Oil & Natural Gas Technology

DOE Award No.: DE-FE0001243

Topical Report

CORE-BASED INTEGRATED SEDIMENTOLOGIC, STRATIGRAPHIC, AND GEOCHEMICAL ANALYSIS OF THE OIL SHALE BEARING GREEN RIVER FORMATION, UINTA BASIN, UTAH

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Prepared for:
United States Department of Energy
National Energy Technology Laboratory

April 2011

Office of Fossil Energy

Core-based integrated sedimentologic, stratigraphic, and geochemical analysis of the oil shale bearing Green River Formation, Uinta Basin, Utah

Topical Report

Reporting Period: October 31, 2009 through March 31, 2011

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Report Issued: April 2011

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Abstract

An integrated detailed sedimentologic, stratigraphic, and geochemical study of Utah's Green River Formation has found that Lake Uinta evolved in three phases 1) a freshwater rising lake phase below the Mahogany zone, 2) an anoxic deep lake phase above the base of the Mahogany zone and 3) a hypersaline lake phase within the middle and upper R-8. This long term lake evolution was driven by tectonic basin development and the balance of sediment and water fill with the neighboring basins, as postulated by models developed from the Greater Green River Basin by Carroll and Bohacs (1999). Early Eocene abrupt global-warming events may have had significant control on deposition through the amount of sediment production and deposition rates, such that lean zones below the Mahogany zone record hyperthermal events and rich zones record periods between hyperthermals. This type of climatic control on short-term and long-term lake evolution and deposition has been previously overlooked.

This geologic history contains key points relevant to oil shale development and engineering design including:

1) Stratigraphic changes in oil shale quality and composition are systematic and can be related to spatial and temporal changes in the depositional environment and basin dynamics.
2) The inorganic mineral matrix of oil shale units changes significantly from clay mineral/dolomite dominated to calcite above the base of the Mahogany zone. This variation may result in significant differences in pyrolysis products and geomechanical properties relevant to development and should be incorporated into engineering experiments.
3) This study includes a region in the Uinta Basin that would be highly prospective for application of in-situ production techniques. Stratigraphic targets for in-situ recovery techniques should extend above and below the Mahogany zone and include the upper R-6 and lower R-8.

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Introduction

The Green River Formation is the record of an Eocene, continental interior, terminal lake basin system that covered a significant area across northeastern Utah, western Colorado (Uinta-Piceance Basin respectively, Lake Uinta), and southwestern Wyoming (Greater Green River Basin, Lake Gosiute) (Figure 1). It is one of the most well-cited examples of an ancient lacustrine system and is particularly well known for detailed sedimentary study in the Greater Green River Basin of Wyoming (e.g., Carroll and Bohacs, 1999). In Utah, the Green River Formation hosts a vast oil shale resource in the Uinta Basin, estimated at 1.32 trillion barrels in-place (USGS, 2010) with approximately 77 billion barrels of oil as a potentially economic resource (Vanden Berg, 2008) (Figure 2). Nevertheless, a solid geologic framework for the Green River Formation in the Uinta Basin is less developed compared to the neighboring Piceance and Greater Green River Basins, and a predictive sequence stratigraphic framework is lacking. In particular, there has been relatively little effort focused on the facies and stacking patterns in the mudstone-dominated basin depocenter as compared to the alluvial and shallow lacustrine facies on the basin margin. The goal of this study is to use a detailed sedimentologic and stratigraphic description of a ~24-mile-long core transect through the basin's paleo-depocenter to: (1) document the vertical and lateral facies heterogeneity, with particular focus on how these changes might affect various oil shale recovery engineering applications, and (2) provide an understanding of the controls on the ancient depositional system in order to build a predictive sequence stratigraphic framework.

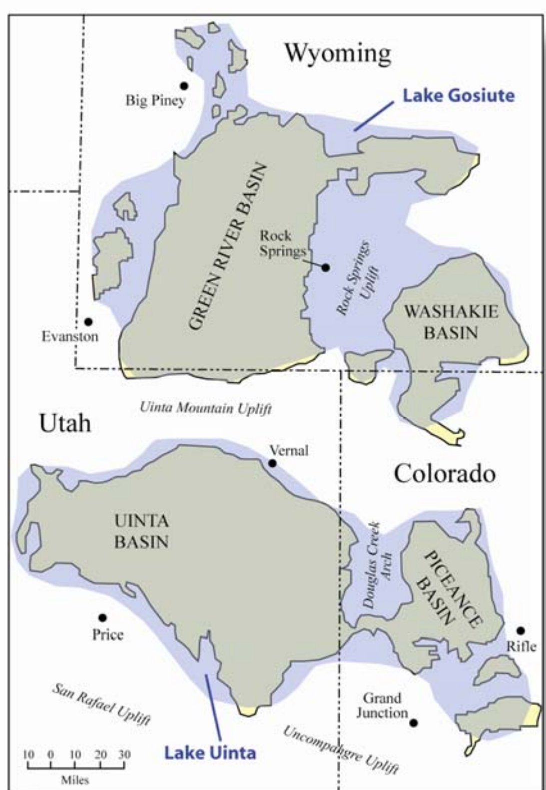

Figure 1. Paleogeography of Eocene lake system, with modern basin margins in Utah, Colorado, and Wyoming.

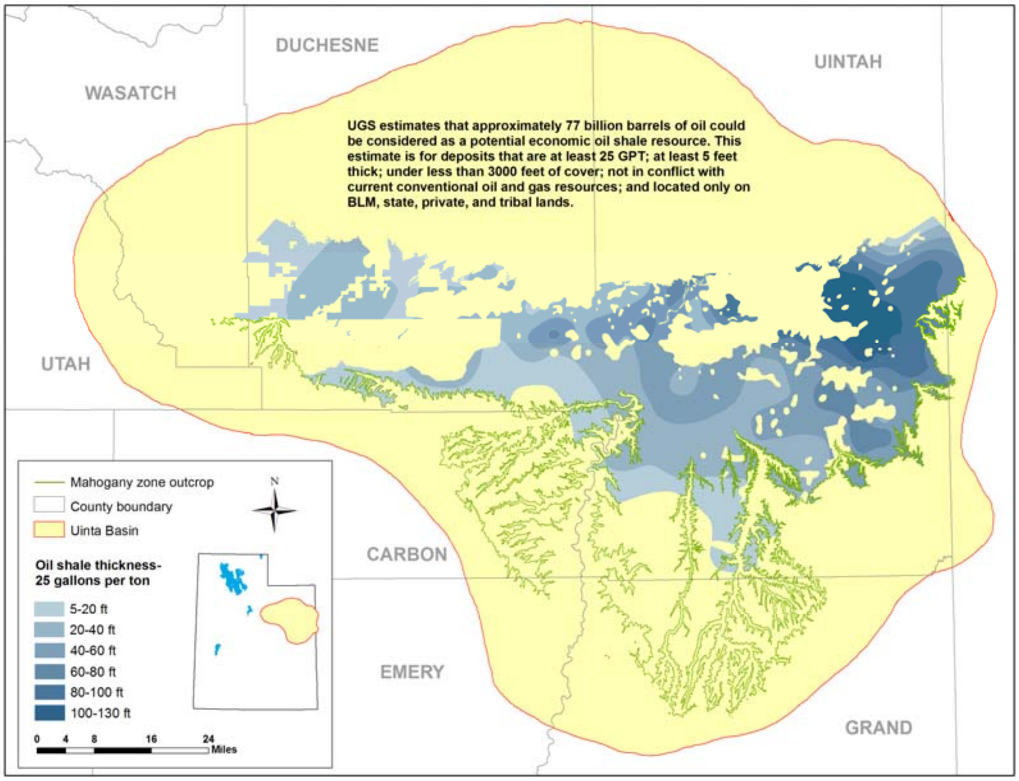

Figure 2. *Oil shale resource assessment in Uinta Basin from Vanden Berg (2008).*

Background

With the exception of a limited area of thermally mature shale in the northern Uinta Basin, the Green River Formation oil shale resource is thermally immature (Figures 3 and 4). Consequently, successful oil shale resource development requires pyrolysis and production in a manner that is economically viable and environmentally sustainable. Historically, Green River oil shale development efforts have waxed and waned in phase with crude oil prices. For example, oil shale mining and surface retort efforts in the 1970s and early 1980s at the White River Mine site were sparked by the 1970s domestic energy crisis, but were then curtailed by the energy surplus of the mid-1980s. The rise of oil prices over the past ten years has revived economic interest in oil shale development. In the Uinta Basin, private companies are currently pursuing one of two development methods: (1) oil shale mining, followed by crushing, homogenization of the ore, and subsequent retorting (heating) to produce a marketable oil product, or (2) surface mining combined with confined retorting techniques, such as the EcoShale™ In-capsule technology, in which rubblized ore is heated within a capsule constructed on the mining site, marketable petroleum product is collected, and the site is reclaimed with the capsule in place. The former is an established technique, whereas the latter has yet to be proven at the commercial scale. These mining-based oil shale extraction methods are in contrast to in-situ development techniques being pursued in the neighboring Piceance Basin, in which oil shale is heated and hydrocarbons are extracted at depth. The contrast in oil shale development methods between the Uinta and Piceance Basins is driven by the depth and richness of the entire

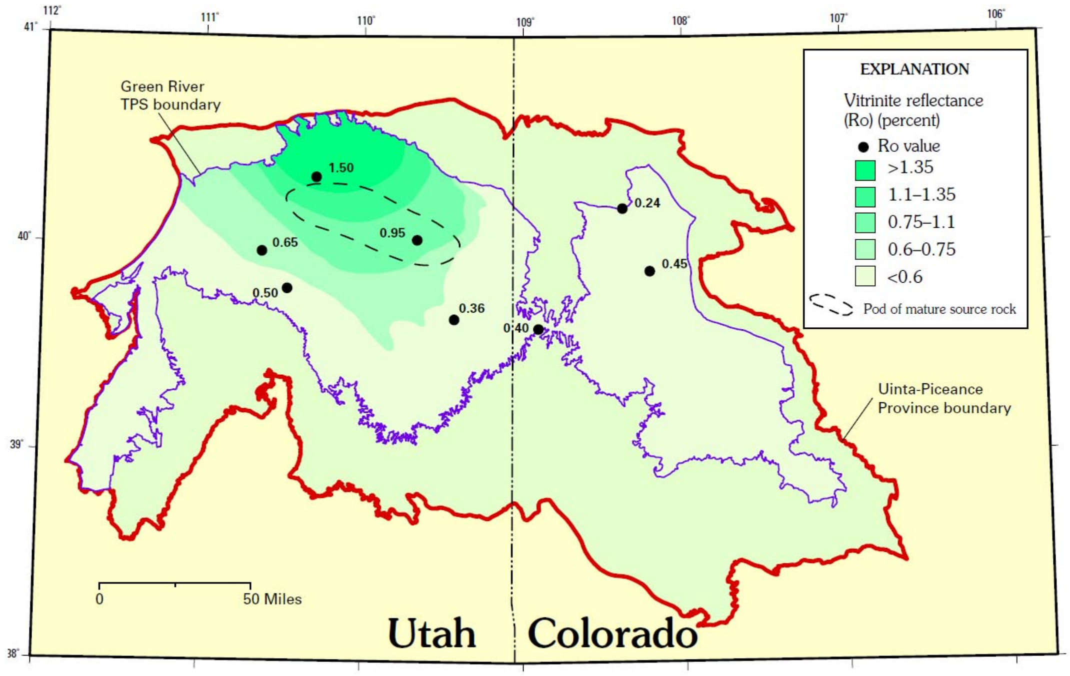

Figure 3. *Basin maturity map of the Green River Total Petroleum System, Uinta-Piceance Province, illustrating that throughout most of the Uinta Basin the Green River Formation is immature. Note a geographically limited pod of mature source rock. From Nuccio and Roberts (2003).*

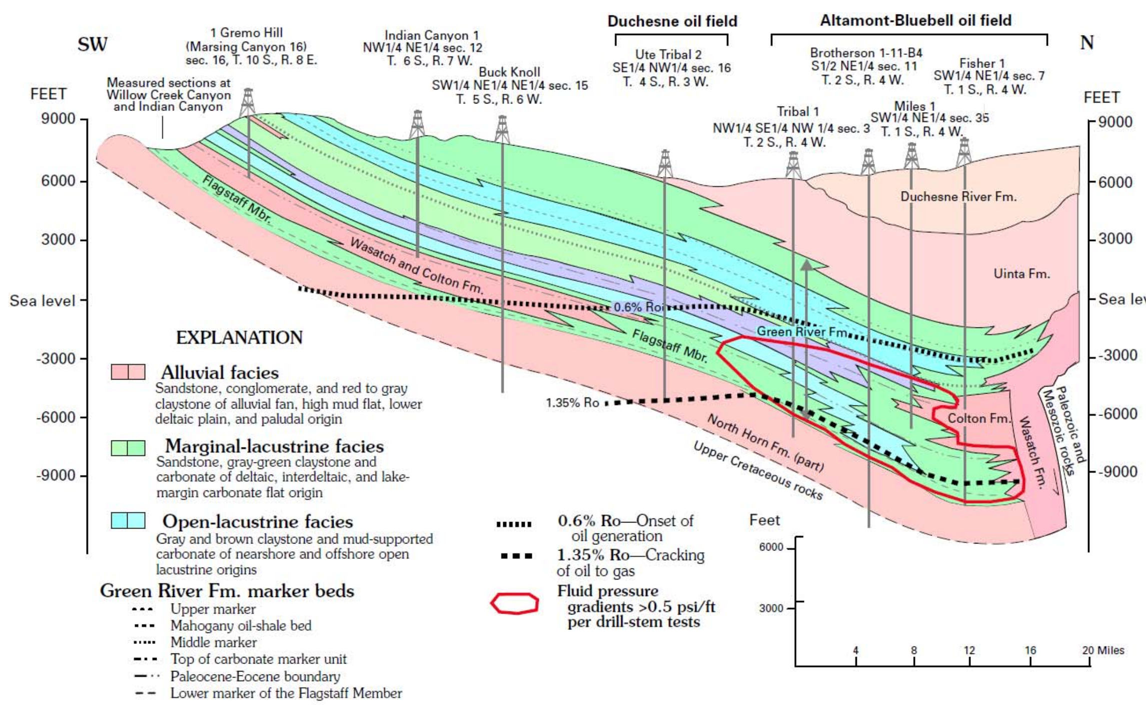

Figure 4. *Generalized stratigraphy of the Uinta Basin; north-south cross section from the western portion of the basin. From Dubiel (2003).*

oil shale interval. In the Uinta Basin, the relatively thin target interval (~100 feet), currently only the Mahogany zone, is exposed at surface over broad areas, encouraging mining operations. Significantly higher overburden to ore ratios in the Piceance Basin, as well as much thicker (~1000 ft) and richer deposits have driven the focus towards in-situ development.

During the Eocene, Lake Uinta stretched across modern day northeastern Utah and western Colorado, and Lake Gosiute covered modern day southwestern Wyoming. Lake Uinta is recorded in the Green River Formation of the Uinta and Piceance Basins of Utah and Colorado, respectively. Lake Gosiute is recorded in the Green River Formation of Wyoming. Alluvial sediment was delivered to the lake basin system from surrounding highlands uplifted during the Laramide Orogeny. Specifically, sediment was delivered to the Uinta Basin from active uplifting of the Uinta Mountains to the north, and from highlands to the south such as the Uncompahgre Uplift and the San Rafael Swell.

The degree of interconnectedness of the Uinta, Piceance, and Greater Green River lake basins varied through time based on the balance of subsidence, as well as sediment and water fill within and between the basins. The Douglas Creek Arch was a structural high that acted as a paleotopographic sill between the Uinta and Piceance Basins (Figure 1). The paleotopographic sill, in combination with temporal variations in lake level and sediment supply as controlled by tectonics and climate, had a profound impact on lake chemistry, lake evolution, and the preserved facies in each basin (Carroll and Bohacs, 1999).

Stratigraphic nomenclature of the Green River Formation in the Uinta Basin is highly variable according to location and author, and has been largely lithostratigraphic in origin (Ryder and others, 1976). Stratigraphically, the Green River Formation in the Uinta Basin is divided into the lower, middle, and upper members (Weiss and others, 1990) (Figure 5). On the southern edge of the basin, lake shoreline facies dominate. The lower member is largely lacustrine carbonate dominated, whereas the middle member is dominated by fluvial-deltaic facies, such as the Sunnyside delta member (Ryder and others, 1976; Morgan and others, 2003). The base of the Mahogany oil shale zone marks the boundary between the middle and upper members. In the center of the basin, an alternative terminology is used. Here, organic-rich (R) and organic-lean (L) zones stack alternately, with the Mahogany zone (R-7) as the richest oil shale zone. Carbonate-dominated rich and lean zones comprise the Parachute Creek Member and fluvial-deltaic facies below are defined as the Douglas Creek Member (Cashion, 1957; Ryder and others, 1976; Ruble and Philp, 1998). Detailed depositional-dip-parallel chronostratigraphic correlations are lacking and would provide critical insight into facies changes relevant to oil shale development and depositional controls on the ancient lake system. These correlations will be addressed in the FY2010 investigations.

Methods

A systematic detailed sedimentologic, stratigraphic, and geochemical study was performed on four cores (P-4, Coyote Wash 1, Utah State 1, and EX-1) ranging in length from 960 to 1640 ft, along an east-west transect through the basin's paleo-depocenter (Figure 6, Table 1). Key features noted in each core include grain size, lamination style, sedimentary structures, mineralogy, bioturbation, biotically influenced features, body fossils, and plant fossils. Nondestructive qualitative X-ray fluorescence (XRF) analysis was used to help determine inorganic mineralogy, which is difficult to detect in these mudstone-dominated rocks based on

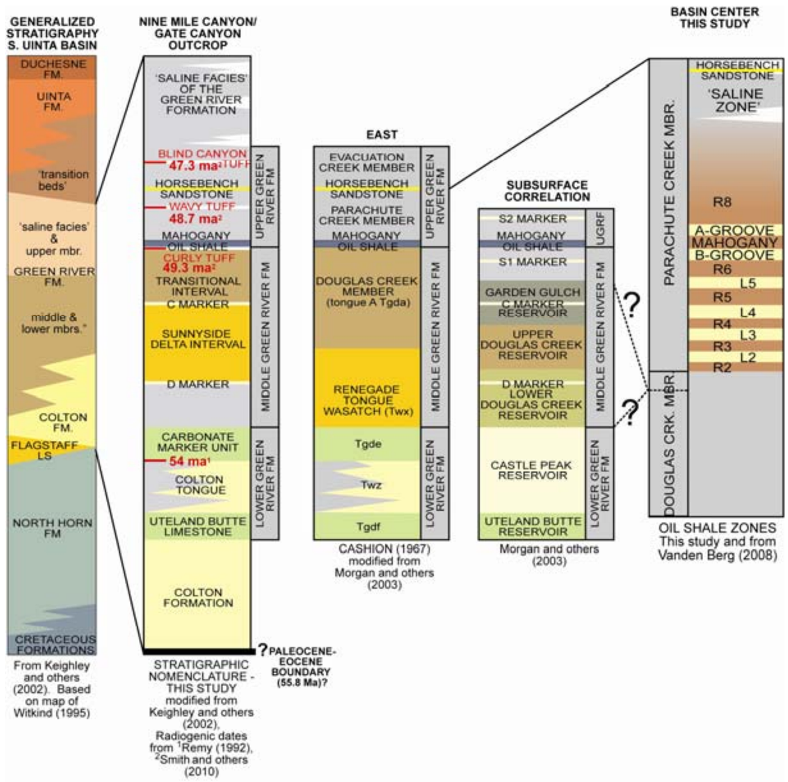

Figure 5. *Generalized stratigraphy of the Uinta Basin, with detailed stratigraphy of the Green River Formation at the southern margin and basin center. Studied stratigraphic interval shown (red box, far right).*

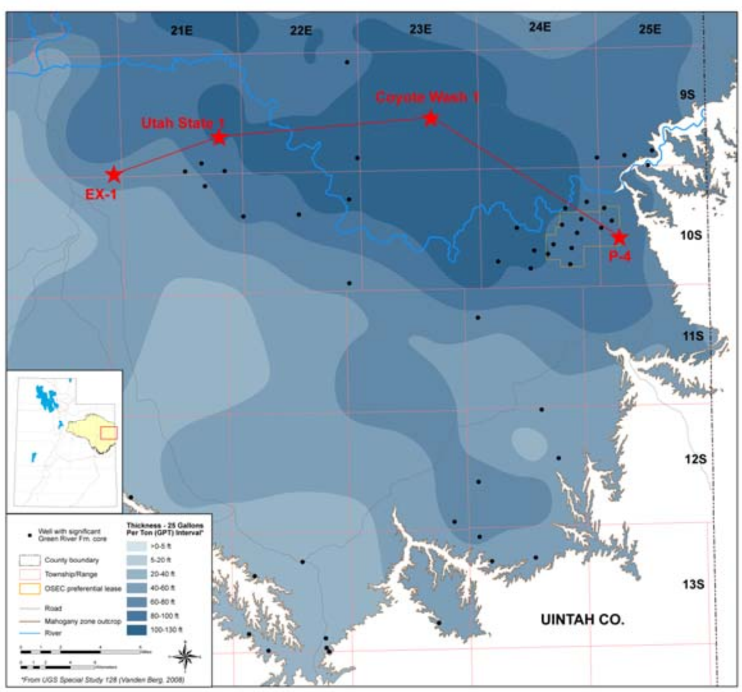

Figure 6. *Location map for this study showing locations of four cores examined to construct an east-west cross section (Plate 5). Shades of blue indicate thickness of a continuous interval of oil shale averaging 25 gallons per ton, with color shading darkening with increased thickness.*

Table 1. *Unit thicknesses in studied cores.*

	EX-1				Utah State 1				Coyote Wash 1				P-4			
	Top	Base	Thickness	Oil Yield	Top	Base	Thickness	Oil Yield	Top	Base	Thickness	Oil Yield	Top	Base	Thickness	Oil Yield
	depth in ft	depth in ft	ft	gpt	depth in ft	depth in ft	ft	gpt	depth in ft	depth in ft	ft	gpt	depth in ft	depth in ft	ft	gpt
Cored interval	1767	2969	1202	--	1570	2600	1030	--	1817	3460	1643	--	214	1173	959	--
Uinta Fm.	--	1541 ?	--	--	--	1510 ?	--	--	--	1509	--	--	--	145 ?	--	--
Green River Fm.	1541 ?	--	--	--	1510 ?	--	--	--	1509	--	--	--	145 ?	--	--	--
Parachute Creek Mbr.	1541 ?	--	--	--	1510 ?	--	--	--	1509	2992	1483	--	145 ?	--	--	--
Lower R-8 - R-4	2050	3003	953	8.9	2037	--	--	--	1945	2908	963	12.7	487	--	--	--
Upper R-8	1541	1807	266	4.9	1510	1798	288	6.1	1509	1704	195	--	--	--	--	--
Middle R-8	1807	2050	243	9.8	1798	2037	239	9.1	1704	1945	241	--	--	--	--	--
Lower R-8	2050	2254	204	14.7	2037	2261	224	15.0	1945	2175	230	14.4	487	672	185	11.8
Big 3	*2050*	*2067*	*17*	*--*	*2037*	*2054*	*17*	*--*	*1945*	*1963*	*18*	*--*	*487*	*504*	*17*	*--*
Stillwater	*2091*	*2102*	*11*	*--*	*2077*	*2089*	*12*	*--*	*1988*	*2002*	*14*	*--*	*527*	*536*	*9*	*--*
Four Senators	*2123*	*2149*	*26*	*--*	*2110*	*2137*	*27*	*--*	*2026*	*2053*	*27*	*--*	*561*	*592*	*31*	*--*
A-Groove (L-7)	2254	2267	13	6.1	2261	2274	13	6.8	2175	2191	16	6.9	672	683	11	4.2
Mahogany Zone (R-7)	2267	2356	89	21.7	2274	2376	102	25.2	2191	2320	129	24.4	683	785	102	23.0
Mahogany Bed	*2302*	*--*	*--*	*--*	*2314*	*--*	*--*	*--*	*2232*	*--*	*--*	*--*	*719*	*--*	*--*	*--*
B-Groove (L-6)	2356	2446	90	1.6	2376	2463	87	2.6	2320	2384	64	4.1	785	822	37	6.6
Upper R-6	2446	2539	93	12.1	2463	2565	102	13.6	2384	2509	125	14.5	822	926	104	11.0
Middle R-6	2539	2603	64	1.1	2565	--	--	--	2509	2558	49	4.5	926	957	31	3.6
Lower R-6	2603	2646	43	8.2	--	--	--	--	2558	2593	35	12.8	957	990	33	10.5
L-5	2646	2737	91	3.3	--	--	--	--	2593	2683	90	5.4	990	1063	73	3.6
R-5	2737	2830	93	7.8	--	--	--	--	2683	2798	115	11.4	1063	1140	77	10.3
L-4	2830	2911	81	0.1	--	--	--	--	2798	2832	34	5.0	1140	--	--	--
R-4	2911	3003	92	8.6	--	--	--	--	2832	2908	76	12.7	--	--	--	--
L-3	3003	--	--	--	--	--	--	--	2908	2919	11	3.5	--	--	--	--
R-3	--	--	--	--	--	--	--	--	2919	2943	24	9.1	--	--	--	--
L-2	--	--	--	--	--	--	--	--	2943	2978	35	2.4	--	--	--	--
R-2	--	--	--	--	--	--	--	--	2978	2992	14	8.1	--	--	--	--
Douglas Creek Mbr.	--	--	--	--	--	--	--	--	2992	--	--	--	--	--	--	--

gpt = gallons shale oil per ton of rock as measured by Fischer assay

Rows in italics are individual oil shale beds as opposed to zones visual inspection alone. XRF was performed on whole-rock samples according to key lithologic changes at roughly 10-foot intervals. The dominant inorganic mineralogy of the mudstones was defined based on the following XRF criteria:

1) Calcareous mudstone, >25% CaO, <40% SiO_2, <10% MgO,
2) Dolomitic mudstone, >25% CaO, <40% SiO_2, >10% MgO,
3) Clay-rich mudstone, <25% CaO, >40% SiO_2, <10% MgO.

Siltstones and sandstones were identified based on visual inspection. Once the geologic description was completed and the XRF data collected, a detailed core log was constructed to graphically represent the data (Plates 1, 2, 3, and 4). An east-west cross section was drafted with the core logs plotted next to geophysical log curves and Fischer assay oil yield data (Plate 5). Correlations were made between similar oil shale zones, highlighting how these zones change across the basin.

Results

The east-west core-based cross section is displayed on Plate 5. Whole-rock qualitative XRF results indicate that the inorganic mineral matrix of oil shale units changes significantly from clay mineral/dolomite dominated (brown or green on core logs, respectively on Plate 5) to calcite dominated (blue on core logs on Plate 5) above the base of the Mahogany zone. We recommend further chemical, pyrolysis, and geomechanical tests on clay mineral/dolomite dominated oil shale units (e.g., upper R-6) and calcite dominated oil shale units (e.g., Mahogany zone) in order to determine potential effects of inorganic mineralogy on extraction techniques, pyrolysis products, and other considerations relevant to in-situ technologies, mining, or retorting. Furthermore, oil shale intervals that have historically not been considered economic (e.g., lower R-8 and upper R-6), may be of economic value for in-situ, modified in-situ, or open pit operations and should be considered in development plans. The stratigraphically lower R-5 and R-4 zones alternate between organic-rich, clay-rich mudstones and organic-lean, dolomitic mudstones in roughly 10-foot cycles. This alternation significantly dilutes the available kerogen in these zones, making them less ideal for mining operations, but they could still be economical for in-situ technologies.

In general, rich oil shale zones are thickest and richest in the basin's paleo-depocenter, represented by the Coyote Wash 1 core, while lean zones significantly thin to the east (e.g., the B-Groove in the EX-1 core is 90 feet thick, but thins eastward to only 37 feet in the P-4 core) (Plate 5, Table 1). This observation suggests that the most economic area for in-situ recovery in the Uinta Basin would be where the rich zones are thickest and the lean zones are thinnest, in the area between the Coyote Wash 1 and P-4 cores (within T. 9-10 S., R. 22-23 E., Salt Lake Baseline and Meridian).

The top of the economical oil shale region was picked at the top of the lower R-8 zone (top of the Big Three rich oil shale beds). This zone was selected to avoid the abundant saline minerals found in the overlying saline zone, which often contains water with high levels of total dissolved solids (TDS). If saline minerals (and high-TDS water) do not adversely affect potential extraction techniques, the top of the economical oil shale could be extended to include the middle R-8, but only in the basin's paleo-depocenter (west side of cross section).

The middle to upper Green River Formation succession contains twelve lithofacies (Table 2, Figures 7-9). Facies are grouped into six facies associations (Table 3, Figures 7-9): 1) progradationally stacked, high-sediment-supply, siliciclastic mouthbar deposits (L zones below Mahogany), 2) aggradational to retrogradationally stacked, low-sediment-supply, littoral to sub-littoral carbonate deposits (R-5 and R-4), 3) low-sediment-supply, sub-littoral to profundal carbonate deposits (R-6), 4) sediment-starved, profundal lake-center deposits (Mahogany and lower R-8), 5) evaporite-bearing deposits (middle to upper R-8), and 6) volcaniclastic deposits (within R-8 to the east).

Table 2. *Facies of the middle and upper Green River Formation.*

Facies	Description	Color on core log	Stratigraphic occurrence
F1	Organic-lean clay-rich mudstone	Brown	Within L zones below the Mahogany
F2	Siltstone to sandstone with ripples	Yellow	Within L zones below the Mahogany
F3	Erosionally based sandstone channels	Yellow	Base of Coyote Wash 1, Douglas Creek Member
F4	Organic-rich, clay-rich or dolomitic mudstone (oil shale)	Brown or green, respectively	Oil shale w/in R zones below Mahogany
F5	Organic-poor, dolomitic mudstone	Green	Within R-5, R-6, & A-Groove
F6	Organic-poor dolomitic limestone or limestone	Green or blue, respectively	Within R zones, R-5 and below
F7	Organic-rich calcareous mudstone (oil shale)	Blue	Oil shale above the base of the Mahogany
F8	Oil shale breccia		Most common in Mahogany
F9	Evaporite bearing calcareous mudstone	Blue	Upper to middle R-8 saline zone; limited occurrence in Mahogany within Coyote Wash 1 and Utah State 1
F10	Evaporite bearing volcaniclastic sandstone	Yellow	Upper R-8 on eastern side of basin (P-4)
F11	Volcaniclastic sandstone	Yellow	Upper R-8 on eastern side of basin (P-4)
F12	Tuff	Red or very thin yellow	Most common above base of Mahogany

Ten-foot scale siliciclastic coarsening upwards packages (FA1), interpreted as parasequences, stack repeatedly at the 100-foot scale in an overall coarsening upward, or progradational pattern to make up the lean zones below the Mahogany (Figure 10, Plate 5). Alternately, 10-foot scale carbonate dominated parasequences (FA2 and FA3) stack repeatedly at the 100-foot scale in an aggradational or retrogradational pattern to make up the rich zones below the Mahogany. The carbonate dominated parasequences (FA2 and FA3) are composed of organic-rich and clay-rich or dolomitic claystone (F4) that grades upwards into organic-poor limestone, dolomitic limestone (F5), or dolomitic mudstone (F6) of littoral to sub-littoral origin (Figure 10, Plate 5). At the several-100-foot scale, rich and lean zones below the Mahogany zone record more distal facies upwards, displaying a longer term transgressive or retrogradational trend (Figure 10, Plate 5).

Discussion

Within the interval of study (R-4 to the base of the Uinta Formation, Plate 5), we propose the lake evolved in three phases 1) a freshwater rising lake phase below the Mahogany zone, 2) an anoxic deep lake phase above the base of the Mahogany zone and 3) a hypersaline lake phase within the middle and upper R-8.

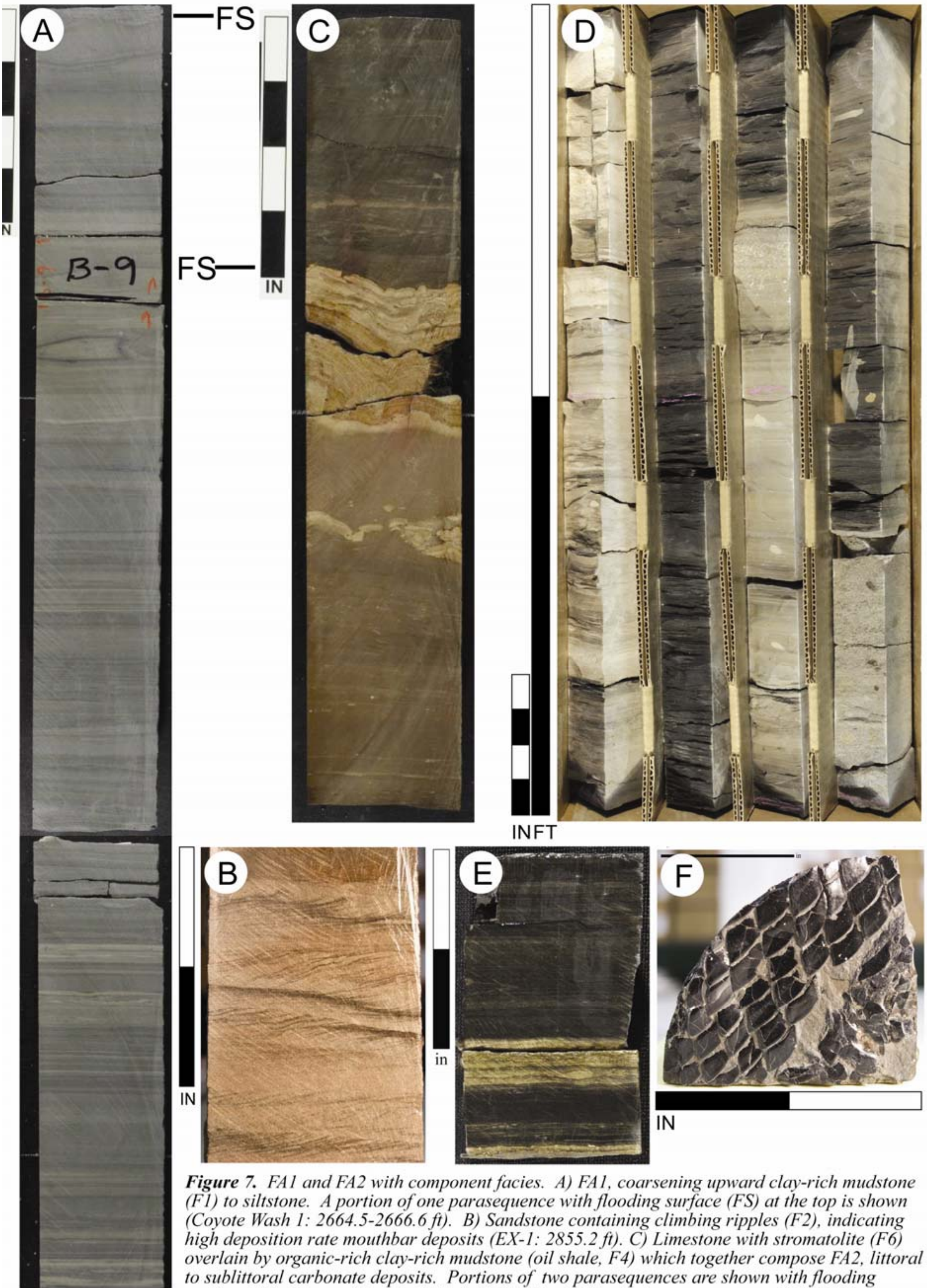

Figure 7. *FA1 and FA2 with component facies. A) FA1, coarsening upward clay-rich mudstone (F1) to siltstone. A portion of one parasequence with flooding surface (FS) at the top is shown (Coyote Wash 1: 2664.5-2666.6 ft). B) Sandstone containing climbing ripples (F2), indicating high deposition rate mouthbar deposits (EX-1: 2855.2 ft). C) Limestone with stromatolite (F6) overlain by organic-rich clay-rich mudstone (oil shale, F4) which together compose FA2, littoral to sublittoral carbonate deposits. Portions of two parasequences are shown with flooding surface (FS) (Coyote Wash 1: 2945.0-2945.7 ft). D) Stacked parasequences of FA2 (EX-1: 2922.0-2930.0 ft). E) F4 clay-rich or dolomitic mudstone (oil shale) (EX-1: 2500.7-2501.0 ft). F) Gar fish scales found commonly in FA2 (EX-1: 2757.8 ft).*

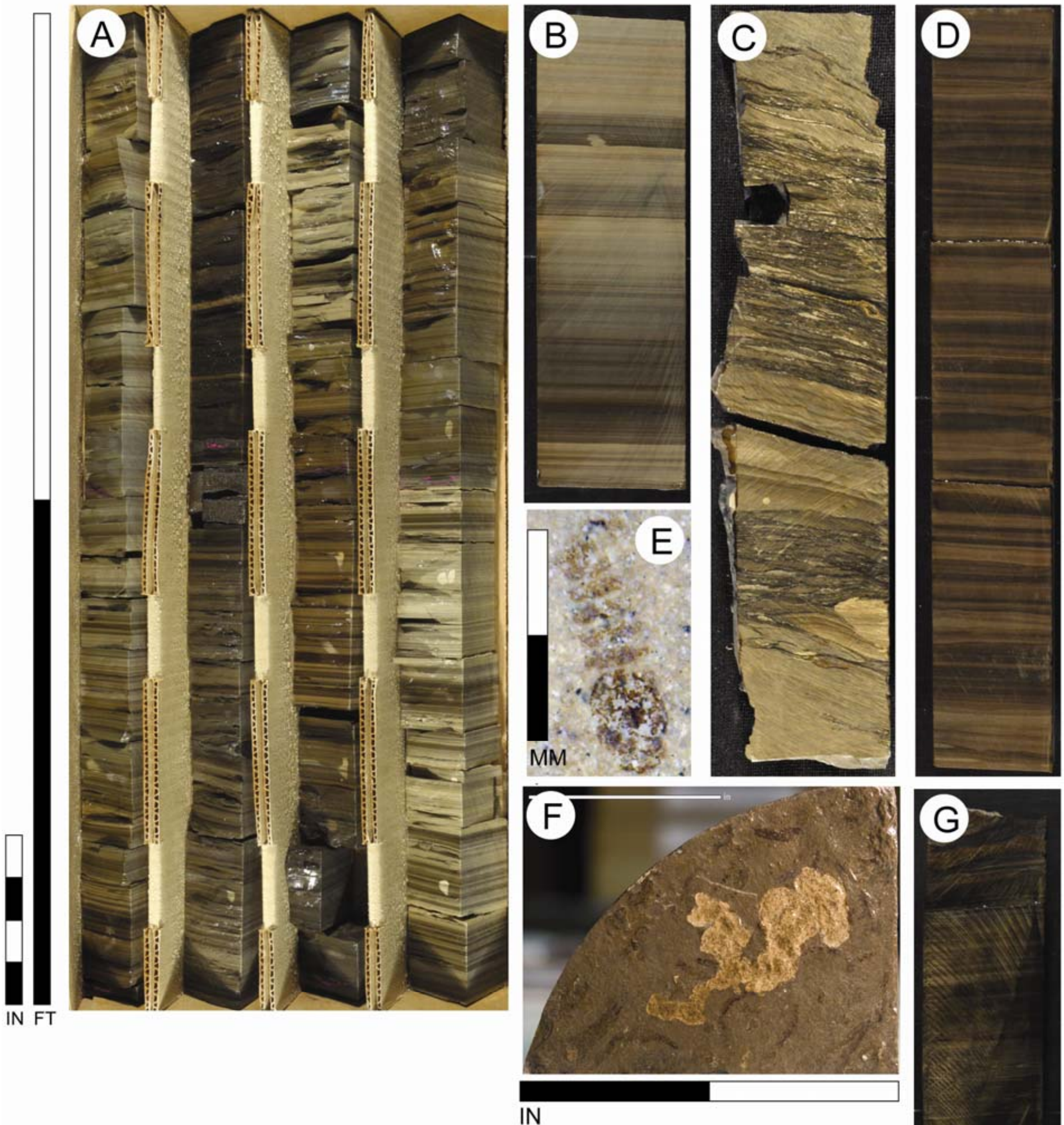

Figure 8. *FA3 and FA4 with component facies. A) FA3, sub-littoral to profundal carbonate deposits composed of cycles of F4 (organic-rich, clay-rich or dolomitic mudstone, oil shale) alternating with F5 (organic-poor dolomitic mudstone) (EX-1: 2464.0-2472.0 ft). B) Dolomitic mudstone with dewatering structure (Coyote Wash 1: 2432.3-2432.9 ft). C) F8, calcareous oil shale breccia, a component facies of FA4, profundal lake center deposits (EX-1: 2448.9-2449.4 ft). D) F7, organic-rich calcareous mudstone (oil shale), the dominant facies that comprises FA4, profundal lake center deposits (Coyote Wash 1: 2244.1-2245.0 ft). E) Insect larvae (?) found at limited intervals withing FA4, profundal lake center deposits (P-4: 685.4 ft). F) Worm burrows found at limited intervals within FA4, profundal lake center deposits (EX-1: 2108.0 ft). G) F7, organic-rich calcareous mudstone (oil shale), the dominant facies that comprises FA4, profundal lake center deposits (Coyote Wash 1: 2318.3-2319.3 ft).*

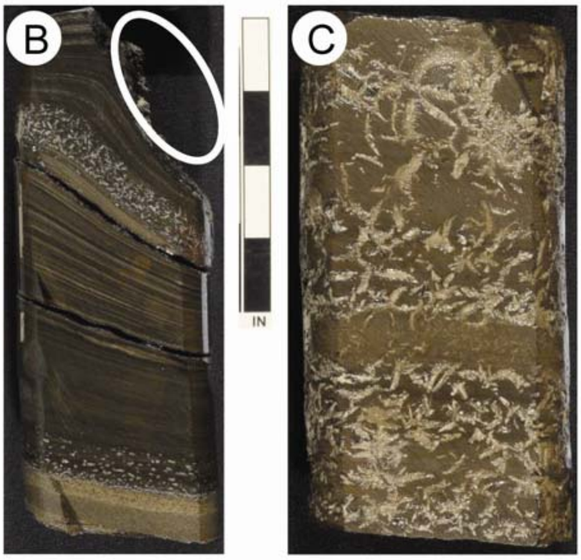

Figure 9. *FA5, evaporite deposits, and FA6, volcaniclastic deposits with component facies. A) F9, evaporite bearing calcareous mudstone. Nahcolite nodules and layers (Utah State 1: 1933.1-1938.7 ft). B) Displaced and deformed laminations as a result of nahcolite nodule growth at the sediment-water interface. Nahcolite nodule is now dissolved (white circle) (P-4: 362.5-363.3 ft). C) F9, evaporite bearing calcareous mudstone. Shortite, a secondary diagenetic hydrothermal mineral, is shown (P-4: 355.3-355.8 ft). D) F11, volcaniclastic sandstone deposit with visible crystals, deformed intraclasts, and a tuffaceous texture (P-4: 312.0-314.0 ft). E) the Curly Tuff (F12) (P-4: 778.8-780.5 ft).*

Summary of stacking patterns observed in rich and lean zones below the Mahogany zone (Lake Phase 1: freshwater rising lake)

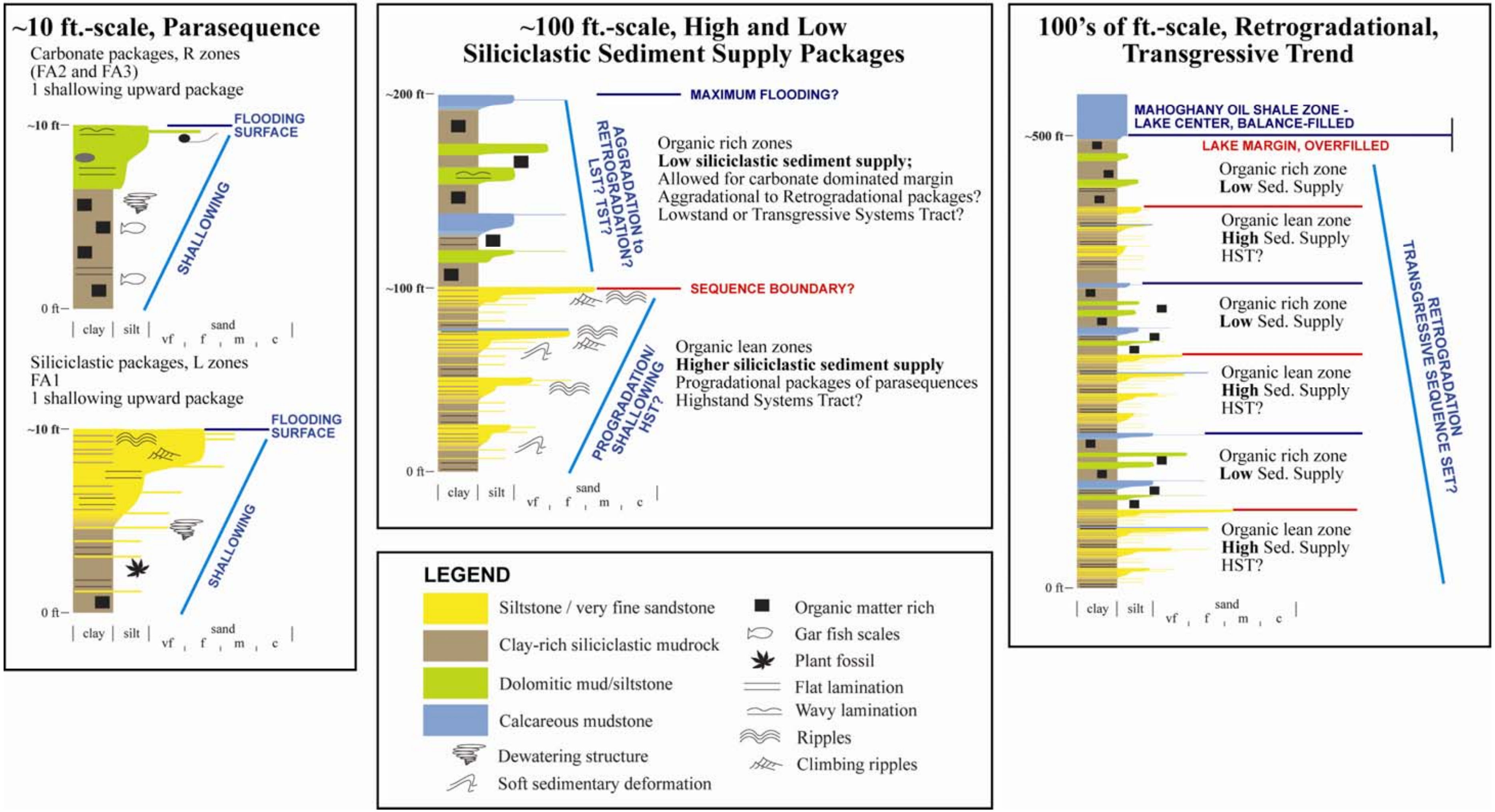

Figure 10. *Summary of stacking patterns observed in rich and lean zones below the Mahogany zone during interpreted lake phase 1, freshwater rising lake.*

***Table 3.** Facies associations of the middle and upper Green River Formation.*

Facies Association	Description	Component facies	Stratigraphic occurrence
FA1	Progradational, high sediment supply siliciclastic mouthbar deposits	F1, F2, F3	L zones below Mahogany
FA2	Aggradational to retrogradational, low sediment supply littoral to sub-littoral carbonate deposits	F4, F5, F6	R zones R-5 and below
FA3	Low sediment supply sub-littoral to profundal carbonate deposits	F4, F5	R-6
FA4	Sediment-starved profundal lake center deposits	F7, F8	Mahogany and R-8
FA5	Evaporite deposits	F9, F10	Saline zone, with the middle to upper R-8
FA6	Volcaniclastic deposits	F11, F12	Upper R-8, only on eastern side of basin (P-4)

This long term lake evolution was driven by tectonic basin development and the balance of sediment and water fill with the neighboring basins, as postulated by models developed from the Greater Green River Basin by Carroll and Bohacs (1999). The three lake phases proposed above correspond to Carroll and Bohacs (1999) model in the following manner. During lake phase 1, the Uinta Basin was "overfilled" with sediment (sensu Carroll and Bohacs, 1999) with respect to the neighboring Piceance Basin. During lake phase 2, the Uinta Basin and Piceance Basin became connected across the Douglas Creek Arch and were "balance filled." Finally, during lake phase 3, the Uinta Basin became the terminal lake basin, in which the only outlet for water was through evaporation. The Uinta Basin was "underfilled" relative to the neighboring Piceance Basin.

There are significant similarities and differences in facies, and hence depositional controls between the Greater Green River, Piceance, and Uinta Basins. In relation to the other basins, the Greater Green River Basin received the highest siliciclastic sediment input, as evidenced by the high volume of fluvial-deltaic facies preserved. The Piceance Basin received the lowest siliciclastic sediment input, which is reflected in the rich oil shale and carbonate record in the Piceance Basin. In terms of alluvial sediment input, the Uinta Basin was intermediate between the other two systems, with a relative balance between siliciclastic, oil shale, and carbonate facies.

Previously, the mechanisms for shorter term changes in facies and stratigraphic packaging have not been addressed or have been generally attributed to Milankovitch cyclicity. Specifically, herein we interpret the alternation of regionally extensive oil shale lean (L) and rich (R) zones below the Mahogany zone to record periods of high and low sediment supply, respectively (Table 4). This interpretation is supported by a recent integrated sedimentologic, stratigraphic, and stable isotope geochemical investigation of coeval outcrops on the southern margin of the Uinta Basin by Plink-Bjorklund and others (2009), Birgenheier and others (2009), Plink-Bjorklund and others (2010), and Golab and others (2010). Specifically, these studies conclude that early Eocene abrupt global-warming events (hyperthermals) caused an increase in weathering and sediment production rates, as well as increased precipitation intensity and seasonality, resulting in episodic high sedimentation rates, which is expressed in laterally extensive stratigraphic changes in fluvial channel style and geometry, along with lake level changes through the Colton and lower to middle Green River Formations (Plink-Bjorklund and others, 2009; Birgenheier and others, 2009; Plink-Bjorklund and others, 2010; Golab and others, 2010). Plink-Bjorklund and others (2009) concluded that while hyperthermal events record periods of more arid conditions overall, they were characterized by highly seasonal, short, flashy fluvial discharge events, typical of a monsoonal climate regime. Alternately, periods between hyperthermals record a less seasonal climate regime with more stable fluvial discharge and a system that was wetter overall. There are 7 lean zones below the Mahogany zone that we interpret to record periods of high sediment supply. There are also 7 documented early Eocene hyperthermal events (Nicolo and others, 2007; Sexton and others, 2006; Cramer and others, 2003; Lourens and others, 2005). Therefore we propose that the 7 lean zones below the Mahogany zone record 7 documented early Eocene hyperthermal events, and R zones record non-hyperthermal deposition (Figure 11). This interpretation is within available age constraints on the stratigraphy, including tuffs dated by Smith and others (2008; 2010) and within known ages of early Eocene hyperthermal events (Figure 11), as provided by Nicolo and others (2007), Sexton and others (2006), Cramer and others (2003), and Lourens and others (2005). We also propose that during periods of high sediment supply (lean zones), lake level was relatively low due to decreased accommodation associated with increased sedimentation and basin fill rates. And vice versa, rich zones record periods of relatively higher lake level, as subsidence outpaced sedimentation rates. Abrupt changes in lake water chemistry, reduced sedimentation rates, and persistent anoxia recorded at the base of the Mahogany zone correspond to the end of Eocene hyperthermal events and likely record a major climate shift out of the Eocene Climatic Optimum and episodic hyperthermal events (Figure 11). Therefore, in contrast to the model of Carroll and Bohacs (1999), which relies heavily on tectonic controls on lake development, we contend that significant climatic control on short-term and long-term lake evolution has been previously overlooked. We propose to test this model in the next phase of investigation through 1) constructing a north-south core-based cross section that will provide an improved understanding of facies changes along depositional dip, and 2) linking our proposed Uinta Basin depositional model with models being developed in parallel in the Piceance Basin.

Table 4. *Interpretation of rich and lean zones below the Mahogany zone.*

	Sediment supply	**Relative lake level**	**Climate**
Lean zones	High	Low	Hyperthermal; arid overall with highly, flashy seasonal discharge during monsoonal events
Rich zones	Low	High	Between hyperthermals; stable climate regime, wet

Conclusions

An integrated, detailed sedimentologic, stratigraphic, and geochemical study of Utah's Green River Formation has found that Lake Uinta evolved in three phases 1) a freshwater rising lake phase below the Mahogany zone, 2) an anoxic deep lake phase above the base of the Mahogany zone and 3) a hypersaline lake phase within the middle and upper R-8. This long term lake evolution was driven by tectonic basin development and the balance of sediment and water fill with the neighboring basins, as postulated by models developed from the Greater Green River

Basin by Carroll and Bohacs (1999). In addition, early Eocene abrupt global-warming events may have had significant control on deposition through the amount of sediment production and deposition rates, such that lean zones below the Mahogany zone record hyperthermal events and rich zones record periods between hyperthermals. This type of climatic control on short-term and long-term lake evolution and deposition has been previously overlooked.

This geologic history contains key points relevant to oil shale development and engineering design including:

1) Stratigraphic changes in oil shale quality and composition are systematic and can be related to spatial and temporal changes in the depositional environment and basin dynamics.
2) The inorganic mineral matrix of oil shale units changes significantly from clay mineral/dolomite dominated to calcite above the base of the Mahogany zone. This variation may result in significant differences in pyrolysis products and geomechanical properties relevant to development and should be incorporated into engineering experiments.
3) This study includes a region in the Uinta Basin that would be highly prospective for application of in-situ production techniques. Stratigraphic targets for in-situ recovery techniques should extend above and below the Mahogany zone and include the upper R-6 and lower R-8.

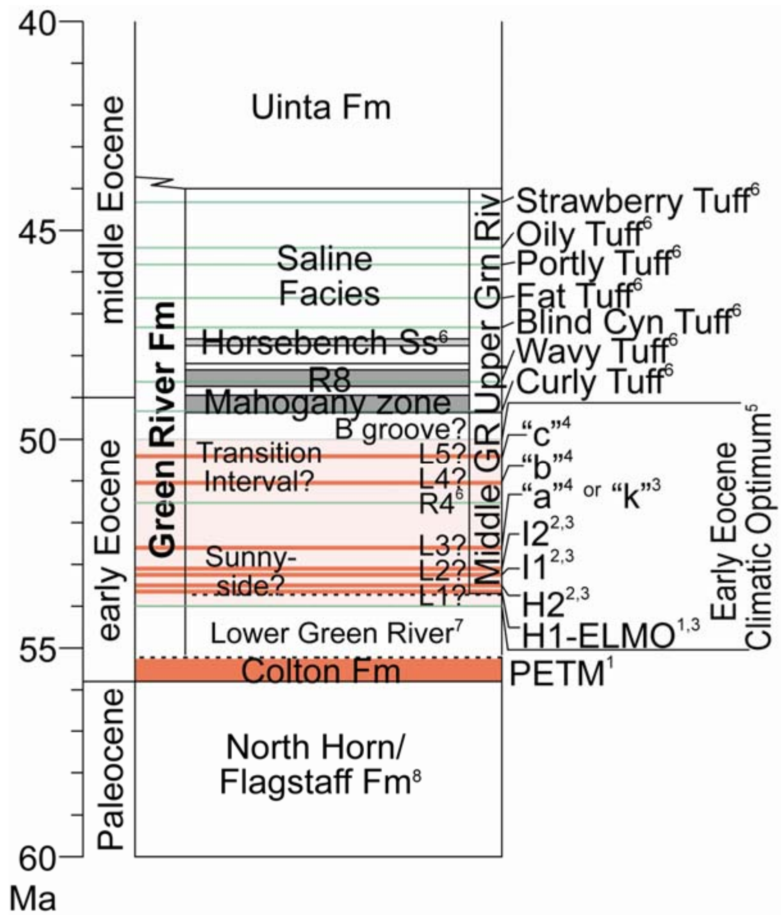

Figure 11. *Green River Formation stratigraphy plotted against known hyperthermal events, using all available age constraints on stratigraphy and hyperthermal events. The Paleocene-Eocene Thermal Maximum (PETM in red) is shown along with 7 documented early Eocene hyperthermal events (red) and Early Eocene Climatic Optimum (pink), with published age references noted. Seven lean zones below the Mahogany (L1-L5, middle R-6, and B-groove) are part of the middle Green River (GR) Formation and are interpreted as the record of hyperthermal events. Note that the constrained age of the middle Green River Formation falls within the published age constraints for 7 documented early Eocene hyperthermal events. Green lines indicate known ages of tuffs within the Green River Formation (Smith and others, 2010; Remy, 1992). Timescale of Gradstein and others (2004).*

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Plate 1

Well name: EX-1 (U043)
Operator: Western Oil Shale Corp.
Location: T9S, R20E, Sec. 36
UTM E 619748, UTM N 4426886 (NAD 27)
Ground Elevation: 4941 ft
Year drilled: 1969
Cored interval: 1767-2969 ft (slabbed)
Core location: Utah Core Research Center

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ENERGY & GEOSCIENCE INSTITUTE AT THE UNIVERSITY OF UTAH

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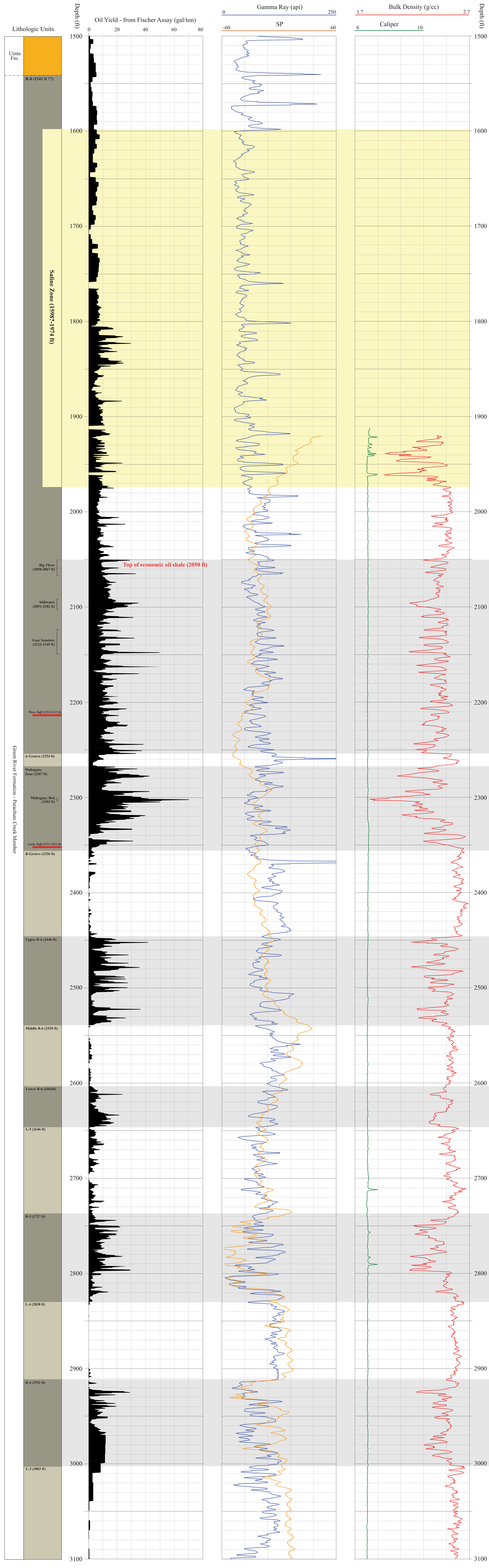
Core Log Explanation

- Calcareous mudstone - slightly dolomitic
- Siltstone / sandstone
- Clay-rich mudrock - slightly calcareous/dolomitic
- Dolomitic mud/siltstone - slightly calcareous
- Ash / tuff
- Nahcolite bed ($NaHCO_3$)
- Abundant fractures filled with shortite [$Na_2Ca_2(CO_3)_3$]
- Sample analyzed with XRF
- Nahcolite nodule
- Small shortite/nahcolite crystals
- Thin nahcolite/shortite layers
- Pyrite/ Marcasite/ Pyrrhotite crystals
- Flat/planar lamination
- Low angle lamination
- Wavy lamination
- Ripples
- Soft sediment deformation/ convolute bedding
- Dewatering structure
- Load casts
- Synaeresis cracks
- Mudcracks
- Burrows/bioturbation
- Worm
- Snail
- Scour with massive fill
- Bitumen concentrations
- Mudrock intraclast
- Organic detritus
- Organic-rich interval
- Plant material
- Bone fragments
- Lithophypoderma sp. (botfly larvae)
- Gar fish scales
- Shell debris
- Algal influenced lamination
- Insects
- Stylolites
- Near-vertical fracture
- Microfaulting



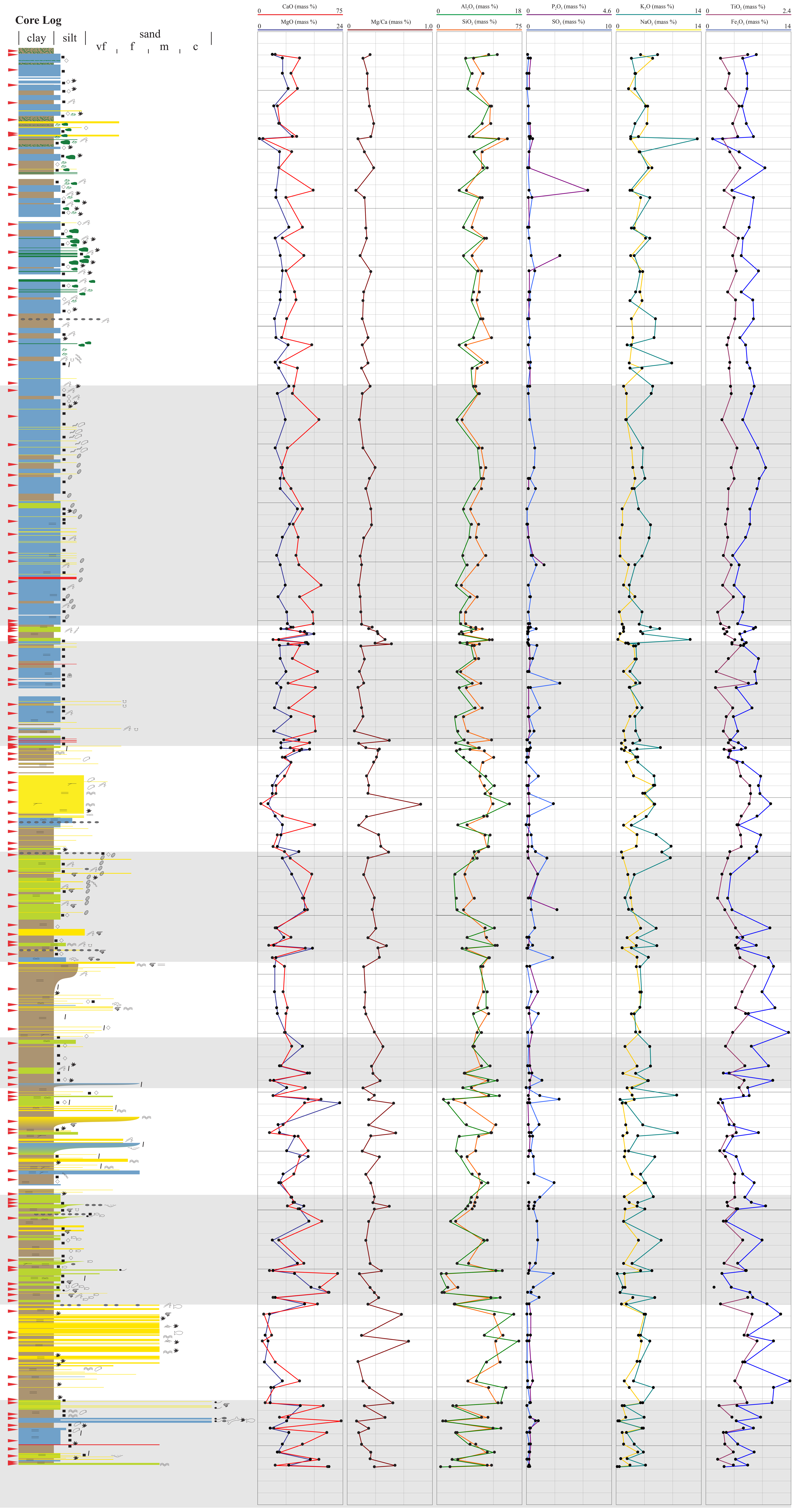


Plate 2

Well name: Utah State 1 (U102)

Operator: Tosco Corp.

Location: T9S, R21E, Sec. 26

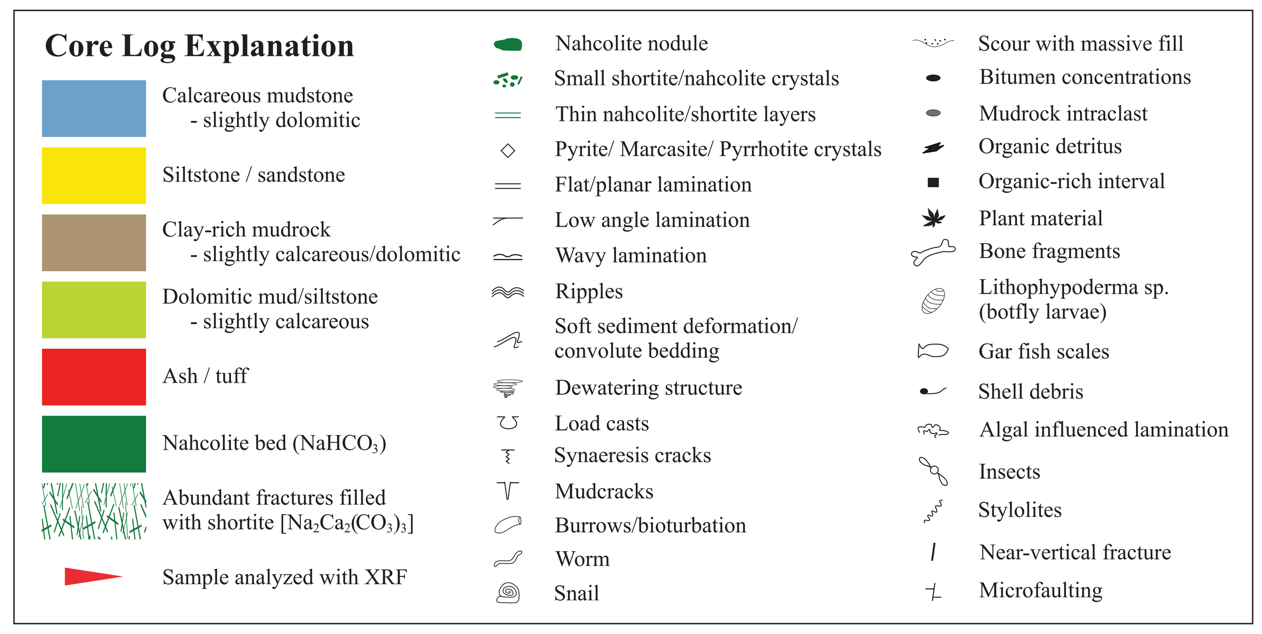
UTM E 627029, UTM N 4429992 (NAD 27)

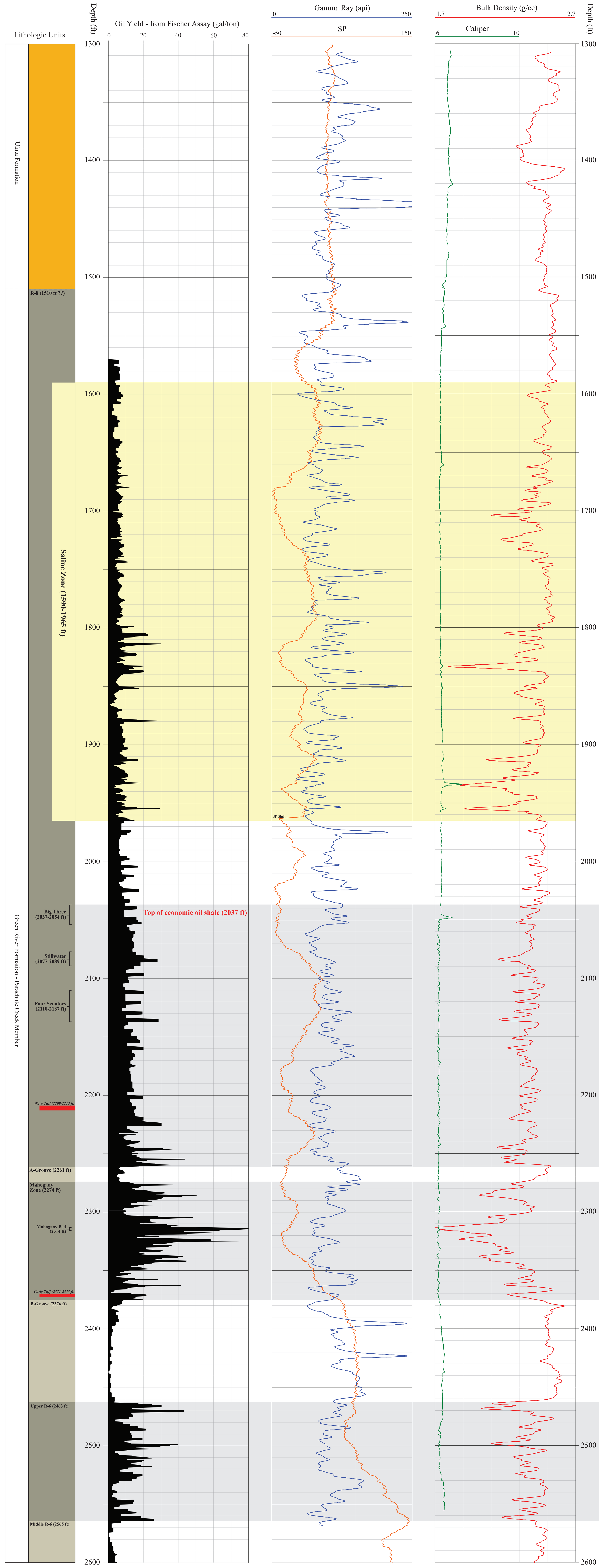
Ground Elevation: 4911 ft

Year drilled: 1974

Cored interval: 1570-2600 ft (slabbed)

Core location: Utah Core Research Center





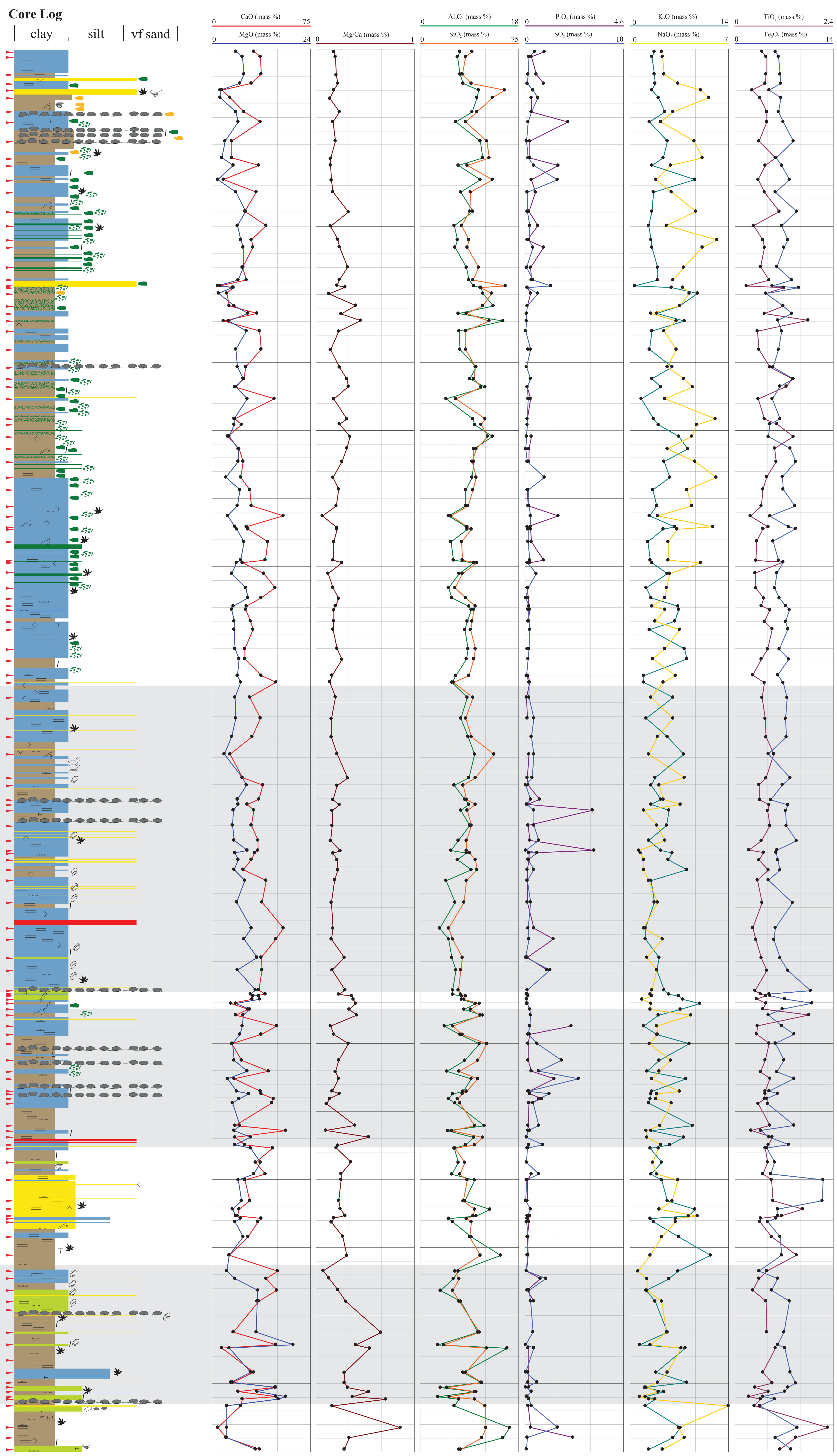


Plate 3

Well name: Coyote Wash 1 (U044)

Operator: USGS

Location: T9S, R23E, Sec. 22

UTM E 644158, UTM N 4431449 (NAD 27)

Ground Elevation: 5067 ft

Year drilled: 1981

Cored interval: 1817-3460 ft (slabbed)

Core location: USGS Core Research Center

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Core Log Explanation

- Calcareous mudstone - slightly dolomitic
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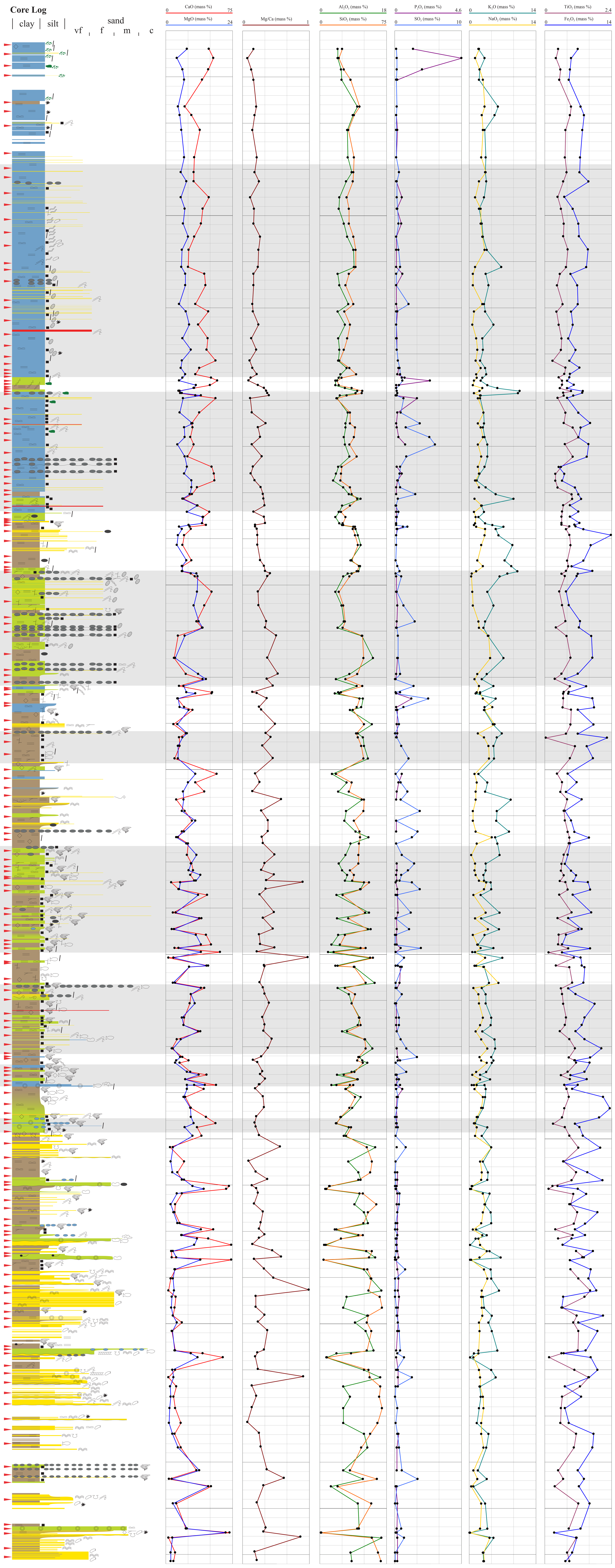


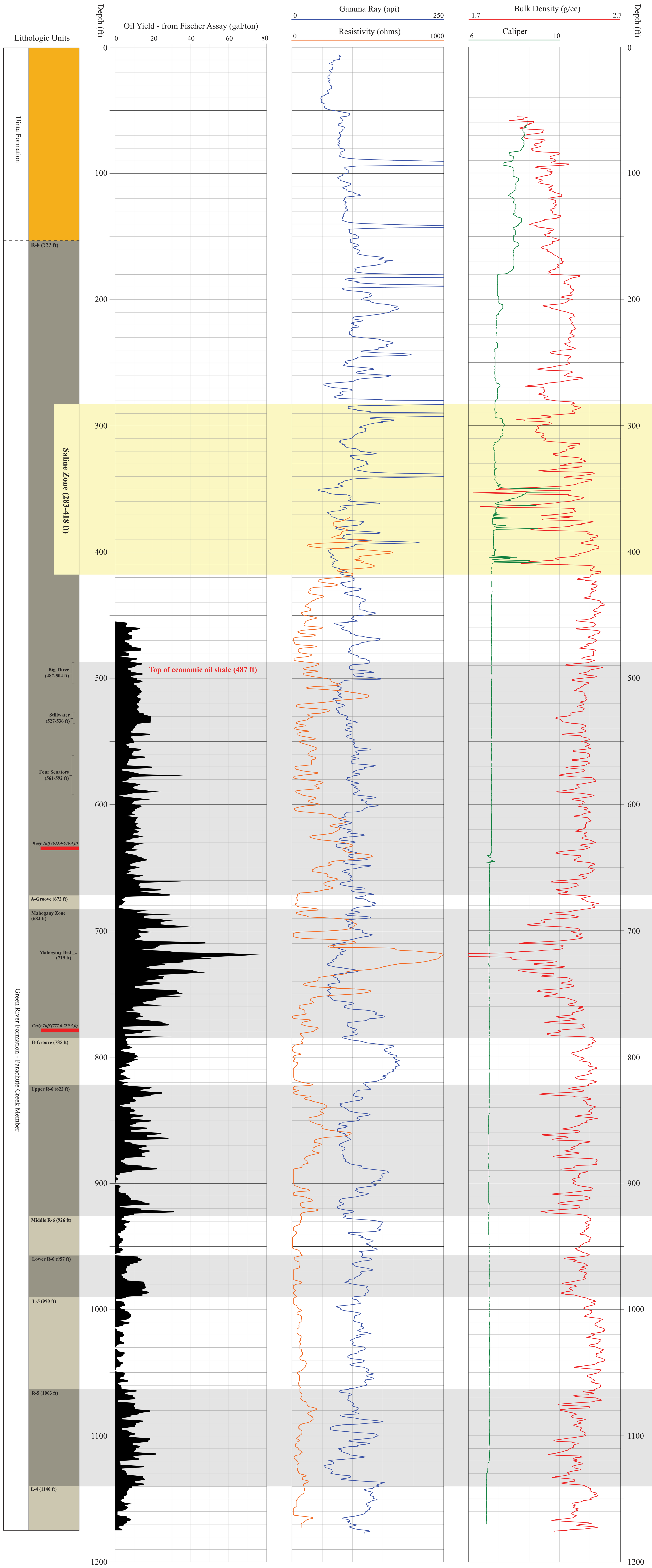
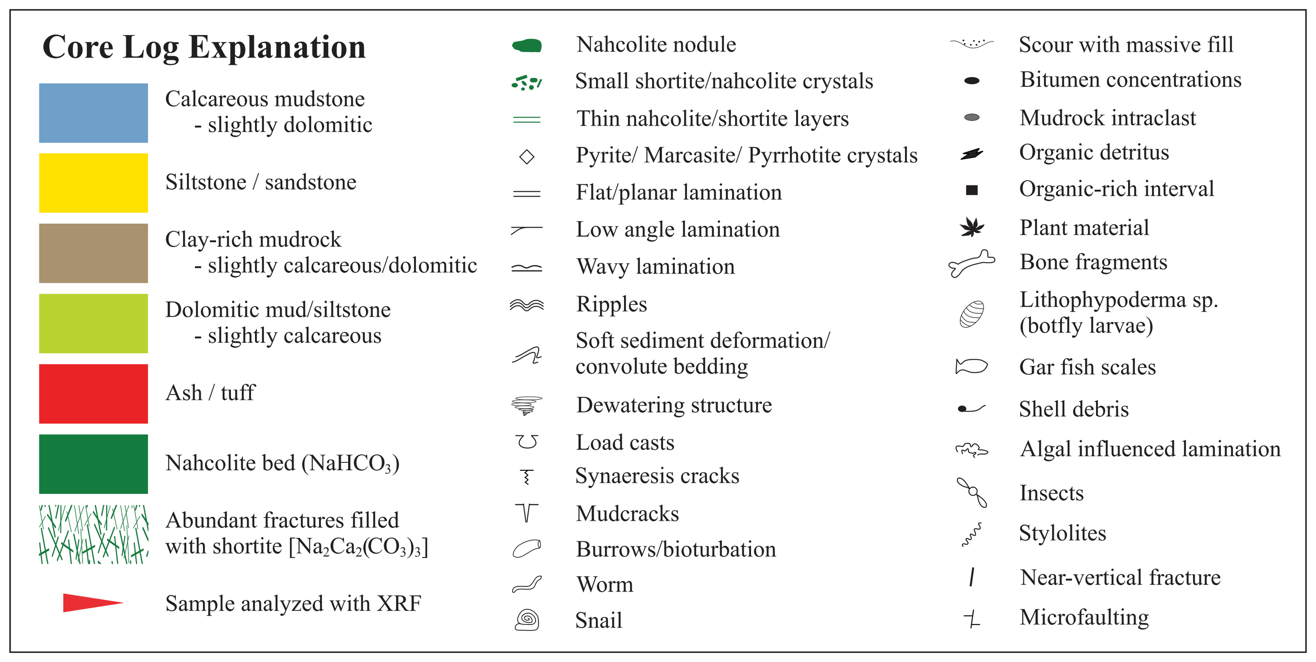


Plate 4

Well name: P-4 (U059)

Operator: White River Shale Project
Location: T10S, R25E, Sec. 19
UTM E 659426, UTM N 4421812 (NAD 27)
Ground Elevation: 5719 ft
Year drilled: 1974
Cored interval: 214-1173 ft (slabbed)
Core location: Utah Core Research Center



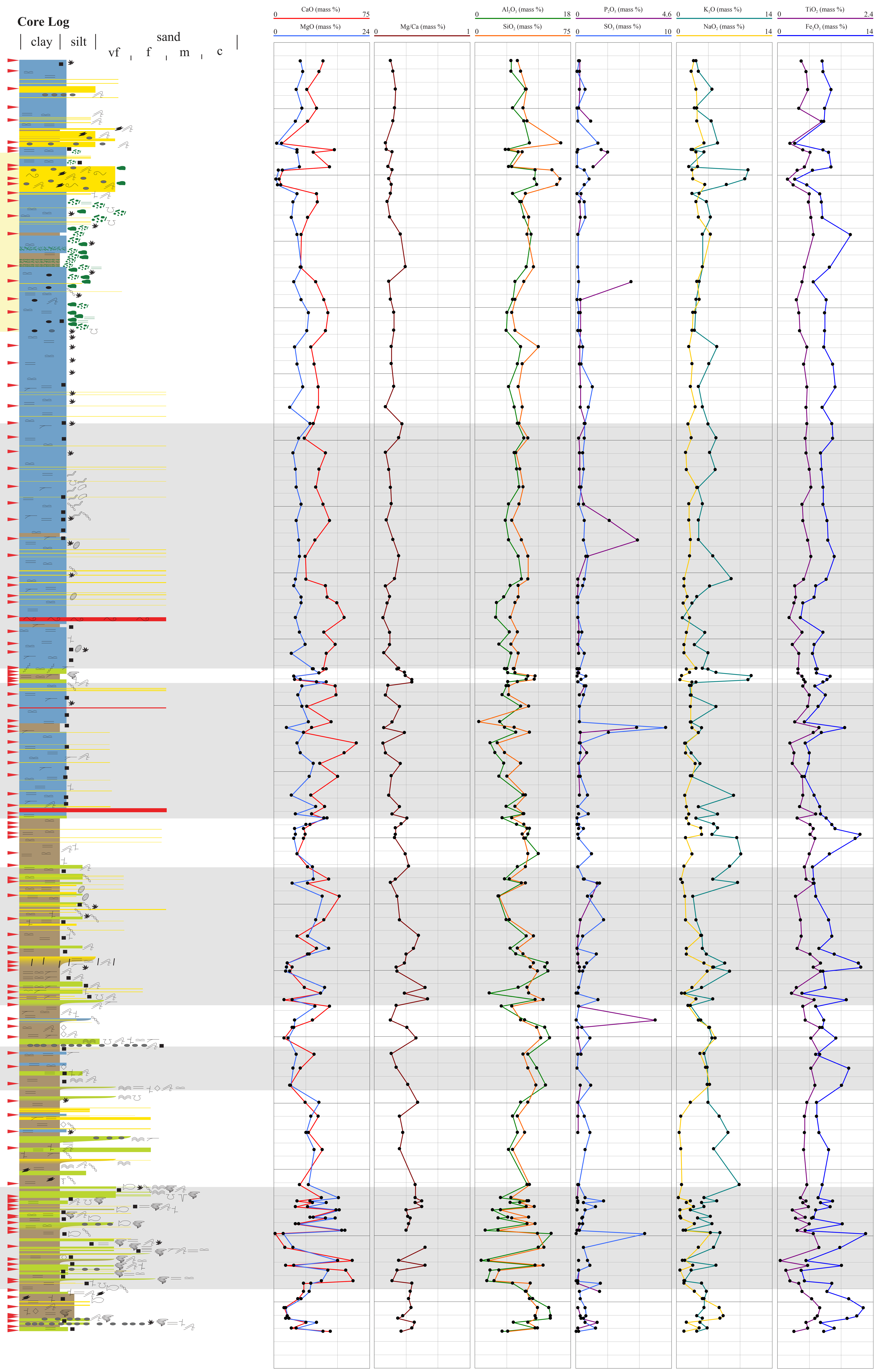


Plate 5

East-West Core-Based Cross Section Through the Middle to Upper Green River Formation, Eastern Uinta Basin, Utah

Michael D. Vanden Berg - Utah Geological Survey
Lauren P. Birgenheier - Energy and Geoscience Institute - University of Utah

Funding provided by: Institute for Clean and Secure Energy - University of Utah, U.S. Department of Energy, and Utah Geological Survey

Well name: EX-1 (U043)
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Location: T9S, R20E, Sec. 36
UTM E 619748, UTM N 4426886 (NAD 27)
Ground Elevation: 4941 ft
Year drilled: 1969
Cored interval: 1767-2969 ft (slabbed)
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Well name: Utah State 1 (U102)
Operator: Tosco Corp.
Location: T9S, R21E, Sec. 26
UTM E 627029, UTM N 4429992 (NAD 27)
Ground Elevation: 4911 ft
Year drilled: 1974
Cored interval: 1570-2600 ft (slabbed)
Core location: Utah Core Research Center

Well name: Coyote Wash 1 (U044)
Operator: USGS
Location: T9S, R23E, Sec. 22
UTM E 644158, UTM N 4431449 (NAD 27)
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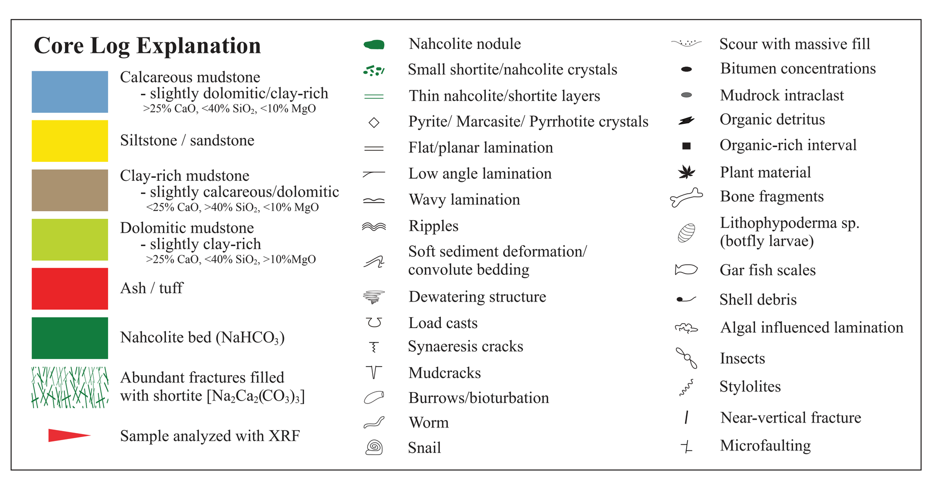
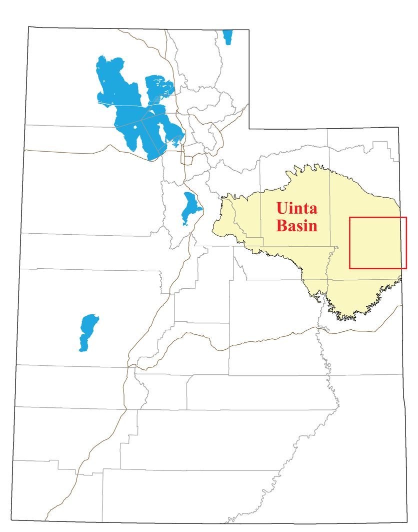
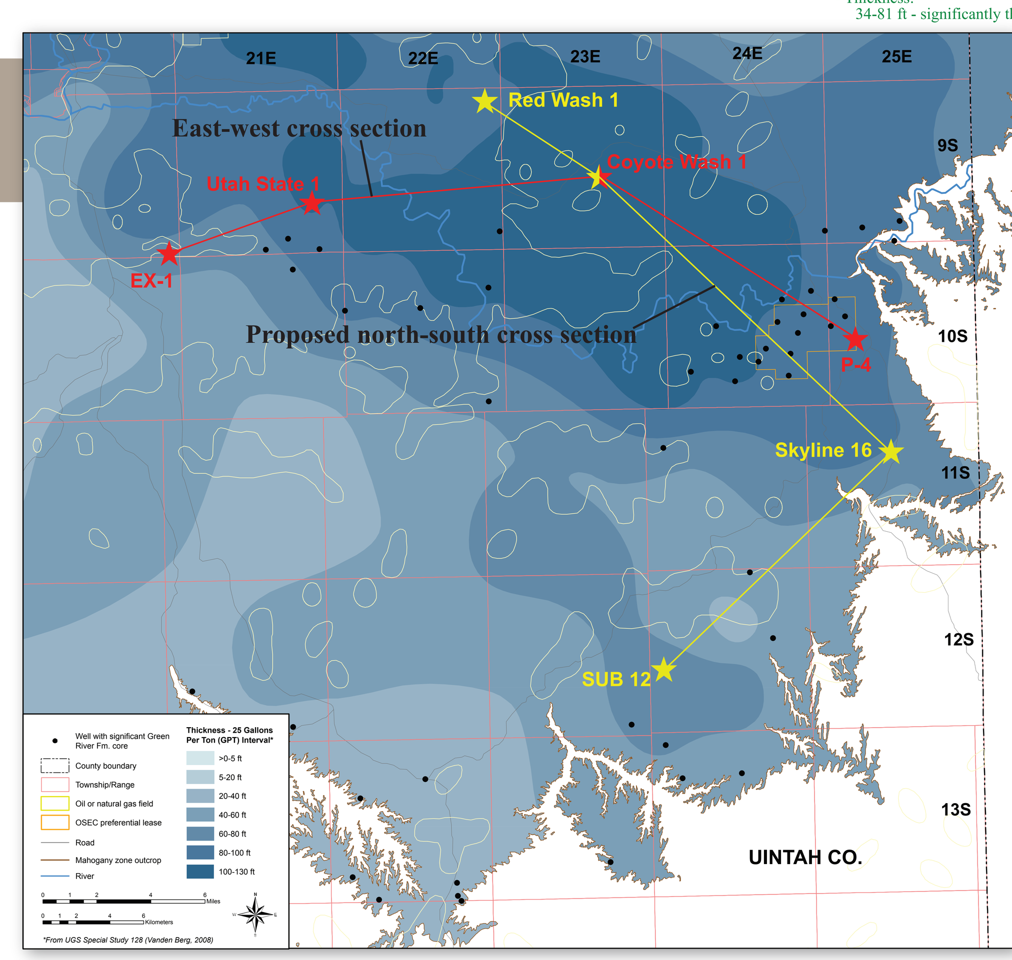
Location: T10S, R25E, Sec. 19
UTM E 659426, UTM N 4421812 (NAD 27)
Ground Elevation: 5719 ft
Year drilled: 1974
Cored interval: 214-1173 ft (slabbed)
Core location: Utah Core Research Center

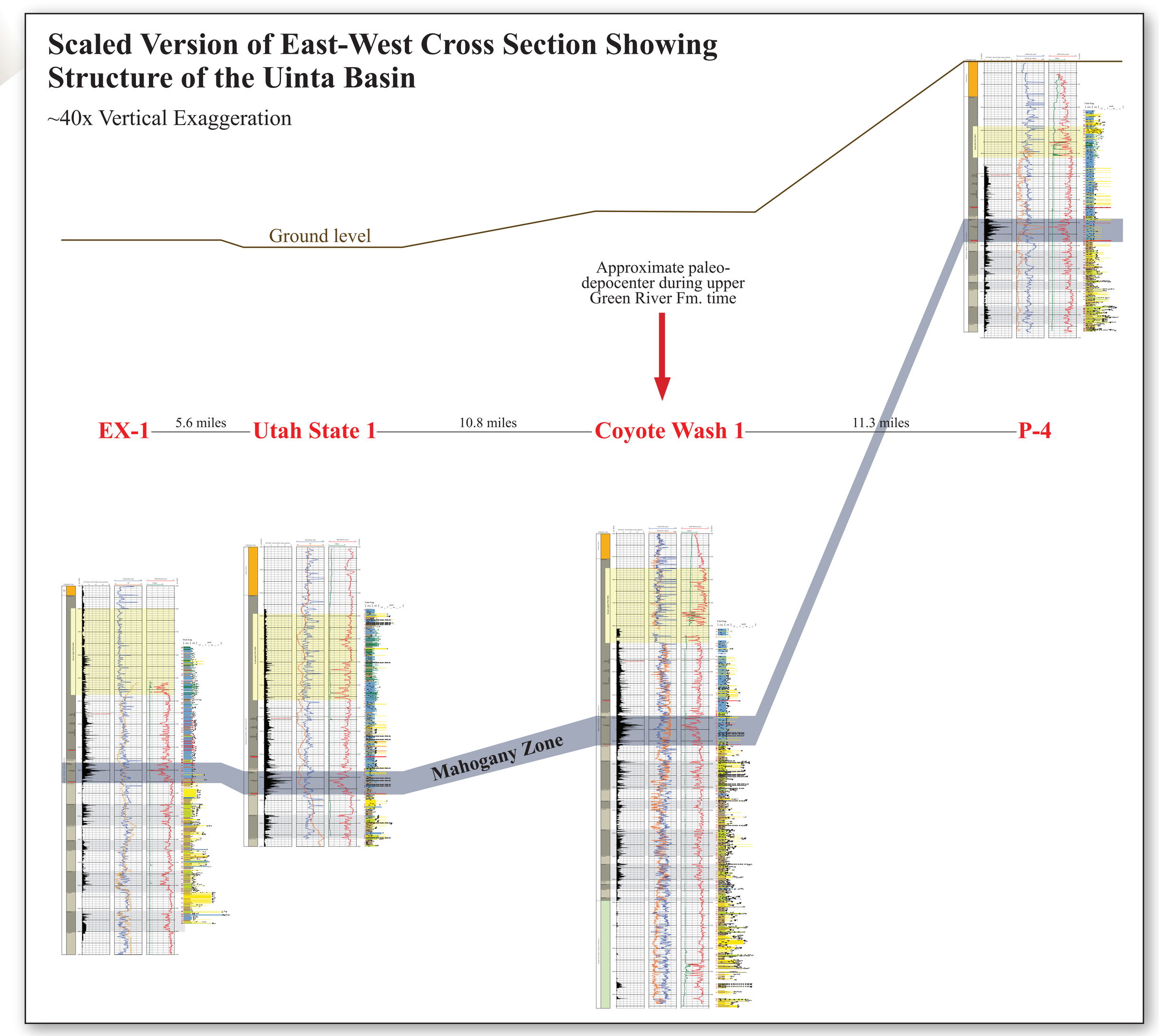
Conclusions/observations from cross section:

- The top of economic oil shale was picked at the top of the lower R-8 zone (top of the Big Three rich oil shale beds). This zone was selected to avoid the abundant saline minerals found in the overlaying saline zone, which often contains high-TDS water. If saline minerals (and high-TDS water) do not adversely affect potential extraction techniques, the top of economic oil shale could be extended to include the middle R-8, but only in the basin's paleo-depocenter (west side of cross section).
- The base of economic oil shale will depend on specifications of potential extraction technologies. Maximum depth might be the base of the R-4 zone.
- The Mahogany zone (MZ), the richest oil shale zone, and the lower R-8 are dominantly calcareous mudstone, with thin beds of clay-rich and dolomitic mudstone.
- The upper and lower R-6 zones are dominantly dolomitic to clay-rich mudstones.
- The R-5 and R-4 zones alternate between organic-rich clay-rich mudstones and organic-lean dolomitic mudstones in ~10 ft cycles.
- The higher MgO (R-6, R-5, R-4) and more calcareous, lower MgO (MZ, R-8) oil shale zones will most likely have somewhat different thermodynamic properties, affecting potential extraction techniques.
- In general, rich zones are thickest and richest in the basin's paleo-depocenter represented by the Coyote Wash 1 core.
- Lean zones are composed of organic-lean mudstone, siltstone, and sandstone and thin significantly to the east.
- Siliciclastic-dominated lean zones record periods of high sediment supply sourced from active basin margin delta or mouthbar systems.
- Carbonate-dominated rich zones record periods of low detrital sediment supply.









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