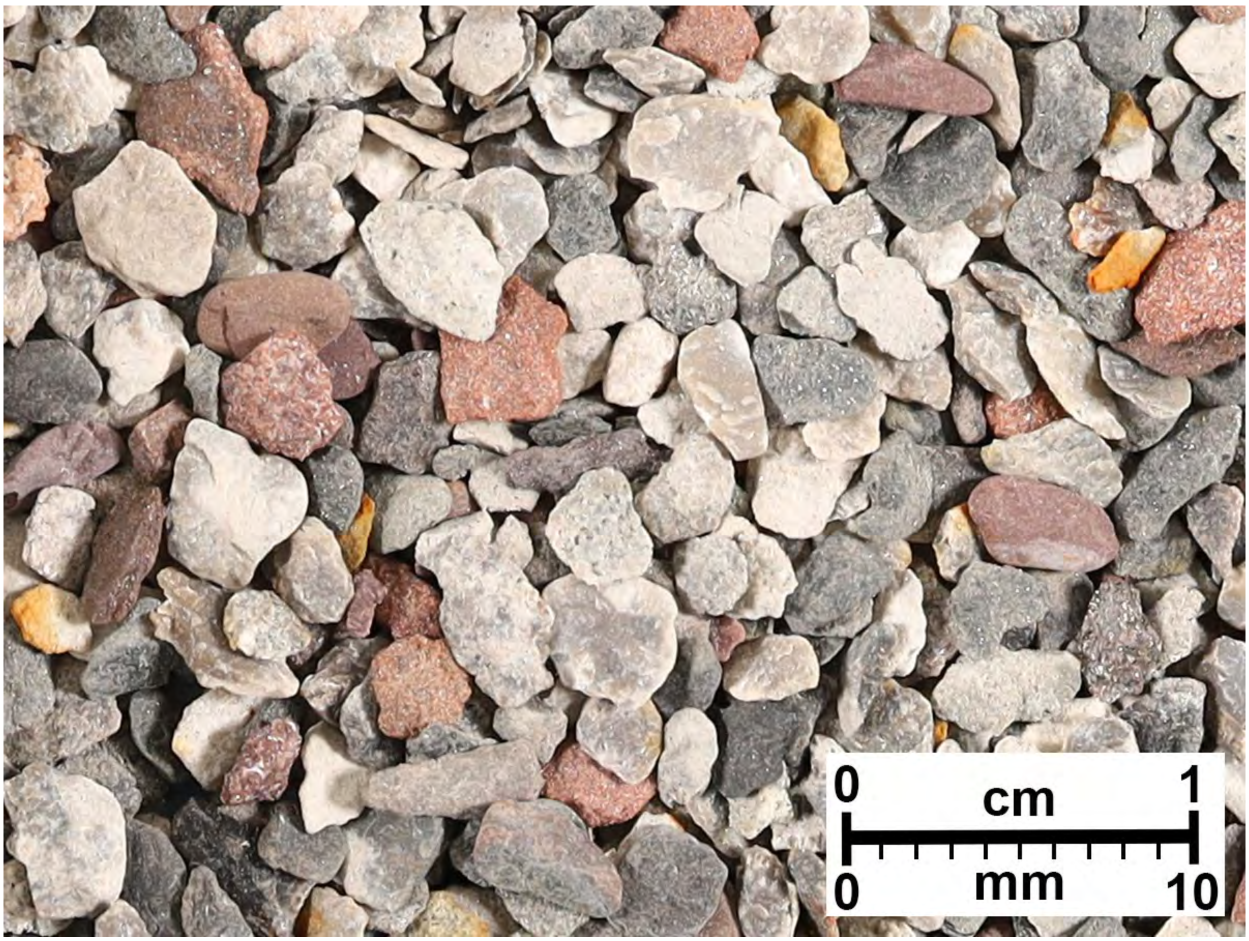

Figure A20. Limestone, dark gray to light gray to gray-brown, mudstone to wackestone, cryptocrystalline to microcrystalline, massive, calcareous; sandstone, red-brown to gray to light orange, translucent to frosted, firm to hard, fine to medium grained, sub-angular to sub-rounded, moderately to well sorted, calcareous cement, trace of dark gray shale.

Cutler Formation, Upper Member

Long Canyon 1
Section 9, T. 26 S., R. 19 E., SLBL&M, Grand Co., Utah
API No.: 43-019-15925

1362–1393 feet

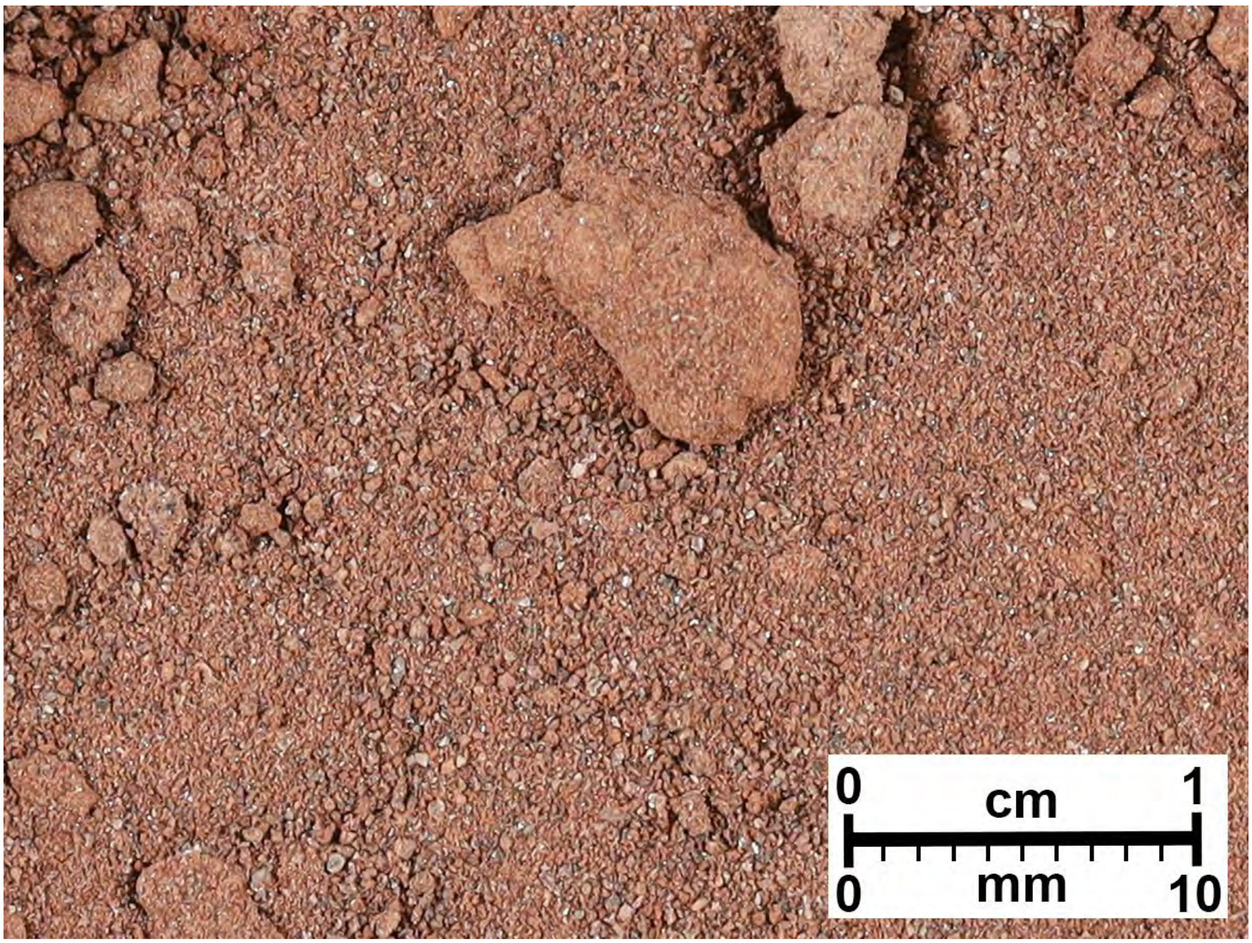

Figure A21. Arkose, dark red to orange, friable, very fine to medium grained, angular to sub-angular, moderately to well sorted, occasional small gray lithic fragments, calcareous cement; distinctively very small sized cuttings.

Cutler Formation, Lower Member

Long Canyon 1
Section 9, T. 26 S., R. 19 E., SLBL&M, Grand Co., Utah
API No.: 43-019-15925

2127–2158 feet

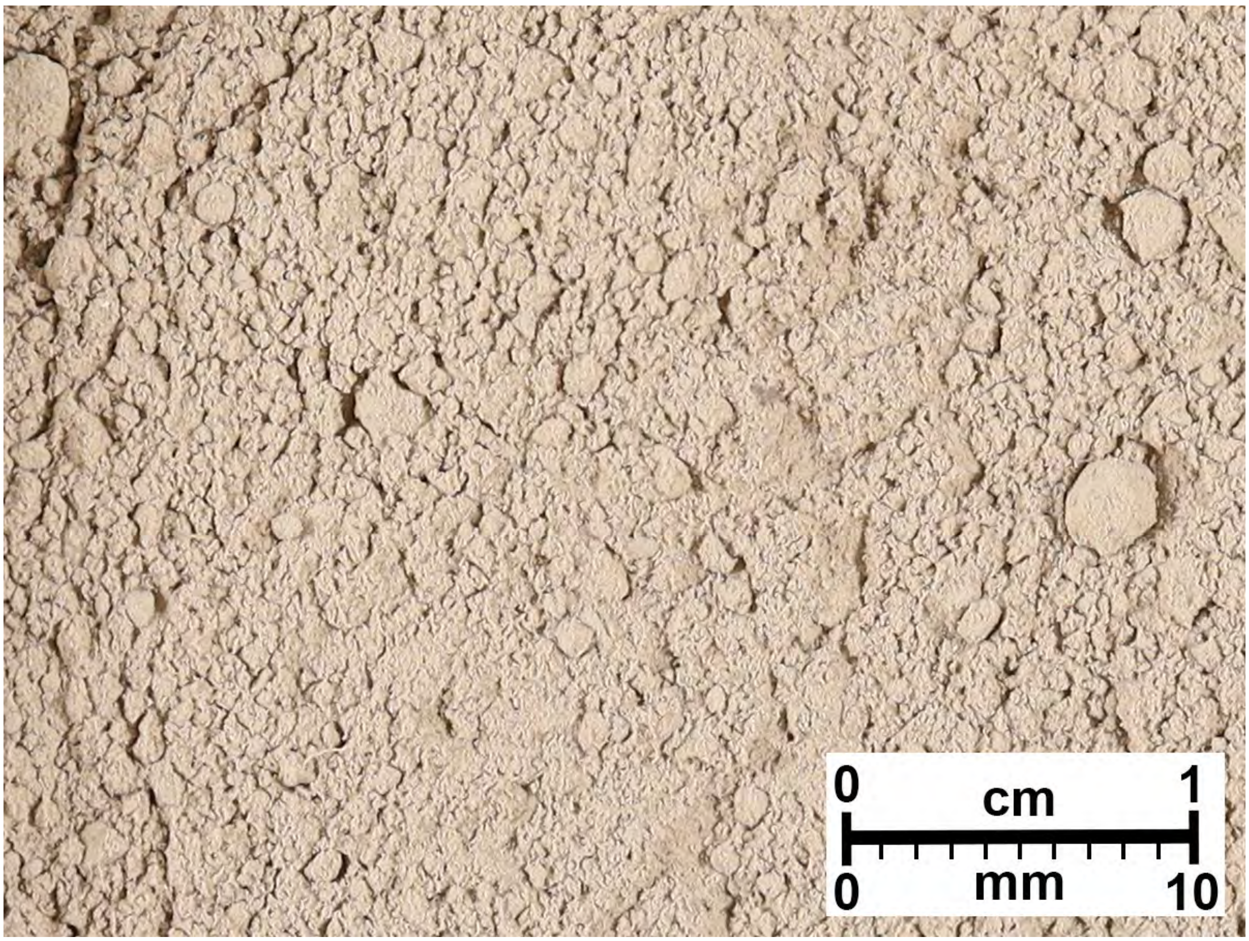

Figure A22. Limestone, light gray, friable, mudstone to wackestone, slightly argillaceous, calcareous; distinctively very small sized cuttings.

Honaker Trail Formation

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

5300–5350 feet

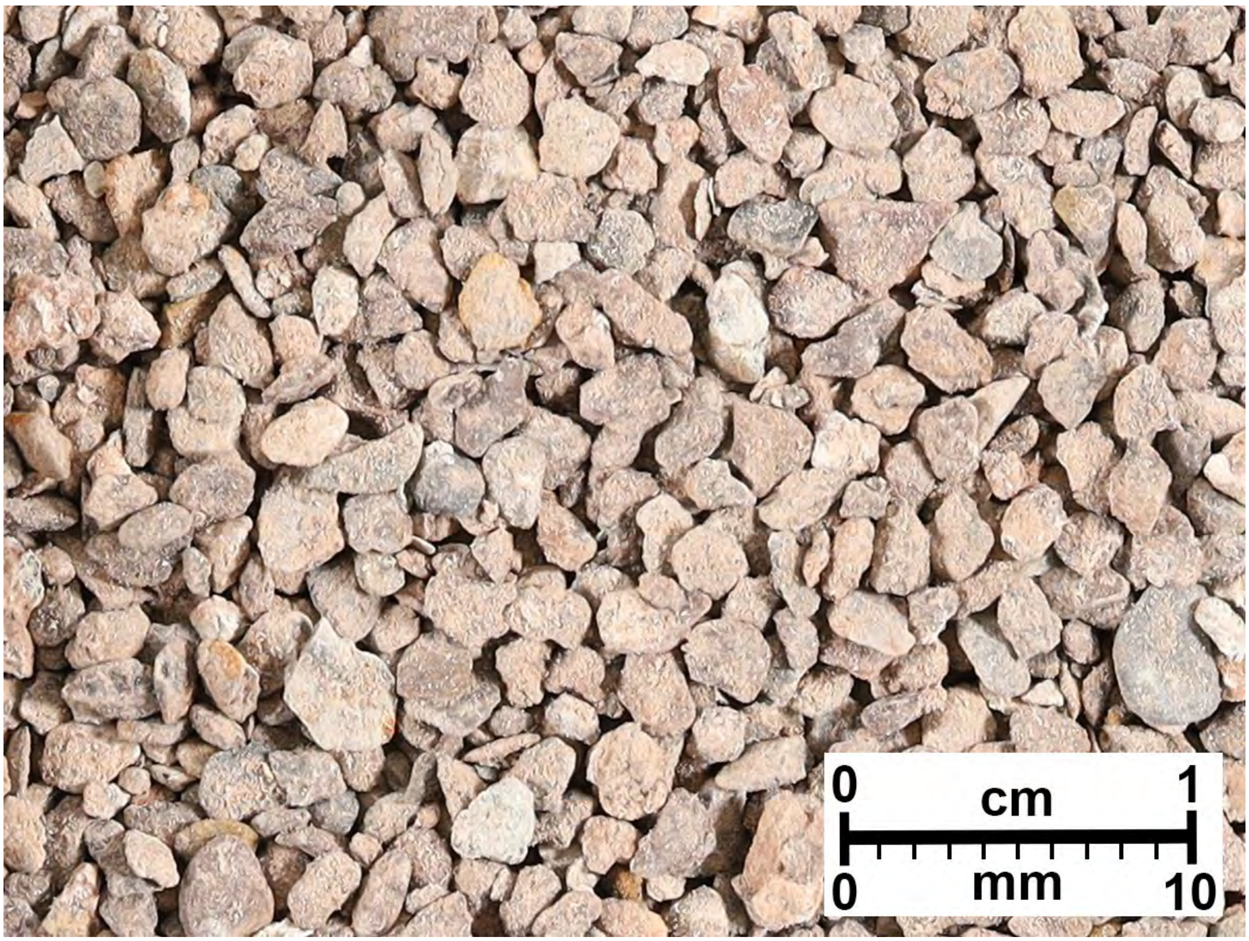

Figure A23. Siltstone, light brown to brown, slightly sandy in part, brown argillaceous matrix, occasional mica, calcareous; interbedded with limestone and sandstone; limestone, dark gray to brown-gray to gray, wackestone to mudstone, microcrystalline to cryptocrystalline, massive, calcareous; sandstone, light gray to translucent, frosted, firm, very fine to fine grained, sub-angular to sub-rounded, moderately to well sorted, calcareous cement.

Paradox Formation

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

6250–6300 feet

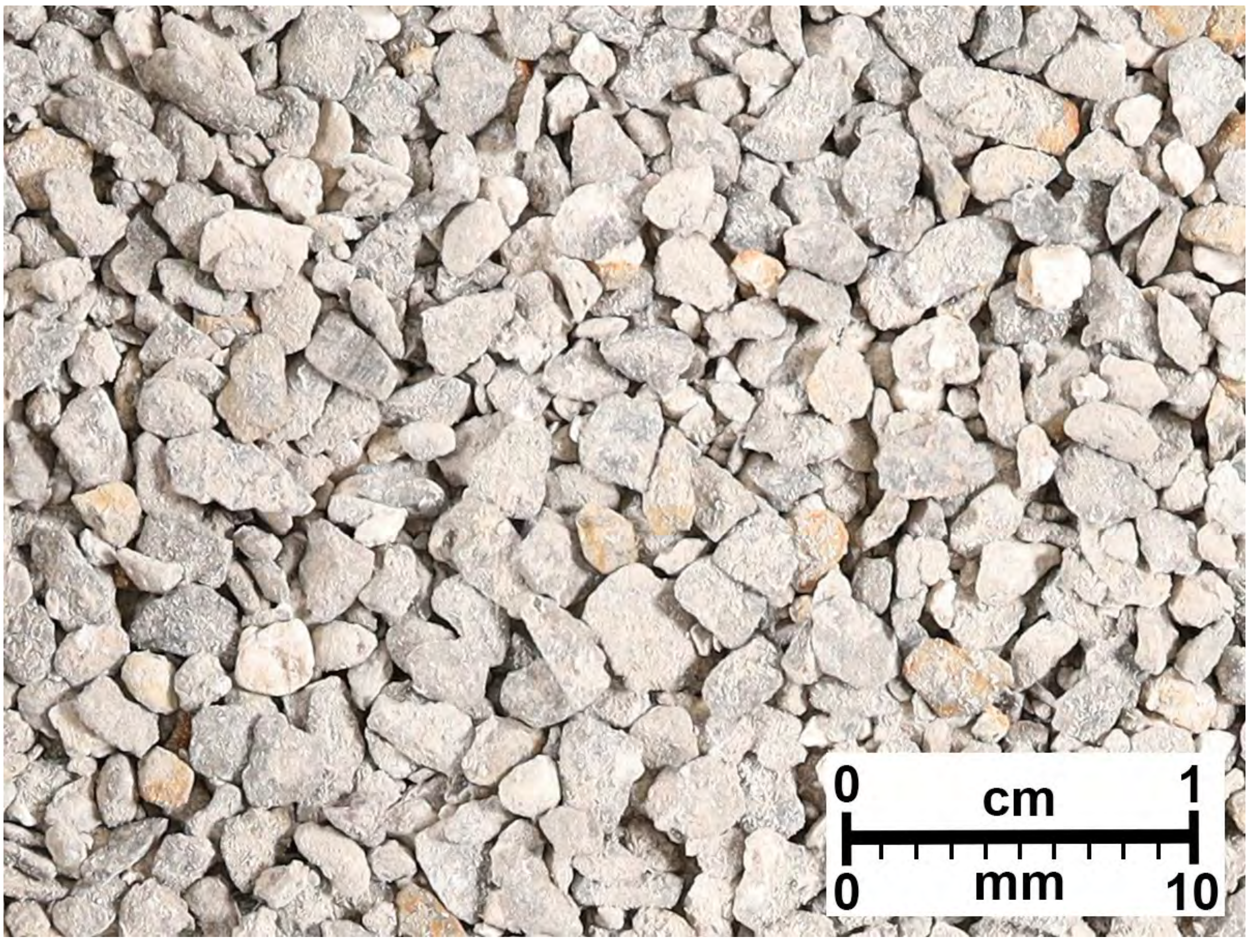

Figure A24. Dolomite, limestone in part, light to medium gray, laminated, microgranular to silty, slightly argillaceous, anhydrite blebs; anhydrite, white, soft.

Paradox Formation, Clastic Cycle 1A

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

6421–6432 feet

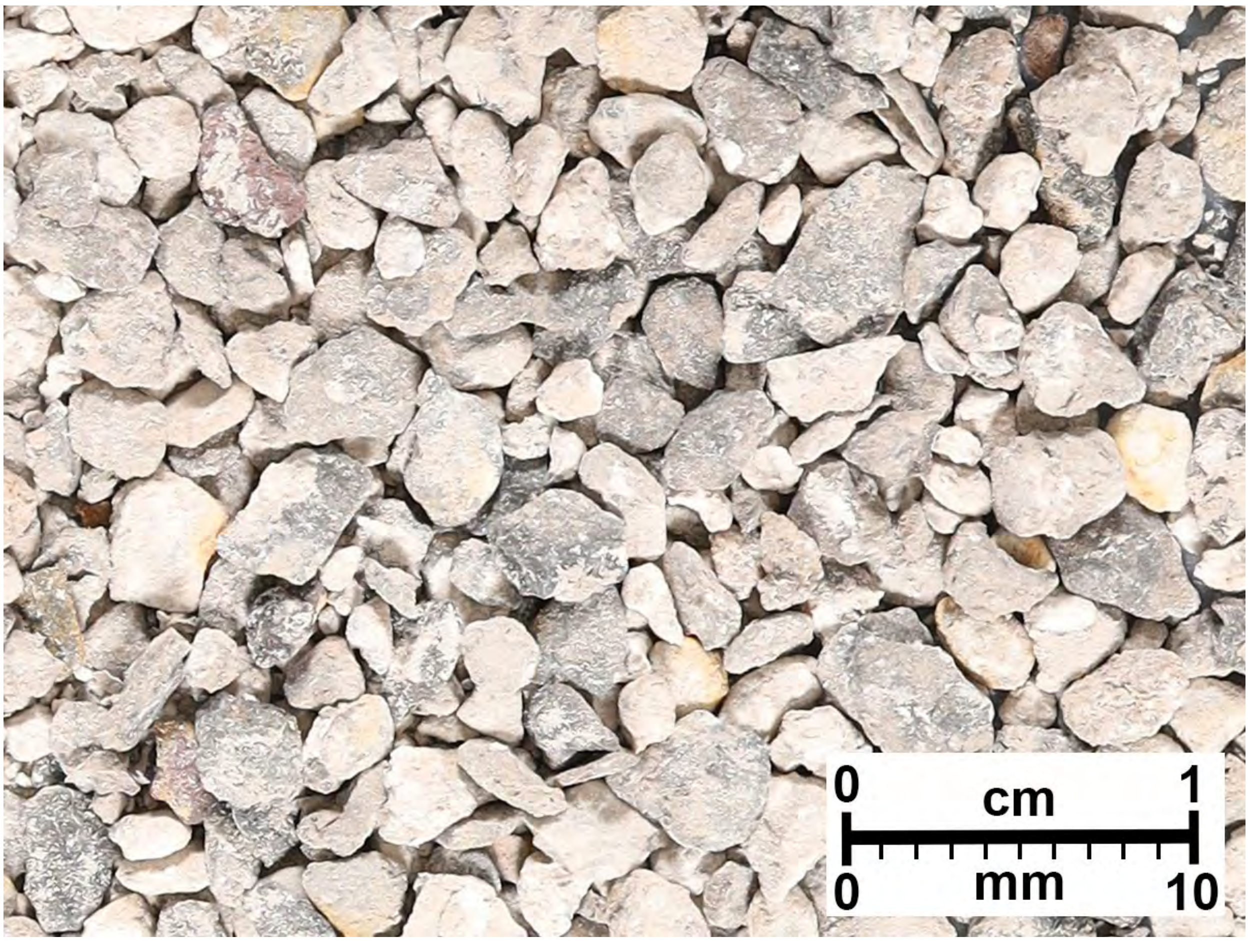

Figure A25. Dolomite, gray-brown, wackestone to packstone, microcrystalline; shale, black to dark gray, firm, blocky, calcareous; anhydrite, white, soft, microcrystalline, amorphous, noncalcareous.

Paradox Formation, Salt Cycle 1

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

6510–6570 feet

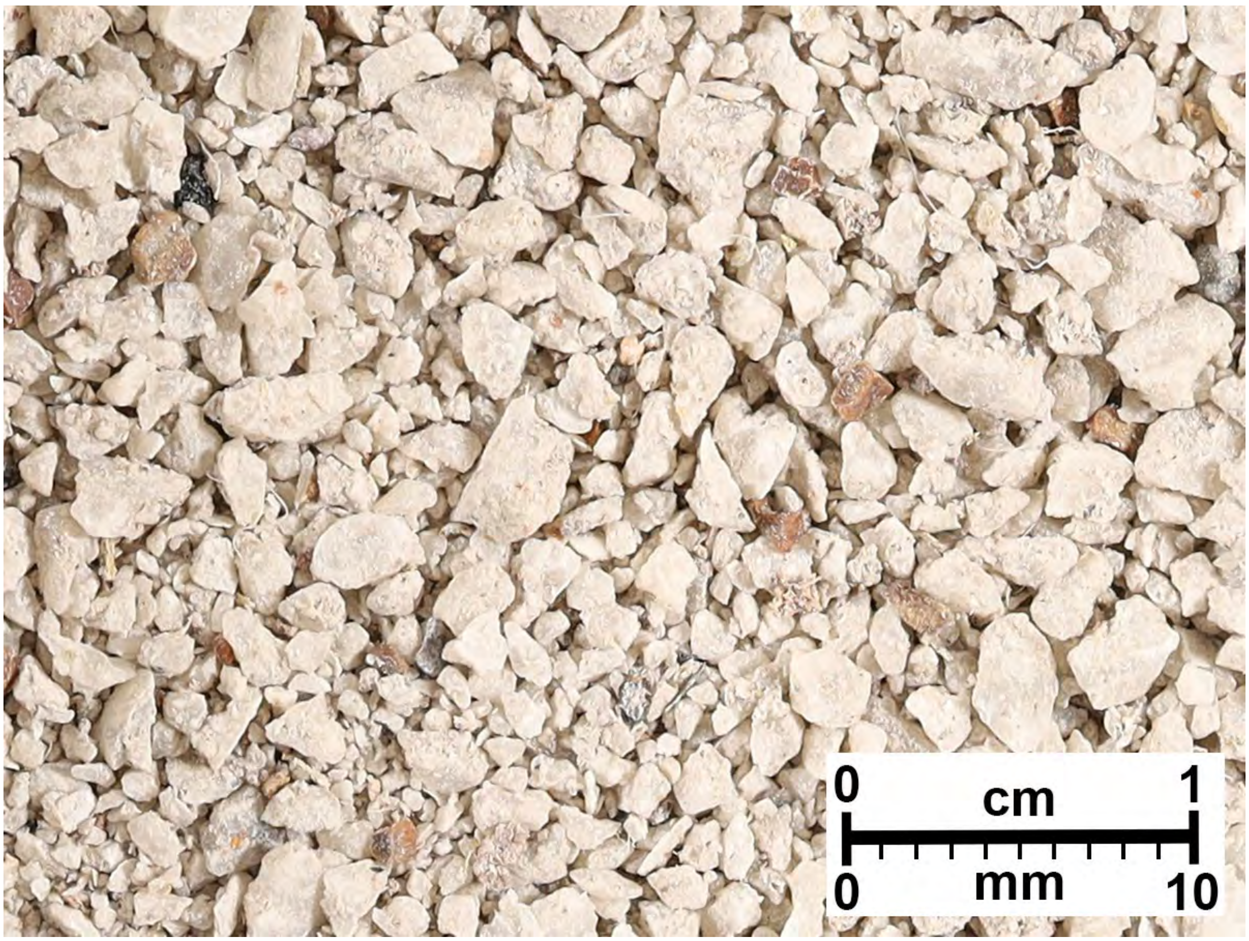

Figure A26. Halite (salt), white to off white, translucent to opaque, crystalline, brittle to hard; this description applies to all subsequent halite beds.

Paradox Formation, Clastic Cycle 1

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

7060–7070 feet

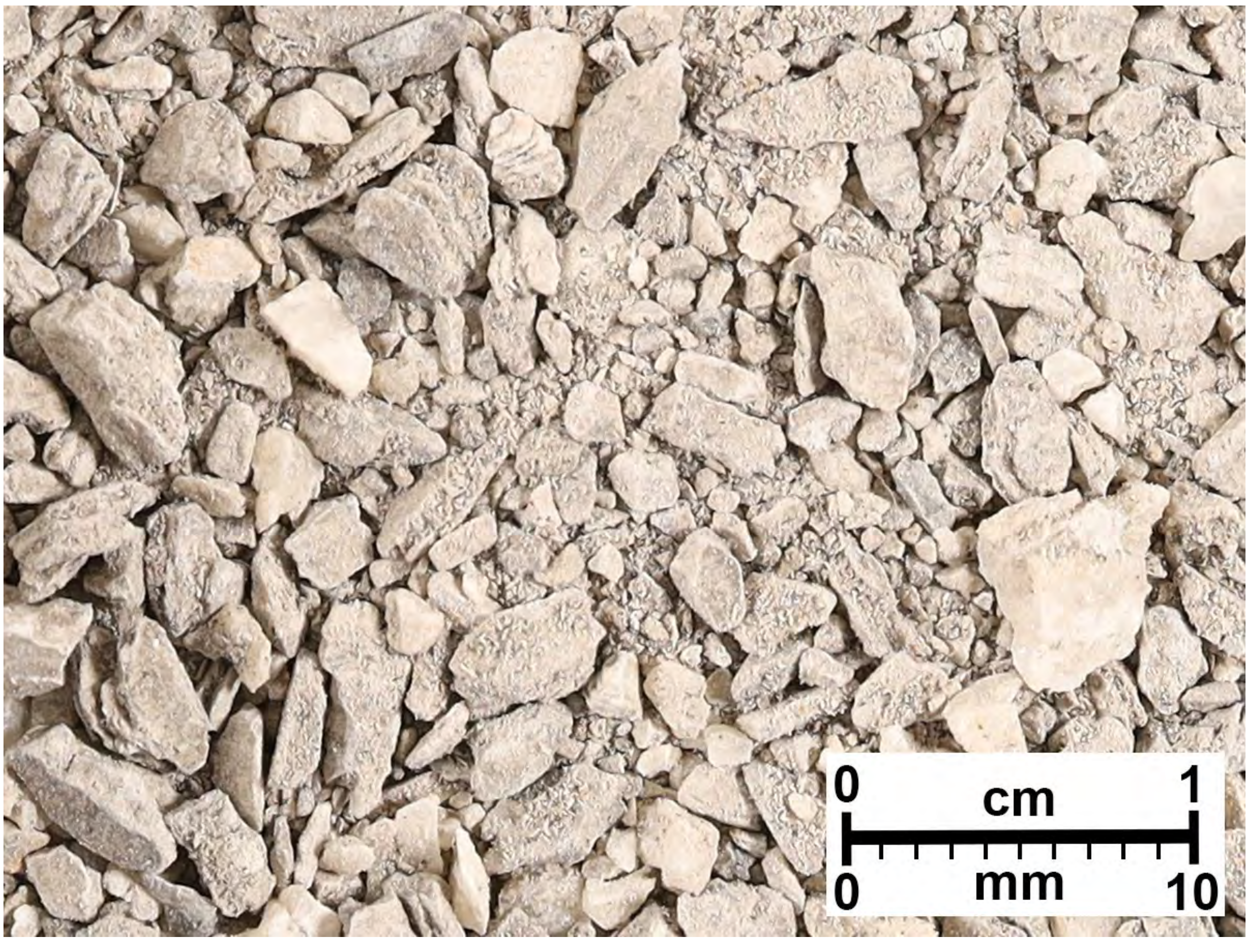

Figure A27. Limestone, gray, mudstone, cryptocrystalline, bitumen alteration, rippled appearance; shale (below limestone [not shown]), black, earthy to waxy, occasionally carbonaceous, calcareous.

Paradox Formation, Clastic Cycle 7

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

8020–8040 feet

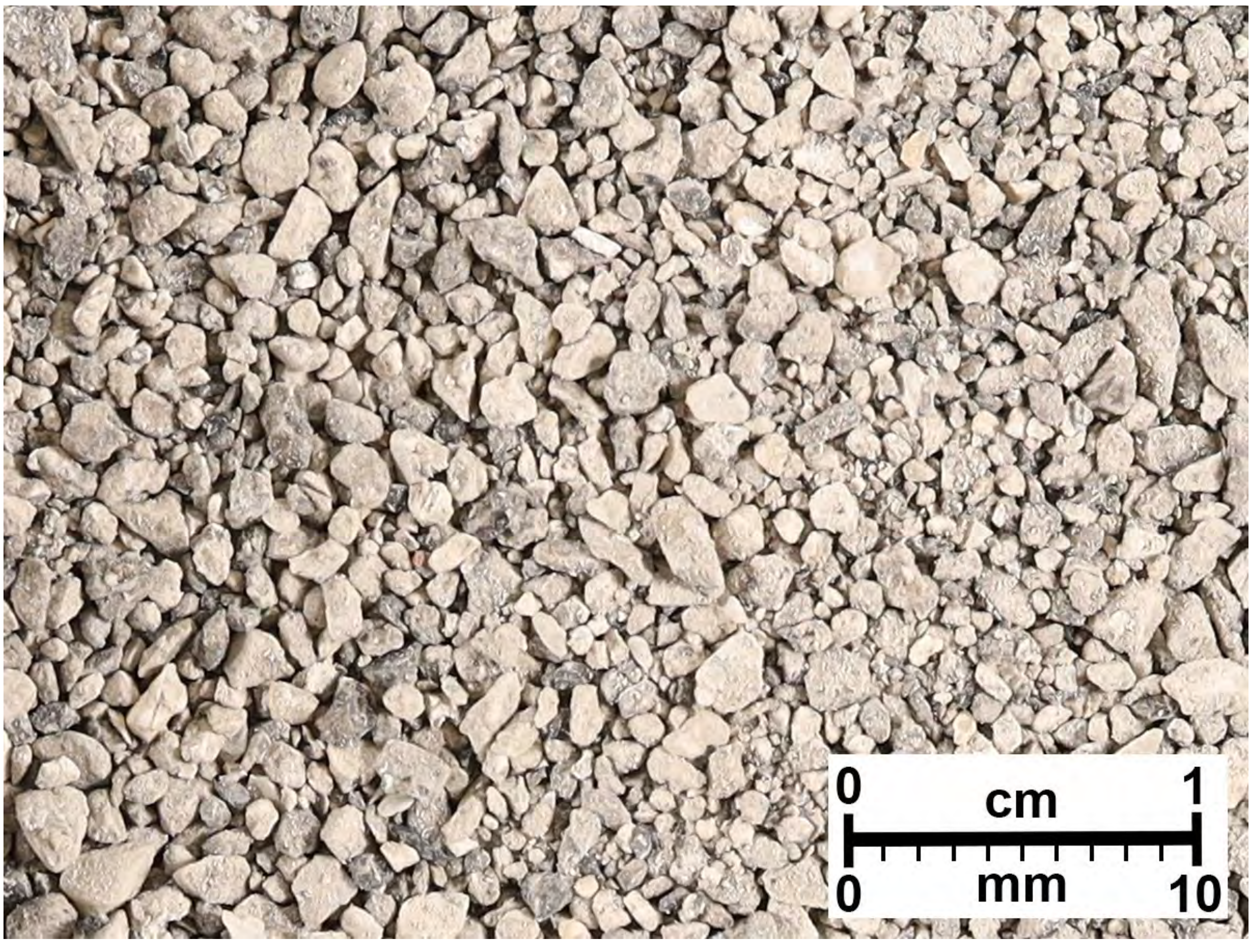

Figure A28. Dolomite, light to dark gray, laminated, argillaceous to shaly; shale (10% to 15%), medium to dark gray, organic-rich, carbonaceous (sooty); anhydrite (5% to 10%), white, soft to firm, slightly to moderately calcitic.

Paradox Formation, Clastic Cycle 8

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

8220–8250 feet

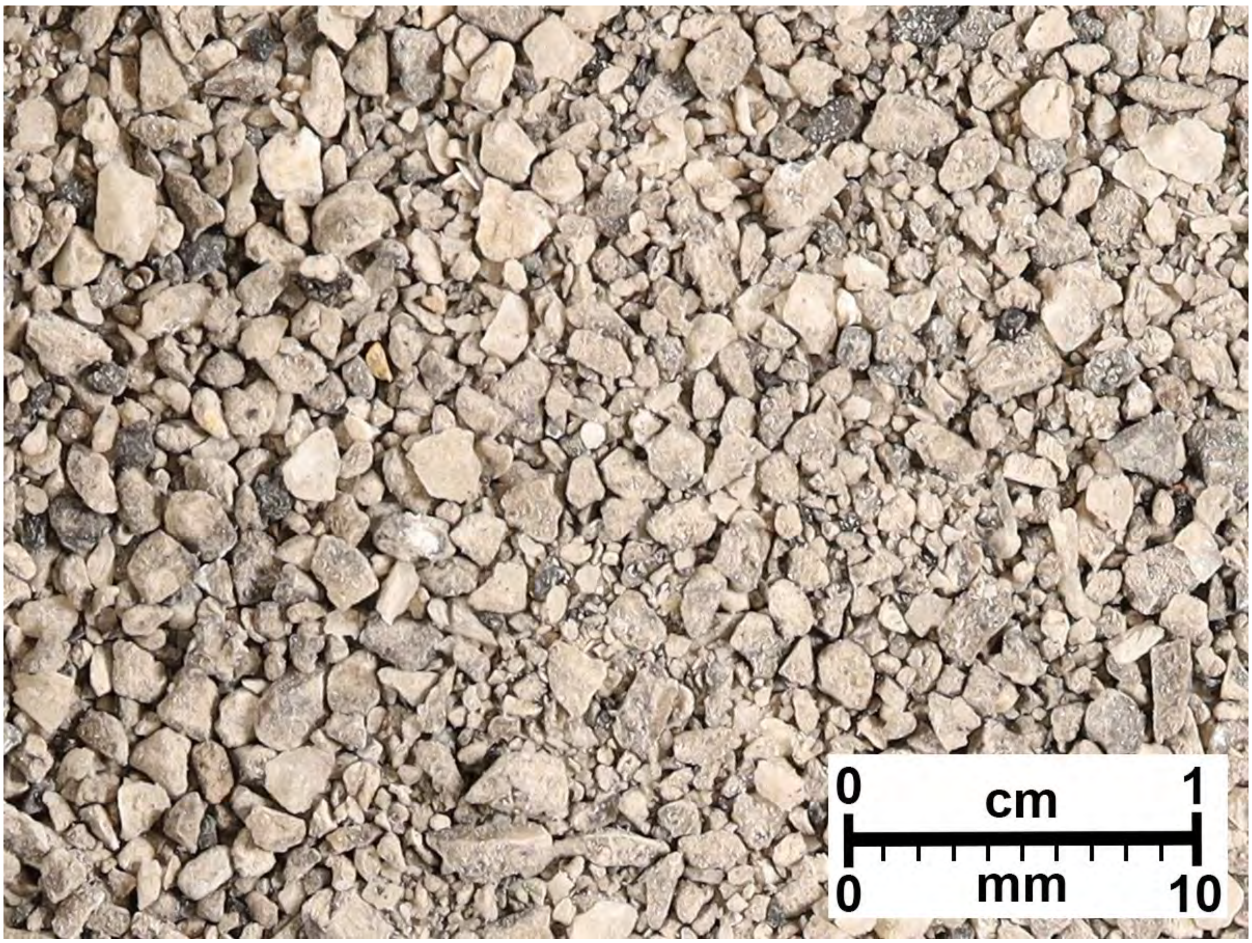

Figure A29. Dolomite, light to dark gray, laminated, argillaceous to shaly in part; shale (10% to 15%), medium to dark gray to black, organic-rich, carbonaceous (sooty); anhydrite (5% to 10%), white, soft to firm, slightly to moderately calcitic.

Paradox Formation, Clastic Cycle 10

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

8480–8500 feet

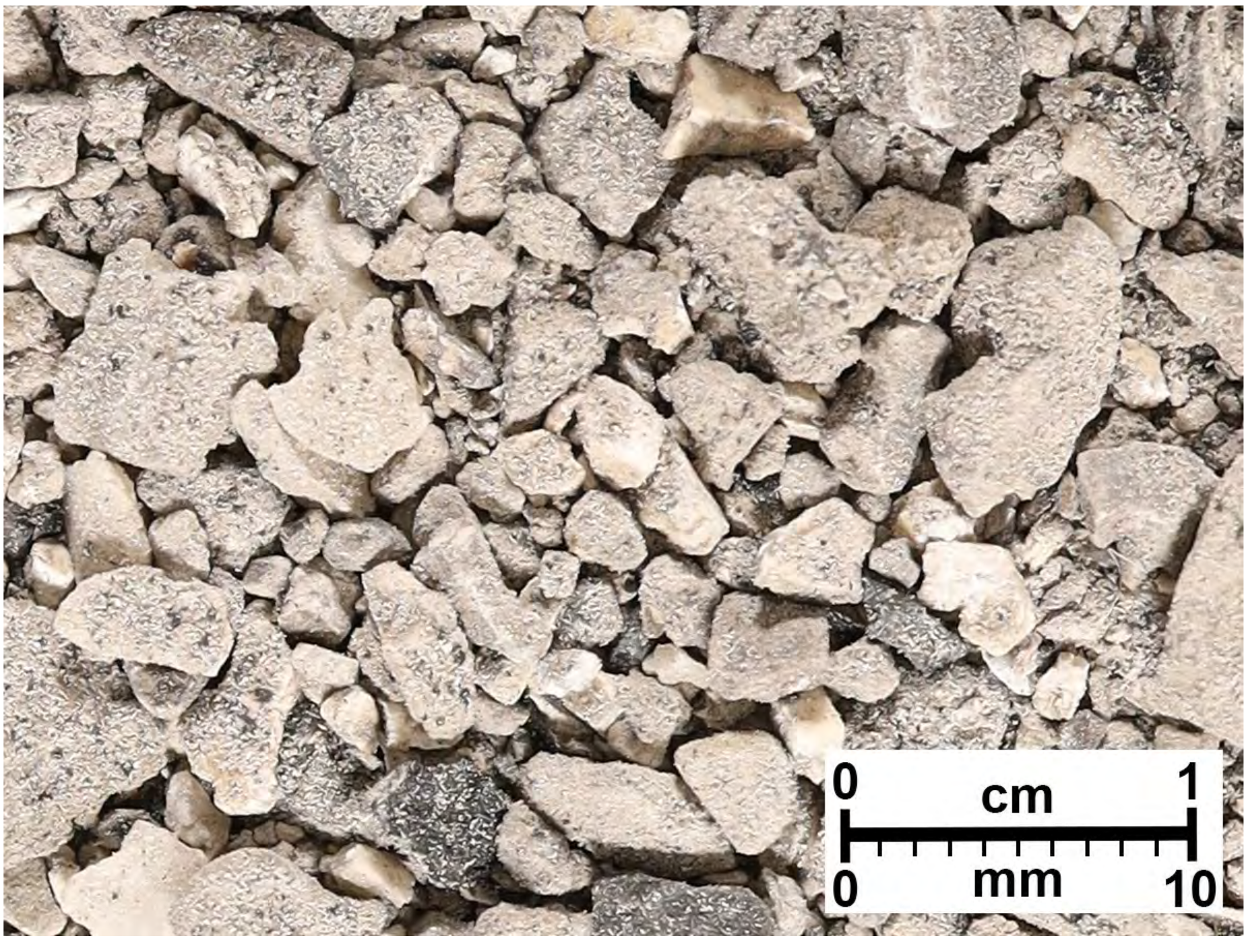

Figure A30. Dolomite (40%), gray to light gray, finely laminated in part; halite (30%); shale (15%), black, firm to soft, earthy to waxy in part, calcareous to slightly calcareous, occasionally carbonaceous (sooty) appearance; anhydrite (15%), white, soft to firm, slightly to moderately calcitic; distinctively larger-sized cuttings than clastic intervals above.

Paradox Formation, Clastic Cycle 14

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

8800–8830 feet

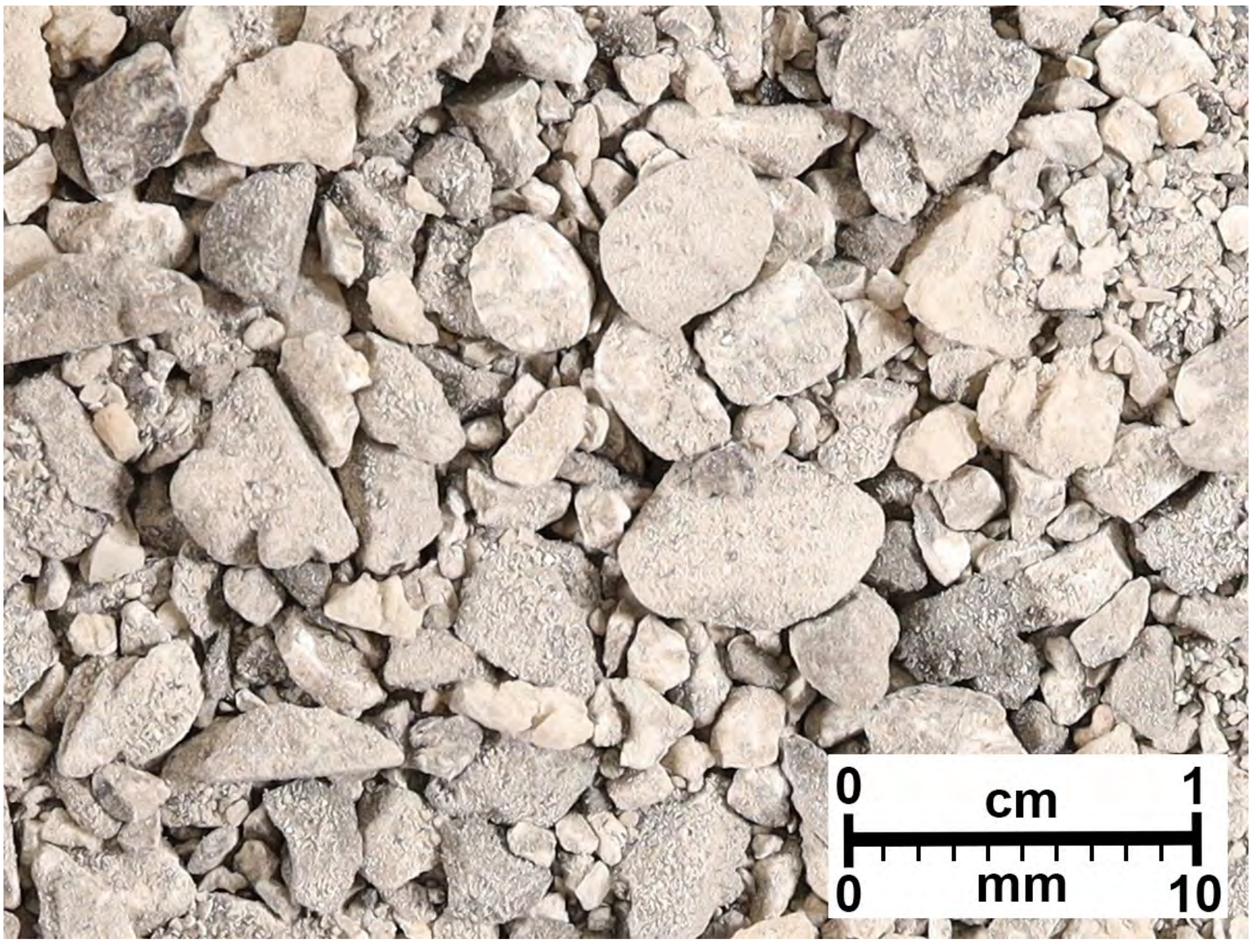

Figure A31. Dolomite, light gray, mudstone to wackestone, cryptocrystalline to microcrystalline in part, argillaceous, calcareous; shale, black, firm to soft, blocky to platy, earthy to waxy, occasionally carbonaceous (sooty) appearance, slightly calcareous.

Paradox Formation, Clastic Cycle 18

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

9260–9270 feet

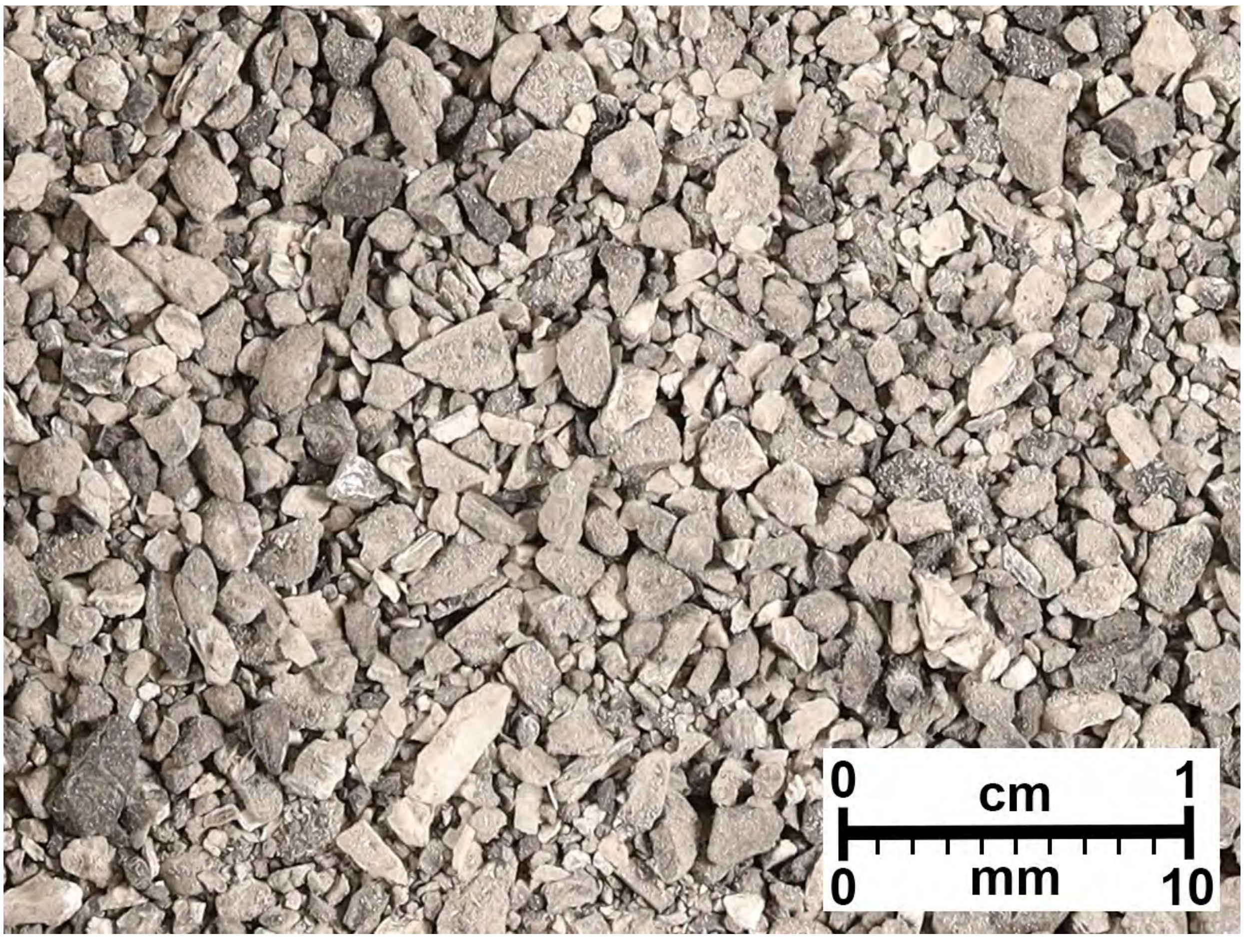

Figure A32. Shale, black to dark gray, soft to firm, organic-rich, carbonaceous (sooty), bitumen, calcareous; dolomite, light to medium gray, chalky to micro sucrosic; anhydrite, light gray to white, soft, chalky; halite.

Paradox Formation, Cane Creek Shale (Cycle 21), A Interval

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

9633–9638 feet

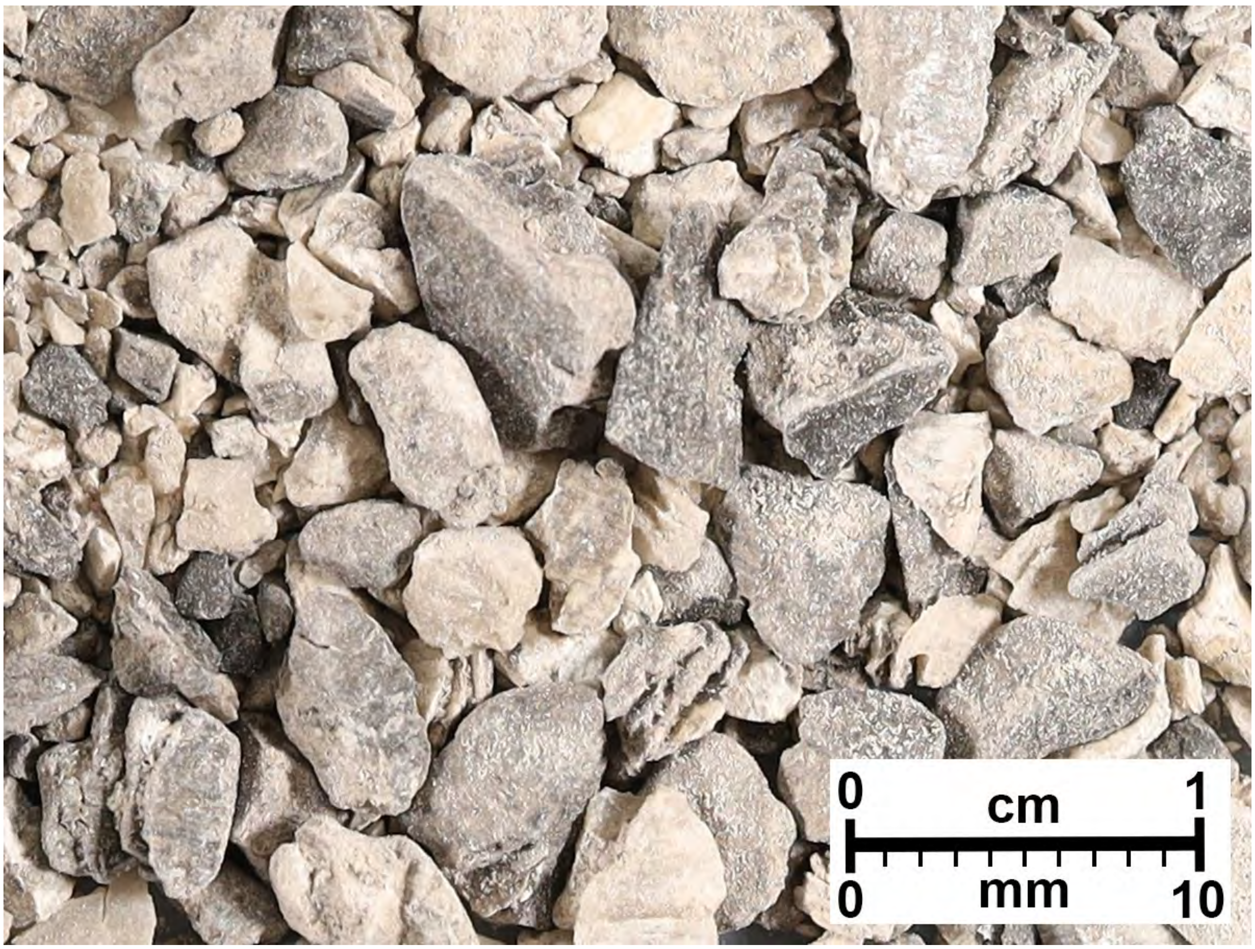

Figure A33. Siltstone, dark to medium to light gray, sandy, fine grained; dolomite, dark to medium to light gray, mudstone, anhydritic; shale, black, firm, blocky, carbonaceous (sooty appearance), earthy, very slightly calcareous; anhydrite, white, chalky, occasionally microcrystalline.

Paradox Formation, Cane Creek Shale, B Interval

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

9670–9680 feet

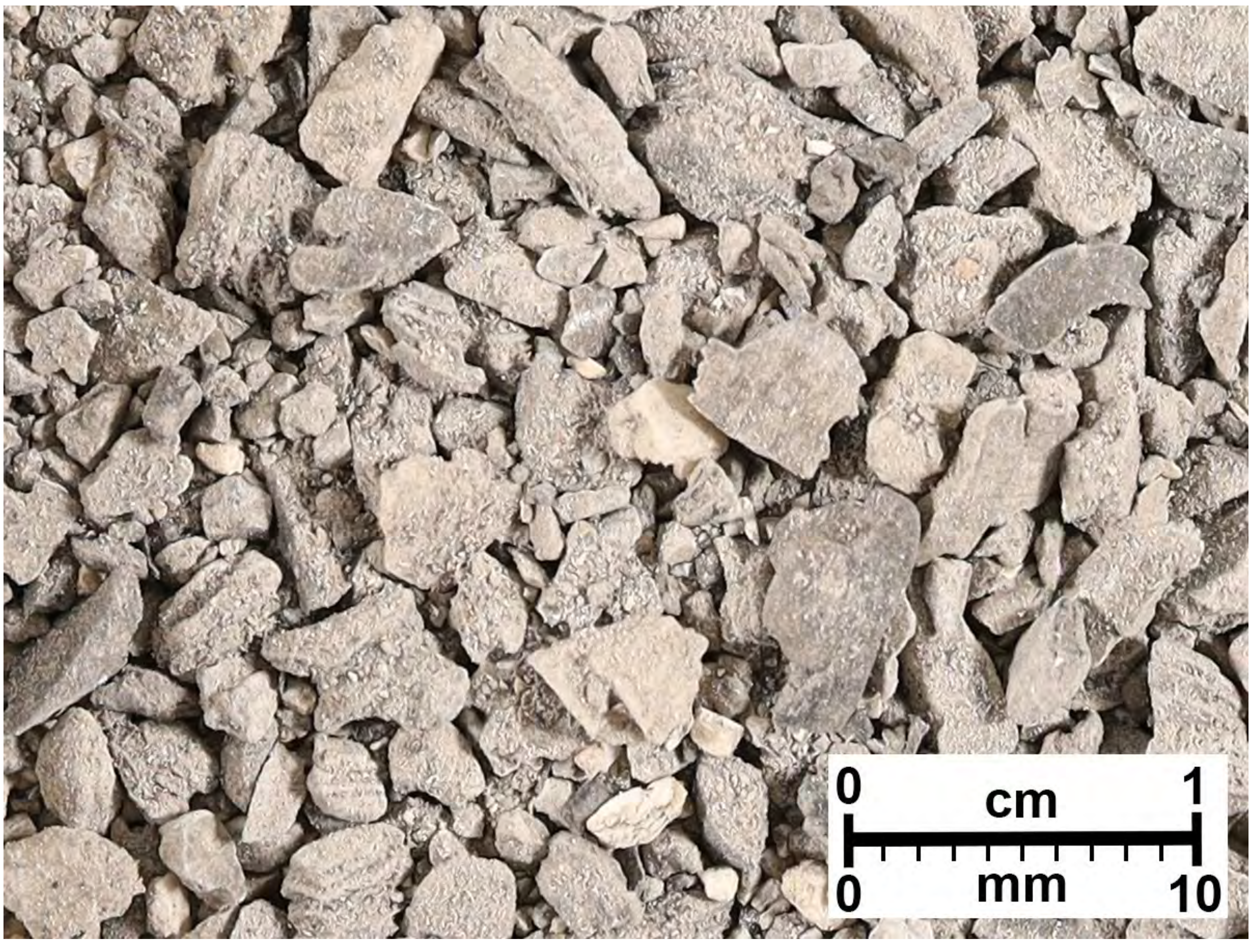

Figure A34. Siltstone, light to medium gray, sandy, fine grained; limestone, light to medium gray, silty, dolomitic, brittle, mudstone; shale, black, firm to hard, blocky, earthy to waxy, organic-rich (sooty appearance), calcareous in part.

Paradox Formation, Cane Creek Shale, C Interval

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

9700–9710 feet

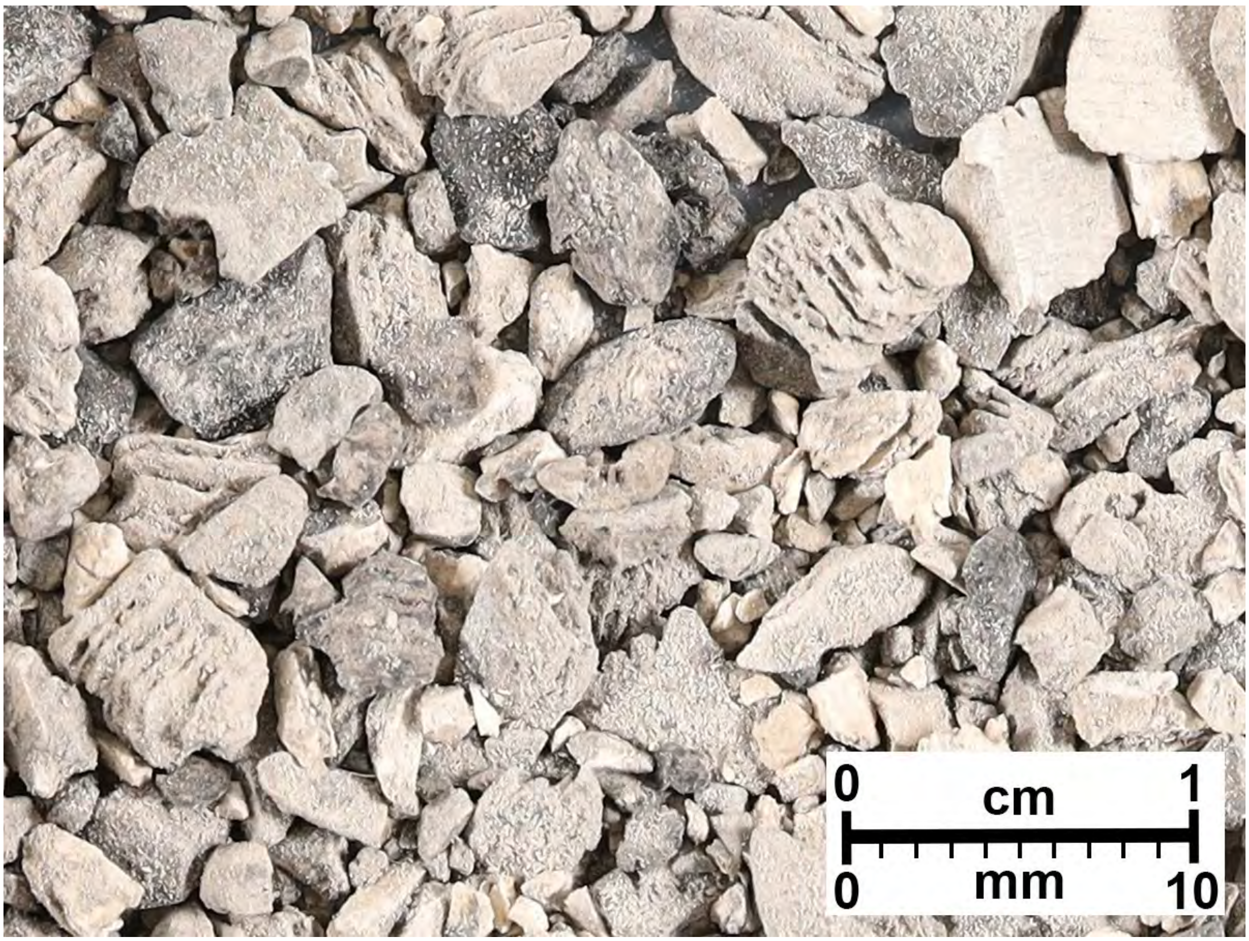

Figure A35. Siltstone, dark to medium to light gray, sandy, fine grained; dolomite, light gray to gray, silty, laminated, mudstone to wackestone, cryptocrystalline to microcrystalline, firm, anhydritic to argillaceous, calcareous in part; shale, black, firm to hard, blocky, earthy to waxy, organic-rich (sooty appearance), calcareous in part.

Paradox Formation, Salt Cycle 21 and Clastic Cycle 22

State 16-2
Section 16, T. 22 S., R. 17 E., SLBL&M, Grand Co., Utah
API No.: 43-019-50089

9730–9740 feet

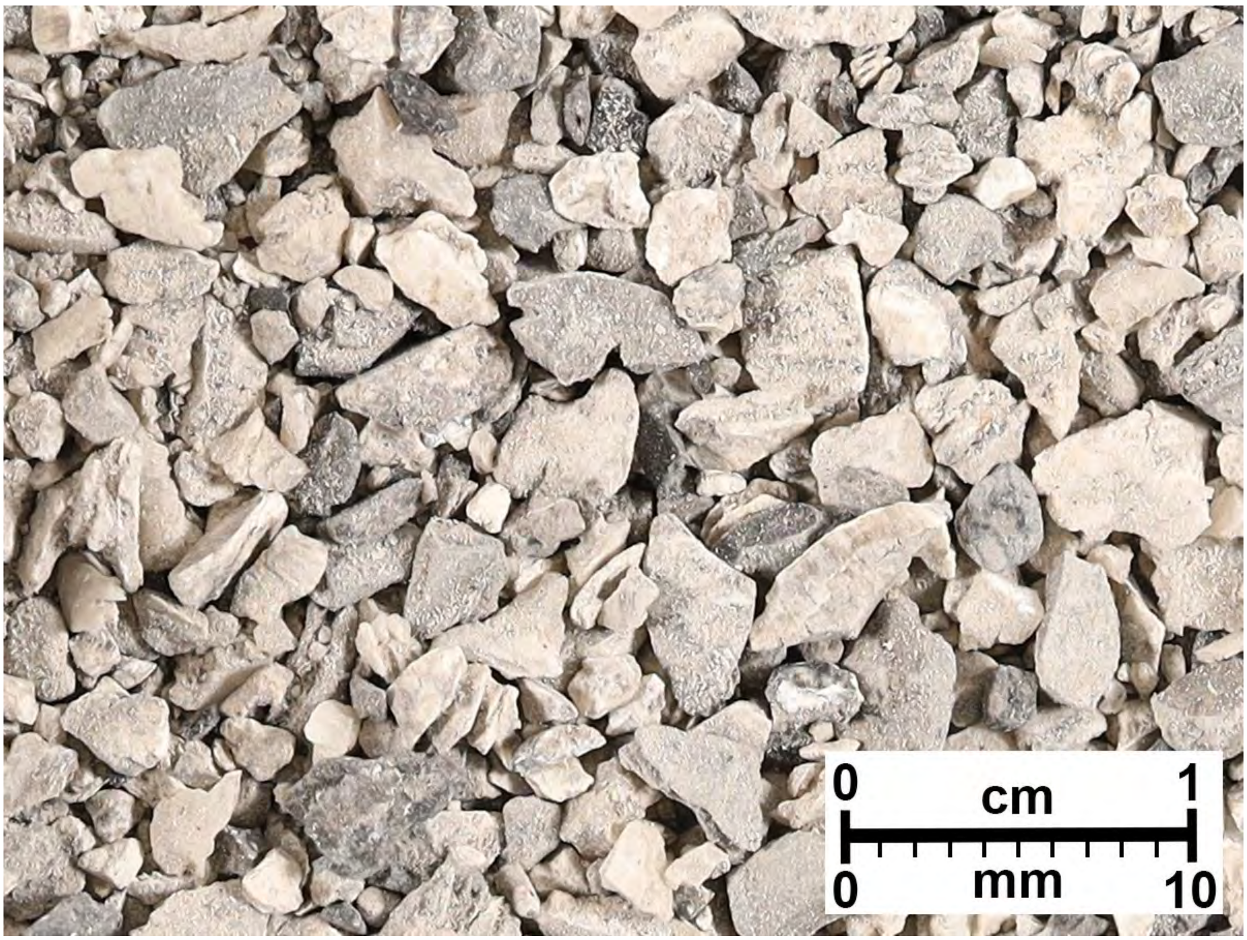

Figure A36. Halite, white to opaque to light brown, coarse, crystalline, brittle to hard; dolomite, light to medium gray, laminated to massive, calcareous to anhydritic, silty to organic-rich, mudstone; shale, black, dense, organic-rich.