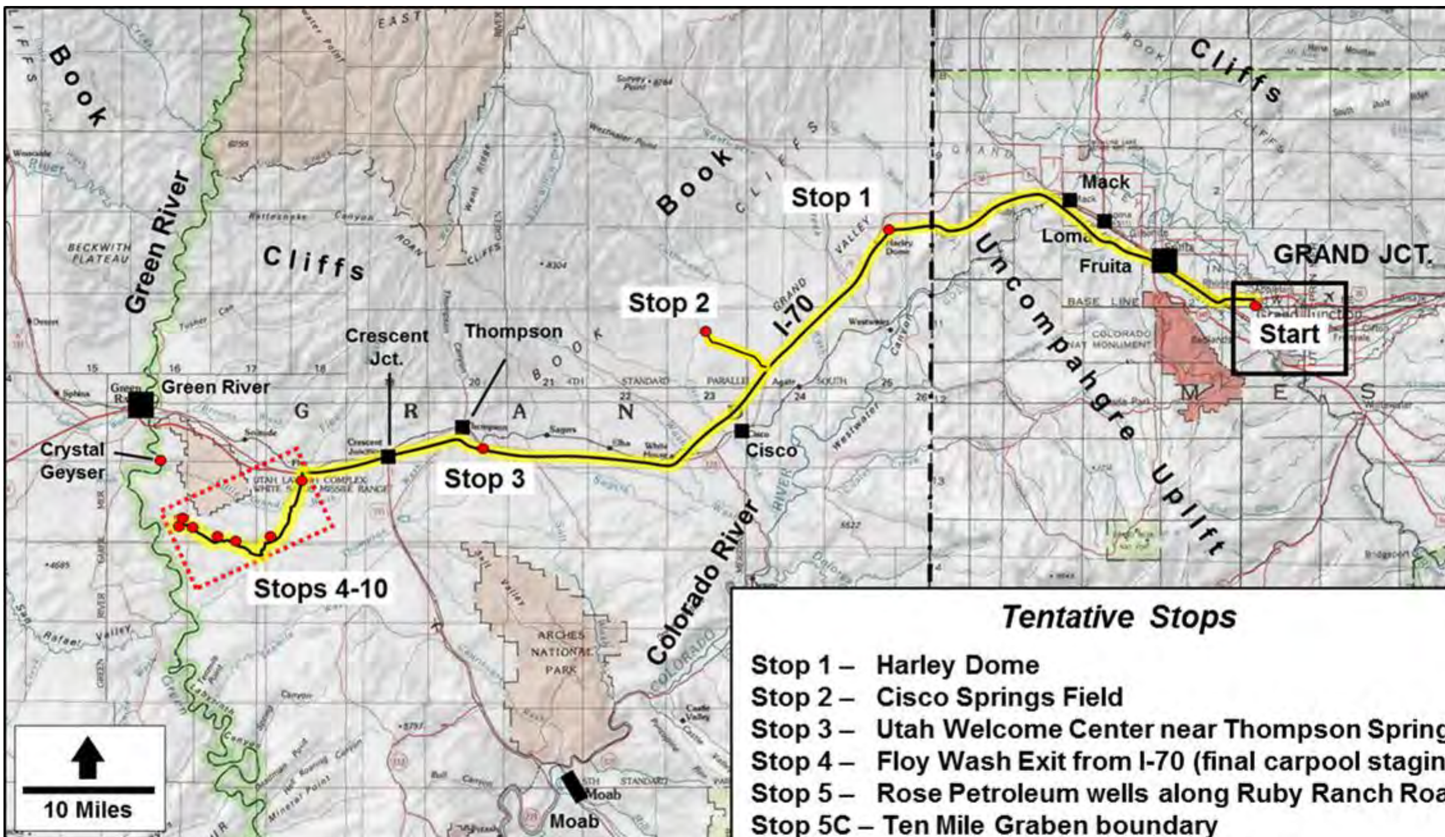
Field-Stop Descriptions

by

Bill Hood, Rex Cole, Brann Johnson, and Russell Davies



Tentative Stops

- **Stop 1 – Harley Dome**
- **Stop 2 – Cisco Springs Field**
- **Stop 3 – Utah Welcome Center near Thompson Springs**
- **Stop 4 – Floy Wash Exit from I-70 (final carpool staging)**
- **Stop 5 – Rose Petroleum wells along Ruby Ranch Road**
- **Stop 5C – Ten Mile Graben boundary**
- **Stop 6 – Oil-saturated Entrada Sandstone**
- **Stop 7 – Ten Mile Graben boundary**
- **Stop 8 – Elephant Butt Butte**
- **Stop 9 – Ten Mile Geyser and travertine quarry**
- **Stop 10 – Big Bubbly Spring**

Note – The following was completed about two weeks prior to the field trip and may not contain the latest information and additions. These changes will be made after the trip. An errata sheet may also be prepared.

Stop 1 – Harley Dome Anticline

(Lat. 39.19029º; Lon. -109.11533º; Elev. ~ 4,841 ft)

Topics:

- Welcome, logistics, safety, and handout organization
- Geologic setting and background
- Helium resources on Harley Dome Anticline
- Mancos Shale stratigraphy and chemo-stratigraphy
- Research on the lower Mancos Group at Westwater Creek
- Lateral stratigraphic changes in the Book Cliffs

Stop Description

Stop 1 is on the Bitter Creek Anticline, which plunges to the northwest. To the west are the Bryson Wash Syncline and Harley Dome Anticline (**Figure S1-1**). There are numerous old natural-gas and oil wells in the area that have been plugged and abandoned, or shut-in (see **Utah Division of Oil, Gas and Mining; https://ogm.utah.gov/**). As discussed below, there are also recent helium wells that appear to be shut-in. A cross section (X-X') is shown in **Figure S1-2**.

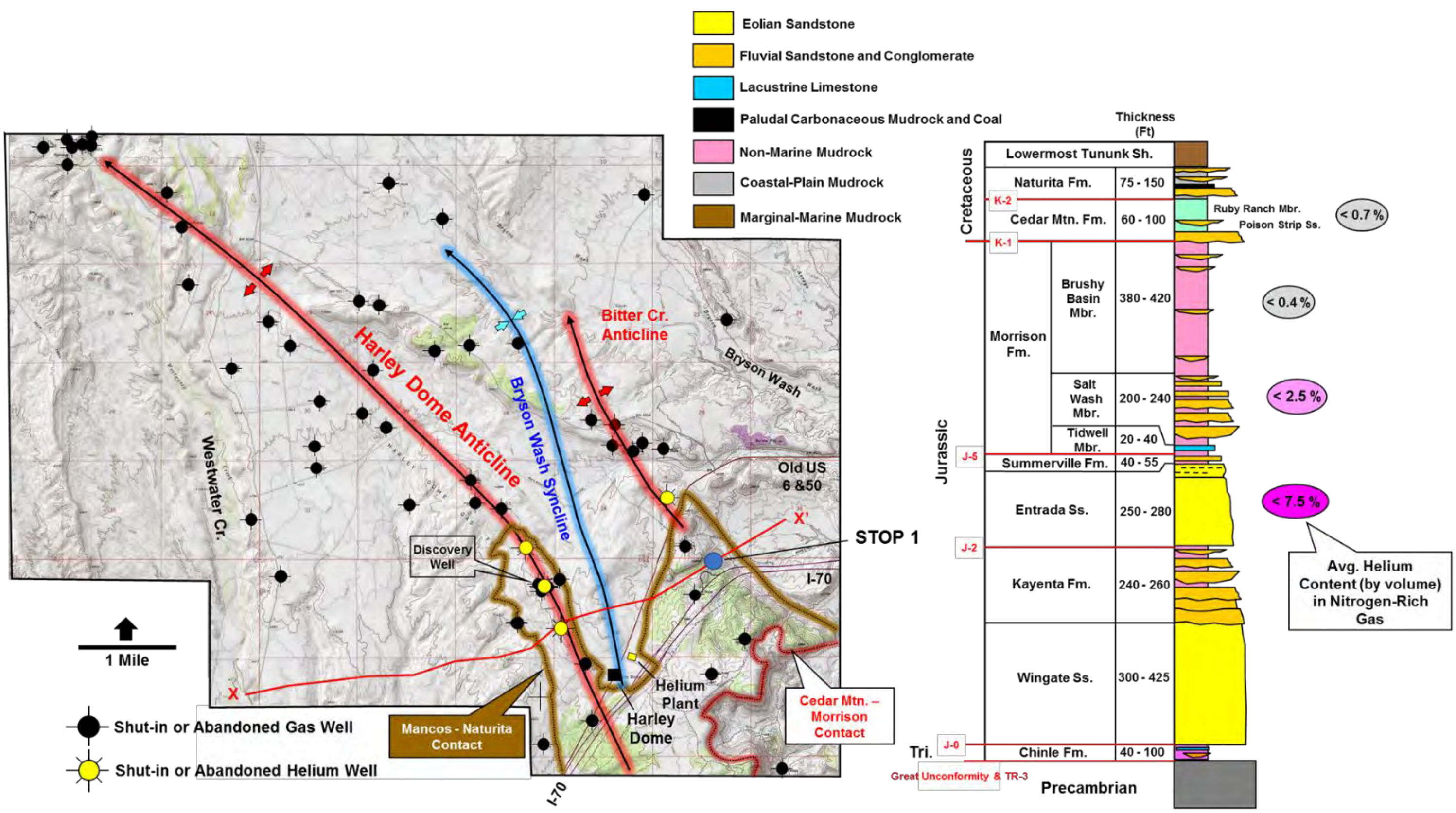


Figure S1-1. Topographic map of the Harley Dome area, showing wells and major folds. **Stop 1** is on the crest of the Bitter Creek Anticline. Section on the right shows the stratigraphy in this area. The ovals represent average helium concentrations (volume %) in produced gas, which is dominated by nitrogen. Sources: **Willis (1994)** and **Wiseman and Eckels (2020)**.

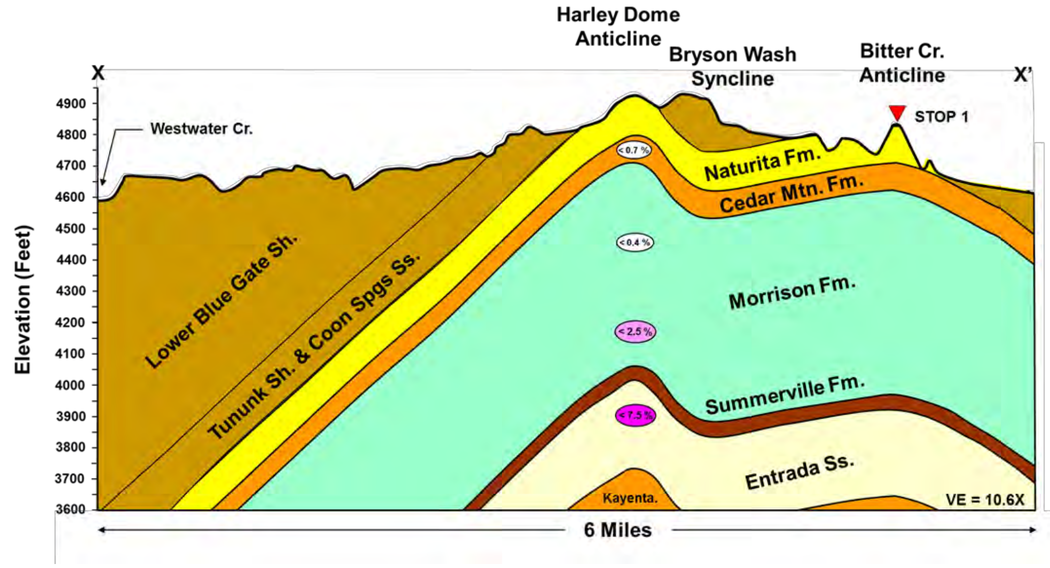


Figure S1-2. East-west cross-section X-X' from Westwater Creek to **Stop 1**, based on structure-contour lines (top Naturita) from the Harley Dome Quadrangle (**Willis, 1994**). Thickness values are also from same source. Ovals represent average helium concentrations (volume %) in natural gas. Part of the Harley Dome geologic map is displayed in **Figure S1-6**.

Willis (1994) provides thickness values for the stratigraphic units between the base of the Mancos Group to the Precambrian (**Figure S1-1**). The total is approximately 1,800 feet, which is similar to what occurs in the Colorado National Monument (**Figure RL1-8)**. The total Mancos Group is about 4,000 feet thick. Photos of the units and structures at Stop 1 are provided in **Figure S1-3**.

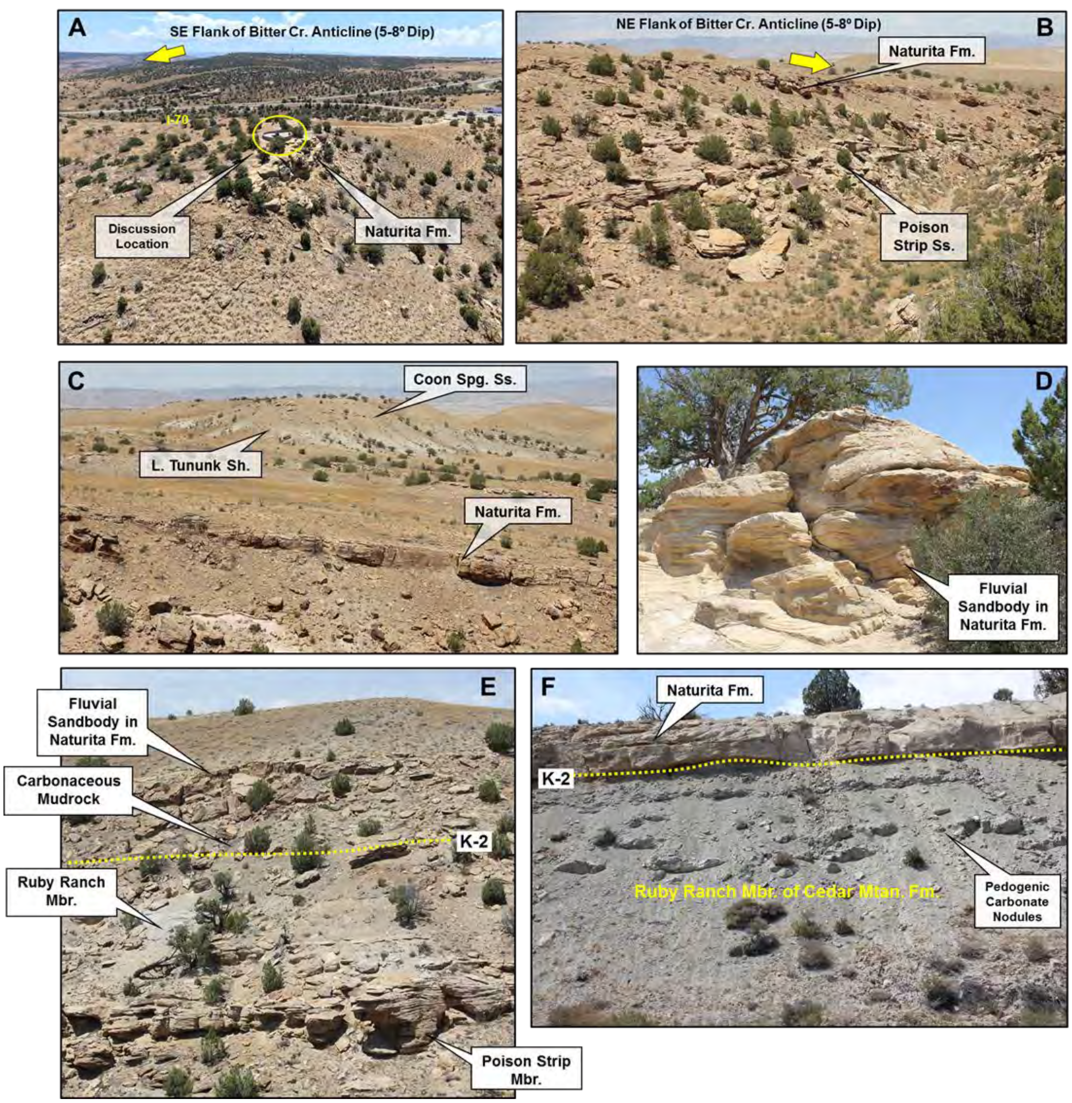


Figure S1-3. Aerial and ground photos of the **Stop 1** area. **Photos A-C** show the Bitter Creek Anticline and the Cedar Mountain-lower Mancos strata. **Photo D** illustrates a cross-stratified fluvial sandbody in the Naturita Formation at the view spot. **Photo E** shows the Cedar Mountain-Naturita interval, and **Photo F** illustrates pedogenic carbonate nodules in the Ruby Ranch Member of the Cedar Mountain in a roacut for eastbound I-70. Photos by R. Cole.

Helium [Note -- the following is summarized from **Willis (1994)** and **Wiseman and Eckels (2020)**, which contain numerous references.]

Harley Dome (Anticline) is probably the only dedicated helium field in Utah. Numerous wells have encountered helium concentrations from Jurassic and Cretaceous reservoirs at depths less than 1,000 feet (**Figures S1-1 and S1-2)**. The Harley Dome discovery well (Bashor No. 1; API 43-019-11513; TD = 802 ft) was drilled in 1925 on the crest of the anticline (see **Figure S1-1**). In June, 1932, a small area on the crest of Harley Dome, was designated as the Federal Helium Reserve #2 by the President, but was later rescinded and reopened for leasing in 1964. The field has had many operators since then. A recent attempt (2013-2018) to produce helium by IACX Energy was abandoned; the remains of their plant is near the former Harley Dome townsite (**Figure S1-1**). IACX utilized a proprietary, non-cryogenic recovery process to extract and purify helium from the nitrogen-rich gas to over 99% purity and with minimal helium loss.

Production and exploration at Harley Dome field is problematic because the reservoirs are under-pressured and contain highly saline formation water. A typical gas analysis from a well on the crest of the anticline (Lansdale Govt. 4: API – 43-019-30003) is: nitrogen (86.10 v%), carbon dioxide (0.91 v%), helium (7.31 v%), methane (5.56 v%), ethane (0.11 v%), and propane (0.01 v%). Helium is most concentrated in the Entrada, with minor shows in Salt Wash and Brushy Basin members of the Morrison Formation, and the Cedar Mountain. The production-drive mechanism in the Entrada is by solution-gas expansion. Mudrock intervals in the Summerville and Morrison (Tidwell Member and Brushy Basin members) provide bottom and top seals, respectively.

The source of the helium at Harley Dome and across the Colorado Plateau is unclear. Possibilities include primordial and radiogenic helium escaping from the upper mantle and alpha decay during the uranium-to-lead decay series (note: an alpha decay particle is the same as the nucleus of a helium atom). The uranium could be from granitic rocks in the Precambrian basement or uranium minerals in sedimentary rock (e.g., Cutler Formation, Salt Wash Member of Morrison, and/or uriniferous Paleozoic mudrock or phosphate). Mobilization of helium from the source rock is facilitated by diffusion along fractures, joints and unconformities, porous and permeable carrier beds (usually sandstone), and ground water.

As may be discussed at **Stop 2**, helium is also a target in the greater Cisco area, which includes the Cisco Dome, Cisco Townsite, Cisco Springs, Cisco Springs-North, Cisco Wash, Danish Wash, and Seiber Nose fields (**Figure BG-23**). More than 600 shallow wells have been drilled for oil and gas trapped in the Castlegate Sandstone, Mancos Shale, Dakota (Naturita) Sandstone, Cedar Mountain Formation, Morrison Formation, and Entrada Sandstone. The best helium shows occur in wells drilled just north of I-70 along a 6-mile stretch northeast of the Cisco townsite. Published helium values range from 0.50 v% to 1.47 v%. The greater Cisco gas has much higher methane concentrations (70-80%) and much lower nitrogen values (10-15 v%) than the gas at Harley Dome.

Mancos Shale Stratigraphy and Chemo-Stratigraphy

The Mancos Group underlies most of the field-trip route. Its origin and stratigraphic subdivisions are covered in the Background Information (see **Figures BG-17 and BG-18)**. Kerogen-rich intervals of the Mancos are some of the best hydrocarbon source rocks in the Rocky Mountain region, especially the lower 1,000 feet (e.g., Tununk, Juana Lopez, Smoky Hill). Upon burial and maturation, the Mancos has generated large volumes of natural gas and some oil in the Piceance and Uinta Basins. From a geo-history perspective, the Mancos contains important insight into global climate variations during the Cretaceous, evolution of invertebrates (e.g., bivalves, ammonites, foraminifera), tectonism of the Sevier orogenic belt, oceanic circulation, etc. Bill Hood, assisted by Rex Cole and a number of MSC/CMU geoscience students, did a detailed mineralogical (XRD) and geochemical (ED-XRF) study of the entire Mancos interval (4,000-4,500 ft thick) using cuttings (30- and 10-ft intervals) from a well north of Fruita. The samples were donated by Walter Fees III (thanks!). Some of the results are presented in **Figure S1-4**. Selected outcrops around Grand Junction were also examined, sampled, and analyzed mineralogically and geochemically.

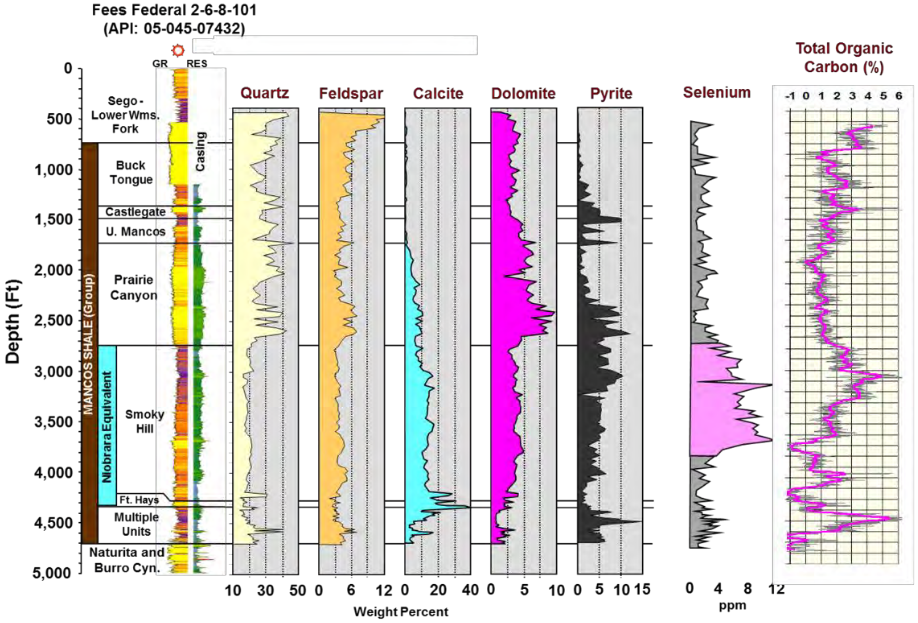


Figure S1-4. Detailed mineralogical evaluation of cuttings (30 ft) from the Fees Federal 2-6-8-101 well, which is located in Big Salt Wash about 15 miles north of Fruita. The mineralogical values were determined by X-ray diffraction, and the selenium values from energy-dispersive X-ray fluorescence. The total-organic-carbon values were calculated from down-hole logs in the nearby Fees Federal 2-11-8-101 well (API: 05-045-I5975). Sources: **Cole** and **Hood (2014)** and **Hood** and **Cole (2016)**.

The results of the studies (**Figure S1-4)** show that Mancos has well-defined mineralogical variations. Since there are numerous well logs trough the Mancos, the data from the Fees Federal 2-6-8-101 well were correlated over large areas of western Colorado and easternmost Utah (**Figure S1-5**).

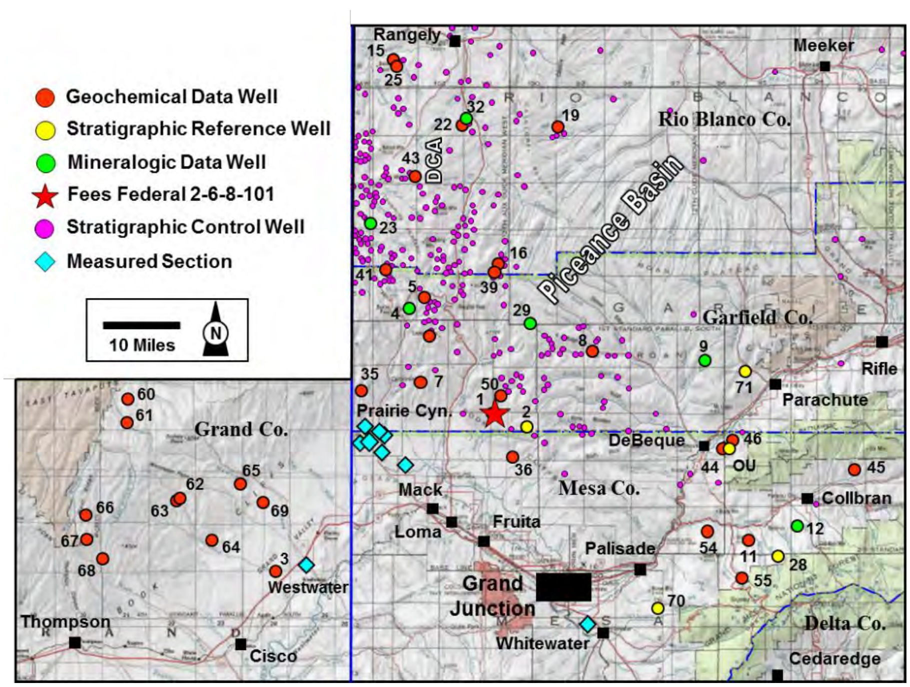
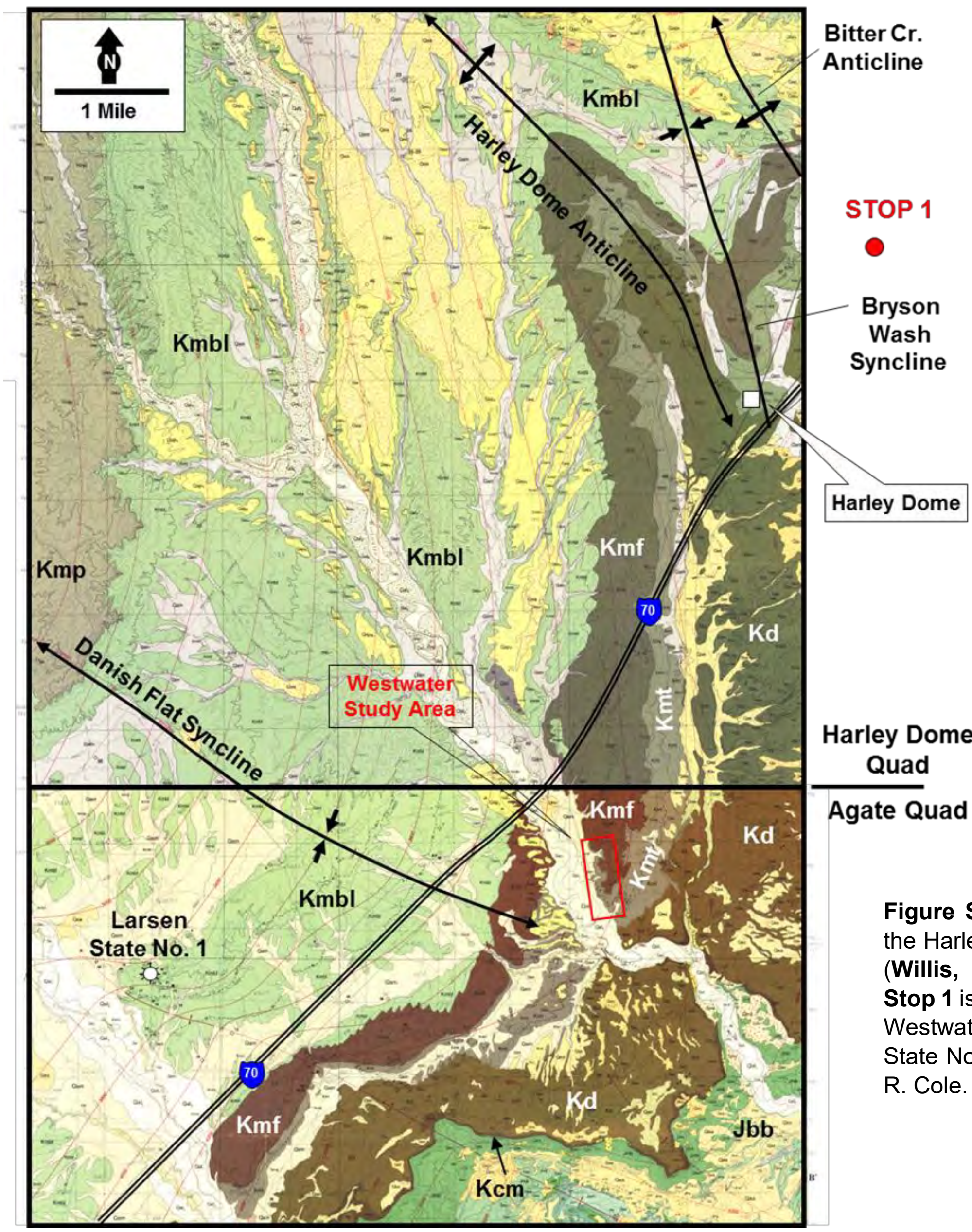
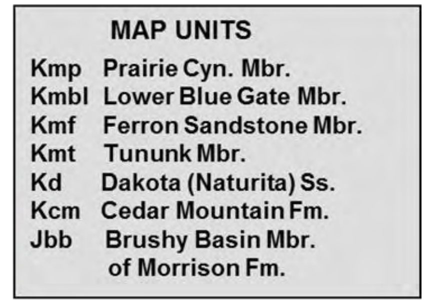


Figure S1-5. Map showing the area involved in the MSC/CMU Mancos study. (source: **Cole** and **Hood (2014)**.

Lower Mancos Research at Westwater

Westwater Creek is an important research site (**Figure S1-6**) for detailed sedimentological and geochemical research on the lower Mancos, which as usual, has a variety of lithostratigraphic names (**Figure S1-7**; also see Background **Figure BG-18**). The site is along BLM Road 191 about 1.2 miles southeast of I-70. Here, an irregular ridge exposes the upper and lower Tununk Shale, Coon Springs Sandstone, Ferron Sandstone, and Juana Lopez (**Figure S1-8**). Two detailed measured sections have been completed here. The first by **Anderson and Harris (2006);** the second, a non-published 2013 section by Rex Cole and Rob Rice (CMU student), funded by Anadarko Petroleum (**Figure S1-9**).





Structure contours on top of Dakota (Naturita) Ss.

Figure S1-6. Partial geologic map from the Harley Dome and Agate Quadrangles (**Willis, 1994** and **Willis, et al., 1996**). **Stop 1** is just off the edge of the map. The Westwater study area and the Larsen State No. 1 well are posted. Compiled by R. Cole.

Age	Stage and Substage		Molluscan Biozone	Gardner and Cross (1994)	Molenaar and Cobban (1991)	Willis et al. (1996)	CMFT 8 (2026)
	Coniacian (part)		*Scaphites ventricosus* *Inoceramus deformus* *Inoceramus erectus*		Mancos (main body)	Blue Gate Mbr.	Lower Blue Gate Mbr.
89 Ma	Turonian	Late	*Prionocyclus quadratus* *Scaphites whitfieldi* *Prionocyclus macombi*	Juana Lopez Sequence	Juana Lopez Mbr.	Ferron Ss. Mbr.	Juana Lopez Mbr. "Bentonite" Mkr. "Hot Shale" Mkr.
	Turonian	Middle	*Prionocyclus hyatti* *Prionocyclus percarinatus* *Collignoniceras woollgari*	Hyatti Sequence Woollgari Seq. Mytiloides Seq.	Ferron Ss. Coon Spg. Ss. Tununk Sh.	Coon Spg. Ss. Tununk Sh.	Ferron Ss. U. Tununk Sh. Coon Spg. Ss. L. Tununk Sh.
	Turonian	Early	*Mammites nodosoides* *Vascoceras birchbyi* *Pseudaspidoceras flexuosum*	Middle Cretaceous Hiatus of Molenaar and Cobban (1991)			
~91.3 Ma	Cenomanian (part)			Dakota Fm.	Dakota Fm.	Dakota Fm.	Naturita Fm.

Figure S1-7. Chronostratigraphic chart for Cretaceous strata in eastern Utah. Modified from **Anderson** and **Harris (2006)**.

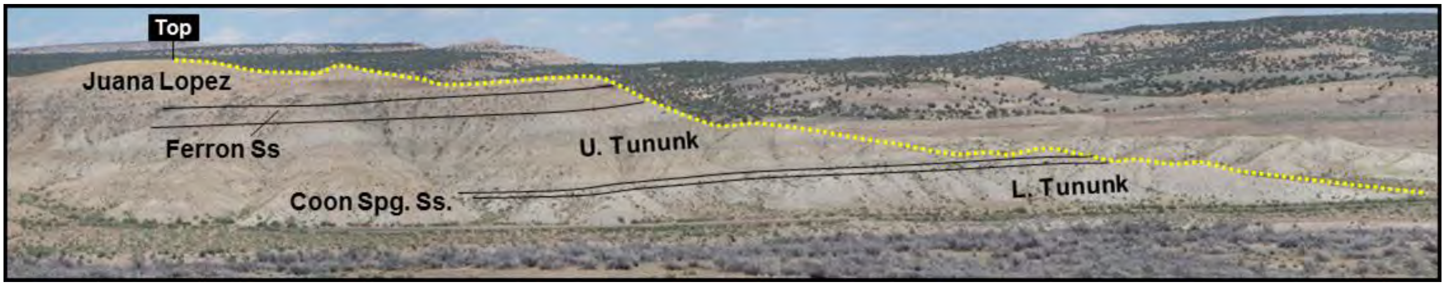


Figure S1-8. Photo of the lower Mancos at the Westwater research site. View is looking east. The yellow line shows the measured section in the following figure.

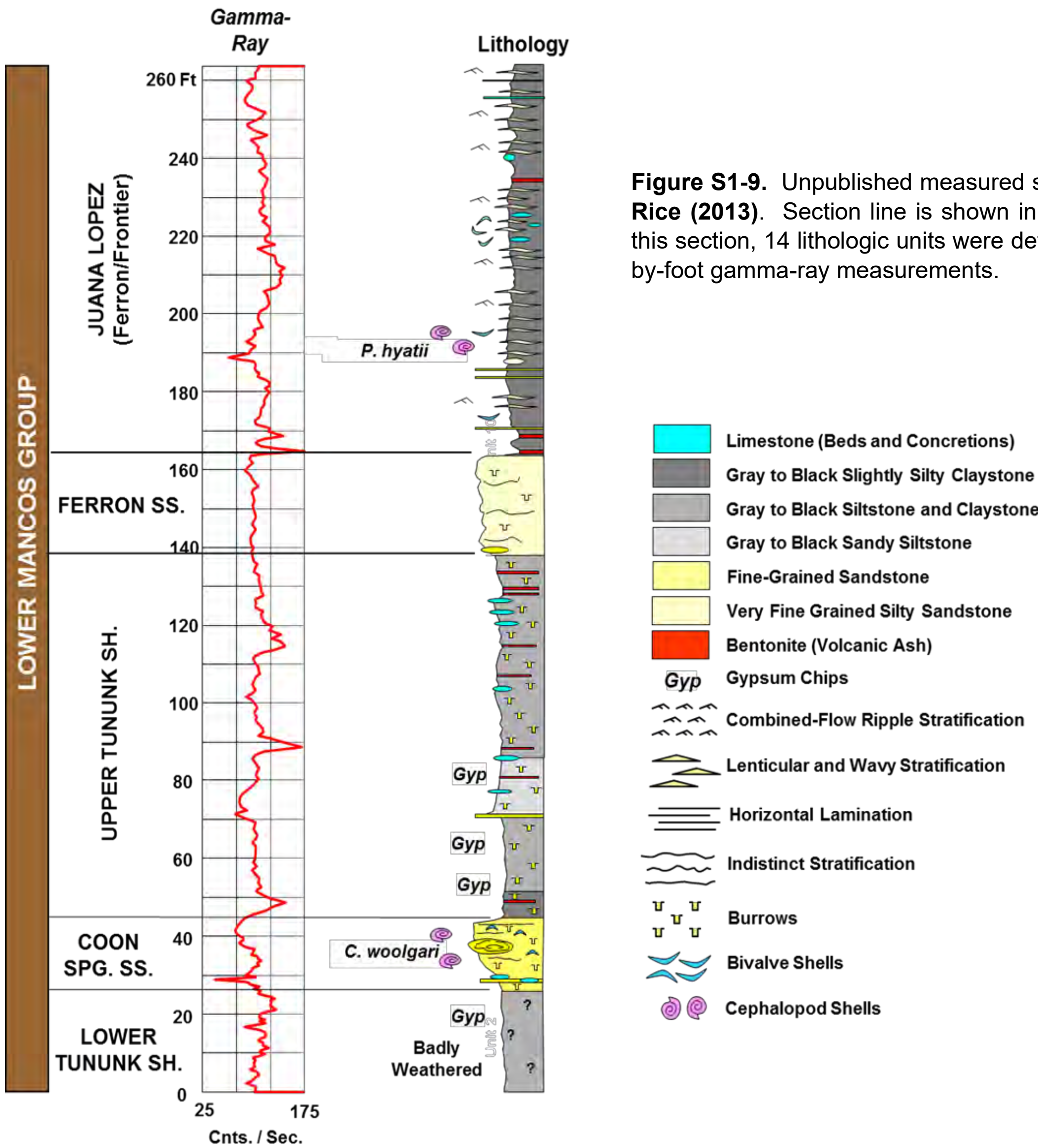


Figure S1-9. Unpublished measured section by **Cole and Rice (2013)**. Section line is shown in previous figure. In this section, 14 lithologic units were defined, aided by foot-by-foot gamma-ray measurements.

One of the most interesting units at Westwater is the Coon Springs Sandstone. Regionally, it crops out from near Green River, UT, to the Utah-Colorado state line. To the west, is it's a continuous shallow-marine sandstone bed, but in the Westwater area it consists of an interval (~20 ft thick) containing large, bioturbated sandstone concretions that contain ammonite and Inoceramid (clams) fossils (**Figure S1-10**). Some of the concretions are up to six feet across and nearly spherical. The reason for the concretions is poorly understood; however, they may represent sea-bottom decay of organic matter. As the decay products (e.g., ammonia) diffuse outward they can trigger precipitation of calcite between the sand grains. [Note - areas between the concretions also consist of fine-grained sand that is more poorly cemented with calcite.] The concretions are also visible north of I-70 in the Rabbit Valley area. Some of the most common invertebrate fossils in the lower Mancos are displayed in Figure **Figure S1-11**.

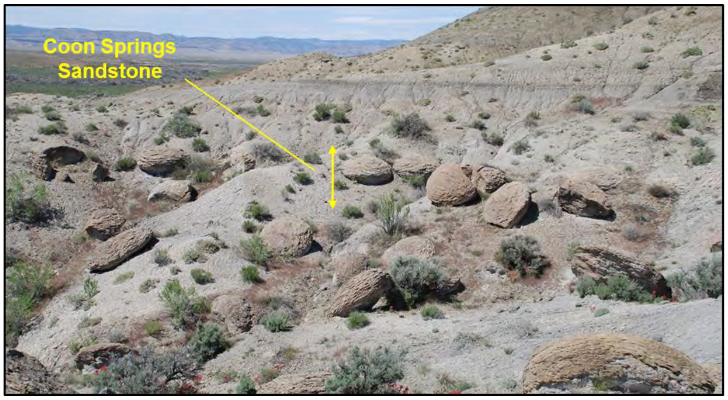


Figure S1-10. Photos of Coon Springs Sandstone concretions at the Westwater study area. Orange field book is about 5 inches long. Photos by R. Cole.

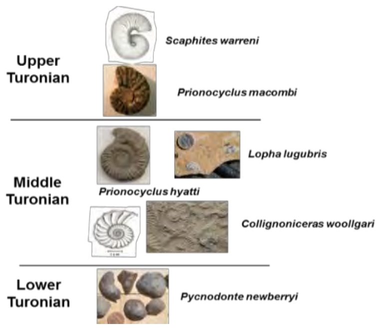


Figure S1-11. Molluscan guide fossils for late Cenomanian and Turonian in Utah and Colorado. Sketches are from **Stokes (1988)**. Some photos are from the internet. The middle and lower Turonian critters are common at Westwater.

Since the lower Mancos is a significant local hydrocarbon source, a major component of the research at Westwater by **Anderson** and **Harris (2006)** was the generation of organic-geochemical (RockEval and total organic carbon), vitrinite-reflectance, kerogen-type, stable-isotopic (C and O of carbonate), X-ray diffraction (rock and clay fraction), and palynological data from the Larsen State No. 1 well, which is about 4.2 miles west of the outcrop. Funded by the Utah Geological Survey, the subsurface study involved 73 cuttings samples from 473 to 1105 feet; units sampled included the uppermost Naturita (Dakota), lower and upper Tununk, Juana Lopez Member, and Lower Blue Gate. The RockEval and total-organic-carbon (TOC) are summarized in **Figure S1-12**. These data show that the best source-rock interval is in the Juana Lopez Member. From the Larsen State No. 1, the results can be extrapolated into the Book Cliffs, as shown in **Figure S1-13**.

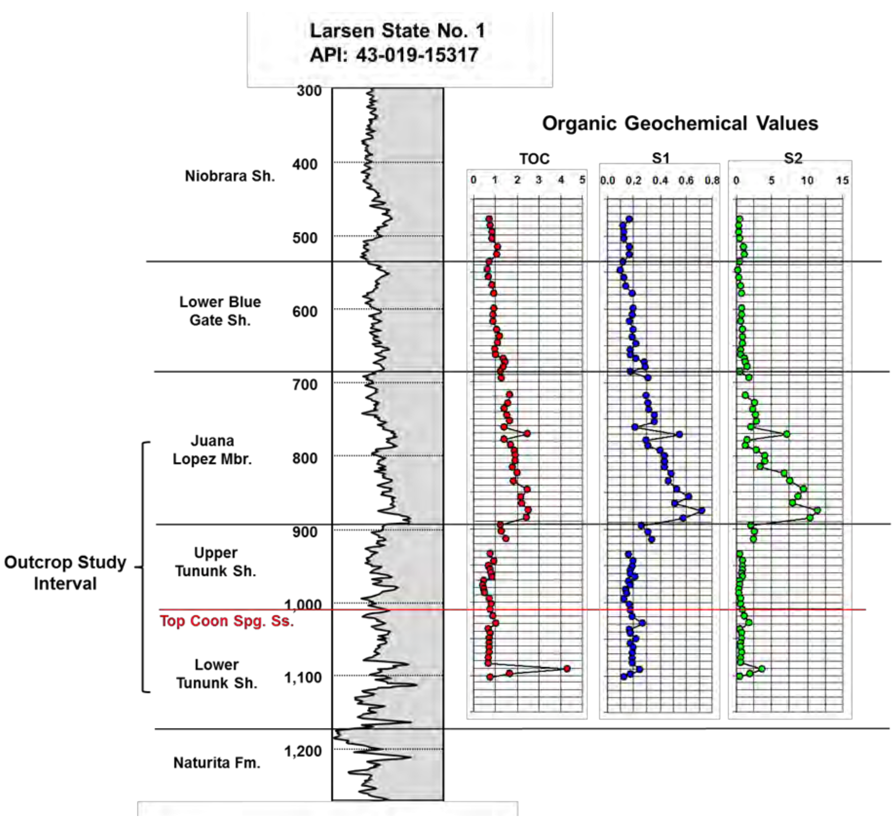
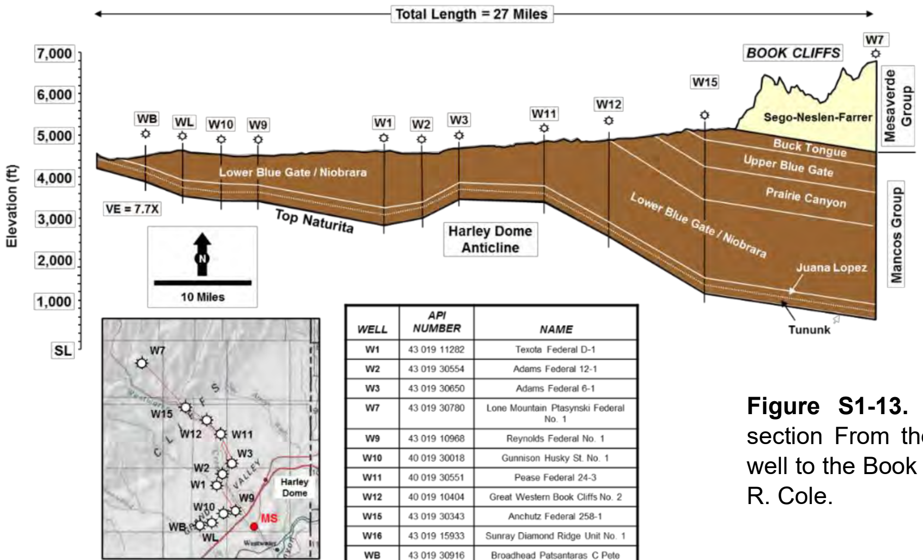


Figure S1-12. Organic-geochemical data for the Larsen State No. 1 well. Curve on the left is the gamma ray. The S1 and S2 values are from the RockEval analyses. Total-organic values are in weight %. S1 and S2 values are in milligrams of hydrocarbon per gram of rock. S1 indicates the free hydrocarbons already present in the sample, whereas S2 indicates the hydrocarbon potential of the sample if heated during subsurface burial and maturation. Source: **Anderson** and **Harris (2006)**.



WELL	API NUMBER	NAME
W1	43 019 11282	Texota Federal D-1
W2	43 019 30554	Adams Federal 12-1
W3	43 019 30650	Adams Federal 6-1
W7	43 019 30780	Lone Mountain Ptasynski Federal No. 1
W9	43 019 10968	Reynolds Federal No. 1
W10	40 019 30018	Gunnison Husky St. No. 1
W11	40 019 30551	Pease Federal 24-3
W12	40 019 10404	Great Western Book Cliffs No. 2
W15	43 019 30343	Anchutz Federal 258-1
W16	43 019 15933	Sunray Diamond Ridge Unit No. 1
WB	43 019 30916	Broadhead Patsantaras C Pete
WL	43 019 15317	Carter Larsen State No. 1

Figure S1-13. Log-based cross section From the Larsen St. No. 1 well to the Book Cliffs. Compiled by R. Cole.

Book Cliffs Stratigraphy

Although the Book Cliffs are about 10 miles distant, the marginal-marine, coastal-plain, and alluvial-plain stratigraphic units are visible on a clear day. Driven by sea-level change, sediment supply variations from the Sevier Highlands, and tectonic variations in the Western Interior Basin, lateral intertonguing of the shoreline sandstones with the Mancos Shale have been documented by Bob Young, as shown in **Figure S1-14**. In the Palisade area, the typical "Mt. Garfield" sequence is present (Corcoran, Cozzette, and Rollins Members of the Iles) (**Figure S1-15A)**. Moving west (landward) the three shoreline sandbodies merge (intertongue) with the coastal-plain mudrock and coal of the Neslen Formation and alluvial-plain mudrock and sandstone of the Farrer Formation; five coal zones are present (Anchor, Palisade, Chesterfield, Carbonera, and Cameo). This part of the story can be seen at Hunter Canyon (**Figure S1-15B**). Beginning near the Book Cliff Mine, a series of new shoreline sandbodies begin and thicken to the west and intertongue with the Mancos to the east. These units are recognized as the Sego Sandstone. It consists of two intervals with an interbed of Mancos, called the Anchor Mine Tongue. Also beginning at the state line (Prairie Canyon), yet another shoreline sandbody, the Castlegate appears (**Figure S1-15C**).

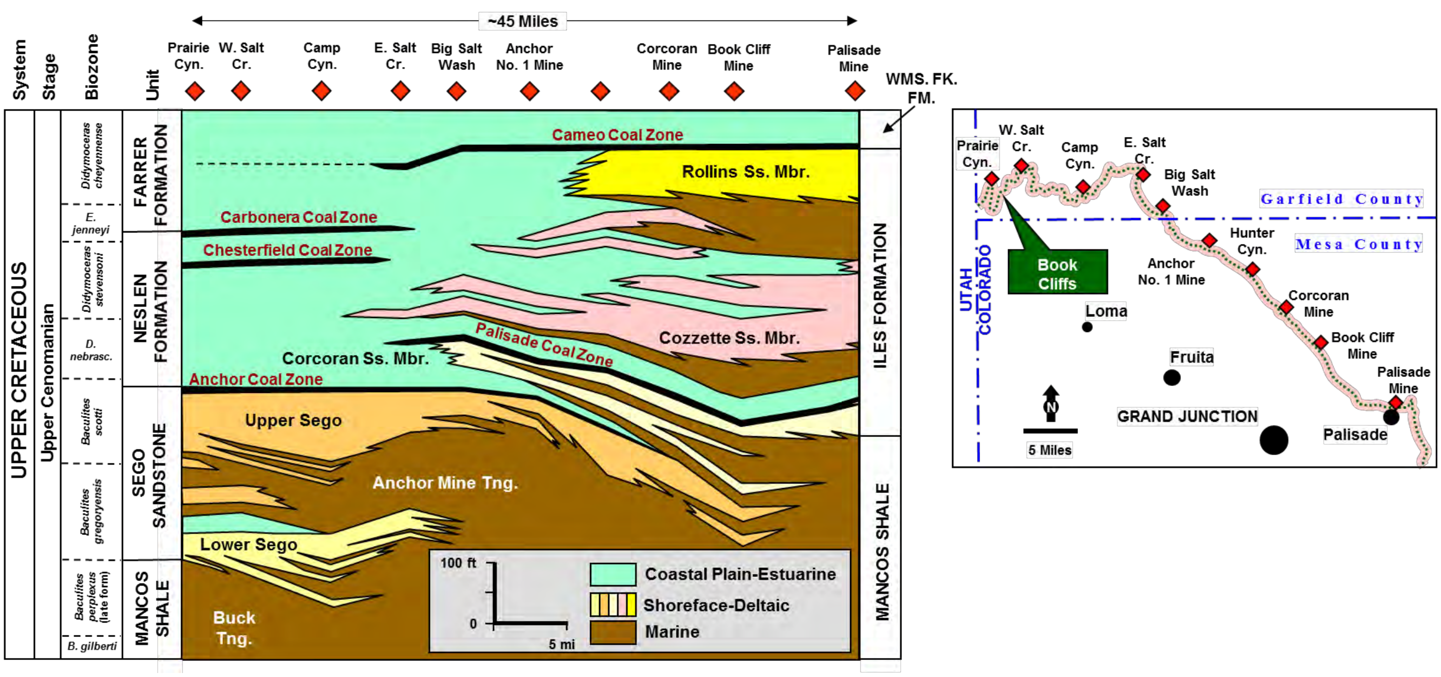


Figure S1-14. Stratigraphic relations in the lower Mesaverde Group from Palisade, CO, to the Utah-Colorado line. Correlation of the Anchor, Chesterfield, Carbonera, and Cameo coal zones are also shown. Modified from **Young (1983)**.

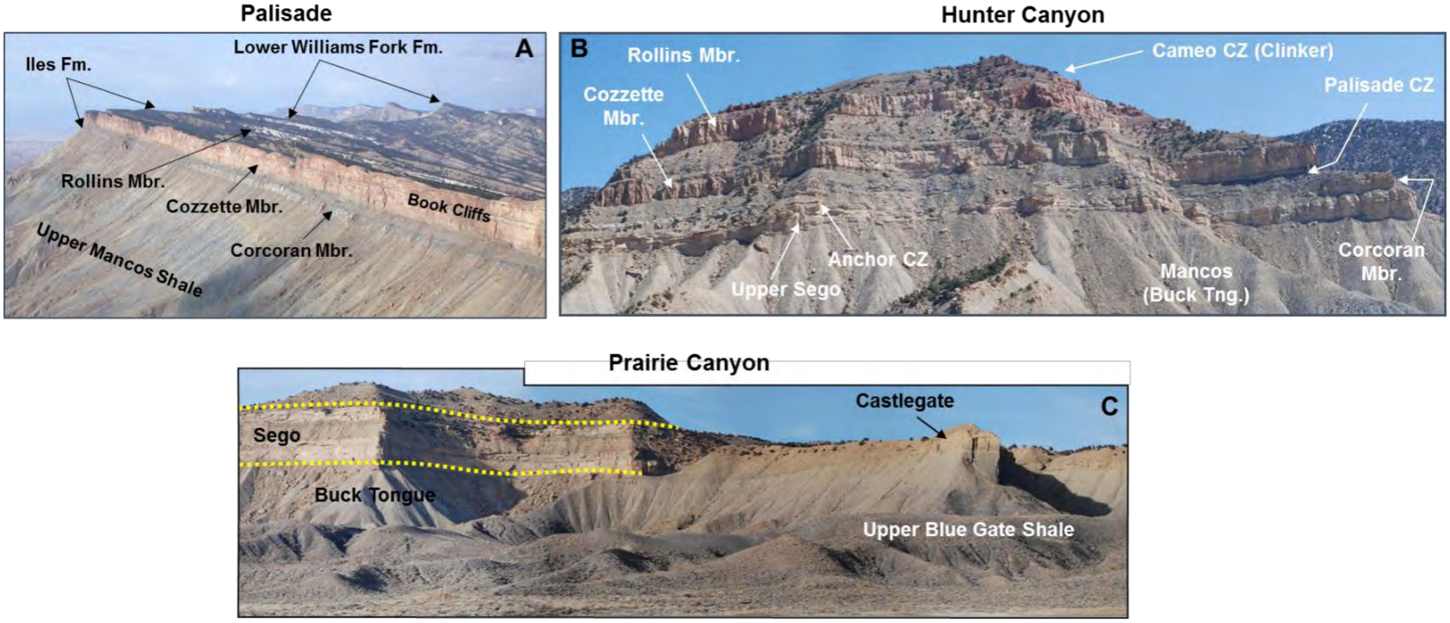


Figure S1-15. Photos of the Book Cliffs strata at three locations: **A.** -- shows the stratigraphic units along the Book Cliffs, as viewed from Mt. Garfield. The tilt is due to the Mt. Garfield monocline (Laramide age). **B. --** General view of uppermost Mancos (Buck Tongue), Sego Sandstone, Iles/Neslen Formation, and lowermost Williams Fork Formation (Cameo coal zone) at the mouth of Hunter Canyon. **C**. -- Photopan of the Book Cliffs about 1.3 miles north of **Stop1** in Prairie Canyon, showing outcrops of the Sego Sandstone, Buck Tongue, and Castlegate Sandstone. The darker colored slopes and hills below the Castlegate represent the Upper Blue Gate Member of the Mancos, which is also called the Sharon Springs Member. Photos by R. Cole.

Stop 2 – Cisco Springs Field

(Lat. 39.0868º; Lon. -109.3818º; Elev. ~ 4,850 ft)

Topics:

- Steve Tedesco's discussion of the petroleum geology in the greater Cisco area.

Stop Description

Stop 2 is located near the base of the Book Cliffs, about 6.5 miles northwest of I-70 (**Figure S2-1**). To get to the access road, please take the Danish Flat Exit (# 214). The access road is not paved.

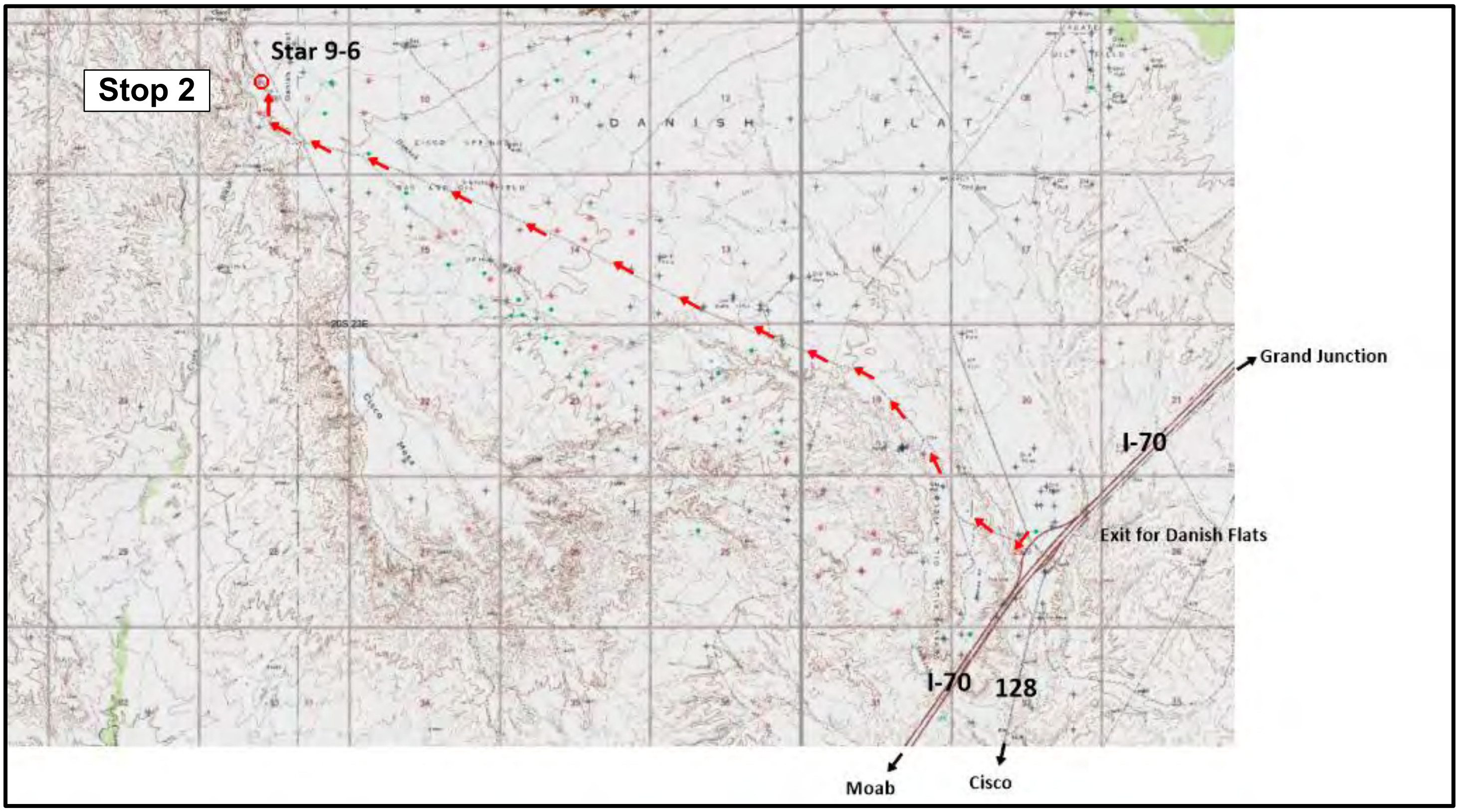


Figure S2-1. Map showing the location for **Stop 2** near Cisco Springs.

Possibly, Steve Tedesco will have additional text and figures.

Stop 3 – Utah Welcome Center

(Lat. 39.95210º; Lon. -109.68304º; Elev. ~ 5,106 ft)

Note: If needed, fuel is available at the Thomson exit just down the highway.

Topics:

- **Rest rooms** !
- Lateral stratigraphic changes in the Book Cliffs strata and Mancos Shale

Stop Description

Stop 3 is primarily a comfort stop at the Utah Welcome Center (mile marker 190), which is approximately 2.1 miles southeast of Thompson (**Figure S3-1**). A secondary objective is a summarization of the stratigraphic changes in the Book Cliffs from **Stop 1** to **Stop 3**. The discussion will be at an observation kiosk about 720 feet east of the Welcome Center or in the open area north of the parking area.

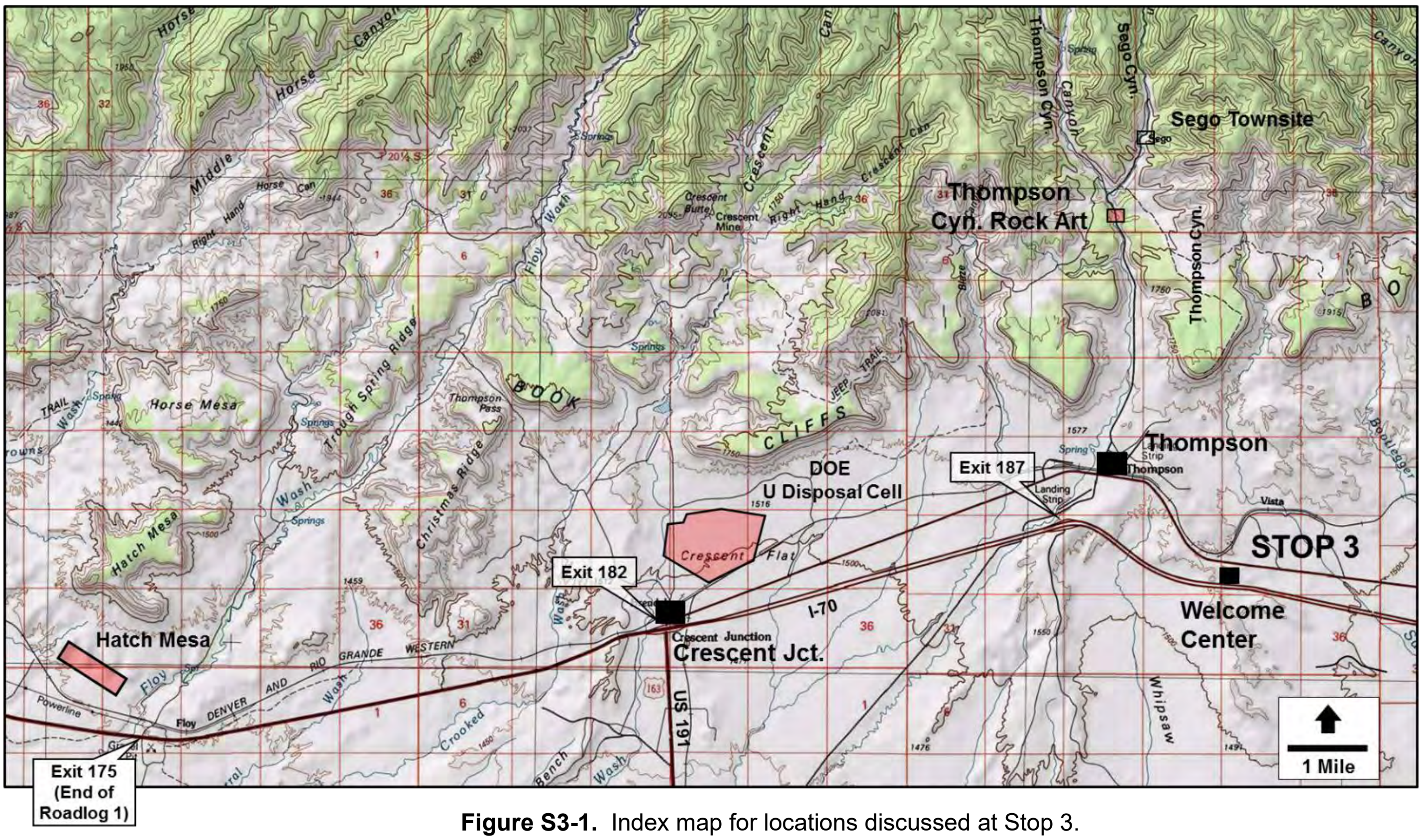


Figure S3-1. Index map for locations discussed at Stop 3.

Book Cliffs

Stop 3 is on the Prairie Canyon Member of the Mancos Shale, which is approximately 5,000 feet thick. Above the Mancos, in the cliffs, are the Grassy and Desert Members of the Blackhawk, followed upward by the Castlegate Sandstone, Buck Tongue (Mancos), Sego Sandstone, Neslen Formation, Bluecastle Formation (equivalent), Farrer Formation, Tuscher Formation, Dark Canyon sequence, and Wasatch Formation (**Figure S3-2**). The total thickness of the Upper Cretaceous units from the base of the Desert Member to the top of the Dark Canyon is approximately 1,800 feet. The Dark Canyon sequence (~150 ft thick) marks the Late Cretaceous - Early Paleogene boundary and was created during the Laramide Orogeny. It is equivalent to the Ohio Creek interval in western Colorado. A significant hiatus is associated with the Dark Canyon (**Figure S3-3**).

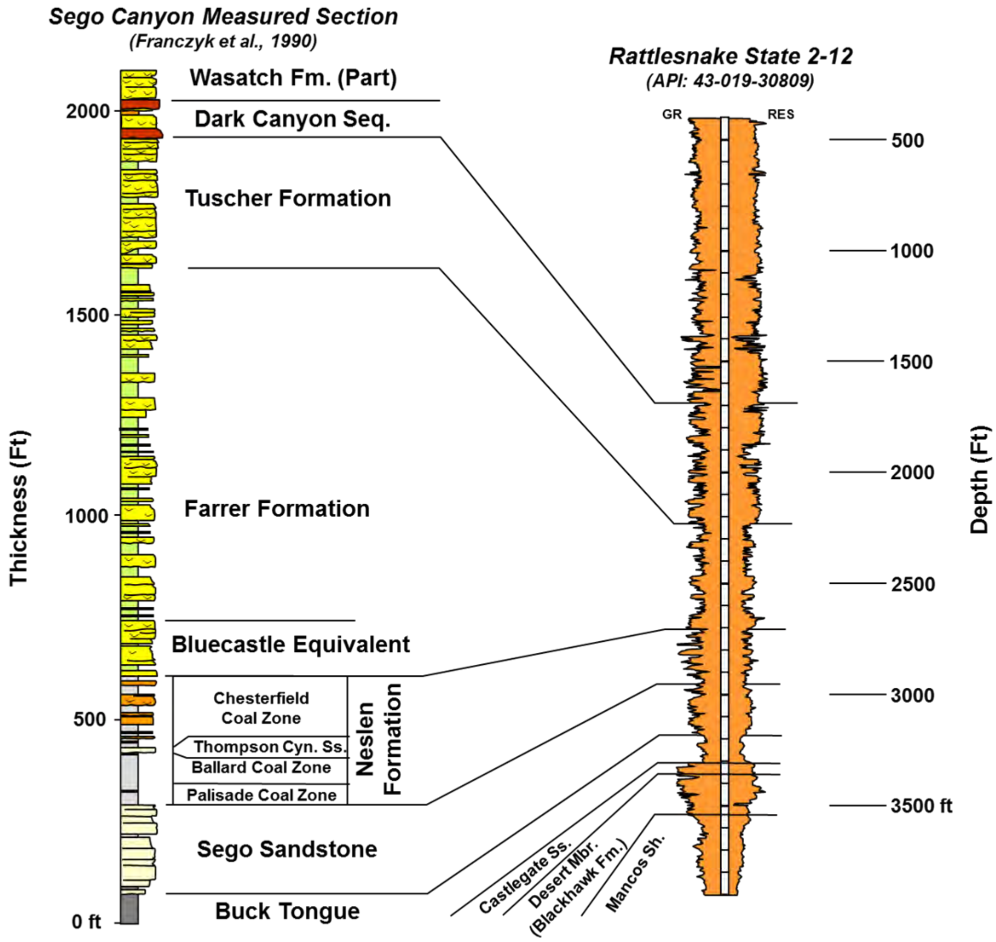


Figure S3-2. Measured section for the Sego Canyon area and nearby reference well. Sources: **Fisher (1936), Franczyk et al. (1990)** and **Hettinger and Kirschbaum (2002)**. The well is about 11 miles northwest of the head of Sego Canyon.

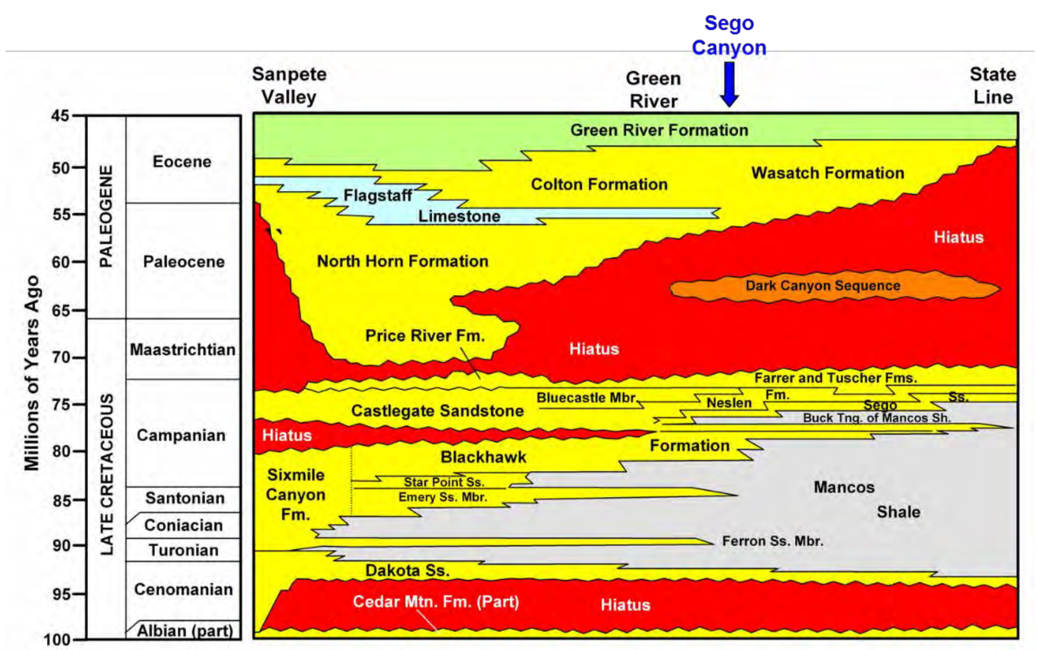


Figure S3-3. Chrono-stratigraphic chart for the Uinta Basin. Note that a very significant hiatus exists between the Tuscher Formation and the Dark Canyon sequence. Source: **Franczyk et al. (1992)**.

As discussed at **Stop 1**, the Book Cliffs provide a world-famous outcrop panorama that documents the lateral transitions between alluvial-plain, coastal-plain, marginal-marine, and shallow-marine depositional systems in a foreland basin. Over the last 75 years, thousands of petroleum, government, and academic geoscientists have worked or visited the Book Cliffs, because the lithofacies in these cliffs provide significant models that can be applied to global petroleum exploration. Again, Bob Young's dissertation research (Ohio State Univ.) was the trigger. As discussed in the background information, Bob created a "mega" stratigraphic cross section from Price, UT, to Palisade, CO (see **Figure BG-17**). The Book Cliff segment from Palisade to **Stop 1** was summarized in **Figure S1-14**). The remainder of the Book Cliffs panorama is shown in **Figure**

S3-4. All of the members of the Blackhawk Formation play out along this section, and the Castlegate Sandstone (fluvial and shoreline) becomes significant. An unconformity (sequence boundary) separates the Blackhawk from the Castlegate (**Figure S3-3**).

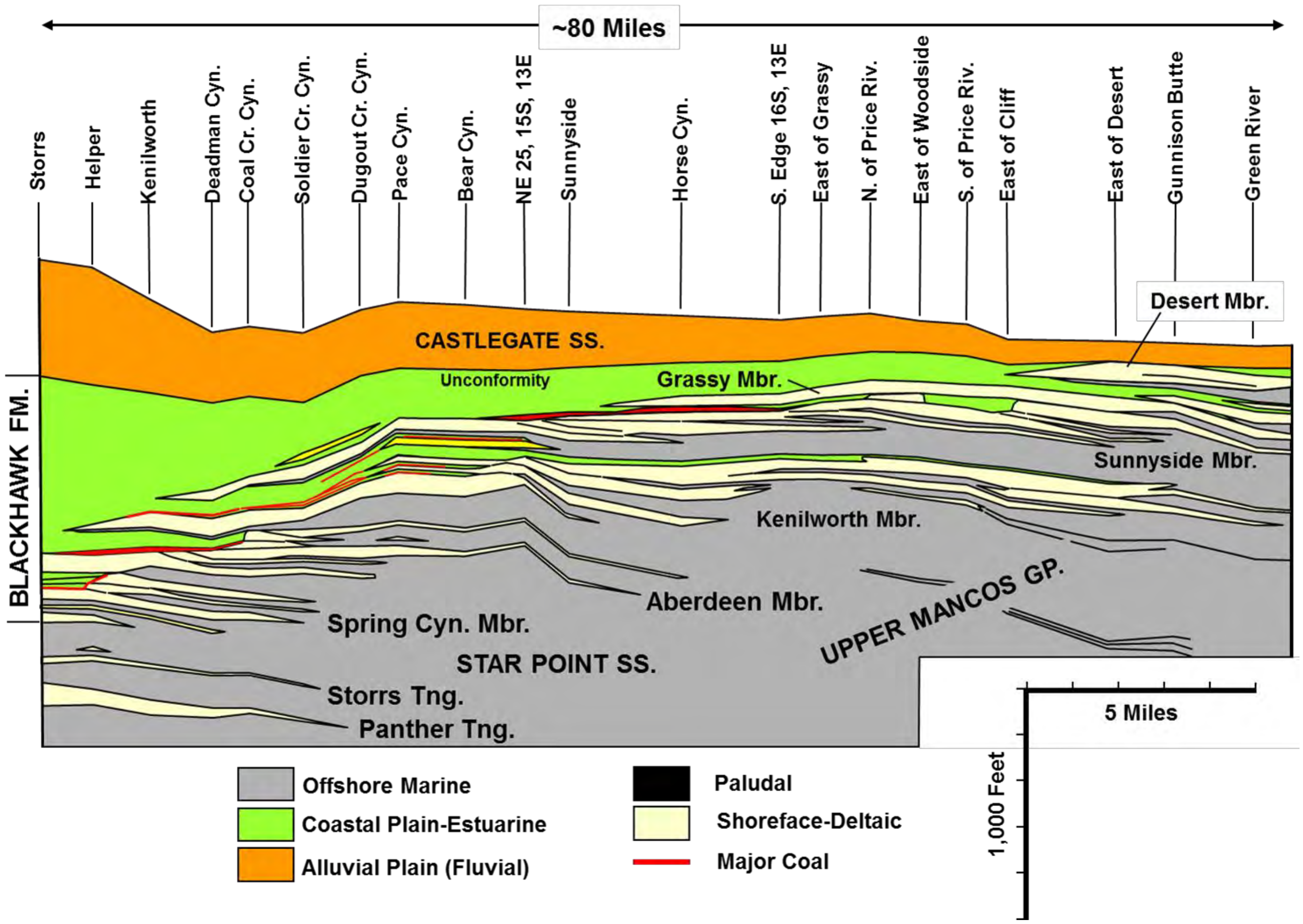


Figure S3-4. Stratigraphic cross section from Price, UT, to Green River, UT, which is approximately 24 miles west of **Stop 3**. Source: **Young (1955)**. Note the seaward pinch-outs of the shoreface-deltaic units into the Mancos Shale. Compiled by R. Cole.

The strata discussed above can be accessed by a road (GCR 159 / BLM 159) leading from Thompson, through lower Thompson Canyon, then up Sego Canyon. This road is partly unimproved and prone to flash flooding. Sego Canyon is one of the most scenic and geologically interesting drainages in the southern Uinta Basin. Anderson **et al. (2008)** provide a road log from the Thompson Exit to the top of Sego Canyon (~14.4 miles). At the head of Sego Canyon, the road intersects tribal lands of the Uintah and Ouray Ute Indian Reservation. As one enters the Book Cliffs in Thompson Canyon, the uppermost Mancos Shale, Desert Member of the Blackhawk Formation, and Castlegate Sandstone "guard" the entrance (**Figures S3-5 and S3-6**). The Desert and Castlegate come to road level at the BLM rock-art site (**Figure S3-1**).

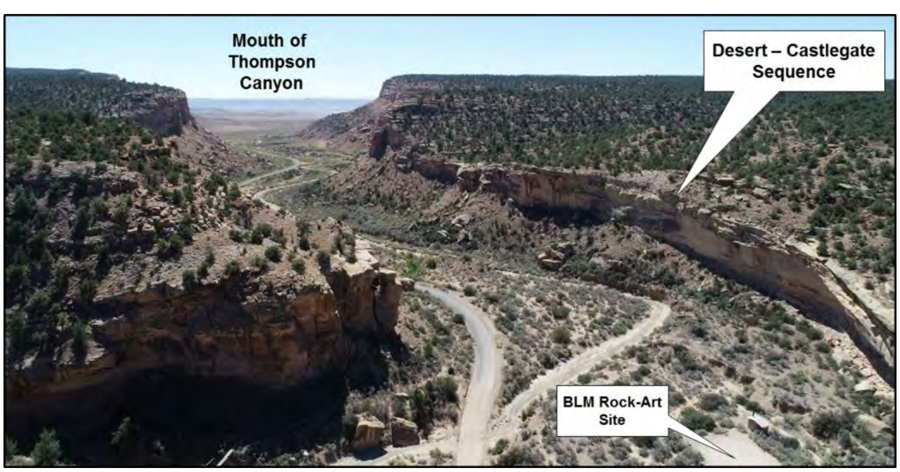


Figure S3-5. Aerial photo of the mouth of Thompson Canyon showing the base of the Mesaverde Group, which is defined by the Desert Member of the Blackhawk Formation and the Castlegate Sandstone. Beds are dipping north into the Uinta Basin. View is looking south. Photo by R. Cole.

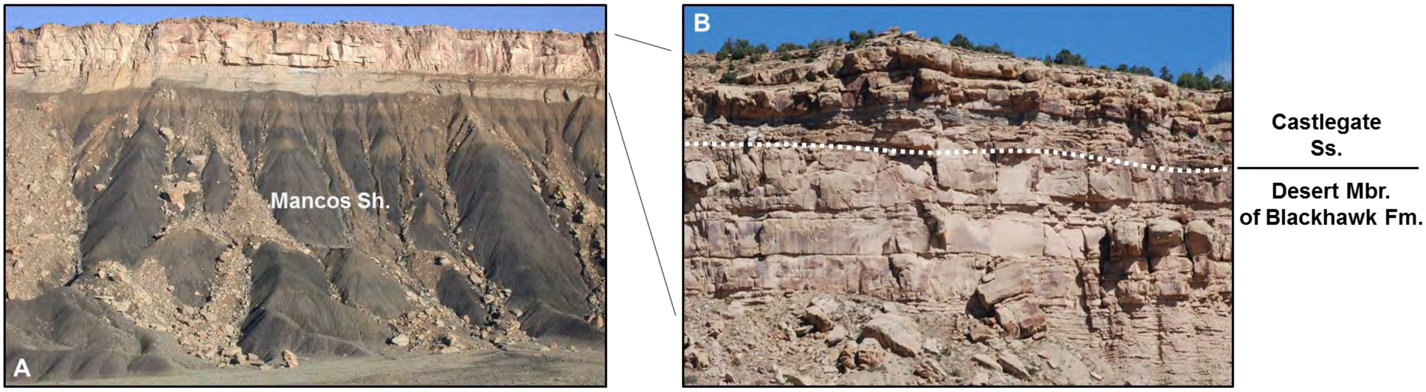
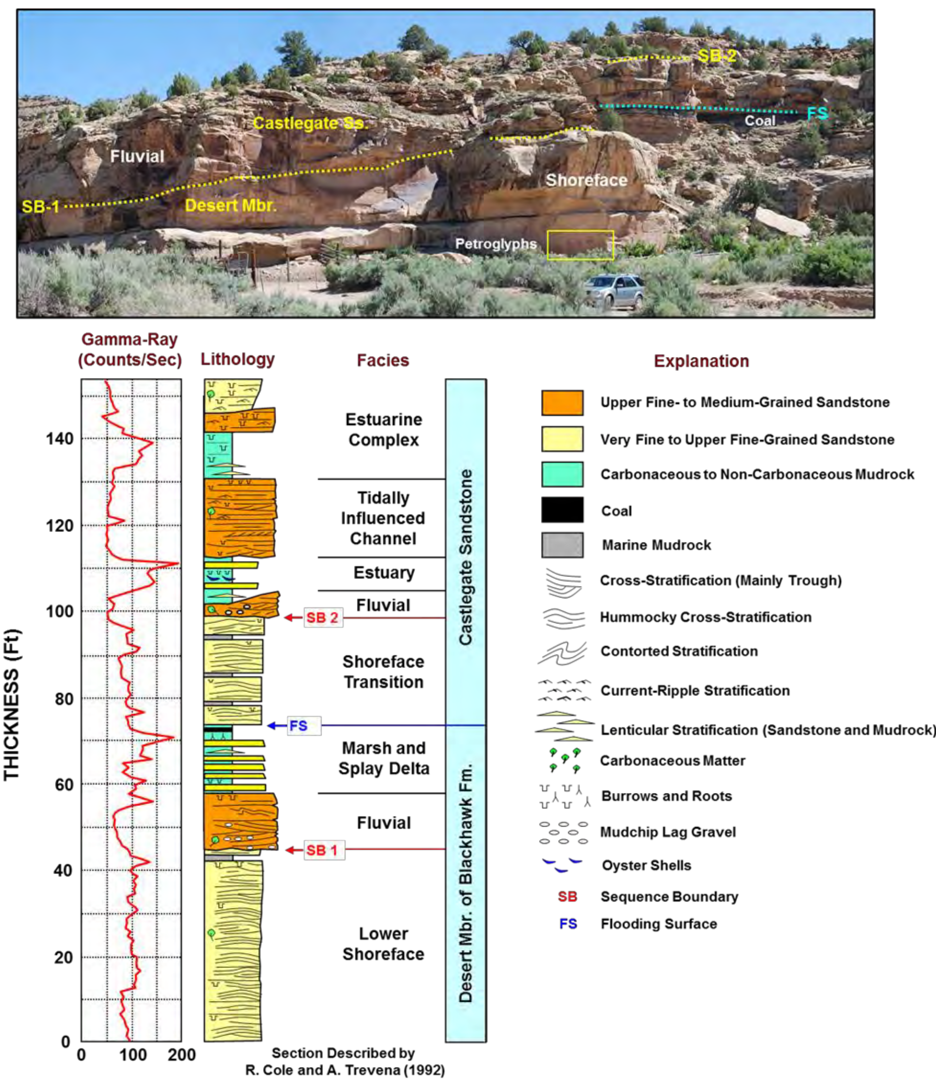


Figure S3-6. Photos the Book Cliffs rim at the mouth of Thompson Canyon. **A**. – General view. **B**. – Close-up view, showing that the Desert Member consists of three stacked marginal-marine sandstones, whereas, the Castlegate is a heterolithic assemblage of coastal-plain, estuarine, and fluvial sandstones, interstratified with coal and mudrock. Photos by R. Cole.

The Desert-Castlegate outcrops at the BLM rock-art site are one of the most frequently visited locations in the Book Cliffs by petroleum and academic geologists. This is one of the locations where Exxon/Mobile developed their famous model for sequence stratigraphy in marginal-marine sandstone sequences (**Van Wagoner, et al., 1991**). Multiple geologic field trips have visited this convenient site. **Figure S3-7** illustrates what all the "excitement" is about.

Figure S3-7. Photo of the Desert-Castlegate interval at the BLM rock-art site. A prominent erosional surface (i.e., sequence boundary) separates the two units, as shown in the measured section. An impressive assortment of depositional facies is present. The Desert Member is a wave-dominated (lower shoreface) sandstone probably deposited in 50-100 feet of water. It is erosionally truncated by the sequence boundary and overlain by a fluvial channel. Obviously, a fall in sea level was required. The fluvial sandstone is beveled by a marine flooding surface produced by waves during a subsequent rise in sea level. This is the traditional contact between Desert and the Castlegate. Next, as sea level rose, another shallow-marine sandstone was deposited. A second erosional surface (sequence boundary), created by a second sea-level fall, truncates the second shoreface sandstone. Above this surface, the Castlegate consists of estuarine sandstone and mudrock with oyster shells and marine trace fossils. The Castlegate is eventually truncated by another marine flooding surface (not shown), which is overlain by the Buck Tongue of the Mancos. Photo by R. Cole; measured section by R. Cole and Art Trevena when they worked for Unocal.



Aside from the sedimentologic story of sea-level rise and fall, the archaeological features at the BLM site are also excellent. The various panels with pictographs and petroglyphs of animals, people, and spirts are posted on fine-grained, well-sorted, tightly cemented, shoreface sandstone of the Desert Member. Apparently, this facies was an ideal canvas for the various Indigenous groups who passed through Thompson Canyon. According to the BLM signages, three separate cultures are represented: (1) Barrier Canyon-Archaic; (2) Fremont-Anasazi; and (3) Historic Ute. Signs posted in front of the panels provide brief descriptions. Numerous websites (e.g.,: https://www.greatamericanhikes.com/post/the-haunting-rock-art-of-sego-canyon) discuss the panels in more detail.

Continuing north from the BLM site, Thompson Canyon intersects Sego Canyon after about 0.7 miles. The road also splits. Near the intersection is the Sego Cemetery. The cliffs above the road represent the lower Sego Sandstone (shallow marine), which rests conformably on the Buck Tongue of the Mancos (**Figure S3-8**). Yes, the type locality for the Sego Sandstone is in Sego Canyon.

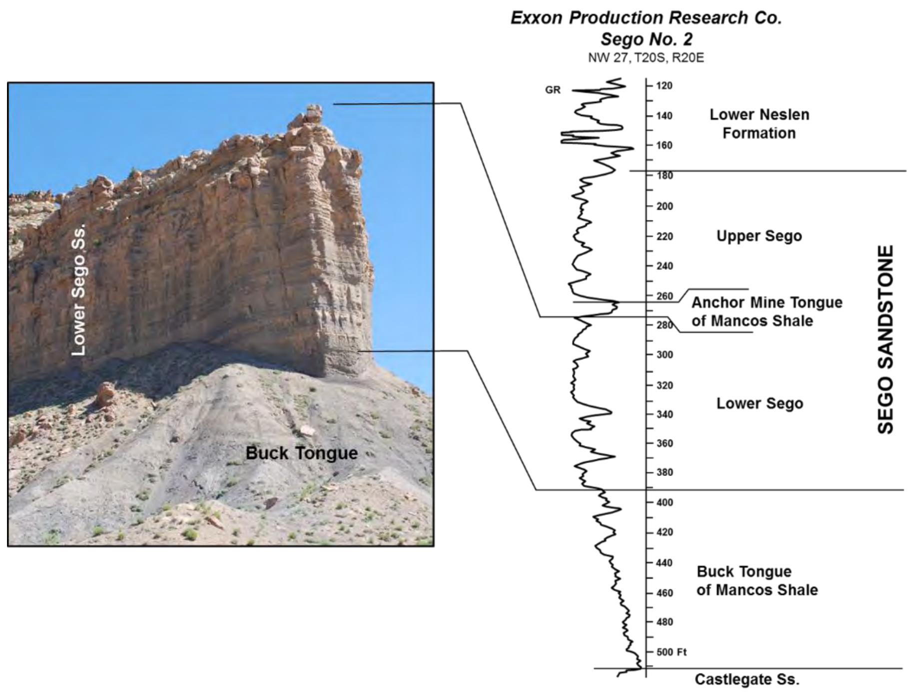


Figure S3-8. Well log on the right is from a core hole drilled in Sego Canyon by Exxon (**Van Wagoner et al., 1991)**. It shows two coarsening-upward shallow-marine sequences in the Sego Sandstone. The photo shows the lower Sego. The lower part the interval consists of interstratified sandstone shale, but transitions upward into only sandstone. This transition reflects the shallowing of water as sand prograded in from the west. Photo by R. Cole.

Up-canyon from the cemetery (~ 0.9 miles), the road enters the Sego townsite (abandoned). Sego was once a prosperous coal-mining town that supplied fuel to the Denver and Rio Grande railroad and nearby towns. A store, boarding house, coal-wash facility, and tipple were constructed around 1914, as a railroad spur from Thompson was constructed. Coal production ended in the early 1953 after the railroad converted from steam to diesel locomotives. Three coal zones occur in the Neslen Formation: Palisade, Ballard, and Chesterfield (**Figures S3-2** and **S3-9**). Most coal production came from the Ballard and Chesterfield coal zones (**Clark, 1914; Doelling and Graham, 1972; Willis, 1986**). Many abandoned portals, adits, haulage structures, railroad grades, spoil piles, and collapsed stone dwellings are scattered throughout the Sego Canyon.

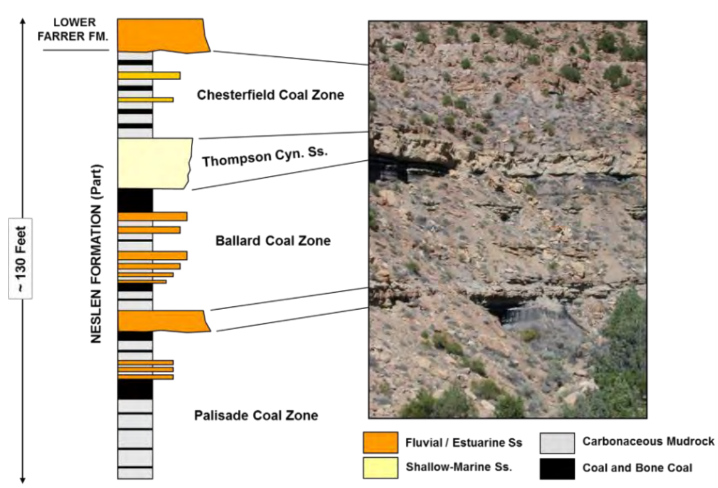


Figure S3-9. Photograph and section of the Neslen Formation. Photo by R. Cole.

Continuing up Sego, the road follows the stream bed and intersects the Bluecastle (equivalent to a unit around Wellington, UT), Farrer, Tuscher, Dark Canyon, and Wasatch (**Figure S3-2**). Photos are provided in **Figure S3-10**.

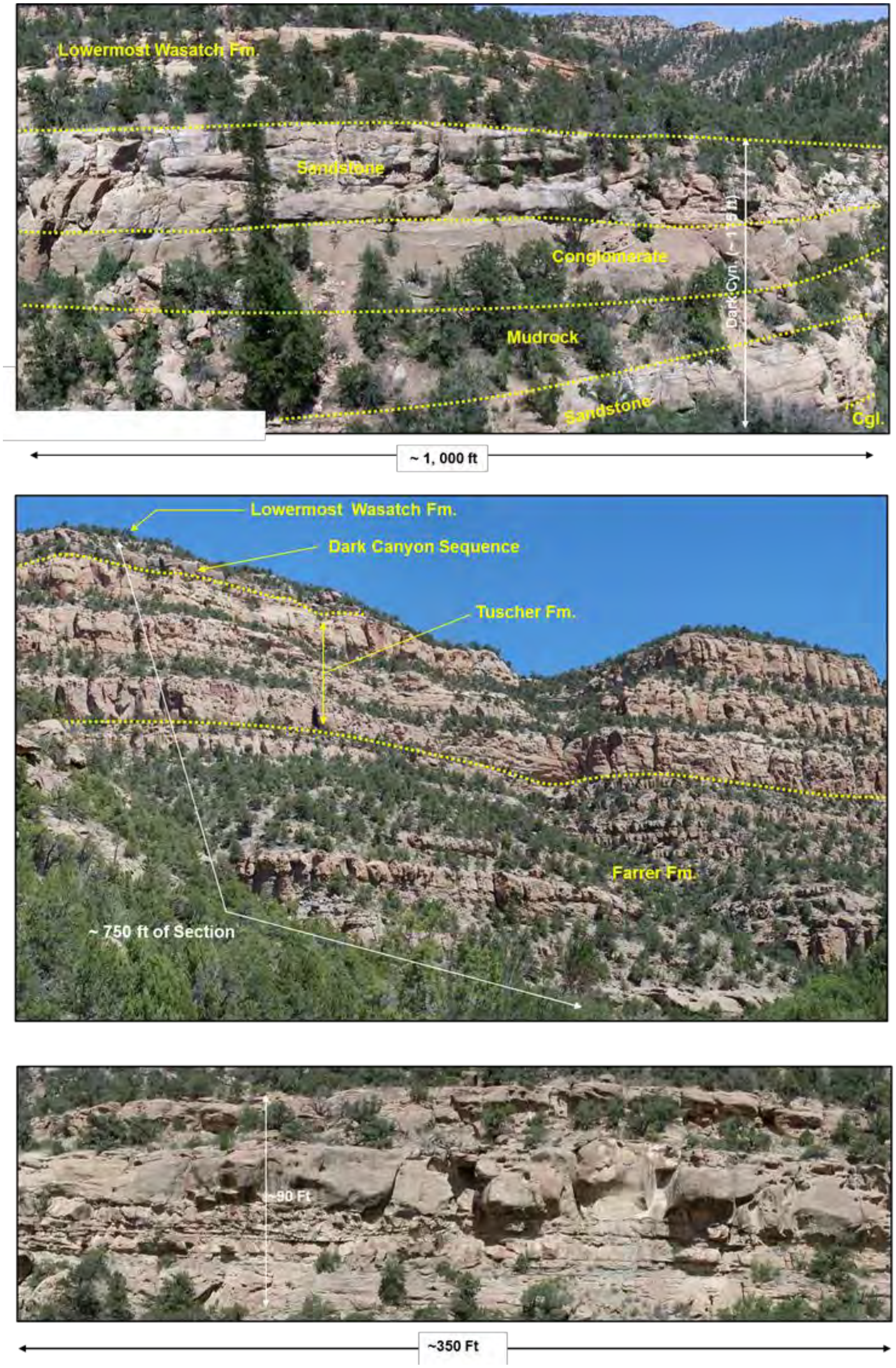


Figure S3-10. Photos of the impressive strata in scenic Sego Canyon, north of the Sego townsite. **Lower photo** shows fluvial and floodplain deposits in the Bluecastle equivalent. **Middle photo** illustrates the Farrer Formation, which is mainly high-energy fluvial sandbodies interbedded with floodplain deposits, and the Tuscher Formation, which consists of amalgamated fluvial sandbodies with minor floodplain deposits. The Dark Canyon and lowermost Wasatch are at the top. **Upper photo** is a more detailed view of the Dark Canyon Sequence, which consists of two chert-pebble conglomerates interstratified with coarse-grained conglomeratic sandstone. The Dark Canyon represents the Laramide Orogeny. Source: **Anderson, et al. (2008)**.

Hatch Mesa Sandstone

An unusual stratal unit is present within the upper Mancos Shale between Crescent Junction and the turnoff for the Ten Mile Graben (**Figure S3-1**). Called the Hatch Mesa Sandstone complex, it is totally encased in the Upper Blue Gate Shale, and is positioned about 500 feet stratigraphically below the Grassy Member of the Blackhawk (**Figures S3-11** and **S3-12**). The complex is approximately 150 feet thick and has two sandstone packages that were deposited by sea-bottom turbidity currents. A regional channelized interval called the Emery Interval (also the Pinto Wash Interval and the Beckwith Sandstone) occurs below the Hatch Mesa complex. Approximately 60 feet below the Hatch Mesa Sandstone is a two- to five-foot thick interval consisting of en-echelon lenses of hematitic, oolitic, medium- to coarse-grained, cross-stratified sandstone that contains fish teeth and bones, shell fragments, and internal molds of ammonites and bivalves.

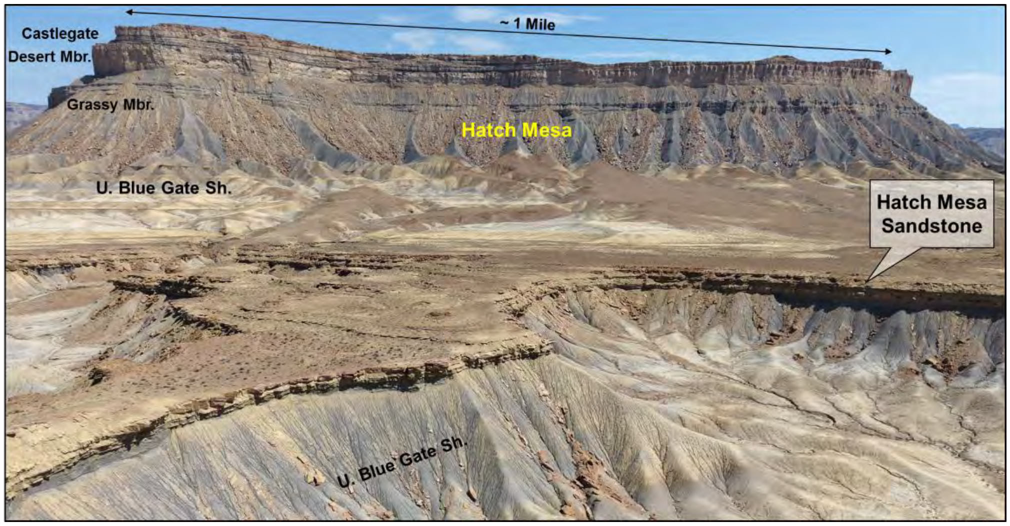


Figure S3-11. Aerial photo of the Hatch Mesa Sandstone complex, which occurs in the upper Blue Gate Shale of the Mancos Group. It also pinches out laterally into the Blue Gate. The cliffs of Hatch Mesa consist of shoreline / deltaic members of the Blackhawk. Photo is by R. Cole and Javier Tellez..

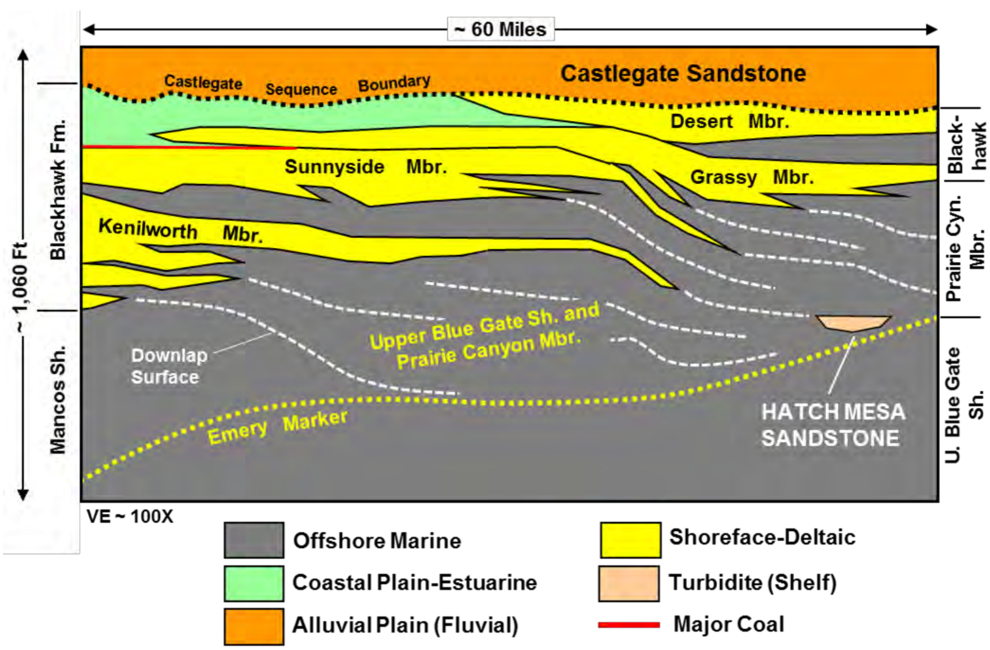


Figure S3-12. Stratigraphic cross section between Woodside and Crescent Junction, UT, showing pinchouts of the Kenilworth, Sunnyside and Grassy Members of the Blackhawk into the Upper Blue Gate Shale. A turbidite-fan, called the Hatch Mesa complex, is present just above the Emery marker. The white lines are downlap surfaces that converge onto the Emery marker. Modified from **Swift et al. (1987)**.

Newman (1985) did a detailed sedimentological study of the Hatch Mesa complex for his Masters Thesis at the University of Utah. This included eight measured sections and collection of abundant paleocurrent data. Newman's study interval is about 250 feet thick and covers about 2.9 miles laterally (**Figure S3-13**).

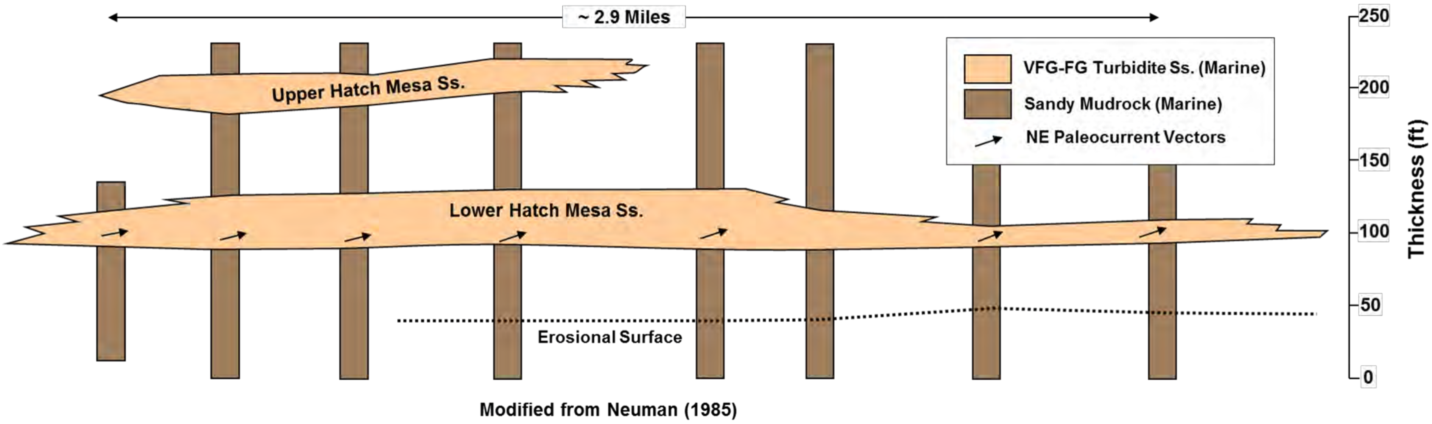


Figure S3-13. Stratigraphic cross section of the Hatch Mesa Sandstone complex between Floy Wash and Browns Wash. Source: **Newman (1985)**. A detailed measured section by Unocal is presented in the following figure.

The thicker beds in the lower Hatch Mesa commonly display pinch-and swell structures, ball-and-pillow structures, flute casts, convoluted lamination, isolated shale clasts, and rippling (**Figure S3-14**). In addition, they also show partial Bouma (graded-turbidite) sequences (i.e., a base with scour surfaces and flute casts overlain by well-sorted fine-grained sandstone with parallel lamination, wavy lamination, ripple lamination, or climbing-ripple lamination). Paleocurrent readings from the flute casts are strongly oriented to the northeast (**Newman, 1985**).

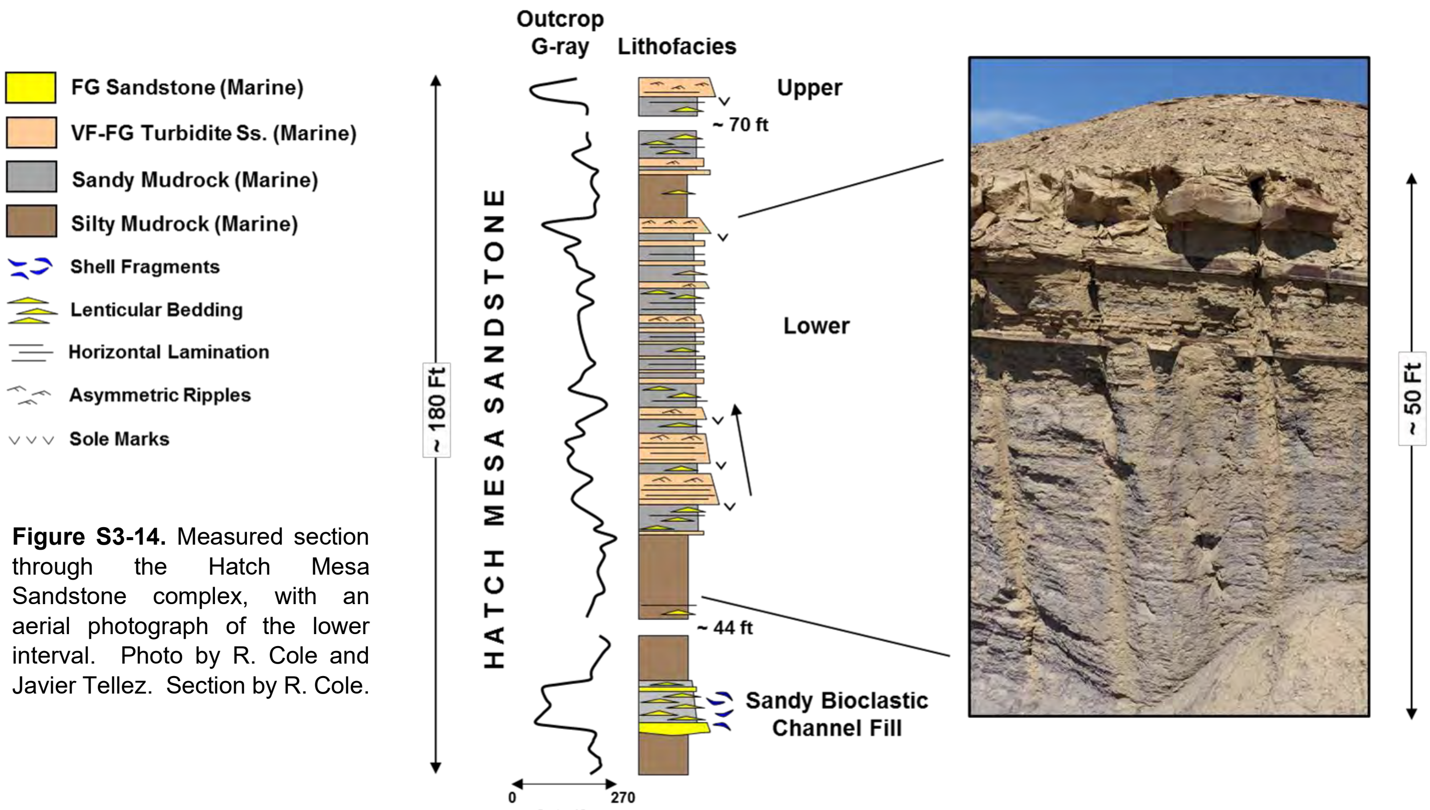


Figure S3-14. Measured section through the Hatch Mesa Sandstone complex, with an aerial photograph of the lower interval. Photo by R. Cole and Javier Tellez. Section by R. Cole.

The Hatch Mesa sequence is probably an offshore, time-equivalent facies of the Kenilworth Member of the Blackhawk Formation, which downlaps onto the Emery interval (**Figure S3-12**). Four possible depositional models have been proposed: 1) turbidite fan (**Balsley, 1980; Taylor and Lovell, 1991**); 2) prodelta plume (**Swift et al., 1987**); birds-foot delta (**Newman, 1985**); and 4) proximal delta lobe (**Newman, 1985**). The sedimentological features (**Figure S2-14**) most closely agree with the turbidite-fan model.

If the turbidite-fan model is correct, it suggests that the Hatch Mesa complex was fed by a submarine feeder channel from the southwest, possibly 5-10 miles southwest of Green River, Utah (**Figure S3-15)**. Unfortunately, Cretaceous rocks in this area have been eroded (on the Laramide San Rafael Swell). Fine-grained sand probably derived from a wave-dominated delta/strandline apparently bypassed the Kenilworth shoreface and was carried down the submarine ramp to the

Hatch Mesa area where the fan system developed. Orientation of the fan is based on paleocurrent data from sole marks. It is likely that this scenario developed during a fall in relative sea level towards the end of Kenilworth time.

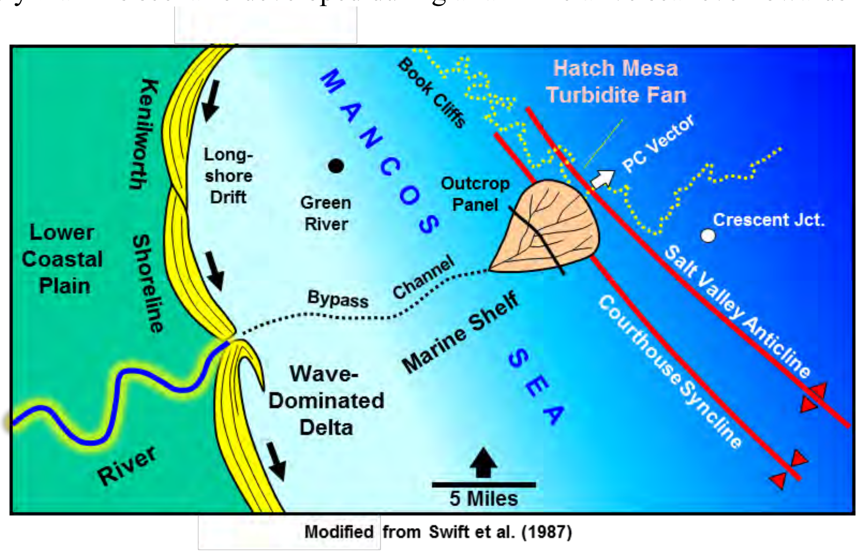


Figure S3-15. Paleogeopraphic cartoon showing a depositional model for the Hatch Mesa turbidite fan. Modified from **Swift et al. (1987)**.

Localization of the fan system was probably controlled by sea-bottom topography. The Hatch Mesa area is along the southwestern nose of the Salt Valley Anticline (projected northwest of Arches National Park). Movement of the Paradox Salt began in the Permian and continued into the Mesozoic. It is speculated that this salt structure had an expression during the Late Cretaceous, probably forming a low-relief submarine ridge several miles across. Density flows encountering the ridge would have decreased in velocity and deposited their sediment load in a shallow northwest-trending basin coincident with the Courthouse Syncline.

Incidentally, the Hatch Mesa Sandstone appears to be a one-of-a-kind occurrence (surface exposure) in Utah.

Stop 4 – Floy Exit

(Lat. 38.917140º; Lon. -109.938911º; Elev. ~ 4,582 ft)

Note: If needed, fuel is available at Crescent Junction.

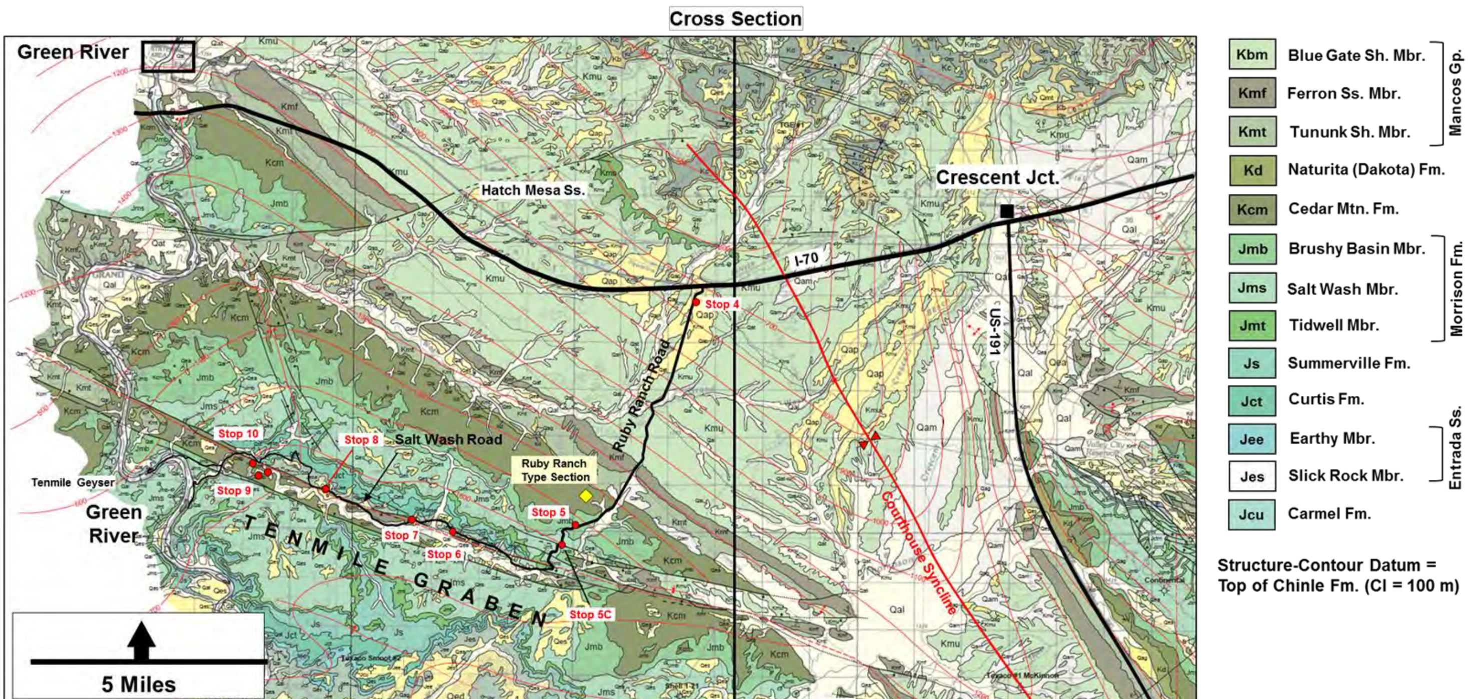
Topics:

- Carpool setup
- Introduction to the Ten Mile Graben area. [Note - The Ten Mile Graben is also called the Tenmile or Ten-Mile Graben on various geologic and topographic maps, and websites.]

Stop Description

Stop 4 is mainly a logistical stop to set up final carpools into the Ten Mile Graben area (**Stops 5-10**). This is where Road Log 2 begins, following the Ruby Ranch and Salt Wash roads. When wet, these BLM roads will be slippery and possibly impassible. Also, there are no services available and no rest rooms/outhouses. Since we are in the San Rafael Desert, significant vegetation is very scarce, to say the least. It should be noted that most of today's stops were visited during a 2004 GJGS field trip led by Craig Goodknight, Dick Dayvault, and Bill Hood.

Below is a geologic map and cross section of the Ten Mile area (**Figure S4-1**). The bedrock beneath **Stop 4** is Blue Gate Shale.



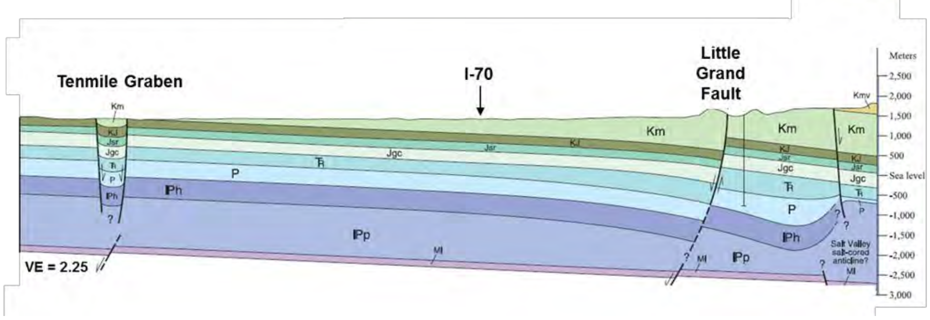


Figure S4-1. Geologic map and cross section of the Ten Mile Graben area. Source: **Doelling (2002)**.

Figures S4-2 provides a more detailed geologic map for Stops 5-10.

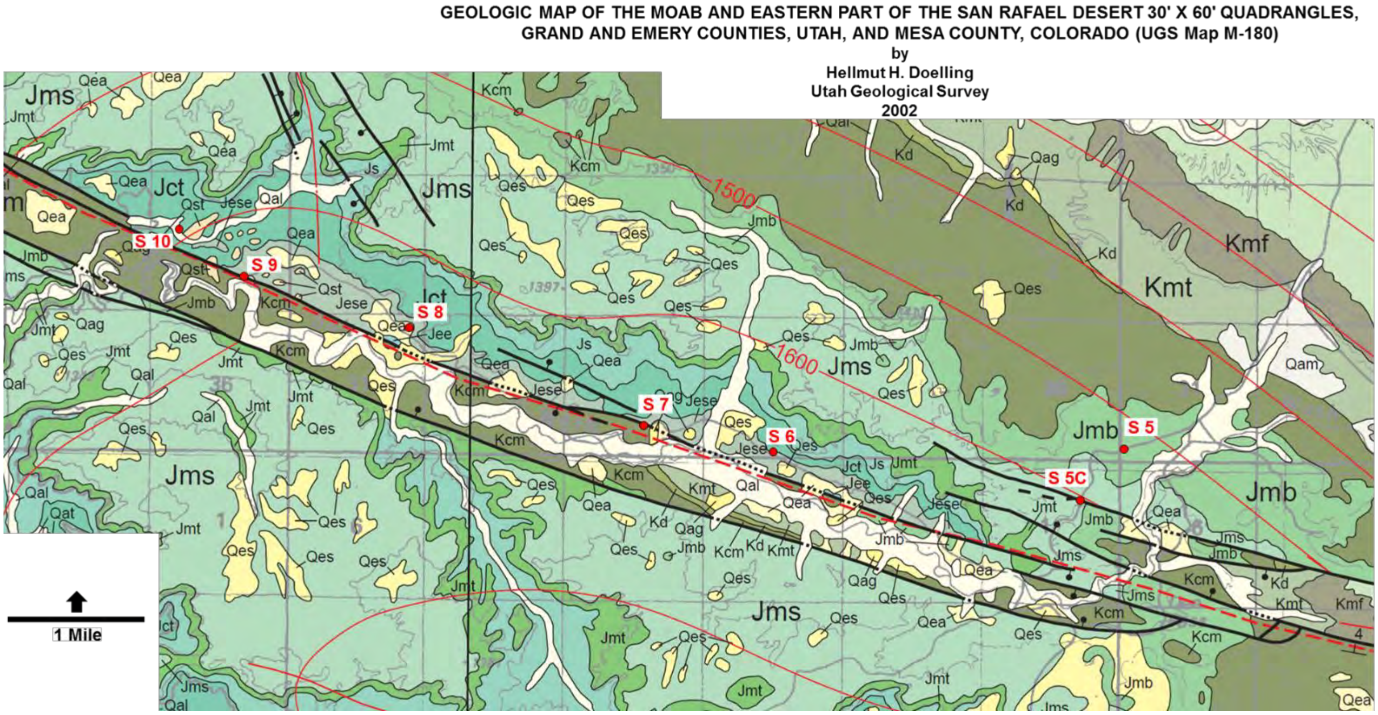


Figure S4-2. Enlarged geologic map the Ten Mile Graben area showing Stops 5-10.. Source: **Doelling (2002)**.

This leg of the field trip is entirely within the northwestern Paradox Basin, which was created during the Ancestral Rocky Mountain Orogeny (**Figure BG-4**). Correspondingly, the surface and subsurface stratigraphic section is very thick (> 25,000 feet) and includes Paleozoic as well as Mesozoic strata (**Figure S4-4**). The thickest unit is the Pennsylvanian Paradox Formation.

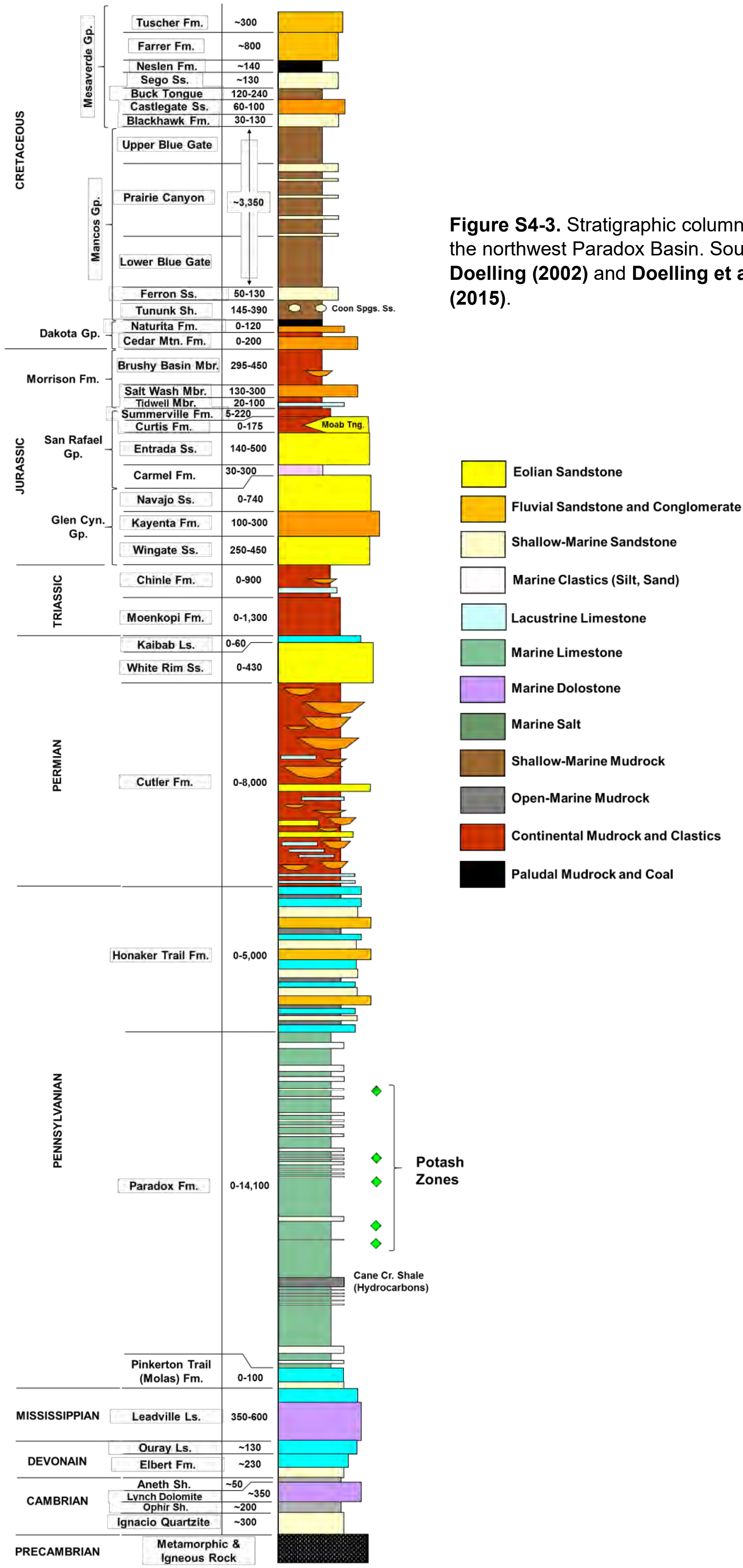


Figure S4-3. Stratigraphic column for the northwest Paradox Basin. Sources: **Doelling (2002)** and **Doelling et al. (2015)**.

Stop 5 – Well Pad

(Lat. 38.848454º; Lon. -109.985694º; Elev. ~ 4,460 ft)

Topics:

- Cedar Mountain Formation
- Petroleum Exploration in the northern Paradox Basin

Stop Description

Stop 5 is located about six road miles from the Floy Wash Exit along the Ruby Ranch Road near a recent oil well drilled by Rose Petroleum. During the drive from **Stop 4**, the road has slowly cut down trough the Blue Gate Shale, Ferron Sandstone/Juana Lopez members, Tununk Shale, Cedar Mountain Formation, and into the Brushy Basin Member of the Morrison. The strata dip about 5º northeast into the Courthouse Syncline (**Figures S4-1** and **S5-1**). **Stop 5** is just off the northeast side of the Ten Mile graben. The Ferron/Juana Lopez forms a noticeable cuesta where a major powerline crosses the road. **Figure S5-2** provides a general photo of **Stop 5**.

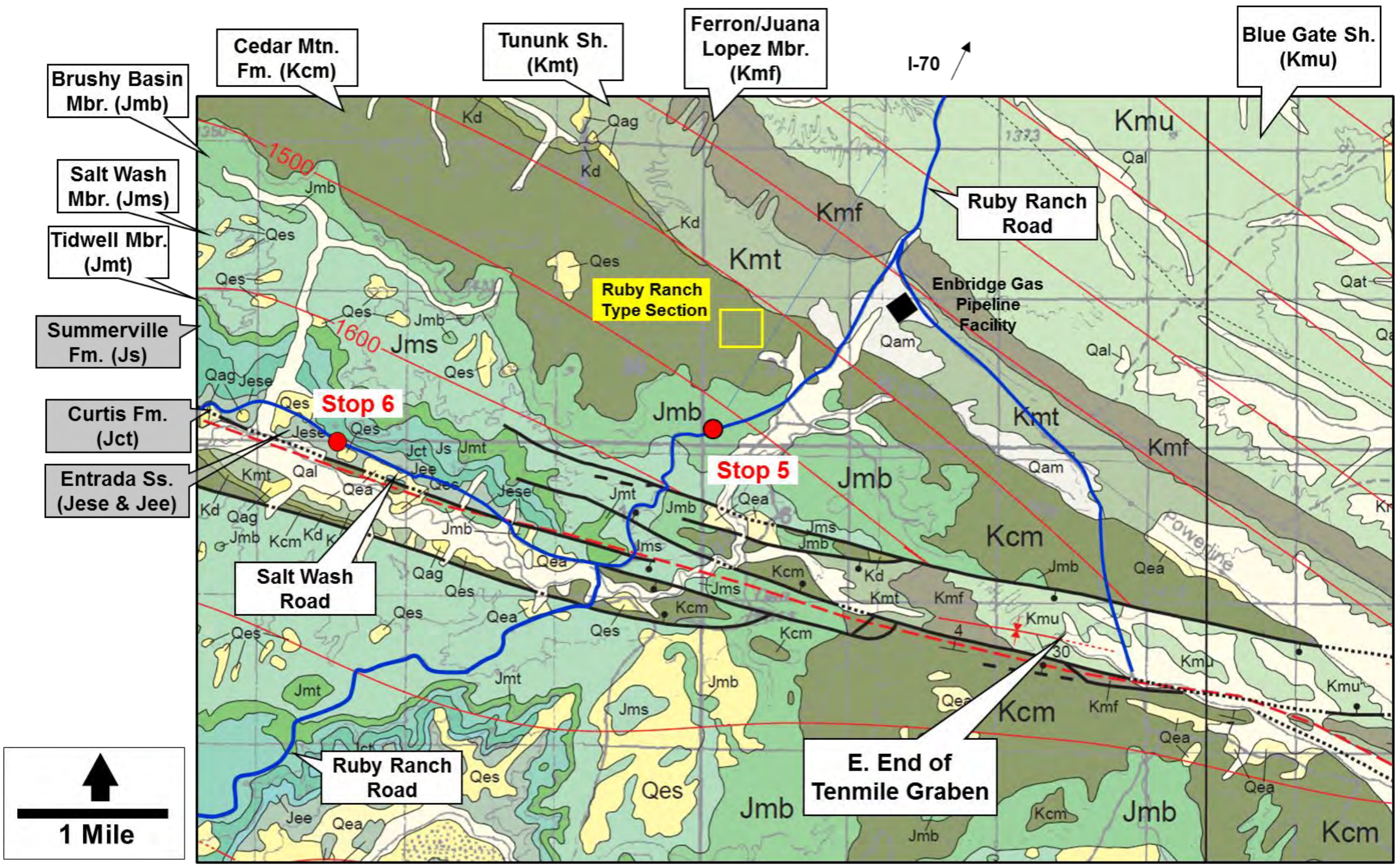


Figure S5-1. Annotated geologic map of the eastern Ten Mile Graben area showing the location of **Stop 5** and the type location of the Ruby Ranch Member of the Cedar Mountain Formation. The datum for the structure-contour lines is the top of the Chinle (in meters; contour interval = 100 m). Source: **Doelling (2002)**.

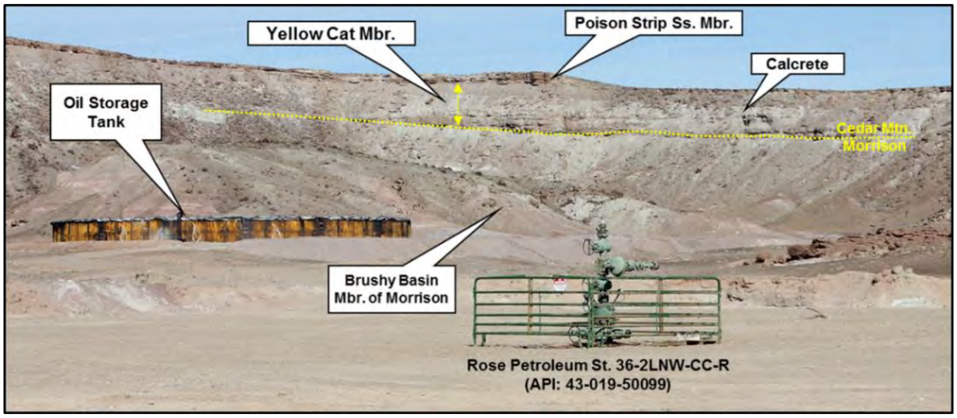


Figure S5-2. Photograph of **Stop 5**. In the background are the uppermost Morrison Formation and lower Cedar Mountain Formation. The yellow tank contains oil, which was probably produced during drilling, completion and testing of the well. As discussed below, the well is a horizontal penetration of the Cane Creek clastic unit in the Paradox Salt (MD = 15,228 ft; TVD = 9,384 ft). Photo by R.Cole.

Cedar Mountain Formation and Naturita (Dakota) Formation

History

As discussed earlier, Cretaceous strata exposed in the Book Cliffs in eastern Utah and western Colorado have received considerable scientific study. Much of the groundbreaking research was conducted by Bob Young in the 1950s. Young was also quite interested in the Mancos Shale, Cedar Mountain Formation, Burro Canyon Formation, Naturita (Dakota) Formation and Morrison Formation. He was truly a stratigrapher's stratigrapher.

After nailing down the framework of the Blackhawk Formation (**Young, 1955**), he unleashed his expertise on the Lower Cretaceous Cedar Mountain-Burro Canyon interval and the Upper Cretaceous Dakota Formation (**Young, 1960**). Conducted while he was employed by the U.S. Atomic Energy Commission in Grand Junction, the new effort involved a regional study of outcrops across Emery, Carbon, and Grand Counties in Utah, and Mesa, Delta, Montrose, Ouray, and Gunnison Counties, Colorado. In total, he visited about 150 locations, documenting the outcrops with measured sections, descriptions, and paleontological observations.

Prior to Young's work, the non-marine Lower Cretaceous strata (with variable nomenclature) had been mapped across the Colorado Plateau (**Figure S5-3**). East of the Colorado River, the term "Burro Canyon Formation" was used with a type locality in Burro Canyon, near Slickrock Colorado (**Stokes, 1944**). West of the river, the term "Cedar Mountain Formation" was used, with a type locality at Cedar Mountain (**Stokes and Phoenix, 1948**). Stokes later subdivided the Cedar Mountain in the type-section area. At the base, he defined the Buckhorn Conglomerate, which was overlain by the Cedar Mountain Shale (**Stokes 1952**). Since the naming of these two units, the Cedar Mountain has received far more scientific attention (~4.75 X) than the Burro Canyon. The reason is that the Cedar Mountain contains a very impressive record of Early Cretaceous dinosaurs, as documented by Jim Kirkland (UT State Paleontologist) and his numerous colleagues. [Note -This group of paleontologists, geochemists, and sedimentologists is herein called the "Kirkland Brigade."]

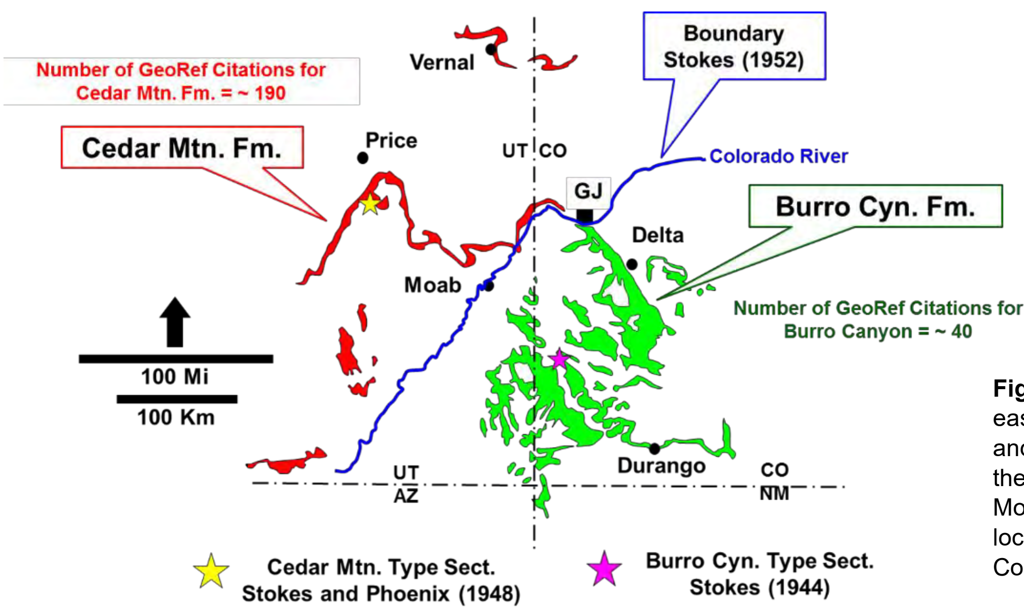


Figure S5-3. Map of western Colorado, eastern Utah, and northernmost Arizona and New Mexico showing the outcrops of the Burro Canyon Formation and Cedar Mountain Formation, plus the type locations for both. Source: **Young (1960)**. Compiled by R. Cole.

At the initiation of Young's work in the late 1950s, the common practice was to include the carbonaceous mudrocks and impure coals at or near the base of the Cretaceous section in the "Dakota Sandstone," "Dakota Formation," or Dakota Group." Unfortunately, the type locality for the "Dakota" term was somewhere in the hills behind Dakota, Nebraska, below the mouth of the Big Sioux River (**Meek and Hayden, 1862**). Recognizing this geographic dilemma, Young recommended dropping the "Dakota" term for carbonaceous strata on the Colorado Plateau and using the term "Naturita" instead. The type locality was near the town of Naturita, Montrose County, Colorado (**Young, 1960**). He also suggested that the Cedar Mountain-Burro Canyon-Naturita interval be combined into the "Dakota Group." Needless to say, these "seismic" nomenclature shifts were met with strong criticisms, mainly by the U.S. Geological Survey (**Craig, 1961; Craig et al., 1961**). Finally, after about 50 years of cuss-and-discuss in the literature, Young's Naturita term has finally replaced the "Dakota" term on the Colorado Plateau (see **Carpenter, 2014**).

Figure S5-4 summarizes the stratigraphic and chronological conclusions by **Young (1960)**. Note that he suggested that the Cedar Mountain and the newly named Naturita were more-or-less time equivalent; thus, the need to define the "Dakota Group." Second, and most importantly, he defined and correlated five fluvial sandstone complexes with basal unconformities (**Figure S5-5**). Three are in the Cedar Mountain and two are in the Naturita.

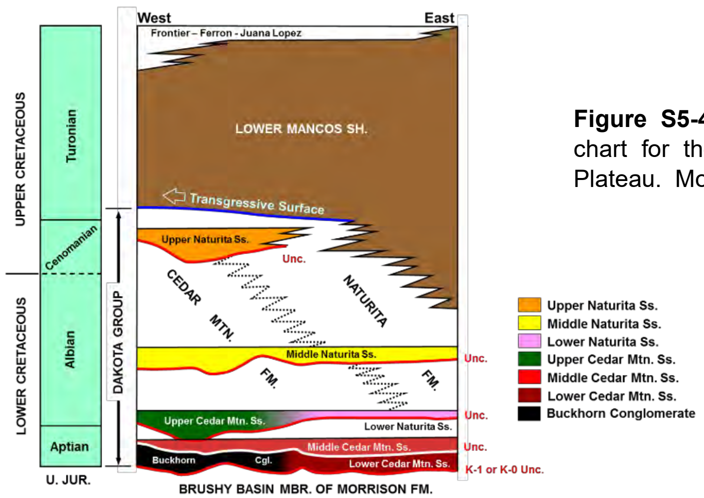


Figure S5-4. Young's stratigraphic correlation chart for the Dakota Group on the Colorado Plateau. Modified from **Young (1960)**.

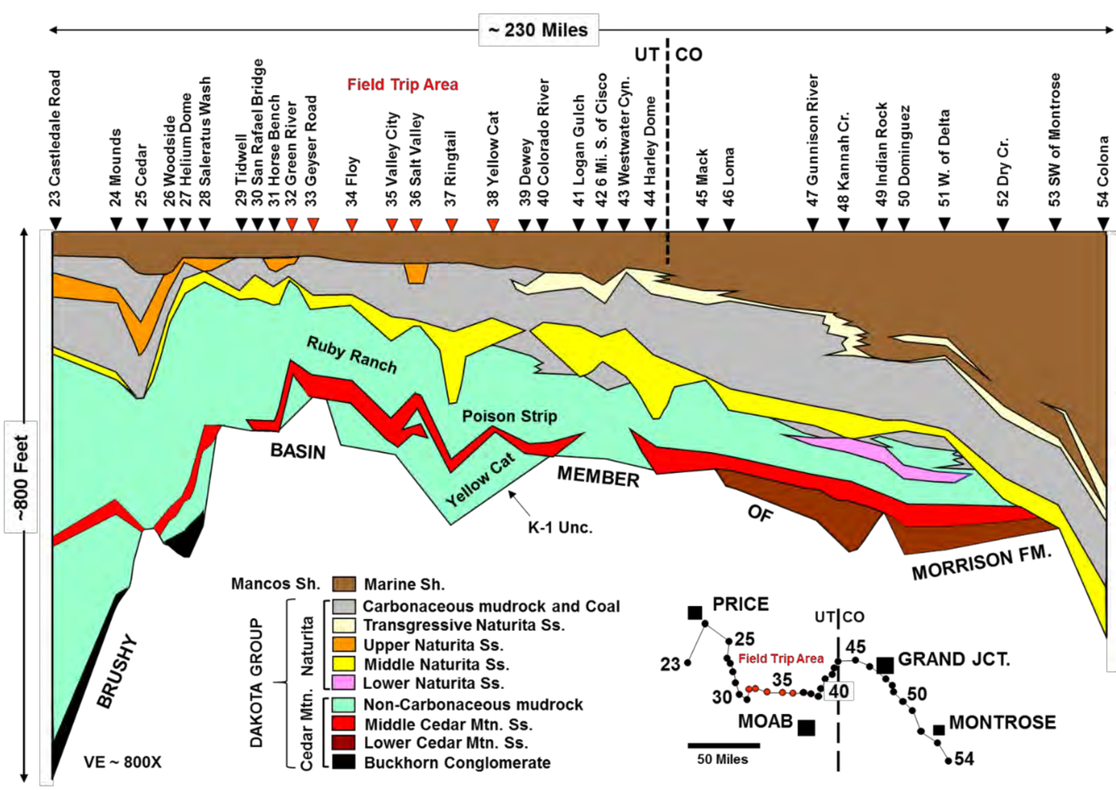
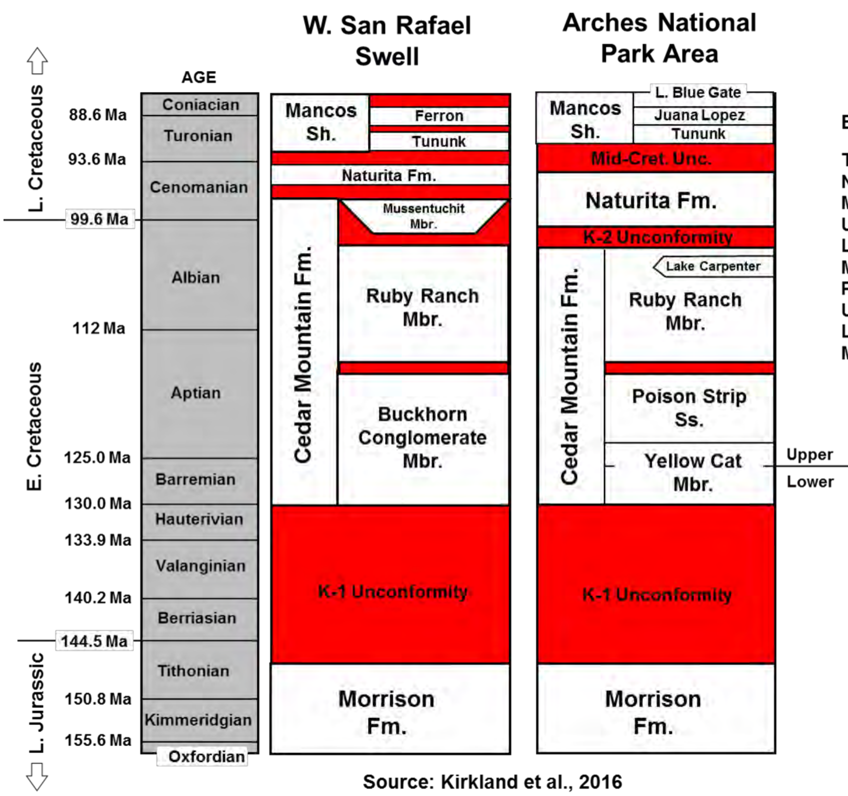


Figure S5-5. **Young's (1960)** correlation of fluvial sandstone complexes in the Dakoa Group between Castle Dale, UT, and Colona, CO. Note that more recent work by the Kirkland Brigade has shown that the Middle Cedar Mountain Sandstone is the same as the Poison Strip Sandsone Member of the Cedar Mountain.

Recent Work

Beginning in the 1990s (perhaps earlier), the Cedar Mountain Formation in eastern Utah became the focus of much research by the Kirkland Brigade. This work built upon the pioneering work by Bob Young; however, numerous details have emerged (see **Kirkland and Madsen (2007)** and **Kirkland et al., (1997, 1999, 2016, 2024)** and the references therein). One of the most significant results is that the new data have allowed for the Cedar Mountain to be subdivided into four members that were deposited between 145 and 98 Ma: Buckhorn Conglomerate (base), Yellow Cat, Poison Strip, Ruby Ranch, and Mussentuchit (**Figure S5-6**). At **Stop 5**, only the Yellow Cat, Poison Strip, and Ruby Ranch are present (**Figure S5-7**), with a combined thickness of about 280 feet.



Bracketed Ages (Kirkland et al., 2024)

Tununk Sh. =	94-92 Ma
Naturita Fm. =	98-94 Ma
Mussentuchit Mbr. =	100-98 Ma
U. Ruby Ranch Mbr. =	108-102 Ma
Lake Carpenter =	116-114 Ma
Main Ruby Ranch Mbr. =	126-110 Ma
Poison Strip Mbr. =	134-126 Ma ?
U. Yellow Cat =	137-135 Ma
L. Yellow Cat =	145-140 Ma
Morrison Fm. =	157-150 Ma

Figure S5-6. Revised chronostratigraphy of the Cedar Mountain Formation in the eastern Colorado Plateau, with the definition of four members. A lacustrine sequence, called the Lake Carpenter facies, is also now recognized in the uppermost Cedar Mountain Formation. Sources: **Kirkland et al. (2016, 2024)**.

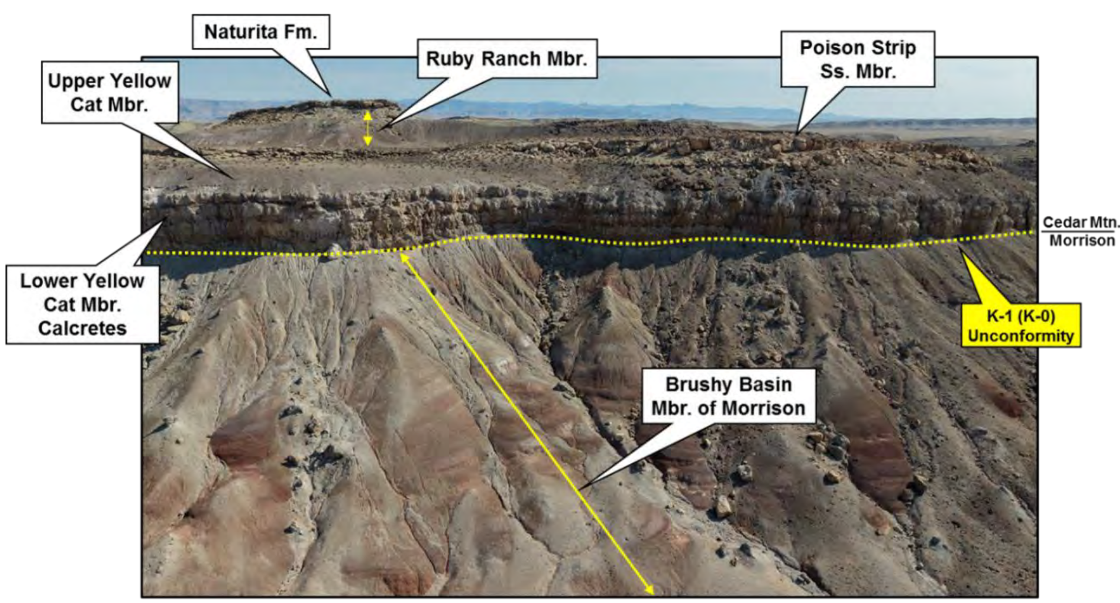


Figure S5-7. Aerial photo of the Jurassic and Cretaceous strata at **Stop 5**. Here, the Cedar Mountain has been subdivided into the Yellow Cat, Poison Strip, and Ruby Ranch Members. A major unconformity (hiatus = ~14.5 Ma) separates the Bushy Basin Member from the overlying Yellow Cat Member. This unconformity is called both the K-0 and K-1. The Naturita Formation is at the top. Photo by R. Cole.

It should be noted that even though new subdivisions of the Cedar Mountain Formation have been defined, Young's paper, which was largely ignored for many years, is now reinstated as a major contribution to the understanding of these rocks. Thus, Young's principal conclusions regarding the Cedar Mountain have been largely confirmed (**Kirkland et al., 1997, 1999**).

The following from **Kirkland and Madsen (2007)** summarizes the characteristics of the new members in the Cedar Mountain: [Note that the many paleontological references have been omitted, plus some minor editing and insertions by R. Cole have occurred.]

The Yellow Cat Member consists of multi-colored mudstone, limestone, paleosols and calcretes, with some sandstone lenses. Regionally, the Yellow Cat is found between the Green and Colorado Rivers, where it is thought to reflect the last effects of salt diapirism in the region around Arches National Park. The type section is west of where the Yellow Cat Road crosses the overlying Poison Strip Sandstone near the Gaston Quarry (~23 miles east of **Stop 5**). This member was originally defined as being underlain by a massive Jurassic-age carbonate paleosol (**Aubry, 1996, 1998**). However, Early Cretaceous fossils have been found below the paleosol, thus requiring a redefinition of the lower boundary. Currently, the contact is placed at the first occurrence of abundant chert pebbles (gastroliths) above typical Morrison swelling clays. The Yellow Cat reflects a complex of fluvial and lacustrine environments deposited under semiarid conditions. Dinosaurs identified in the Yellow Cat include an ankylosaur, iguanodonts, sauropods, a new titanosaurid, a possible camarasaurid, a coelurosaur, a large dromaeosaur (e.g., *Utahraptor*) and an important link between dinosaurs and birds (*Falcarius)*. Other vertebrate remains include crocodilians, turtles, hybodont sharks, lungfish, and other aquatic animals.

The Poison Strip Sandstone Member is the most extensive fluvial complex in the Cedar Mountain Formation, extending from the eastern San Rafael Swell to western Colorado, where it is called the Burro Canyon Formation. The Poison Strip is equivalent to **Young's (1960)** Middle Cedar Mountain Sandstone (see **Figures S5-4** and **S5-5**). The Poison Strip type section is about 24 miles east of **Stop 5** near the Ringtail mine (uranium), on the west end of the Poison Strip (Yellow Cat Mining District). Here, it is about 17.7 feet thick, cross-bedded, medium- to coarse-grained, with chert-pebble lenses. Sedimentological features indicate deposition by low-sinuosity, anastomosing and meandering river systems, with minor floodplain and lacustrine facies. [Note - In the Arches National Park area, former Mesa State College geology student Matt Stikes found that the Poison Strip formed a complex of nested fluvial channels up to 50 feet thick (**Stikes (2006**). He also made a significant dinosaur discovery at "Utahraptor Ridge" and has a quarry named after him.] From a petroleum perspective, the Poison Strip Sandstone is one of the reservoir units in the greater Cisco area (**Figure BG-23**). Non-marine trace fossils are abundant and diverse in the Poison Strip along with petrified logs and cycads (**Dayvault and Hatch, 2005**). Poorly preserved dinosaurs include a large nodosauridan an iguanodont, and a sauropod. Overall, the fossils in the Poison Strip Sandstone suggest persistence of the Yellow Cat fauna.

The Ruby Ranch Member is present everywhere the Cedar Mountain Formation is recognized and thickens to the northwest, perhaps indicating the earliest development of a foreland basin triggered by initial Cretaceous thrust faulting in central Utah. The appearance of the Ruby Ranch is much like the Yellow Cat Member, except that carbonate nodules are much more common in the Ruby Ranch. These nodules represent paleosols created under semiarid conditions. Ribbon sandstones representing low-sinuosity rivers are common. Where the Naturita Formation directly overlies the Ruby Ranch Member (i.e., east of the San Rafael Swell), several meters at the top may be leached to a pale-green color. Although not verified by paleontological data, this green mudrock interval continues into western Colorado where it makes a continuous bed along the Colorado and Gunnison Rivers (**Trump et al., 2022**). In places, the upper "Green Mudrock Interval" contains a porcellanite. Dinosaurs from the Ruby Ranch Member are distinct from those identified in the underlying rocks, including numerous ankylosaurs (e.g., *Gastonia* and *Sauropelta*), a large ornithopod, various sauropods, small dromaeosaurids (similar to *Deinonychus*), and a large carnosaurid. Crocodiles also occur. The fauna suggest that the Ruby Ranch was deposited when flowering plants first radiated and came to dominate the world's floras.

The Mussentuchit Member is well developed only along the west side of the San Rafael Swell, where it is locally separated from the underlying Ruby Ranch Member by a black chert-pebble lag. East of the Swell, the Mussentuchit is overlain by the Naturita Formation. Where the Naturita Formation has been removed by Late Cretaceous erosion, a pebble lag at the base of the Tununk Shale is present (**Willis, 1994**). The Mussentuchit is most readily distinguished by the abundance of smectite (altered volcanic ash), a near absence of carbonate nodules, and the local presence of lignite. A radiometric age of 98.37 + 0.07 million years was obtained from a volcanic ash (Oklahoma Museum of Natural History). The Mussentuchit has yielded significant paleobotanical materials, including the earliest recorded examples of some angiosperm wood taxa. The Mussentuchit also includes numerous species of small mammals (bones and teeth), a diversity of fish, frogs, salamanders, turtles, lizards, crocodilians, birds, a small marsupial, and the oldest North American snake. Dinosaur fossils include a wealth of teeth (ankylosaurids, ornithopods, pachycephalosaurs, a primitive horned dinosaur, sauropods, coelurosaurs, troodontids, dromaeosaurs, and an early tyrannosaurid).

Following **Young (1960)** the Kirkland Brigade has measured numerous sections from the west flank of San Rafael Swell to near Loma (**Figure S5-8**). A more detailed lithofacies version is presented in **Figure S5-9**. **Figure S5-10** continues the cross-section to Escalante Canyon in western Colorado based on work by Rex Cole and Javier Tellez.

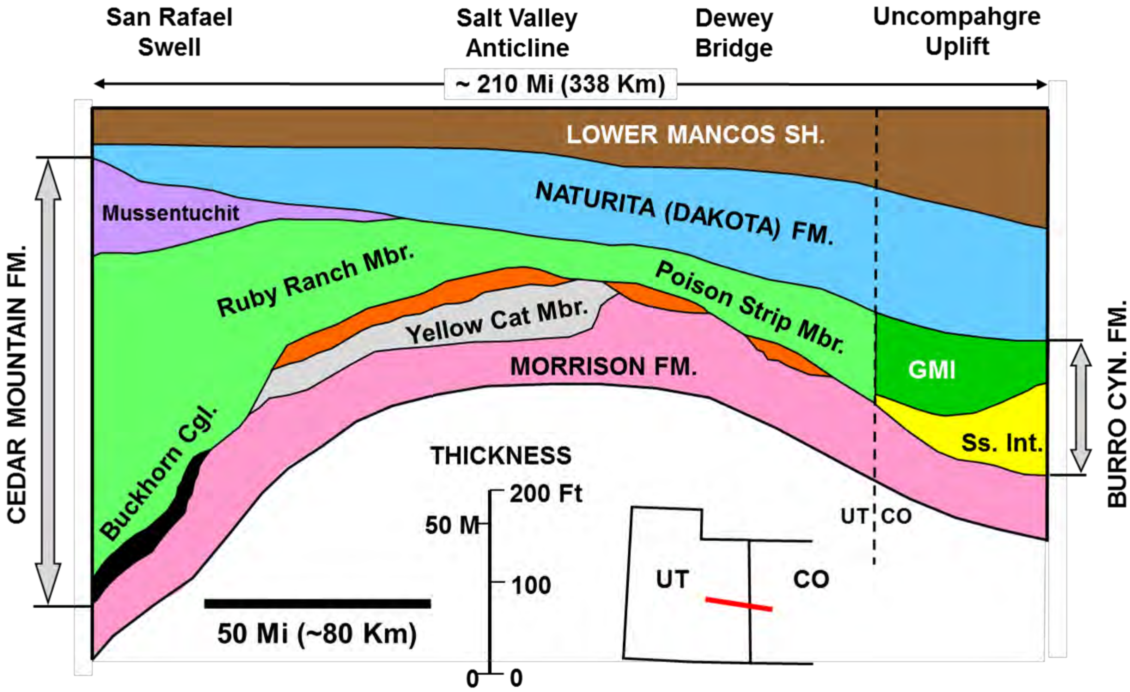


Figure S5-8. Regional stratigraphic cross section of Cedar Mountain Formation from the western flank of the San Rafael Swell to the northeast flank of the Uncompahgre Uplift. Note that the sandstone interval of the Burro Canyon is equivalent to the Poison Strip Sandstone and the "Green Mudrock Interval" (GMI) is corralative with the Ruby Ranch Member. Source: **Kirkland** and **Madsen (2007)** with minor updates by R. Cole.

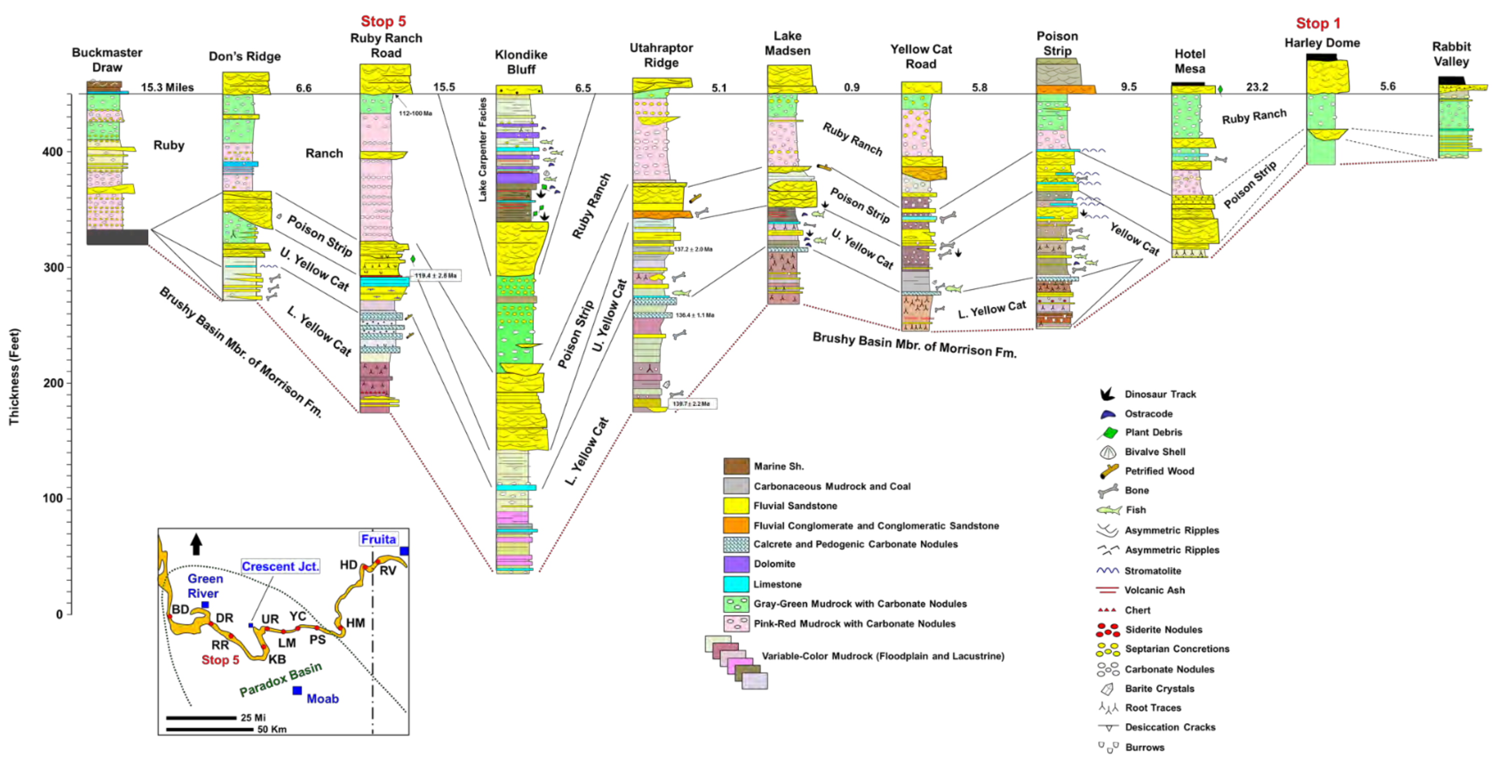


Figure S5-9. Stratigraphic cross section of Cedar Mountain Formation across the northern Pardox Basin. Sources: **Kirkland** and **Madsen (2007)** and **Kirkland et al. (2016** and **2024)**. Note that in the Kirkland versions of this cross section, they used the top of the Poison Strip Sandstone as a datum rather than the base of the Naturita, as shown here. This new approach amplifies the thickening of the Cedar Mountain on the west side of the Salt Valley anticline (Klondike Bluffs section), suggesting that salt tectonism influenced accommodation space. The Lake Carpenter sequence also occurs here. Compiled by R. Cole.

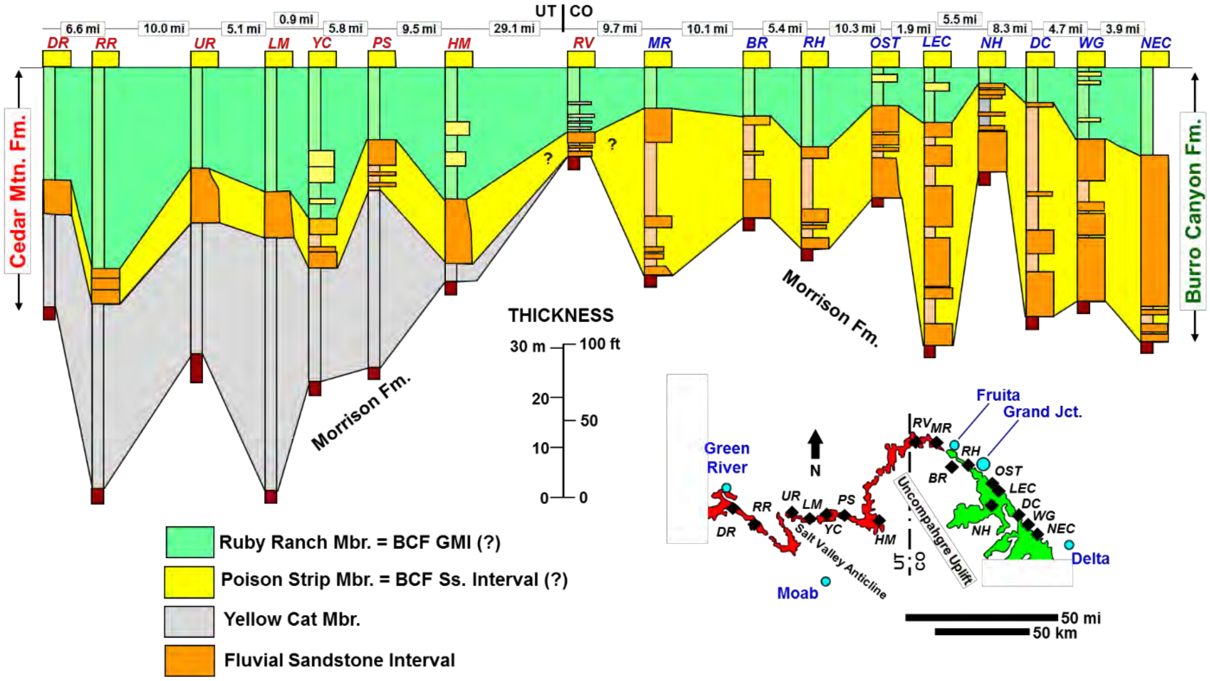


Figure S5-10. Stratigraphic cross section of Cedar Mountain Formation form the east side of the San Rafael Swell to Escalante Canyon in Colorado. Sources: **Kirkland** and **Madsen (2007) Kirkland et al. (2016, 2024)** and **Trump et al. (2022).** Compiled by R. Cole.

Stop 5 Discussion

At **Stop 5** the Cedar Mountain Formation consists of the Yellow Cat, Poison Strip, and Ruby Ranch Members (not visible from ground level) (**Figures S5-2 and S5-7**). The Yellow Cat Member is subdivided into upper and lower intervals (**Figure S5-11**). The lower Yellow cat consists of an impressive sequence of stacked limestones and paleosols (calcretes) that rest unconformably on the Brushy Basin Member. The upper Yellow Cat consists of variegated mudrock and one thin algal limestone.

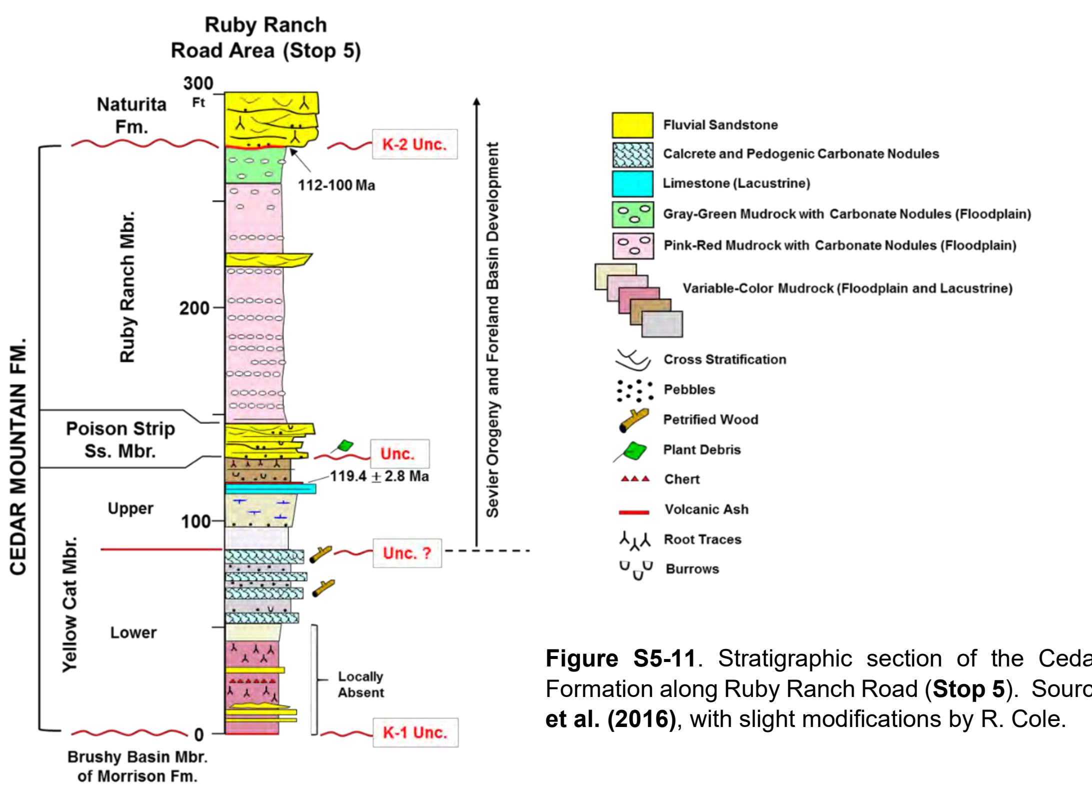


Figure S5-11. Stratigraphic section of the Cedar Mountain Formation along Ruby Ranch Road (**Stop 5**). Source: **Kirkland et al. (2016)**, with slight modifications by R. Cole.

The paleosol-calcrete interval changes across the cliffs north of **Stop 5** from a zero edge to about 30 feet thick (**Figure S5-12A** and **12B**). In places, this sequence consists of stacked paleosols (**Figure S5-12C**), but elsewhere it is massive (**Figure S5-12D**). Burrowing and various scales of rooting are ubiquitous. **Aubrey (1996, 1998)** suggested that the calcrete represented a complex soil horizon developed on the Morrison paleo-surface; however, **Kirkland et al. (2016)** suggest that lacustrine, soil-forming, and post-burial diagenesis played a combined role. The calcrete is not always present; thus, a shale-on-shale contact defines the Yellow Cat–Brushy Basin contact (**Figure S5-11**). In these situations, the contact (K-1/K-0 unconformity) is commonly indicated by a deflation surface with polished chert pebbles (dinosaur gastroliths) (**Stokes, 1944; 1952**). Another criterion used to define the contact is that the Cedar Mountain mudrocks are illitic, whereas the Brushy Basin mudrocks are noticeably smectitic.

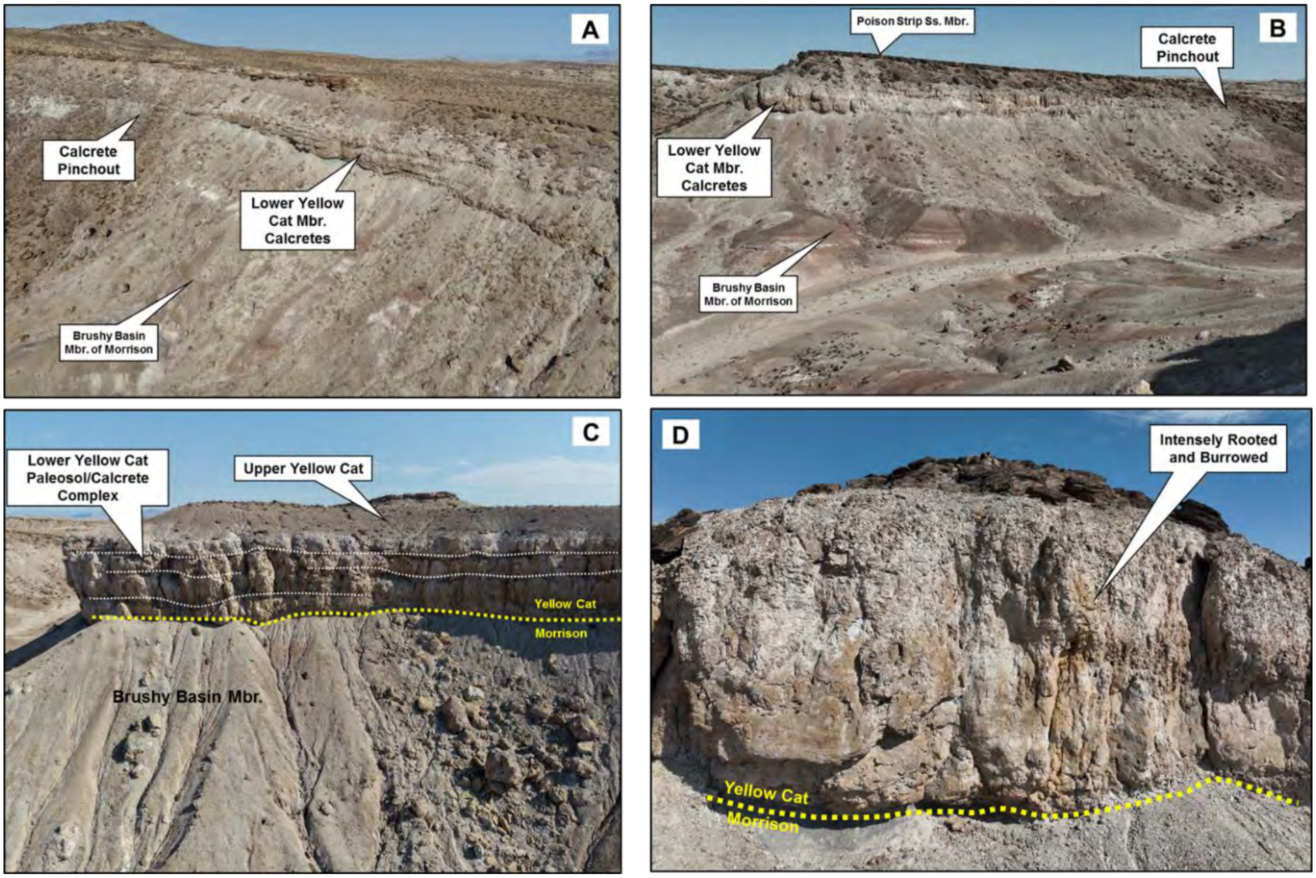


Figure S5-12. Aerial photos of the massive paleosol/calcrete sequence in the lower Yellow Cat Member at **Stop 5**. **Photo A** is a general view showing the thinning and possible pinchout of the calcrete to the west. **Photo B** shows the same thinning to the east. **Photo C** illustrates, that in places, the calcrete is distinctively layered, whereas in other locations it is massive (**Photo D**). Photos A and C are by R. Cole; Photos B and D by J. Tellez.

The Poison Strip Sandstone is poorly developed at **Stop 5**, but thickens to the east. At the type section near the Ringtail Mine, which is about 24 miles east of **Stop 5**, the Poison Strip Sandstone forms a conspicuous, continuous ledge along the north rim of the Poison Strip Valley (**Figure S5-13A**). Below the Poison Strip ledge, the Yellow Cat Member is dominated by variegated mudrock and a thin calcrete horizon (**Figure S5-13B**). The total Poison Strip-Yellow Cat interval is about 200 feet thick. The Poison Strip Sandstone is about 20-35 feet thick and consists mainly of sandy granule-pebble conglomerate and conglomeratic coarse- to very coarse-grained sandstone, with medium- to large-scale cross-stratification and associated scour surfaces (**Figures S5-13 C** and **13D**). Overall, the resemblance of the Poison Strip Sandstone to the Burro Canyon in the Whitewater area (CO) is striking (**Cole** and **Moore, 1994, 2012; Tellez, 2021**; **Tellez et al., 2018a, 2018b, 2019a, 2019b, 2020, 2022; Trump et al., 2022**).

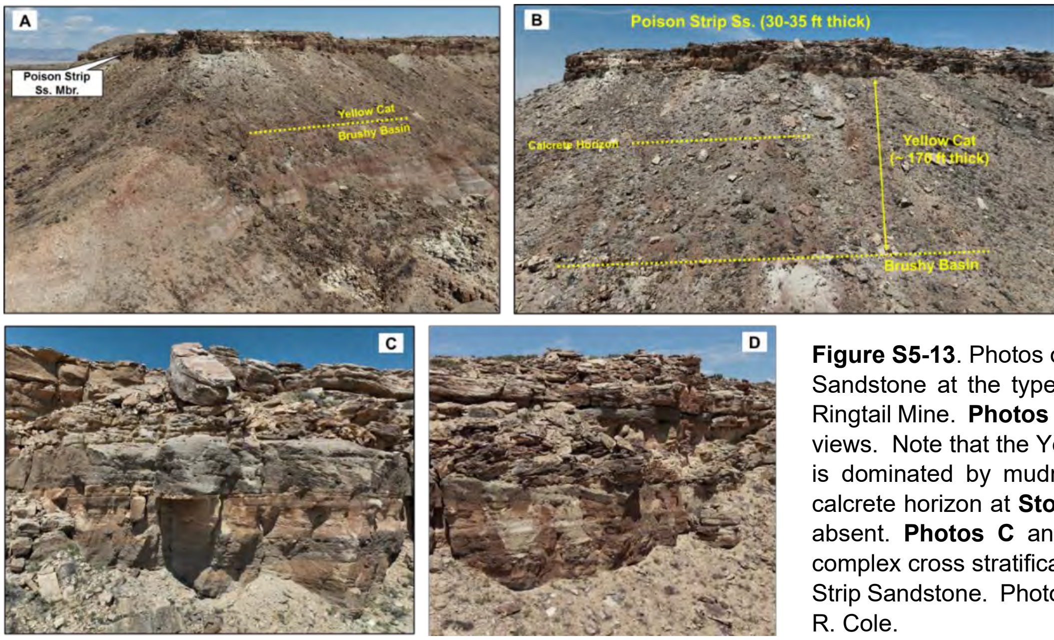


Figure S5-13. Photos of the Poison Strip Sandstone at the type section near the Ringtail Mine. **Photos A** and **B** are aerial views. Note that the Yellow Cat Member is dominated by mudrock and that the calcrete horizon at **Stop 5** is very thin to absent. **Photos C** and **D** illustrate the complex cross stratification in the Poison Strip Sandstone. Photos by J. Tellez and R. Cole.

Petroleum Exploration

The Paradox Basin has a long history of petroleum exploration and development. Major reservoir intervals occur in the Devonian Elbert Formation, Mississippian Leadville Limestone, Pennsylvanian Paradox Formation, and also in Jurassic and Cretaceous strata (minor). The recently drilled wells at **Stop 5** are examples of horizontal drilling of the Paradox Salt (**Figure S5-14**).

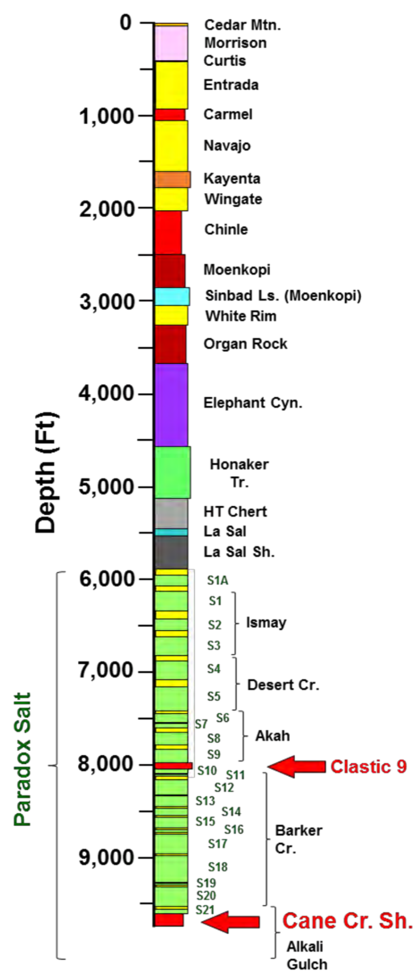


Figure S5-14. Subsurface stratigraphy at the **Stop 5**, based on a drilling prognosis for the Rose Petroleum State 36-2LNW-CC well (API: 43-019-50099; see Utah Division of Oil, Gas, and Mining website). The main target is the Cane Creek Shale in the lower Paradox Salt. The Clastic 9 bed is also of interest. Compiled by R. Cole.

During deposition of the Pennsylvanian Paradox Formation, the Paradox Basin had very poor circulation with the open ocean (**Figure BG-6**). Consequently, the basin saw numerous cycles of salt deposition. The Paradox Salt originally may have been 7,000 to 8,000 feet thick (**Hite et al., 1984**), but has been reduced by salt flowage (**Figure BG-9**). Internally, the Paradox "salt" intervals consist of saline minerals (halite and sylvite), and "clastic" units consist of dark-colored, organic-rich mudrock (a type of oil shale), limestone, dolostone, anhydrite, claystone, siltstone, and very fine- to fine-grained sandstone. There are 29 saline-mineral/clastic cycles, which were produced by glacio-eustatic climate variations (**Hite et al., 1984**). The most important "clastic" unit is the Cane Creek, which is in Cycle 21. In addition, five additional clastic beds, (e.g., Clastic bed 9) above the Cane Creek, are also prospective. Total-organic-carbon values for the Cane Creek interval range between 0.12 and 3.96 wt% (**Hite et al., 1984**). In the area around **Stop 5**, the Cane Creek is about 115-130 feet thick. The Cane Creek oil play (exploration area) is shown in **Figure S5-15** and summarized below.

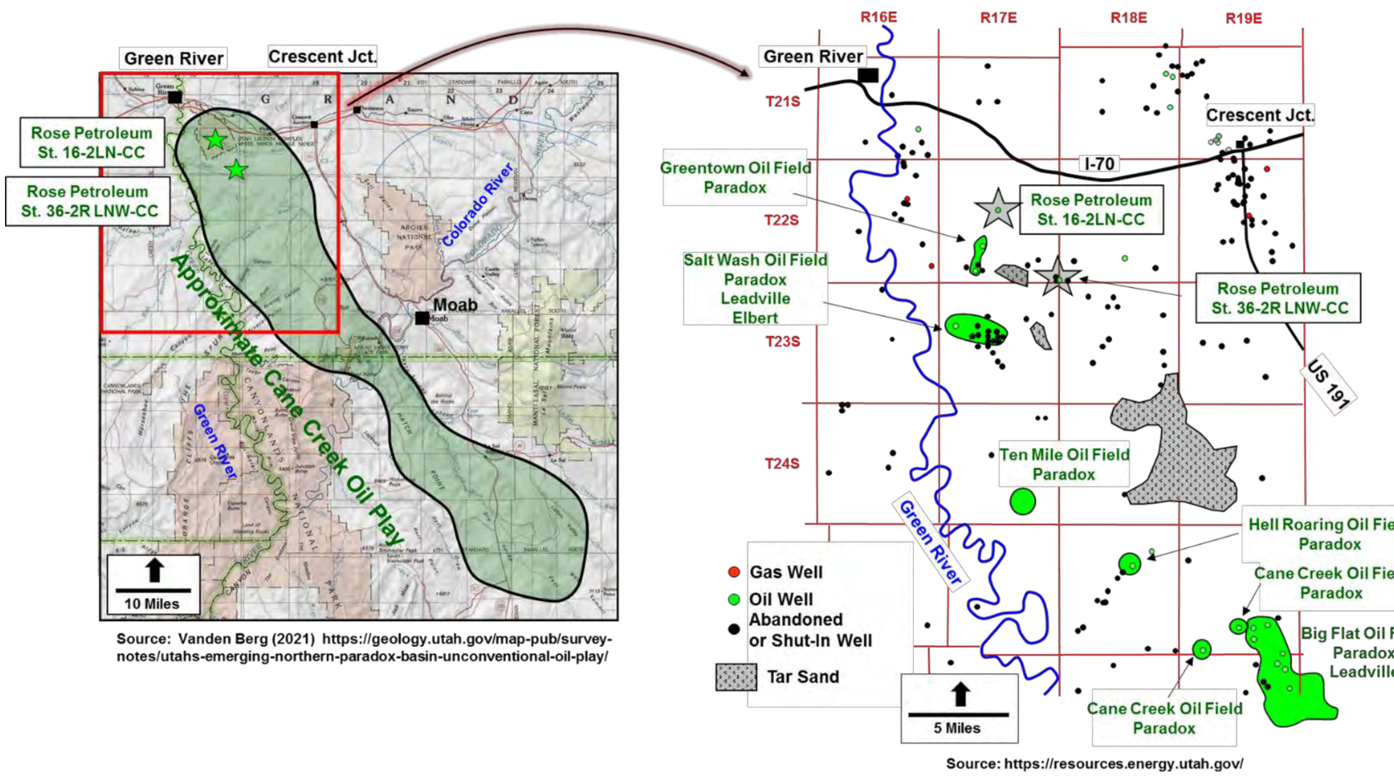


Figure S5-15. Map on the left shows the approximate footprint of the Cane Creek oil play, which is about 70 miles long and up to 15 miles wide. It occurs between Arches and Canyonlands National Parks in the Paradox Basin. Map on the right shows the locations for oil, gas, and abandoned/shut-in wells in the northwestern part of the play. Fields recognized by the Utah Division of Energy and Mining are shown, along with three tar-sand deposits (Jurassic rocks). Locations for the Rose Petroleum 16-2 and 36-2 wells are posted on both maps. **Stop 5** is at the 36-2R well. Sources: **Vanden Berg (2021)** and Utah Geological Survey **https://resources.energy.utah.gov/**.

Vanden Berg (2021) has nicely summarized the Cane Creek play, as follows (with some minor edits and insertions):

> The Cane Creek interval within the Pennsylvanian-age Paradox Formation of the northern Paradox Basin, southeastern Utah, is touted by some as one of the last remaining emerging unconventional oil plays in the United States, with wells capable of producing up to 1,500 barrels of oil per day (initial production). However, the drilling history of the Cane Creek has been fraught with challenges and disappointment. Nearly 100 years ago, one of the very first wells that targeted Paradox Formation reservoirs "blew-out." The rig caught fire and was destroyed, a sinister omen for this troublesome target. Drilling activity increased in the 1950s and 1960s with the discovery of hydrocarbons in the underlying Leadville Formation. While drilling to the Leadville, several vertical wells encountered hydrocarbon shows in the overlying Cane Creek interval. In 1962, Long Canyon 1 was the first well to establish commercial production from the Cane Creek and has produced over one million barrels of oil (and is still producing). Despite the promise of the Long Canyon 1 well, it would not be until the early 1990s that significant exploration activity in the Cane Creek resumed; petroleum prospectors came armed with a new technology in the horizontal well. Although these new wells showed promise in the central part of the play, the prize of massive, play-wide production remained elusive. Fast forward two decades and armed with more advanced horizontal drilling technology, plus new seismic data, the oil company Fidelity (which no longer exists) drilled several new wells around the central play area. Some of the new Fidelity horizontal wells were quite successful, but others were not. With the

crash in oil prices in early 2015, the industry once again stepped back from this troublesome play to reevaluate and ask some fundamental questions.

Numerous factors currently impede the full production potential of the Paradox unconventional oil play. Current experience indicates that the Cane Creek can be a very successful fracture play, meaning the intersection of natural fractures with the wellbore can generate economic production (no hydraulic fracturing needed). However, the clastic target zones are interbedded with several hundred feet of mechanically ductile salt layers. Over time, through the natural burial process, overburden pressure and regional stress regimes have caused the salt layers to flow like toothpaste, creating significant macro- and micro-structures within the reservoir zones. These heterogeneous structures make it difficult to predict natural fracture networks, fracture orientations, and subsequent horizontal well paths.

The Cane Creek play has experienced some success in recent years, with production totaling over 10 million barrels of oil since the first wells were drilled. However, there is an estimated 1.2 billion barrels of potential oil in the Cane Creek, meaning that 99.2 percent of the oil remains in-place. These numbers do not include all the other overlying clastic zones that also have petroleum production potential. As a way to help move the Cane Creek play in the direction of success, the U.S. Department of Energy (DOE) recently awarded $8 million in federal funding to the Energy & Geoscience Institute (EGI) at the University of Utah and the Utah Geological Survey (UGS) to develop the tools and strategies necessary to more completely tap into this underutilized resource, while at the same time minimizing impact. The five-year project will utilize up to $3 million in state and private/industry cost-share funds to help accomplish its objectives. The first research well (Rose Petroleum State 16-2) was drilled in 2020-2021.

Rose Petroleum, LLC Wells

Rose Petroleum (now part of Zephyr Energy, plc) has been active in the northwest Paradox Basin for about 10 years (?) and have drilled three recent wells into the Cane Creek Shale, to date. The wells are within the White Sands Federal Unit (25,000 ac). Prior to drilling, a high-resolution 3D seismic survey was conducted (2017) in the area (~40 mi^2), which helped define drilling locations.

The following was obtained from Zephyr's annual investor reports (2022-2025, https://www.zephyrplc. com/investors/) and public-domain data files available through the Utah Div. of Oil, Gas, and Mining (2026, https:// oilgas.ogm.utah.gov/ oilgasweb/live-data-search/lds-main.xhtml):

Rose Petroleum St. 16-2 (API: 43-019-50089) is a vertical well spudded in December, 2020, that was later converted to a successful horizontal penetration and completion in the Cane Creek in January, 2021. The vertical phase was designed as a research well funded by the U.S. Dept. of Energy and others (see above). Approximately 113 feet of continuous whole core were obtained from the Cane Creek and a number of rotary side wall cores were collected from 11 shallower clastic beds in the Paradox Salt. In addition, gamma-ray, neutron-density, resistivity, formation-litho-scanner and sonic wireline logs were collected though most of the Paradox Formation. Extensive petrophysical, geo-mechanical, and geochemical analyses were subsequently done on the cores in concert with the petrophysical logs. Importantly, the log data provided a calibration link for the previously acquired 3D-seismic data. The lateral phase of the project began in July, 2021, and was completed in August, 2021, (measured depth (MD) = 10,370 ft; true vertical depth (TVD) = 9,745 ft). A subsequent well test (14 stages across 4,020 feet of lateral wellbore) indicated an average rate-constrained daily rate of 716 barrels of oil equivalent per day (BOEPD), with rate-constrained highs of 1,083 BOEPD. Based on the success of the State 16-2 well, the data base that was acquired, and the 3D-seismic data, Rose Petroleum (Zephyr) drilled two additional wells on the large pad at **Stop 5**. The horizontal legs were designed to follow a narrow northwest-trending fold defined by the 3D-seismic data.

Rose Petroleum St. 36-2-LNW-CC (API: 43-019-50098) was a spudded in November, 2022, and drilled vertically to about 9,302 feet where the bottom-hole assembly became stuck in Salt 18. A sidetrack well, that eventually went horizontal, got stuck again at a measured depth of about 10,267 feet (TVD = 9,598 ft). Fishing operations were unsuccessful and the well was plugged and abandoned in November, 2024, and the well head removed. This was a costly dry hole.

Rose Petroleum St. 36-2LNW-CC (API: 43-019-50099) [Note- this well was originally permitted as the St. 36-3-LN-C9, as on the sign, but was never drilled.] The 36-2 CC well was spudded in November, 2022, as a vertical hole. It encountered numerous problems while penetrating the over-pressured salt horizons in the Paradox, and after intersecting the Cane Creek reservoir (9,598 TVD), it experienced a significant influx of oil and gas into the wellbore. The influx was caused by the intersection of a major natural-fracture network that was under high pressure (~9,300 psi). In January, 2025, a sidetrack (State 36-2R) was started, which subsequently led to the horizontal leg (~5,000 ft) through the Cane Creek reservoir. Drilling was completed in May, 2025; the total measured depth (MD = 15,228 feet;

TVD = 9,383.6 ft). State-of-the-art geo-steering was used to keep the horizontal wellbore within the Cane Creek (**Figure S5-16**). Subsequent completion and testing (May, 2025) of the horizontal Cane Creek were successful. Results of the testing, as posted on Zephyr's website (https://www.zephyrplc.com/ assets/paradox-basin/), are as follows:

- Test length (~5,000 ft); hydrocarbons detected over the entire span
- No fracture stimulation needed
- Peak fluid flow rate ~ 2,848 BOEPD
- Natural gas ~ 11.9 MMCFPD
- Water cut was <0.5 %
- No significant pressure drop occurred during testing
- Horizontal leg successfully followed the northwest trend of a seismically defined fold in the Cane Creek reservoir.

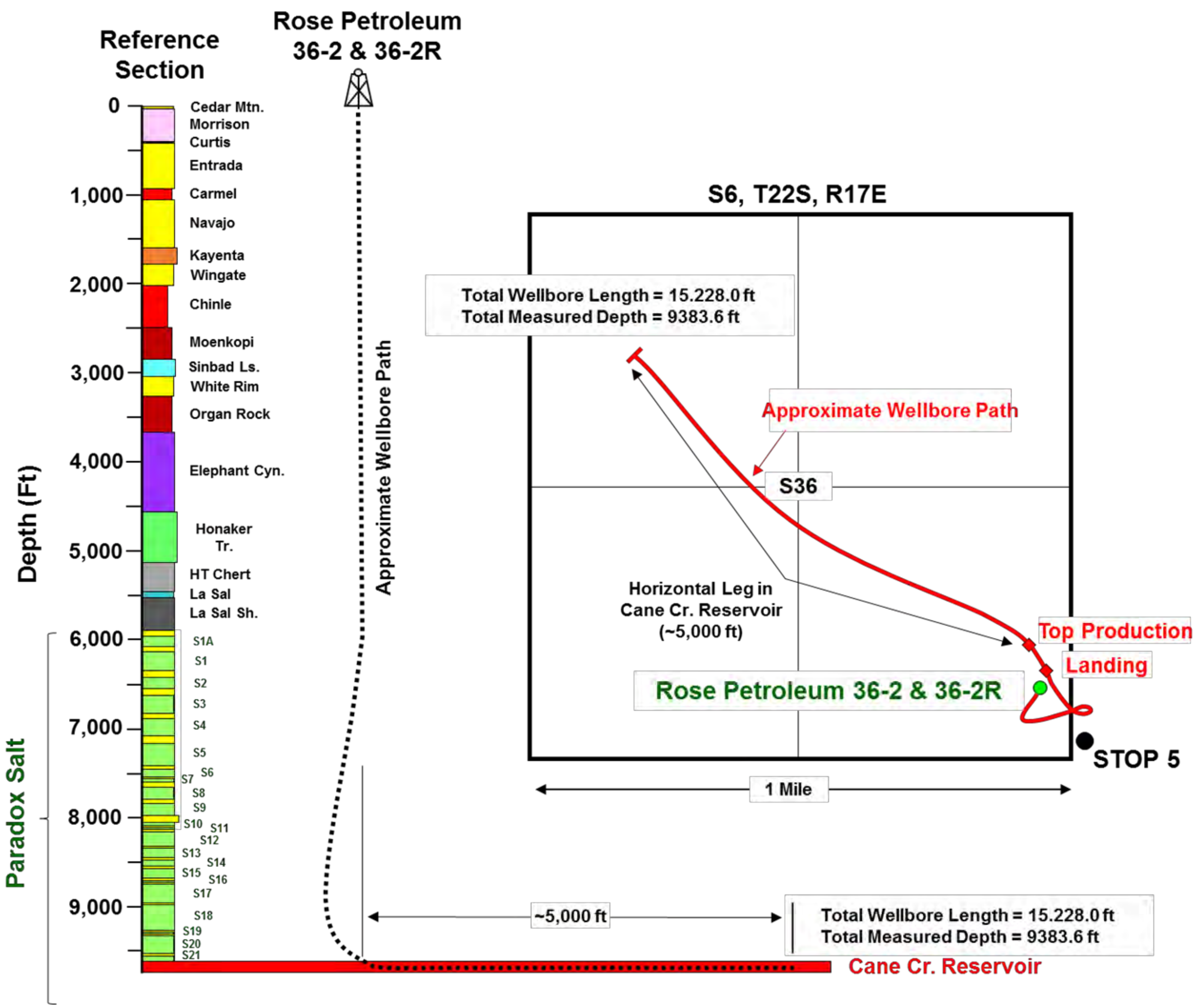


Figure S5-16. Diagrams showing the stratigraphic trajectory and map traverse for the Rose Petroleum 36-2/36-2R wellbore. Diagrams were compiled from Zephyr Energy's annual investor reports (2022-2025, https://www.zephyrplc.com/investors/) and Public-domain data files available through the Utah Division of Oil, Gas, and Mining (2026, https://oilgas.ogm.utah.gov/ oilgasweb/live-data-search/lds-main.xhtml). The stratigraphic reference column is the same as in **Figure S5-14**.

Mud-log data by Field Geo Services, LLC (obtained from the Utah Division of Oil, Gas, and Mining website) collected during the vertical penetration of the Paradox Salt (i.e., 36-2R well) indicated that the salt intervals ranged from 11 to 412 feet thick and the clastic beds, 8 to 124 feet thick. The log data also show that the "clastic" intervals consist mostly of sandstone and siltstone, with minor halite, anhydrite, limestone, and dolomite. The "salt" intervals are mainly halite, with minor siltstone, anhydrite, and dolomite.

Stop 5C – Ten Mile Graben Fault

(Lat. 38.84288°; Lon. -109.99142 °; Elev. ~4448 ft)

Topics

- Fault Zone Architecture
- Deformation Styles
- Evidence of Fluid Migration

Stop Description

During the field trip at **Stops 5C**, **7** and **9** (**Figure S5C- 1**) we will have the opportunity to observe the detailed architecture of the faults along the Ten Mile Graben and Salt Wash Grabens that bound the upper crest of the plunging Green River Anticline. The faults all have normal offset and are the northern bounding faults to the narrow grabens and dip to the south.

At **Stop 5C** we will discuss the detailed fault zone architecture of one of the normal faults and use this stop as a guide for our observations of the faults as we travel west.

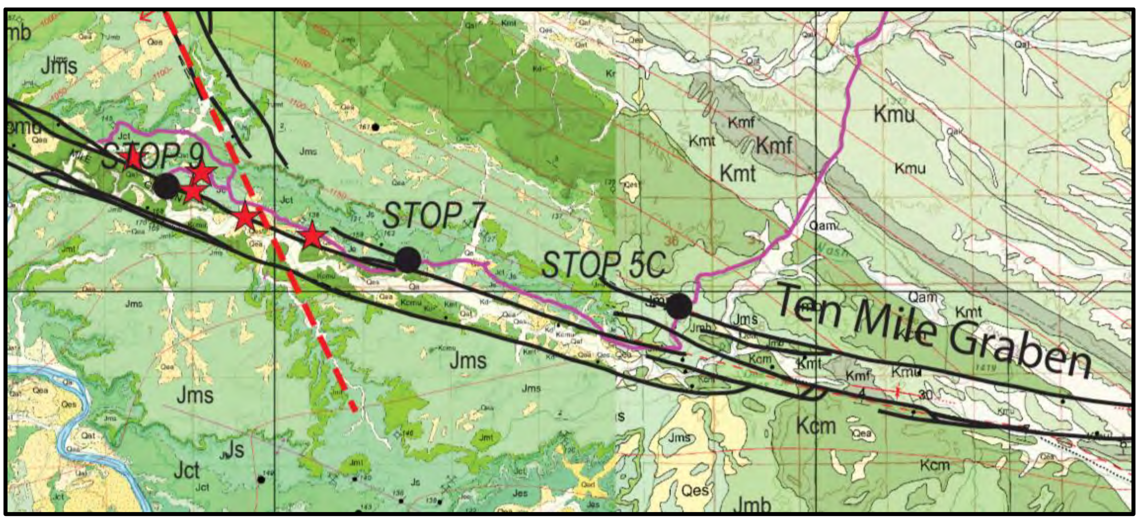


Figure S5C- 1. Geological map with route track in purple and locations of key stops for studying the fault zones. Source: Doelling (2002).

At each fault location consider the fault model (**Figure S5C- 2B**) and look for evidence of outer damage zone, inner damage zone, and fault-core.

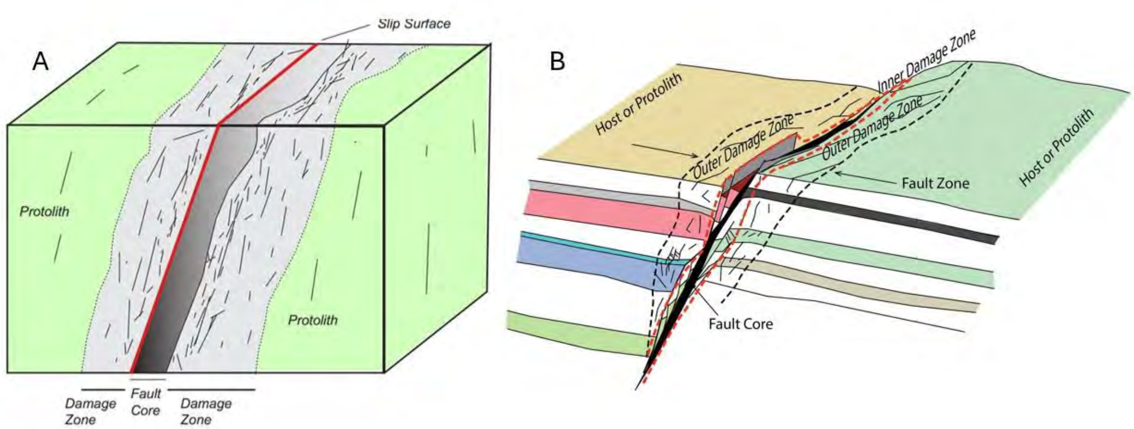


Figure S5C- 2. Fault models. **A**. A standard fault model most frequently described in the literature but relevant to more homogeneous, unlayered brittle sections or layered stratigraphy with limited mechanical differences between the layers. **B**. A complex fault model of the deformation styles expected for a fault zone crossing a layered section with greater mechanical strengths between the layers from brittle to ductile.

Key Questions:

What is the deformation style in the outer damage zone? Do you see deformation bands, Mode I fractures or both? If there are fractures, are they filled with cement and what is their location relative to the structure? What is the timing of the fractures relative to the deformation bands?

Is their evidence of Mode I fractures or deformation bands that are not associated with the damage zone? What is their spacing? Is the spacing regular or does it decrease in density away from the fault-core?

Is there any indication of an inner damage zone? Is this in the footwall or hanging wall or both and if observed does it seem to play a role in the fluid migration?

Can you see the fault-core of fault-rocks? Is there evidence of fluids migrating through the fault-core?

Is their evidence of fluids migrating to the surface, either hydrocarbons or CO_2 and where are these fluids relative to the larger trap geometry and to the fault? Are the fluids observed in the footwall or hanging wall of the fault or both? Are the fluids in the fault zone or across the structure away from the fault?

Stop 5C Fault Style

At this location (**Figure S5C-3** we will have an opportunity to view the northern bounding fault of the Ten Mile Graben approximately 1.5 km from its western tip (**Figure S5C- 1**) that includes the outer and inner damage zones and other small scale deformation including deformation bands and Mode I fractures. The fault-core is more difficult to see because of the erosion and fill.

Figure S5C-3. Drone views east and west along the northern bounding fault of the Ten Mile Graben taken from the road. Drone photograph by R. Cole. Mode I fractures are clearly visible across the Salt Wash sandstone.

The fault is oriented ESE-WNW with a south dip. The road cuts across the strike of the fault. **Error! Reference source not found.** is an aerial drone view showing a perspective view of the fault and the stratigraphic contacts looking both east and west. Some of the more competent sandstones such as the Salt Wash Member of the Morrison Formation are well preserved but much of the stratigraphy along the fault is eroded limiting detailed observations of structural styles and deformation. Note that in the view to the west, two fault segments form a small overlap and hard link to the west.

At this location consider the model of fault-zone architecture (**Figure S5C- 2**, right) and try and identify outer damage zone, inner damage zone and fault-core. What are the structural styles? What do you think about timing of the structures? Is their evidence of cross-cutting relationships? Is there evidence of mineralization in any fractures or pores? Is the deformation different for the different lithofacies? Is there evidence of staining in the rock?

There are a few locations along the fault trace where deformation in the outer damage zone is exposed. The left image in **Figure S5C- 4** is a perspective view from a drone photograph near the road looking south that shows the trace of the fault in red. A second minor fault is interpreted further south. Brann Johnson is at the intersection of the main fault trace and the pipeline for scale.

Figure S5C- 4. Left: Perspective view looking south where the red trace is the fault crossed by the pipeline. Brann Johnson is at the fault contact crossed by the pipeline for scale. **Right**: Drone image looking down at a zone of deformation bands in the Salt Wash sandstone at the location of Brann Johnson in the left figure. The pipeline is in the upper left. Drone photos by R. Cole.

The blocky sandstone in the upper right (**Figure S5C- 4**, left) is the Salt Wash Member of the Morrison Formation in the footwall or upthrown side of the fault juxtaposed against the Brushy Basin Member of the Morrison Formation in the hanging wall. The heterolithic siltstone, sandstones and mudrocks in the hanging wall are rotated (dipping southward) up against the fault-core as representative of deformation in the inner damage zone.

Near the location of Brann Johnson in the figure are sets of deformation bands (**Figure S5C- 4**, right). The location of these deformation bands is consistent with the outer damage zone and are closely-spaced and oriented sub-parallel to the strike of the main fault. If these are related to the fault evolution they would have formed when the rock was porous without significant cementation between the grains. Deformation bands, however, may also form across the structure not associated with fault evolution from local stress perturbations including folding. Is there evidence of deformation bands in this area away from the fault? Does the spacing or density of deformation bands in this location decrease away from the fault-core? Are these sets of deformation bands consistent with our description of an outer damage zone?

A drone image looking down upon a channel sandstone deposit of the Salt Wash Member of the Morrison Formation further along the fault to the west (**Figure S5C- 5**; see **Error! Reference source not found.** top for location) shows a set of Mode I or open fractures with a strike also sub-parallel to the strike of the main fault. These fractures are close to the fault trace and may be in the outer damage zone of the footwall. However, they extend much further than the width of a typical outer damage zone and are evenly spaced suggesting a more regional joint set. There are other similar fracture sets on the Salt Wash sandstone across the structure suggesting that they may have formed under different stress conditions than the faulting. Folding of the rock layers for instance can create local extension along the fold crest nucleating Mode I fractures. Migration of the Paradox salt has also been interpreted to deform the overlying section nucleating regional fractures sets (**Lorenz and Cooper, 2009**).

The timing of the Mode I fractures and the deformation bands is important. Deformation bands are a typical deformation mechanism in porous, granular media such as sandstone. Sandstones can maintain their porosity to depths as great as 3 km. At deeper depths and greater temperatures, however, the pores are cemented and the rock becomes stronger and brittle. These rocks subjected to differential stresses will deform by the development of Mode I fractures. The fractures are later than the deformation bands but the exact timing is difficult to determine. Some of the fractures across the Salt Wash sandstones in these locations may have occurred after the uplift of the Colorado Plateau and be more recent.

Mode I fractures are also evident in cross-section in the Salt Wash Sandstone exposed in the upper right in **Figure S5C-4**, left. We can observe the orientation and vertical extent of these fractures in cross-sectional view (**Figure S5C- 6**).

Figure S5C- 5. Drone photo of fractures in the fault footwall of Salt Wash sandstone. The location of this outcrop can be seen along the fault footwall in the central part of the drone photograph in the upper image in **Error! Reference source not found.**. Drone photograph by R. Cole.

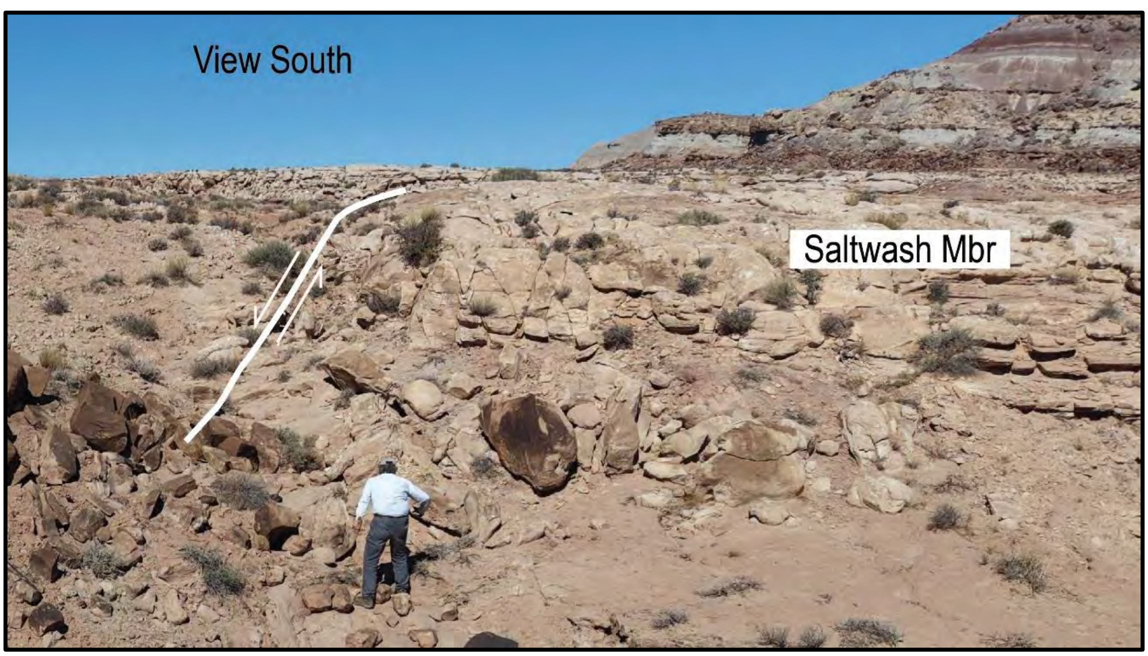


Figure S5C- 6. Cross section showing the extent of fractures and their orientation across a channel sandstone in the Salt Wash Member of the Morrison Formation. The outcrop location is along the fault west of the pipeline in the upper right of the drone photograph in the left image in **Figure S5C- 4**. Drone photograph by R. Cole with Brann Johnson for scale.

This field location at **Stop 5C** is within the anticlinal closure of the faulted Green River Anticline (**Figure SC9-7**) but far down dip and beyond the surface evidence of CO_2 flux from springs or travertine deposits. Our cursory observation at this stop is that the fractures are uncemented and that there are no springs or travertine deposits. This might suggest that the CO_2 did not extend to this depth along the trap but we suggest looking for evidence of any fracture fill to challenge this hypothesis. We will discuss the trap scenarios at **Stops 7** and 9 closer to the crest of the structure where there is evidence of springs and travertine deposits.

As we leave **Stop 5C** we continue to drive a short distance south perpendicular to the fault strike across the northern bounding fault to the Ten Mile Graben, into the graben and the across the southern bounding fault into a relay separating the Ten Mile Graben from the Salt Wash Graben (**Figure S5C- 1**).

At the northern bounding fault to the Salt Wash Graben the road turns to the west and takes us along the strike of the northern bounding fault to the Salt Wash Graben dropping from footwall to hanging wall at several places. As we drive consider the fault zone architecture and stratigraphic controls.

At each Field Stop keep in mind the fault styles and particularly the detailed deformation. Note also that many of the sandstones are red from the oxidation of the iron rich hematite coatings on sand grains but that in places the sandstone is bleached. Bleached halos are also evident around many of the cemented fractures.

The bleaching has been attributed to a reducing fluid such as hydrocarbons that dissolve the iron oxide removing it from the grain coatings. Bleached sandstone around Moab has been attributed to breached hydrocarbon traps (**Chan et al., 2000**).

In this field area, the CO_2 may acidify the groundwater forming carbonic acid that under appropriate conditions reacts with the iron bleaching the rock. If the fluid pathways are open fractures, the bleaching halos are evidence of a zone of migration and fluid-rock interaction. Detailed analysis of diagenesis along fractures including CO_2 has been well documented along the Moab Fault (**Eichhubl et al., 2009**).

We do not include a separate discussion of the fault zone architecture as **Stops 7** and **9**, but the key questions and observations from the fault at **Stop 5C** can serve as a basis for observations at the other stops.

Stop 6 – Dead Oil in Entrada Sandstone

(Lat. 38.8481º; Lon. -110.0325º; Elev. ~ 4,322 ft)

Topics:

- Asphaltic sandstone
- Entrada Sandstone

Stop Description

This brief stop is to examine an outcrop of sandstone saturated with "dead" oil in the Entrada Sandstone in the bed of Salt Wash Road. Dead oil is oil that has lost most or all of the volatile components and so can no longer flow, unless it is either heated greatly or mixed with a solvent. **Figure S6-1** shows the road-side outcrop and **Figure S6-2** illustrates a nearby outcrop of the Earthy Member of the Entrada Sandstone and the overlying Summerville Formation.

Figure S6-1. Exposure of asphaltic sandstone in the upper Slick Rock Member of the Entrada Sandstone at **Stop 6**. Craig Goodknight (red shirt) and Brann Johnson in view. Photo was taken during a recon trip in late March, 2026. Tragically, Craig passed away about four months later. Photo by R. Cole.

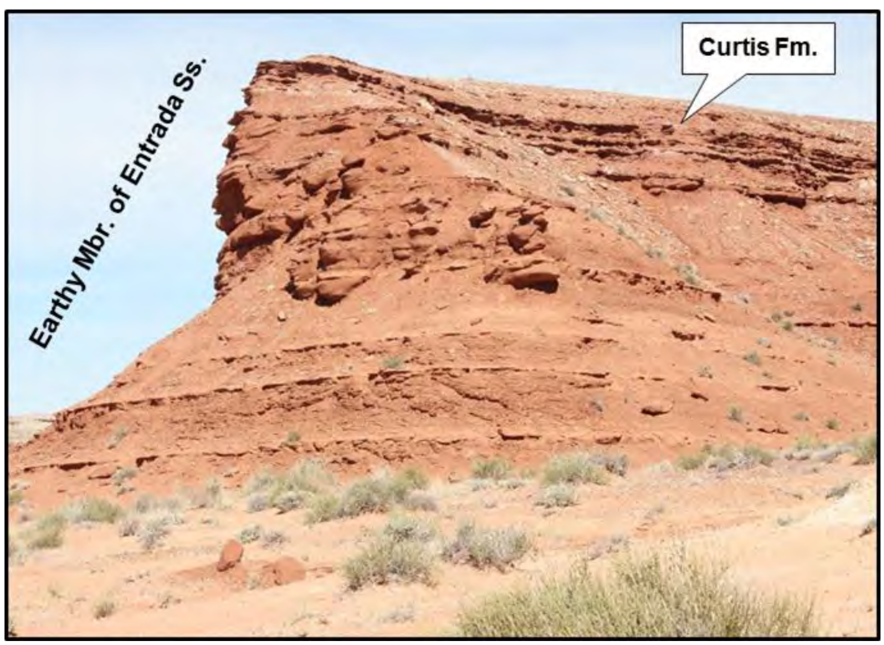


Figure S6-2. General view of the Earthy Member of the Entrada and overlying Curtis Fm. at **Stop 6**. The Earthy Member represents eolian and mudflat sandstones and mudrocks deposited east of the Sundance Sea (see Figure S6-6). Photo by R. Cole.

Previously, we broke off a piece of the dead oil saturated sandstone and will pass it around so that every-one will not have to do it for themselves. **Figures S6-3, S6-4**, and **S6-5** show the asphaltic sandstone at various scales.

Figure S6-3. General view of the Entrada Sandstone that is impregnated with dead oil. The exposure is in the road bed. Photo by W. Hood.

Figure S6-4. Close-up view of the asphaltic sandstone. Photo by W. Hood.

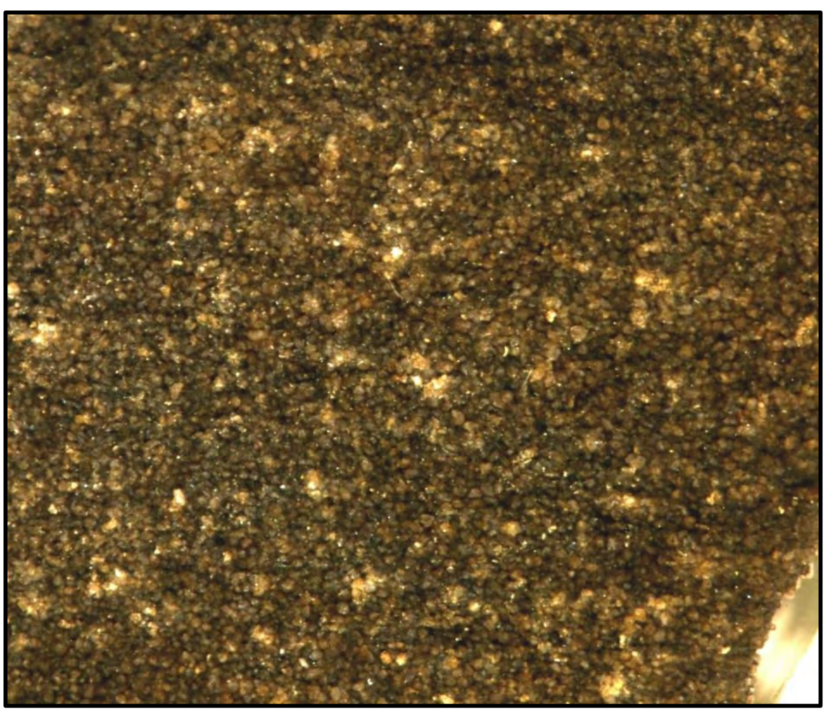


Figure S6-5. Detailed, close-up view of the asphaltic sandstone. Width of image is about 1 cm. Photo by W. Hood.

Field-trip participants may be confused with the appearance of the Entrada Sandstone here in the San Rafael Desert. We are accustomed to a massive pink-colored, cross-bedded, eolian sandstone (Slick Rock Member) overlain by thinner beds of burrowed sand-flat sandstones and mudrocks (“Board Bed Facies”). The reason is that in the Grand Junction area, the wind-blown Entrada was deposited across the remnants of the Ancestral Rocky Mountains (Uncompahgria), which was about 120 miles east of the Sundance Seaway (**Figure S6-6**). This shallow seaway occupied the initial foreland basin that developed during the Sevier Orogeny (i.e., the Sevier fold and thrust belt). In the Green River area, the upper part of the Entrada (i.e., the Earthy Member) was deposited along the eastern side of the Sundance Seaway as it was expanding in size. Thus, the resulting sandstones and mudrocks reflect sedimentation in sand-flat and mudrock settings. **Figure BG-10** shows the lateral facies transitions.

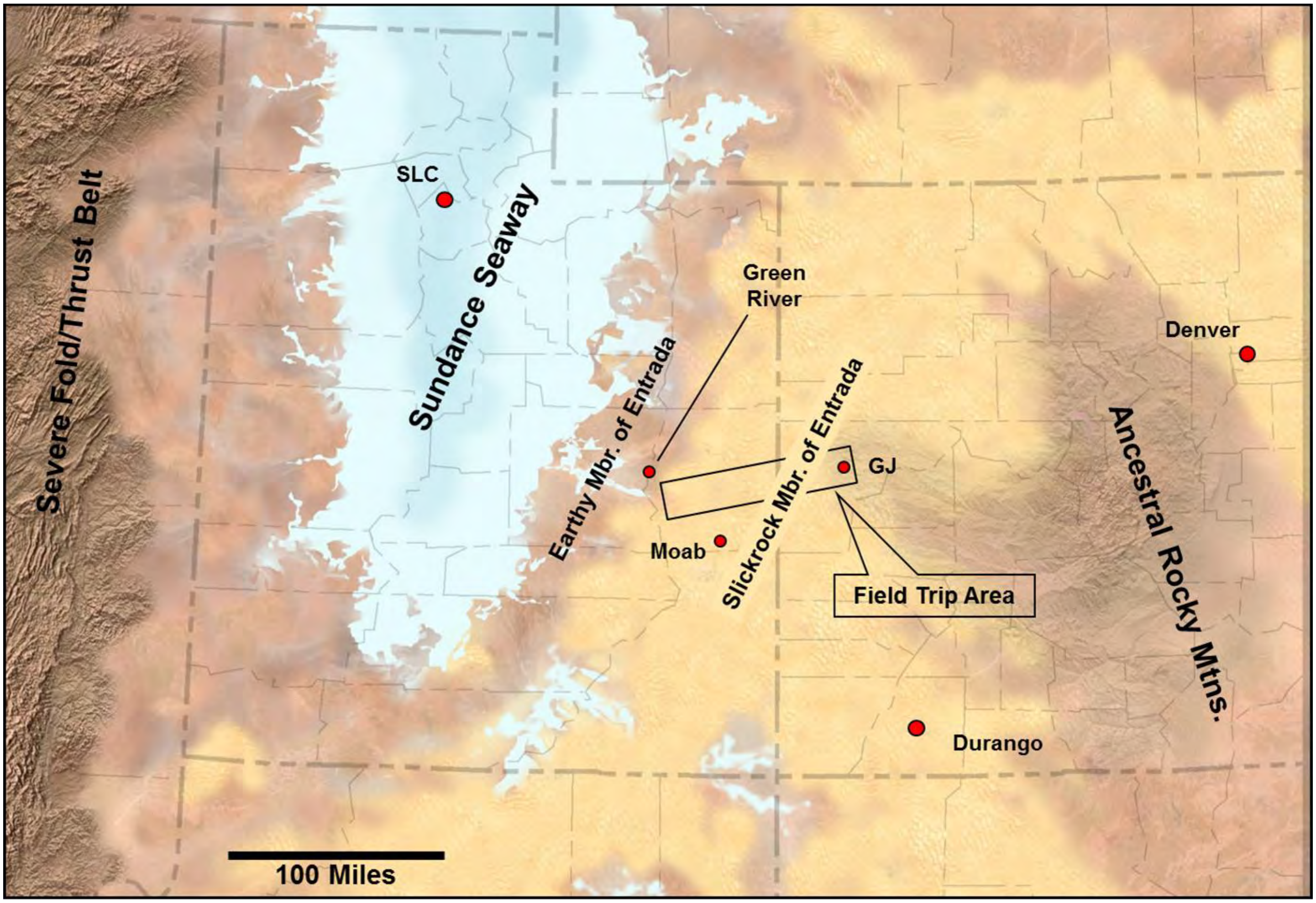


Figure S6-6. Paleogeographic map showing the extent of the Sundance Seaway during the Middle Jurassic, about 170 million years ago. Modified from **Blakey and Ranny (2008)**.

The Earthy Member consists of earthy, red-brown, fine-grained sandstone with nodular to indistinct bedding, and red-brown siltstone and silty, very fine-grained sandstone. The Slick Rock Member is mostly orange-red or banded orange-red and white, fine-grained, well-sorted sandstone with common small sets of eolian cross-stratification. Locally the Slick Rock can be massive with discontinuous partings (**Doelling, 2002; Doelling et al., 2015**). The Slick Rock is conformably underlain by the Dewey Bridge Member of the Carmel Formation and The Earthy Member is disconformably (J-3 unconformity) overlain by the Curtis.

Stop 7 – Ten Mile Graben Fault (Optional)

(Lat. 38.8506º; Lon. -110.0496º; Elev. ~ 4,280 ft)

Topics:

- Structural architecture of the Ten Mile Graben
- Characteristics of the north bounding fault and displacement of strata

Stop Description

Stop 7 is where the Salt Wash Road first crosses into the Ten Mile Graben (see Figure **S4-1** and **S4-2**). The outcrops south of the fault are in the Cedar Mountain Formation; those on the north are in the Entrada Sandstone (**Figure S7-1**).

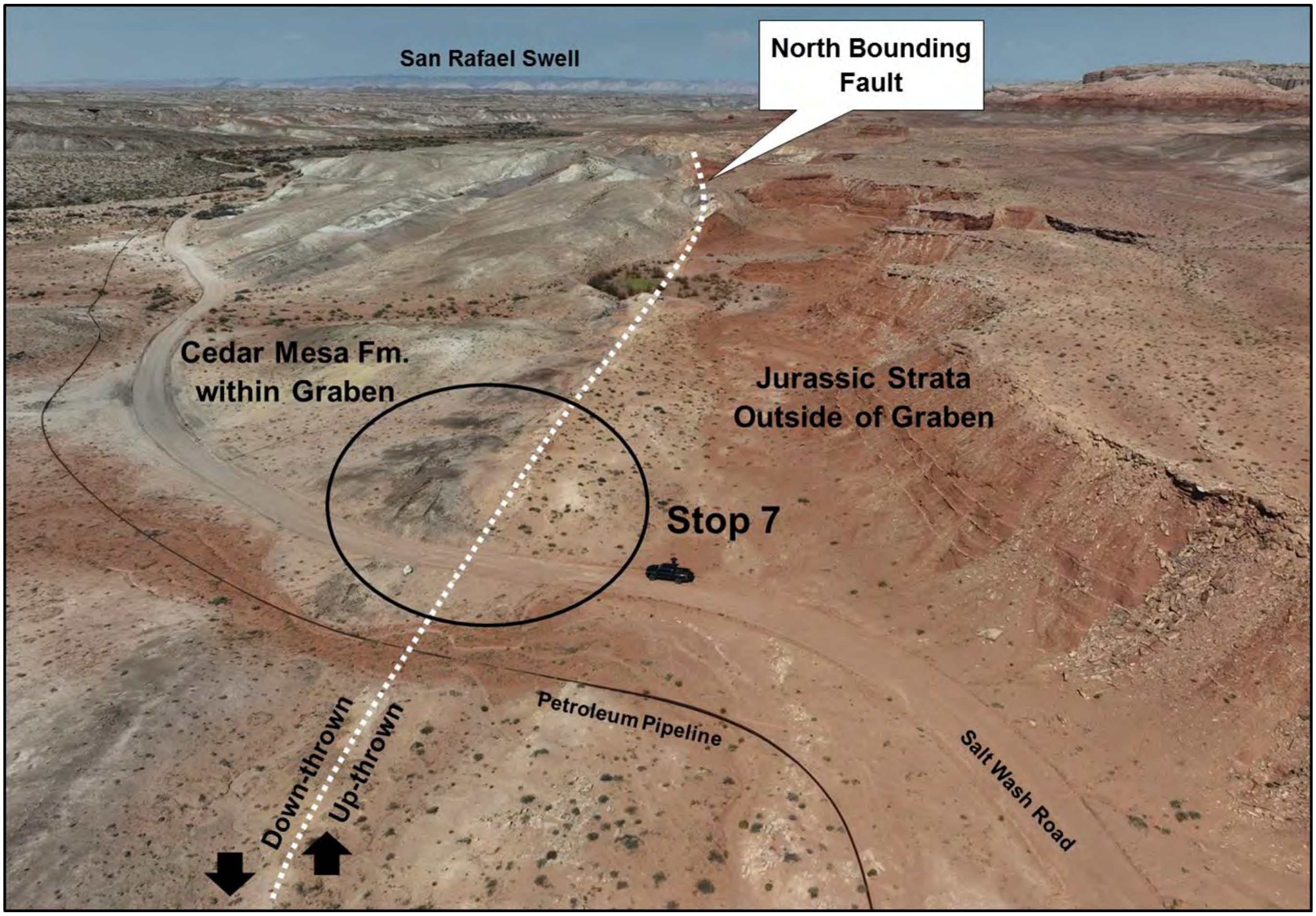


Figure S7-1. Aerial view of the north bounding fault for the Ten Mile Graben at **Stop 7**. View is looking west, with the San Rafael Swell in the far distance (~ 22 mi). The Swell was created during the Laramide Orogeny. Photo by Javier Tellez (2026).

Note: The materials for Stop 5C are appropriate for Stop 7.

Stop 8 – Elephant Butt Butte

(Lat. 38.8610º; Lon. -110.0817º; Elev. ~ 4,200 ft)

Topics:

- Deformation of the Entrada Formation. Soft-sediment? Structural? Both?

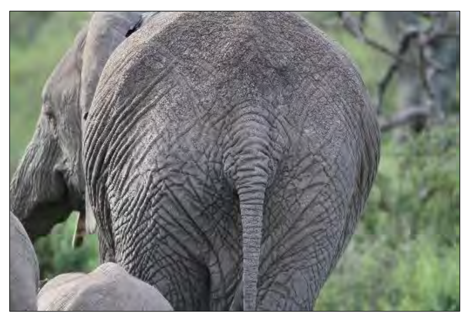
Stop Description

Stop 6 is along Salt Wash Road (see Figure **S4-1** and **S4-2**) where a very unusual outcrop is present. (**Figure S8-1**).

This is a short stop, mainly to look at a small erosional remnant (**Figure S8-1**) that bears a striking resemblance to the view of an elephant walking away from you (**Figure S8-2**). In more geological terms, it shows a good example of differential compaction and draping of beds over a sandstone body in the Entrada Sandstone.

Figure S8-1. Photo of Elephant Butt Butte at Stop 8. This view shows why this feature got its name (Sandra Hood). The outcrop consists of the Earthy Member of the Entrada Sandstone. Photo by W. Hood.

Figure S8-2. Photo of an elephant in the Serengeit National Park in Tanzania. Photo by W. Hood.



From the side looking toward the west, the strata almost look like an angular unconformity (**Figure S8-3**).

Figure S8-3. View of the Butte looking west. Photo by W. Hood.

With a view more to the left and better lighting (**Figure S8-4**), you can see that the layered sediments are filling a pre-existing stream channel.

Figure S8-4. View of the Butte looking north. One can wonder if this complex outcrop is the result of soft-sediment deformation, erosion of a channel-like feature which was later filled by thin-bedded sand and silt, or a combination of processes. Additional examples of this type of deformation will be visible in the next few miles. Photo by W. Hood.

Stop 9 – Ten Mile Geyser and Travertine Quarry

(Lat. 38.8647º; Lon. -110.1076º; Elev. ~ 4,110 ft)

Topics:

- Leaky graben faults
- Origin and mineralogy of travertine deposits
- Role of CO2 in cold-water geysers

Stop Description

Stop 9 is about 500 feet south of Salt Wash Road and is accessed by a faint road. At this location, you to see several features resulting from a "leaky" fault. Here we will discuss such items as the origin of the travertine deposit, the role of carbon dioxide in the geysers in the area, the mineralogy of the travertine, and bleaching of the Entrada Sandstone. Current ideas on these topics are presented in more detail in the paper by Hood in this guide (Ten Mile Supplement).

A general view of the area is provided in **Figure S9-1**, which shows the location of **Stop 9**, Salt Wash, and the Ten Mile Geyser. Because of time constrains, we will probably not visit the geyser.

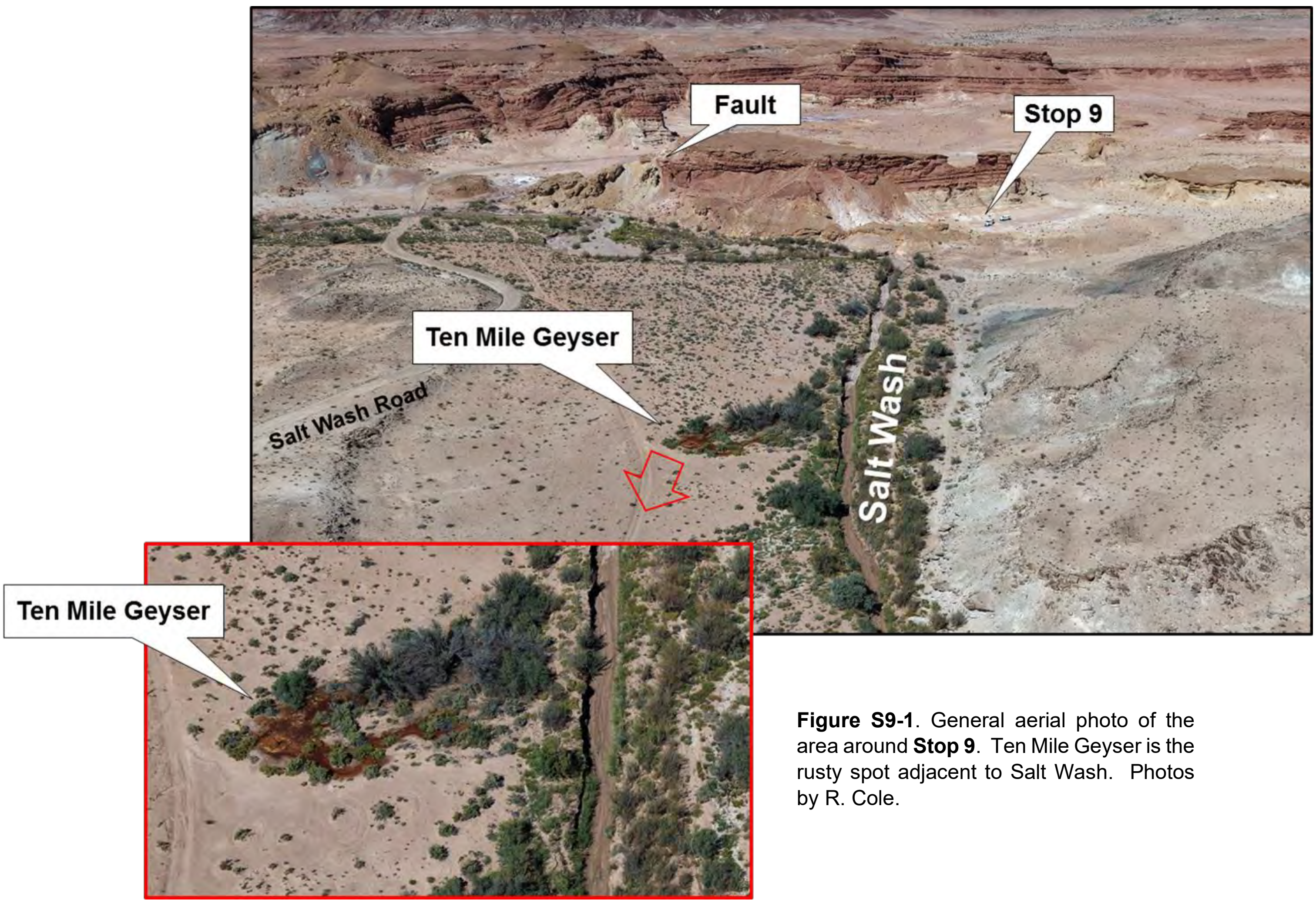


Figure S9-1. General aerial photo of the area around **Stop 9**. Ten Mile Geyser is the rusty spot adjacent to Salt Wash. Photos by R. Cole.

Stop 9 is along the north fault of the Ten Mile Graben, which offsets the Cedar Mountain Formation from Jurassic strata, as shown in **Figure S9-2**.

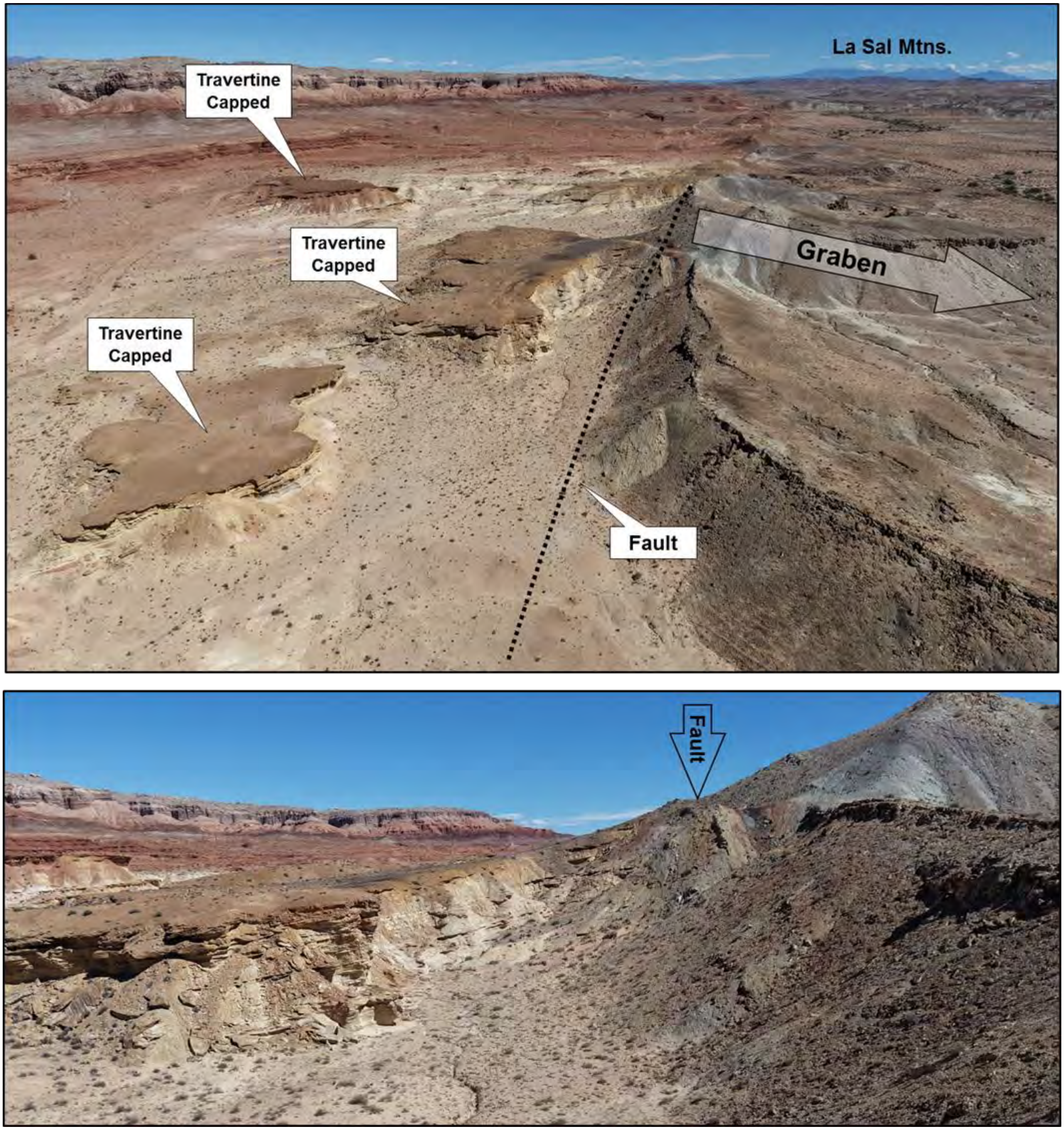


Figure S9-2. Aerial views of the northern fault for the Ten Mile Graben. The Cedar Mountain Formation is within the graben. Thin travertine deposits cap some of the small mesas near the fault. The La Sal Mountains near Moab are visible in the far distance (~ 50 mi). Lower photo shows the bounding fault. Photos by R. Cole.

One of the topics of interest at **Stop 9** is the presence of horizontal veins of calcium carbonate (**Figure S9-3**). Are these veins formed by open space filling or by the force of crystallization? If they are open-space filling, how is the open space maintained with the weight of a significant amount of overburden pressing down? Some of the veins are thicker than the ones shown in **Figure S9-3**. **Figure S9-4** shows a short vein complex with several thin veins and bits of the sedimentary country rock between the veins. **Figure S9-5** shows a piece of travertine about a foot thick. It is obviously not in place.

Figure S9-3. Photo of a travertine-strewn hillslope (white debris), with horizontal (stratiform) layers in bedrock above (Entrada Formation). Photo by W. Hood.

Figure S9-4. Photo of a small float block displaying a travertine vein complex, with country rock visible between two of the veins. Photo by W. Hood.

Figure S9-5. A block of travertine a foot or so thick. We examined the mineralogy of 9 pieces of travertine picked up around this area by x-ray diffraction. All samples were aragonite, not calcite. Photo by W. Hood.

The Entrada at **Stop 9** also shows a good example of bleaching (**Figure S9-6**). Carbon dioxide-charged water is acidic (pH 3 or lower, depending on the P_{CO_2}). Hematite and limonite, especially in very fine-grain sizes that occur as coatings on sand grains, are soluble in acid, given enough time a CO_2-charged solution should be able to bleach a sandstone by dissolving and removing the grain coatings. If, however, a reducing substance such as H_2S or methane is also present to reduce the iron from the +3 to +2 valance state, bleaching is more easily accomplished.

Figure S9-6. Bleached beds in outcrop at **Stop 9**. This bleaching happened long ago, long enough for erosion to cut down and expose the bleached zone and to leave the small pillar, called Red Cap, standing free from the main bleached rock. Photo by W. Hood.

Radiometric dating of travertine beds at the Crystal Geyser site a few miles southeast of Green River, UT, has shown that carbonated, travertine-depositing water has been leaking up the Little Grand Wash fault for at least 400,000 years. It has likely been doing much the same along the north fault of the Ten Mile (or Salt Wash) graben. An erosion rate of a couple of inches a year would be enough for Salt Wash to erode its valley enough to expose this bleached zone.

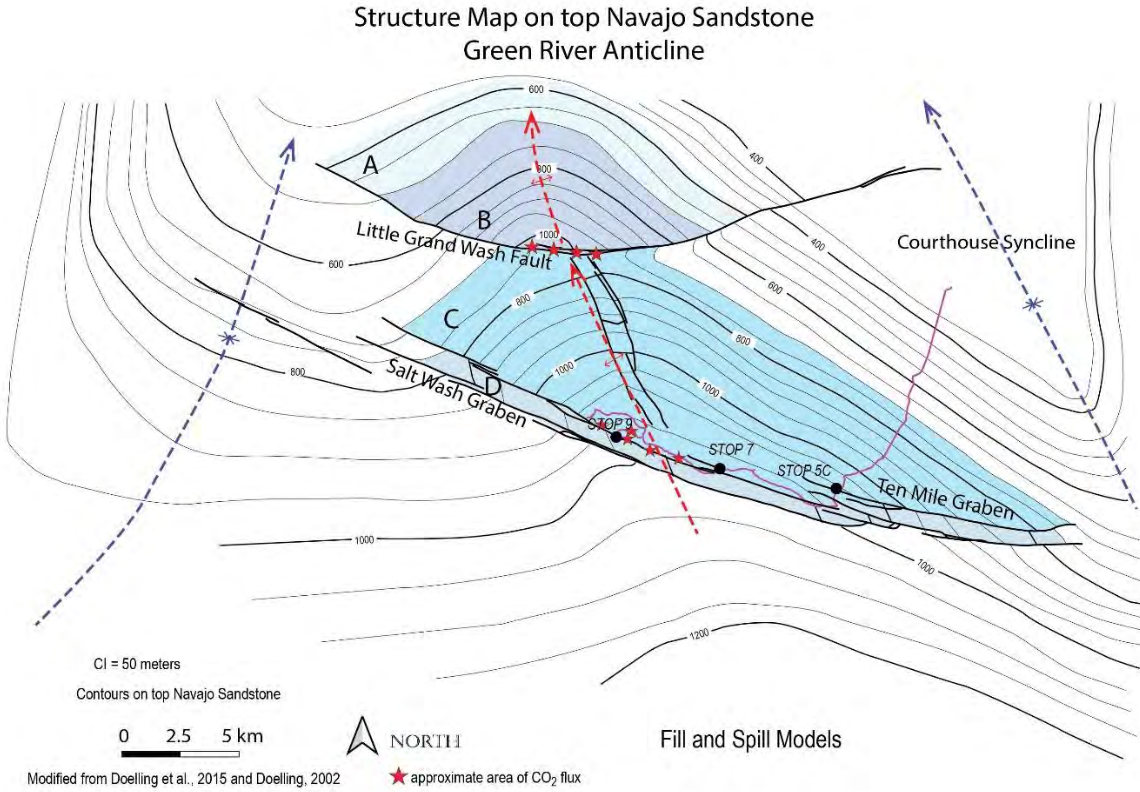


Figure S9-7. Structural contour map across the Green River Anticline with contours on the top Navajo Sandstone. The filled polygons show the maximum spill limits. The contours are modifed from **Doelling et al., 2015** and **Doelling 2002**.

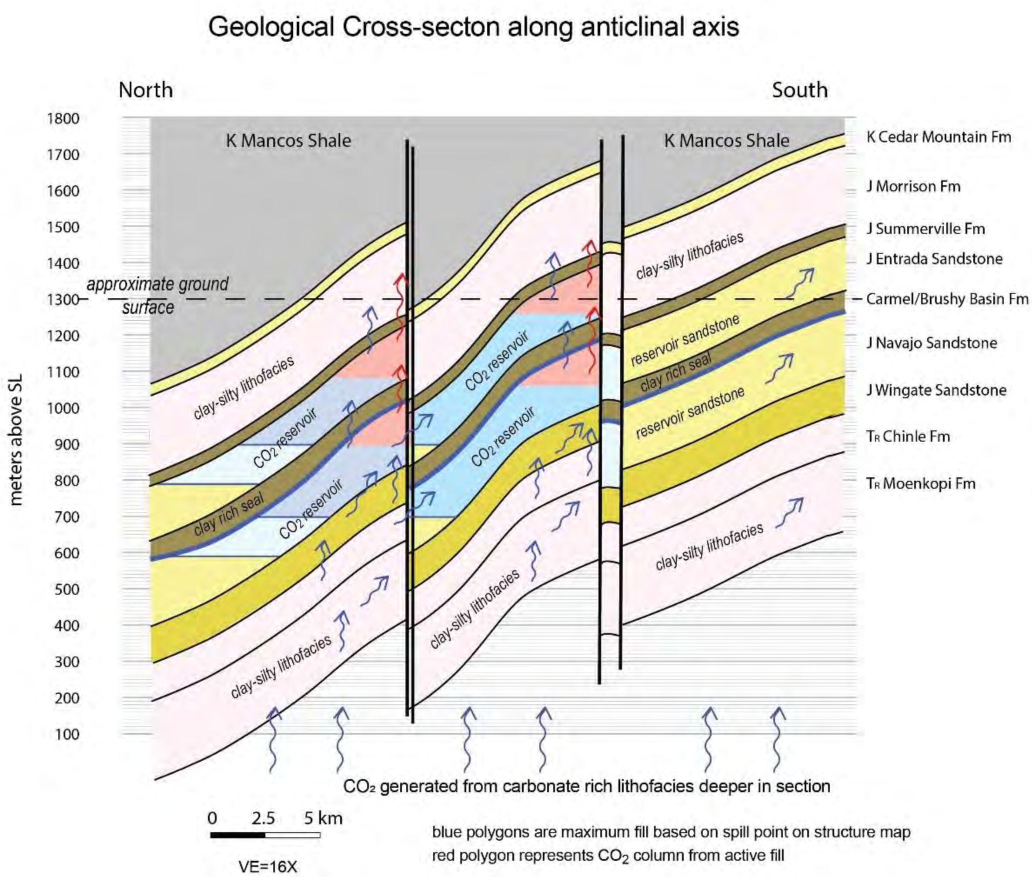


Figure S9-8. Cross-section across the axial trace of the Green River anticline (**Figure S9-7**) with approximate formation thicknesses and inferred fill-to-spill limits from closed contours on structure map. The arrows show deeper charge of migrating CO_2 up into shallow reservoirs with potential migration pathways.

Stop 10 – Big Bubbly Spring

(Lat. 38.8709º; Lon. -110.1116º; Elev. ~ 4,120 ft)

Topics:

- Scenic overlook of the Big Bubbly Spring. It is worth the walk!
- Discussion of cold-water, CO_2-charged springs and geysers

Stop Description

Stop 10 is at a rock bench that overlooks the Big Bubbly Spring, which is near the north boundary of the Ten Mile Graben (**Figure S10-1**). We will walk from the road about 1,100 feet across relatively flat, but uneven ground (**Figure S10-1**). Please take water!

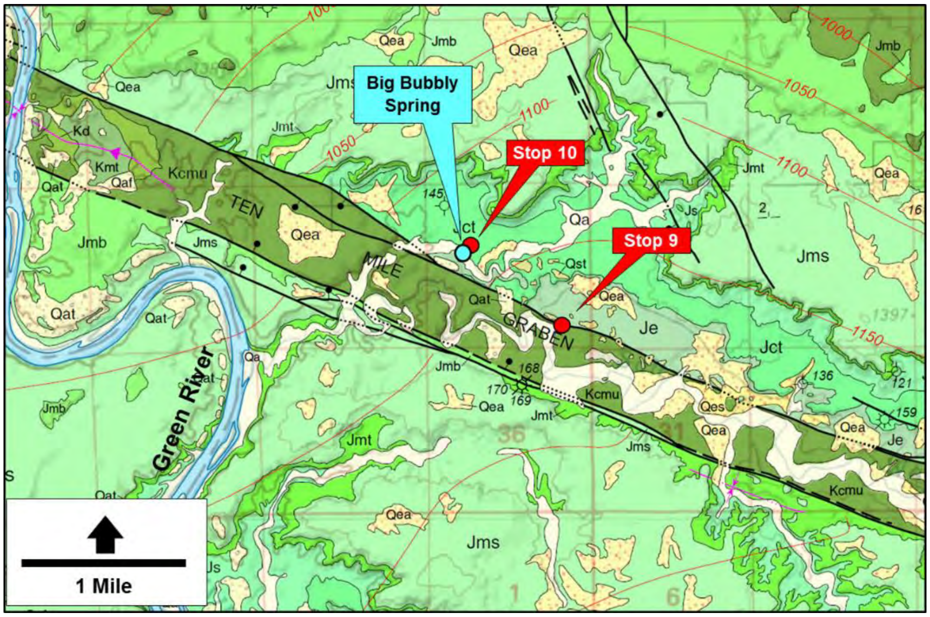


Figure S10-1. Geologic map of the **Stop 10** area showing location of Big Bubbly Spring, which is just north of the Ten Mile Graben. Also shown is **Stop 9**, which is on the north fault of the graben. Unit abbreviations: Je = Entrada; Jct = Curtis; Jms = Salt Wash; Jmt = Tidwell, Jmb = Brushy Basin; Js = Summerville; Kcmu = upper Cedar Mtn.; Kd = Naturita: and Kmt = Tununk. Source: **Doelling et al. (2015)**.

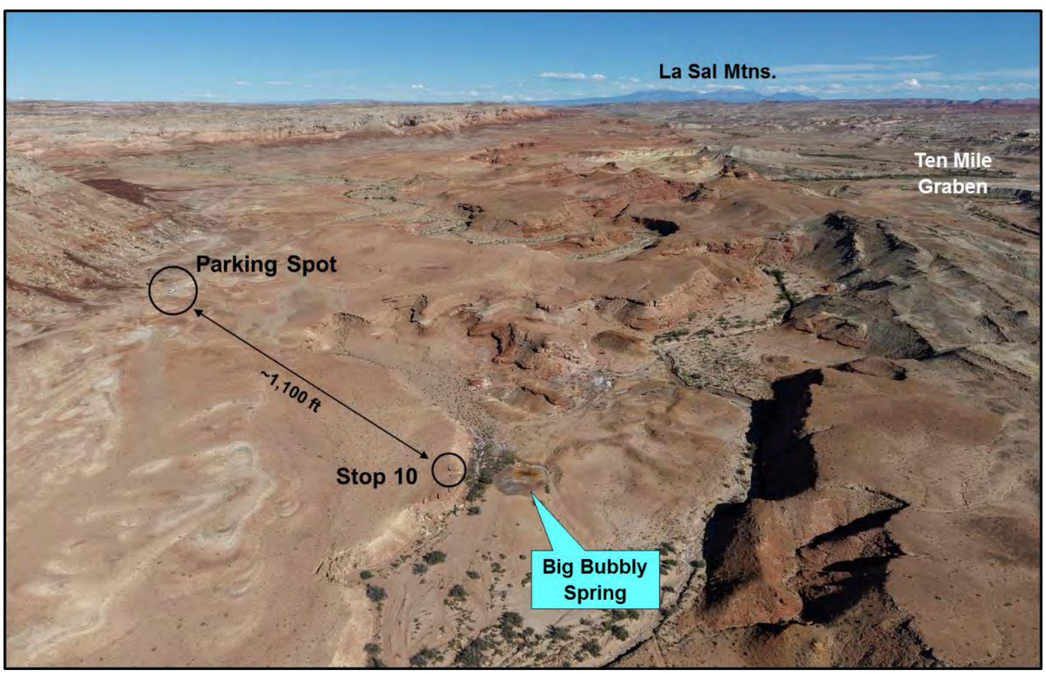


Figure S10-2. Aerial photo of the Stop 10 area. The La Sal laccoliths are visible in the far distance (~50 miles). The walk from the parking spot to the ledge overlooking Big Bubbly Spring is approximately 1,100 feet (one way). There is no trail and the ground is slightly irregular. Photo by R. Cole.

Figure S10-3 provides some aerial views of Big Bubbly Spring. A comprehensive discussion of CO2-charged, cold-water springs and geysers is provided in the Supplemental materials by Bill Hood.

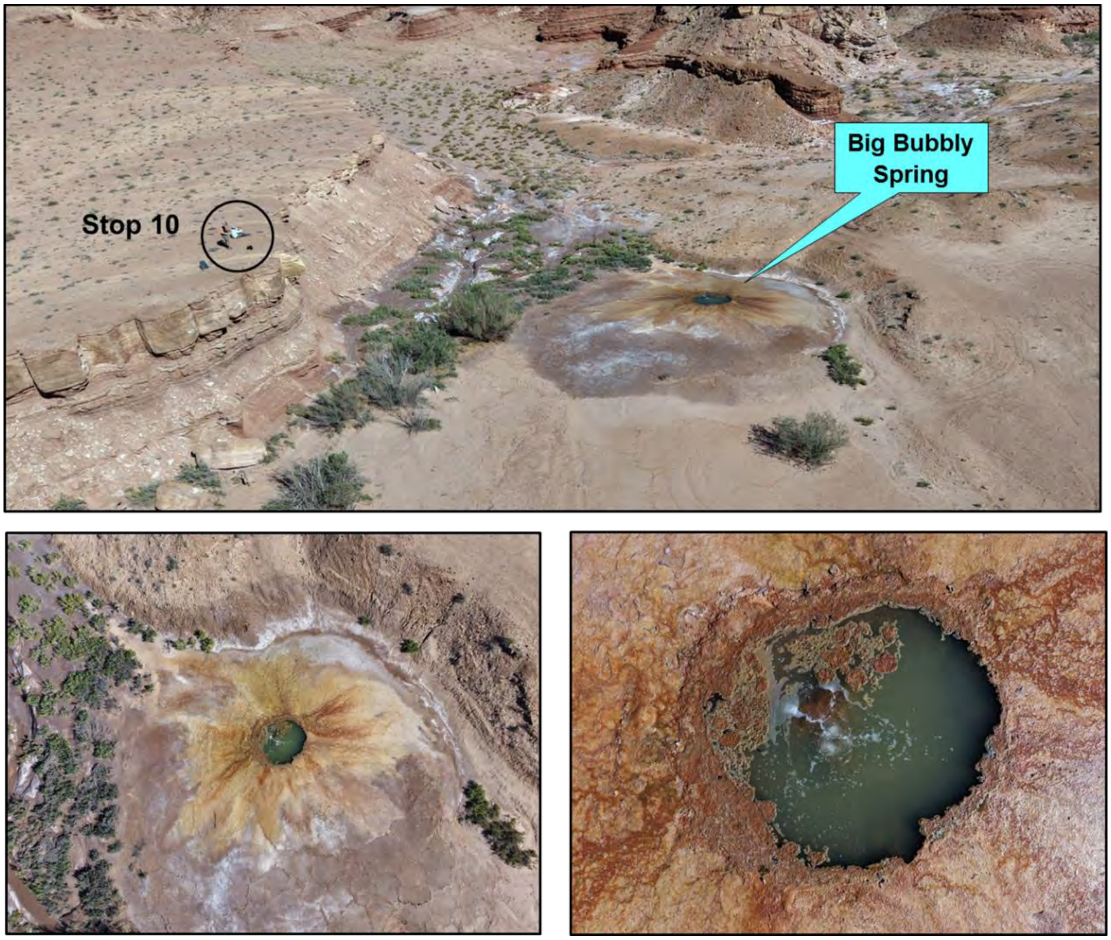


Figure S10-3. Aerial photos of Big Bubbly Spring. Photos by R. Cole.

Big Bubbly Spring is a classic example of CO_2 leakage from depth. On the 2004 field trip, this was nicknamed "Star Spring" because at that time there were four jets of bubbles that made a star pattern on the spring surface. Over the years that has change somewhat and the star pattern no longer exists. Modern literature refers to this spring as "Big Bubbly Spring" (**Figure S10-4**).

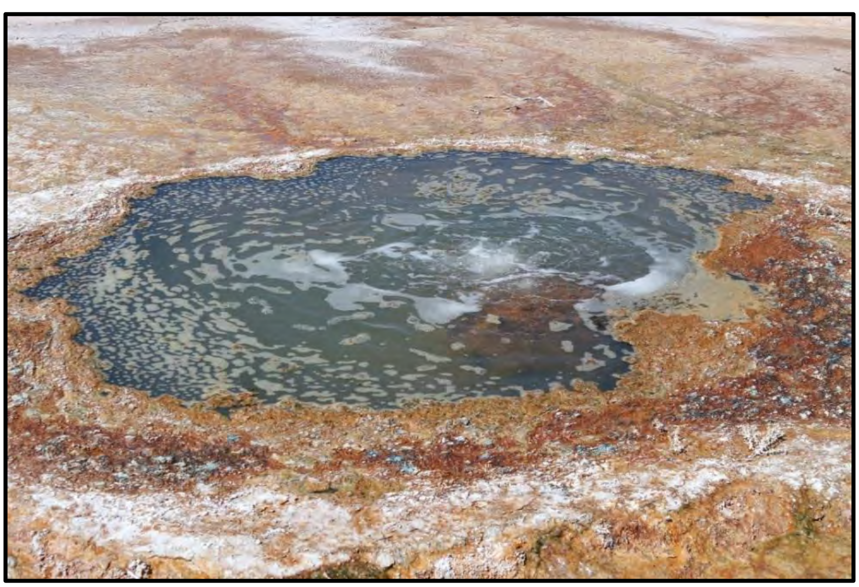


Figure S10-4. Ground-level view of Big Bubbly Spring, as it is called in most of the recent literature. Photo by W. Hood.

In the walls of the unnamed drainage, there are examples of faulting and contortion of the Jurassic strata (**Figures S10-5, S10-6 and S10-7**).

Figure S10-5. Faulted outcrop near Big Bubbly Spring. Photo by W. Hood.

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Figure S10-6. Photo of well-displayed soft-sediment deformation. Notice the nearly vertical orientation of the small-scale layering. Photo by W. Hood.

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Figure S10-7. Closer view of the deformed sediment. Photo by W. Hood.

Also exposed in the drainage is possible evidence of leakage from a deeper source. Visible when it is dry, the white crust (**Figure S10-8**) is composed of a mixture of halite ($NaCl$) and thenardite (Na_2SO_4), as determined by x-ray diffraction.

Figure S10-8.. White crust in drainage. X-ray diffraction identified halite and thenardite in the material. Photo by W. Hood.

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