Geological, Geochemical, and Reservoir Characterization of the Uteland Butte Member of the Green River Formation, Uinta Basin, Utah[1]

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ABSTRACT

The informal Uteland Butte member of the lower part of the Green River Formation was deposited in a major transgressive phase of the early freshwater stage of Eocene Lake Uinta, in the Uinta Basin. It ranges in thickness from around 50 to over 300 ft and contains primarily limestone, dolostone, and organic-rich mudstone and siltstone, with sandstone and ostracodal limestone in marginal areas. The Uteland Butte member is age-equivalent to part of the freshwater Cow Ridge Member of the Green River in the Piceance Basin of Colorado and may correspond to the freshwater Luman Tongue of the Green River in the Greater Green River Basin of Wyoming and Colorado. Of these intervals, only the Uteland Butte was buried deep enough to have resulted in a major petroleum system. Since late 2010, the Uteland Butte has become a successful tight-oil play, with total cumulative oil production of about 4.38 million barrels (as of December 2014) and initial well production ranging from less than 100 up to 1,700 barrels of oil equivalent per day, all produced through the use of horizontal drilling, hydraulic fracturing, and acid treatment in dolomite-rich target zones. Most horizontally drilled laterals in the Uteland Butte average about 5,000 ft, but a few of the more recent wells have reached over 11,000 ft. Organic-rich mudstone, siltstone, and limestone are likely the source of oil in the Uteland Butte, and thin, highly porous dolostones are the primary reservoirs targeted with horizontal drilling.

Uteland Butte oils are generally very waxy and have API gravities ranging between 30° and 40°. The oils are also low in sulfur (<0.3 wt. %) and isotopically light with $\delta^{13}C$ values for saturate and aromatic fractions between -29 and -33 ‰. Molecular parameters show that the Uteland Butte oils are derived from similar organic material as other Green River Formation oils produced in the Uinta Basin. Immature outcrop samples from the eastern and western margins of the basin were examined to obtain estimates of original organic content and kerogen quality for Uteland Butte source rocks. The organic matter in these outcrop samples is predominantly Type I kerogen, but is somewhat less hydrogen-rich than the kerogen present in overlying oil shale deposited during brackish- to saline-lake phases of the Green River Formation based on Rock-Eval hydrogen indices. In core samples, Uteland Butte rocks are in the oil generation window based on a variety of thermal maturity indicators. Basinwide organic richness was examined using historical Fischer assay data. The samples with the highest oil yields occur just to the west of an overpressured region. Chloroform-extractable organic matter content from high-porosity samples from dolomitic intervals is up to four times that of the adjacent mudstones. The thickness of dolomite beds in the Uteland Butte is nonuniform through the stratigraphic interval and is an important factor for production potential due to its high porosity and petroleum content, as determined by Rock-Eval parameters and soxhlet extraction. Formation pressures vary from normal to possibly underpressured in shallow areas, to moderately overpressured along the deep basin trough. In general, wells in the overpressured area are the most productive. Assessment units were defined using basinwide data on organic richness, thermal maturity, and dolomite content, including an overpressured sweet spot in the most productive part of the basin.

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INTRODUCTION

The informal Uteland Butte member (Osmond, 1992) of the Eocene Green River Formation in the Uinta Basin of northeastern Utah resulted from a major transgression of an early freshwater stage of Lake Uinta. This lacustrine interval was deposited prior to the main saline-lacustrine oil shale sequence of the Green River Formation and was not included as part of the recently completed Uinta Basin oil shale assessment (Johnson et al., 2010). The successful development of the Uteland Butte as a tight-oil play using modern horizontal drilling and hydraulic fracturing combined with acid treatment (Anderson and Roesink, 2013; Durham, 2013; Vanden Berg et al., 2014) has led to renewed interest in the unconventional resource potential of lacustrine basins and provides a potential analog for other lacustrine plays. Prior to the recent horizontal drilling, the Uteland Butte was a commonly perforated interval along with many other zones in the Green River Formation, but was rarely a primary target for drilling. Based on production data from late 2010 through the end of 2014, the Uteland Butte has produced approximately 4.38 million barrels of high-API gravity, paraffinic crude oil and 7.34 billion cubic ft of natural gas using these new production techniques (5.65 million barrels of oil equivalent, MMBOE; Utah Division of Oil, Gas, and Mining, 2015).

This study incorporates a wide range of data relevant to production from the Uteland Butte member in order to better characterize this little-studied interval of the Green River Formation in the Uinta Basin and to assess the factors that influence oil production. Fischer assay oil-yield data for the Uteland Butte member in the U.S. Geological Survey (USGS) Oil Shale Assessment database (Johnson et al., 2010) are used to identify the organic-rich areas of the unit. Literature data on the thermal maturity of hydrocarbon deposits in the Uinta Basin (Anders et al., 1992) are examined and compared with recent data collected on Uteland Butte cores and then utilized to delineate areas where Uteland Butte member organic-rich shale can be expected to be thermally mature. Pressure data from drillstem tests for wells completed in the Uteland Butte and in adjacent units were collected and are utilized along with recently published mud weight data (Anderson and Roesink, 2013) to estimate the distribution of overpressure within the Uteland Butte play (Johnson, 2014). Production histories from horizontal wells collected by the Utah Division of Oil, Gas, and Mining (2015) have been examined as part of a recent USGS assessment of the Uteland Butte play (Johnson et al., 2015a) and are used to help define assessment units (AUs) and possible areas of higher production or "sweet spots" in order to relate other properties to that production. It should be noted that the historical vertical drilling data in this area is of little use for examining the producibility of the Uteland Butte, as these tests were completed in multiple lacustrine intervals and it is unclear how much oil was produced from any particular reservoir rock.

Analysis of Uteland Butte member rock characteristics (e.g., porosity, permeability, lithology and mineralogy, and organic geochemistry) derived from core samples obtained from companies operating Uteland Butte wells and the Utah and U.S. Geological Surveys provide the basis for this report. Produced-oil samples from wells and extractable organic matter (EOM) collected from Uteland Butte rocks were also examined, characterized and compared to other Uinta Basin oils. Results from this work are used to evaluate the importance of dolomitic intervals within the Uteland Butte to the productivity of the play.

Although the Piceance and Greater Green River Basins contain freshwater lacustrine rocks similar to those of the Uteland Butte member, only in the Uinta Basin was subsidence after deposition of the organic-rich lacustrine interval sufficient to have facilitated the creation of a substantial petroleum system. In addition to the unique high thermal maturity of the freshwater Uteland Butte member, it also contains porous dolomite intervals that serve as reservoirs and horizontal drilling targets and may not be present in equivalent sequences in the other principal basins of the Green River Formation.

METHODS

Two Uteland Butte cores, 14-1-46 BTR (sec. 1, T. 4 S., R. 6 W.) and 14-3-45 BTR (sec. 3, T. 4. S., R. 5 W.), were donated along with geochemical and geophysical data to the Utah Geological Survey by the Bill Barrett Corporation (Denver, CO). The data from these cores are presented herein, supplemented with additional analyses conducted on samples collected from these cores by USGS personnel. Rock porosity, permeability, and X-ray diffraction (XRD) analyses of samples from these cores were performed by Core Laboratories (Houston, TX). Conventional plug-analysis protocols were used to determine porosity, using a Boyle's Law technique in which grain volume was measured at ambient conditions and pore volume under confining stress, and permeability to air was measured on plugs using an unsteady-state method under confining stress. XRD analyses were conducted on two size-fractions, greater than and less than 20 microns (μm), to determine bulk mineralogy and clay mineralogy using a Core Laboratories in-house method. Rock-Eval and total organic carbon (TOC) analyses were conducted by Geomark Research Ltd. (Humble, TX) using a Rock-Eval 2 instrument (Delsi Inc., Houston, TX) and a LECO® C230 analyzer (LECO® Corporation, St. Joseph, MI), respectively.

Outcrop samples collected by USGS personnel in August 2014 at the White River section (Colorado, sec. 11, T. 1 N., R. 103 W.) were screened using infrared spectroscopy to obtain qualitative information on organic richness and mineralogy. Selected samples were then submitted for Rock-Eval and TOC analysis. Organic geochemistry data for another outcrop sample (930922-1) from the Willow Creek–Indian Canyon outcrop (Utah, sec. 27, T. 11 S., R. 10 E.; Ruble and Philp, 1998) were reported by Ruble (1996) and Ruble et al. (2001) and are included herein for comparison with data from the White River outcrop. The sample from Willow Creek and all of the White River samples were characterized using whole-pattern XRD and analysis of clay separates. Mineral phases were quantified using the Jade® and ClaySim® software packages (Material Data, Inc., Livermore, CA). Whole-pattern fitting in Jade® was used to estimate major and minor mineral weight percentages based on Rietveldt refinement with an internal 20 wt. % corundum standard. Clay mineral phases were identified by XRD analysis of oriented mounts of the <2-μm fraction from each sample following treatment with sodium hypochlorite to remove organic matter. ClaySim® was then used to quantify the amount of each clay mineral present in the whole-rock samples.

Extractable organic matter (EOM) was collected from pulverized core samples using soxhlet extraction with chloroform. Four Uteland Butte member and two Green River Formation (one comingled and one from the Parachute Creek Member of the Green River) oil samples were donated to the USGS by the Bill Barrett Corporation. The oils and EOM samples were characterized to determine C_{15+} saturate-aromatic-resin-asphaltene (SARA) fractions and whole-oil, saturate, and aromatic fraction gas chromatograms and carbon-13 isotopic compositions. API gravity, total C_{15-} volatiles, and sulfur content were also determined on the oil samples. All analyses were performed by the USGS Organic Geochemistry Laboratory (Denver, CO) using methods available online (U.S. Geological Survey Energy Resources Program, 2015).

Fischer assay analyses conducted on samples from the Uteland Butte member were extracted from the USGS Oil Shale Assessment database for the Uinta Basin (Johnson et al., 2010). The Fischer assay method is a standardized laboratory tool for determining oil, water, and gas yield from oil shale (Stanfield and Frost, 1949; American Society for Testing Materials, 1984). A source rock or oil shale sample is crushed and sieved to -8 mesh (<2.38 mm) and a 100 g (0.22 lbs.) aliquot is heated to 500 °C (932 °F) at a rate of 12 °C/min and held at that temperature for 40 minutes. Oil and water vapor generated during pyrolysis are cooled and collected along with the spent shale. Gas generation is determined by the difference between the original sample mass and the sum of the oil, water, and spent rock collected and is designated as gas+loss. When sufficient oil is generated the specific gravity is measured and used to determine the oil yield in gallons per ton (GPT).

GEOLOGIC SETTING AND BACKGROUND

The Paleocene and Eocene Flagstaff Member of the Green River Formation underlies the Uteland Butte and is the oldest lacustrine unit in the Uinta Basin that may have potential as an unconventional petroleum resource play. The Uteland Butte and Flagstaff are separated by the fluvial Colton Formation in marginal areas of the lacustrine interval. Organic-rich shale in the Flagstaff Member is considered to be one of the sources for oil produced out of the Altamont-Bluebell field (Tissot et al., 1978; Fouch et al., 1994; Morgan et al., 2003a) and marginal lacustrine rocks from the Flagstaff Member are productive in that field. The Flagstaff phase of Lake Uinta formed through the coalescence of isolated lakes in the underlying and intertonguing alluvial and paludal Upper Cretaceous to Eocene North Horn Formation (Fouch, 1975). The first descriptions of the Flagstaff Member were on the Wasatch Plateau by Spieker and Reeside (1925) and Spieker (1946, 1949). The Flagstaff Member has been traced in outcrop in the western part of the Uinta Basin (Spieker, 1949) and eastward to near outcrops of the Upper Cretaceous and lower Tertiary strata along the Green River (Fischer et al., 1960). Farther to the east, the Flagstaff appears to grade into sandstone and shale. The Flagstaff has been traced in the subsurface throughout much of the western Uinta Basin by Ryder et al. (1976) and the eastern part of the basin by Johnson (1985) where, at maximum transgression, it extended to within a few miles of the crest of the Douglas Creek arch. Throughout most of its history, however, the lake during Flagstaff time was confined to the trough of the Uinta Basin south of the rising Uinta uplift. The Flagstaff Member in the western Uinta Basin depositionally grades from the lake margins to lake center and lithologically from (1) interbedded sandstone, siltstone, gray calcareous claystone, algal coal, and oncolytic carbonate, to (2) gray, highly fossiliferous mud- and grain-supported limestone, and then to (3) dark-gray, mud-supported limestone (Ryder et al., 1976).

The freshwater lacustrine interval, later informally named the Uteland Butte limestone by Osmond (1992), was first studied by Bradley (1931) when he measured and described a detailed section of these rocks at an exposure in Indian Canyon in the western part of the Uinta Basin. The "basal tongue of the Green River Formation" was the informal name that was applied to this interval by Bradley (1931). There are about 200 ft of Uteland Butte rocks at Indian Canyon, consisting primarily of flaky shales and marlstones containing ostracodes, pelecypods, and gastropods, and are separated from overlying lacustrine rocks by a 380 ft-thick tongue of fluvial Wasatch or Colton Formations.

The majority of the recent horizontal drilling in the Uinta Basin has targeted the Uteland Butte member. This interval represents the most expansive period of the freshwater lacustrine phase of Lake Uinta. It is believed to be equivalent to the most expansive period of the freshwater Cow Ridge Member of the Green River Formation in the Piceance Basin (Johnson, 1985) and the Luman Tongue of the Green River Formation in the Greater Green River Basin (Horsfield et al., 1994). The freshwater lacustrine unit was referred to as the "Uteland Butte limestone" in the subsurface after the Uteland Butte field (Osmond, 1992) and has subsequently been designated the Uteland Butte member. Folsom (1968) also used the term Uteland Butte member to describe a gas-productive, lower Tertiary interval that sourced the Uteland Butte field, but did not attribute it to the Green River Formation. Lithologies found in the Uteland Butte include limestone, dolostone, calcareous mudstone, and occasional sandstone (Morgan et al., 2003b). It has been suggested that the lack of sandstone may have been caused by rapid lake-level rise leading to siliciclastic sediments being deposited in proximal stream channels (Morgan et al., 2003b).

The approximate maximum extent of the offshore carbonate and shale facies of the Uteland Butte member is shown in Figure 1. The true maximum extent of the lake during deposition of the Uteland Butte is not currently known. The resemblance of the marginal lacustrine facies to floodplain rocks has made it difficult to map the extent of that facies based on geophysical logs and the limited availability of lithological descriptions. Figure 2 provides a simplified well log and core log that includes the Uteland Butte interval.

The Uteland Butte member has been described in detail at three localities in the Uinta Basin where it crops out west of the crest of the Douglas Creek arch (Cashion, 1967; Johnson et al., 1988). Two of these locales, the Evacuation Creek and White River sections (Fig. 1), were revisited in August 2014 and the White River section was described as a new outcrop that was better exposed than the one previously studied (Johnson et al., 1988). The lower part (19.5 ft) of the White River section consists of dark-brown, organic-rich

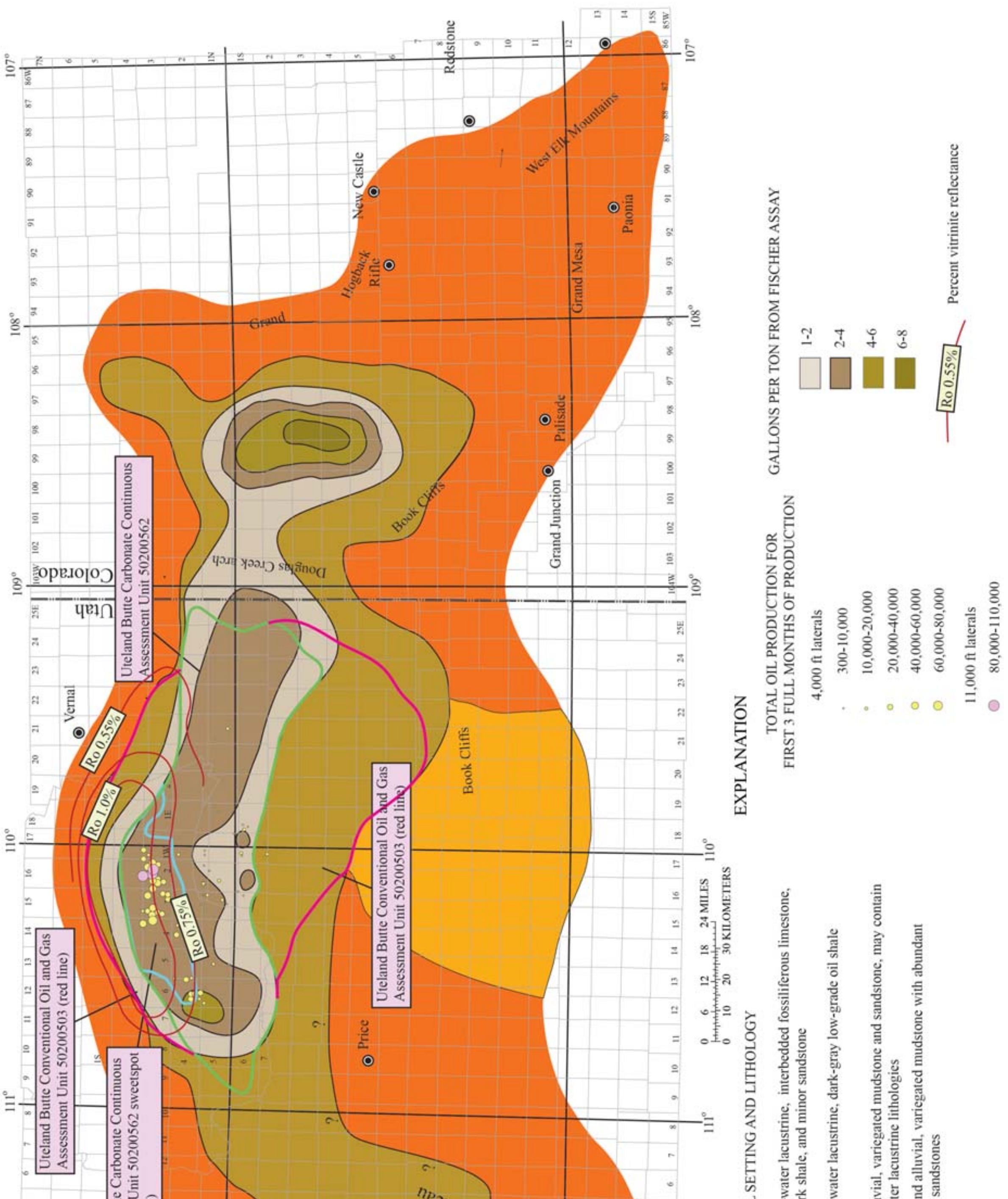

Figure 1. Map of Uteland Butte assessment units showing major lithologies, outcrop features, production data, organic richness (based on Fischer assay), thermal maturity (Ro isopach contours in feet [red line]), overpressured area (shaded pink), and assessment units (thick green and pink lines). ft, feet

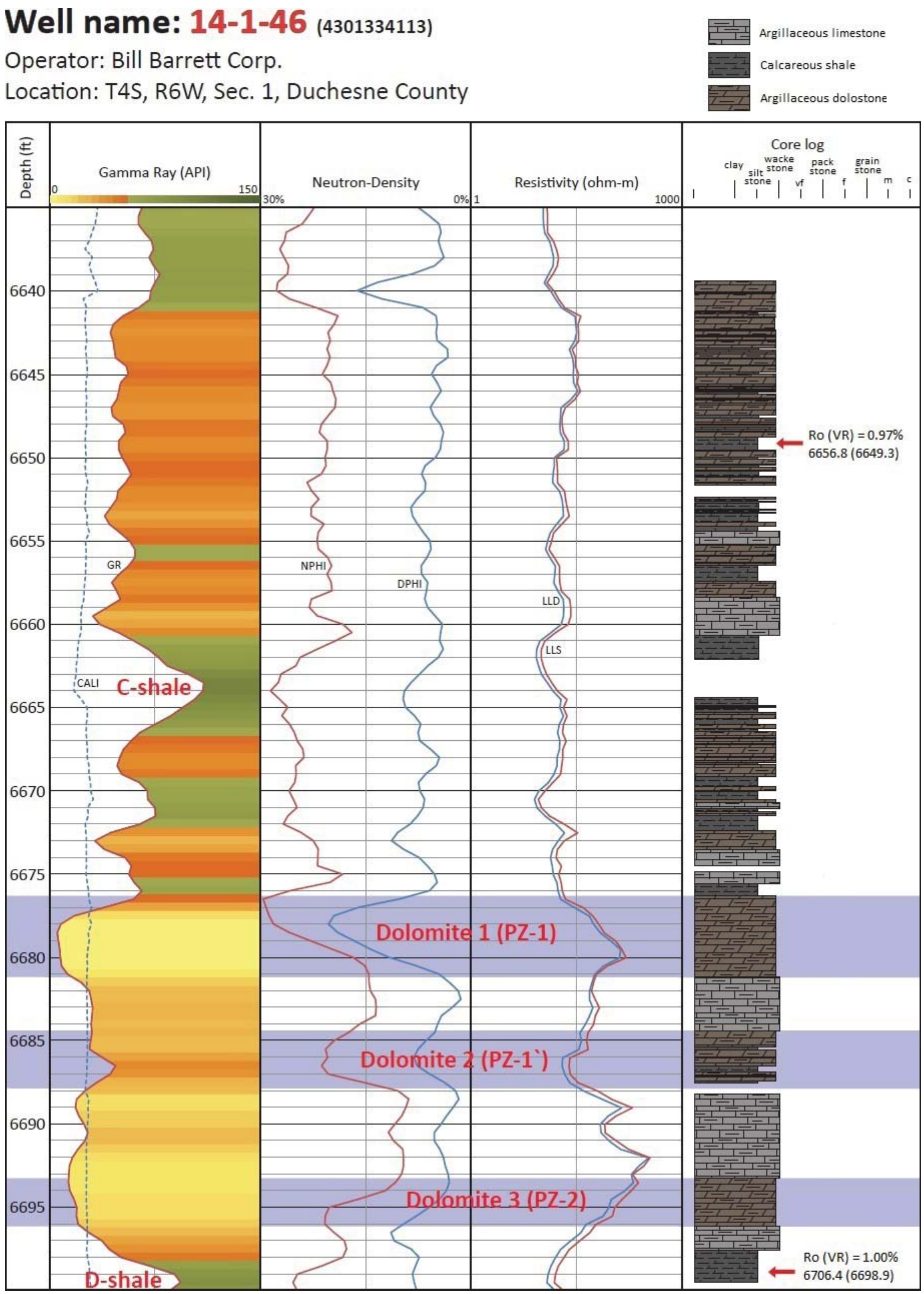

Figure 2. Well logs (gamma-ray, density, neutron porosity, and resistivity) for Uteland Butte well 14-1-46 (API 43-013-34113).

shale, white shell beds of freshwater mollusks, and one discontinuous stromatolite bed. This interval appears to directly overlie variegated mudstones deposited in an alluvial plain environment and was not exposed at the original site described by Johnson et al. (1988). It has been noted that oolite and oncolite beds are common in the freshwater lacustrine interval of the Uinta Basin (Johnson, 1985) and that occasionally stromatolite beds are observed in marginal rocks of the Uteland Butte member. Because stromatolites generally do not develop in the presence of grazing gastropods like those identified in beds adjacent to the stromatolite bed at the White River section, this observation indicates that shell beds found in the Uteland Butte member may represent periodic mortality events as the water in the lake varied from fresh to brackish during deposition.

A slightly thicker interval (32.5 ft) of primarily even-bedded ostracode- and mollusk-rich limestone interbedded with gray mudstone overlies the basal interval at the recently described White River section. From around 50 ft to just under 100 ft above the base of the section, intervals of dark limestone interbedded with gray mudstone are present. There is a very fine to fine-grained sandstone layer located between 99 and 112 ft above the base of the section that is the only significant sandstone in the Uteland Butte. A mostly covered interval of medium-gray mudstone and ostracode- and mollusk-bearing limestone is located above the sandstone. The section description ends 112 ft above the base at the approximate top of the lacustrine rock interval. Above this point are mainly variegated mudstones leading up to the Long Point Bed at the base of the R-0 oil shale zone of the Garden Gulch Member of the Green River Formation (Johnson et al., 2010).

Within the Evacuation Creek section there are interbedded limestones, dark shales, and thin very fine to fine-grained sandstones. Limestone beds are commonly micritic and contain ostracodes, oolites, pisolites, gastropods, pelecypods, and other fossil remains. The base of the Uteland Butte at this location consists of an interval of thin, interbedded sandstone and dark shale beds overlying Wasatch Formation variegated mudstones.

CHARACTERIZATION OF CORE AND OUTCROP ROCKS

A summary of the porosity, permeability, mineralogical, and organic geochemical data collected on the Uteland Butte member cores donated by the Bill Barrett Corp. are shown in Figures 3 through 5. Data collected on outcrop samples are summarized in Tables 1 and 2 and included with or alluded to in Figures 4 and 5. In general, the cores consisted of interbedded calcareous shale, limestone, and dolomite. Core samples are representative of distal facies of the Uteland Butte, while the outcrop samples represent proximal facies. The target dolomitized beds (PZ-1 and similar beds, Fig. 2) for most if not all of the horizontal Uteland Butte wells in the basin are highlighted in the figures and located at depths between 6,680 and 6,710 ft in the 14-1-46 BTR core and 7,370 and 7,380 ft in the 14-3-45 BTR core.

Porosity, Permeability, and Mineralogy

A total of 84 porosity and 61 permeability measurements were performed on samples from the two cores. Porosities varied between 1 and 31 volume percent (vol. %) with the majority of samples (n = 58) having values ranging between 3 and 10 vol. %. Permeability values ranged over six orders of magnitude (~20 nanodarcies to 8.59 millidarcies) and were roughly log-normal in their distribution, with a median and average of 0.004 and 0.337 millidarcies (mD), respectively. The permeability cutoff between conventional and continuous petroleum systems is considered to be around 0.1 mD and good overpressure seals are expected to be in the 10^{-5} to 10^{-4} mD range (Williams, 2012). The Uteland Butte permeability values were, for the most part, at or below the 0.1 mD level and several intervals had sufficiently low permeability to be potential overpressure seals.

Figure 3 clearly shows that within the interval of the Uteland Butte examined in these two cores, dolomite and calcite alternate as the dominant mineralogical phases with few exceptions. Total carbonate content ranged from 33 to 96 wt. %, in all but one sample at the bottom of the 14-1-46 BTR core (15.1 wt. %), and the average carbonate content in samples for the two wells was around 70 wt. %. Dolomite and calcite content were inversely related to each other, with most samples showing a clear dominance of one carbonate mineral over the other.

The porosity and permeability variability is reflected between lithofacies as determined by XRD. Figure 3 shows that the highest porosity samples (>20% porosity, n = 3) were all located within the PZ-1 dolomitic interval (66-85% dolomite). Porosity and permeability data were sorted by lithofacies according to dominant mineralogy (calcite, dolomite, or other) for sample depths that included both types of

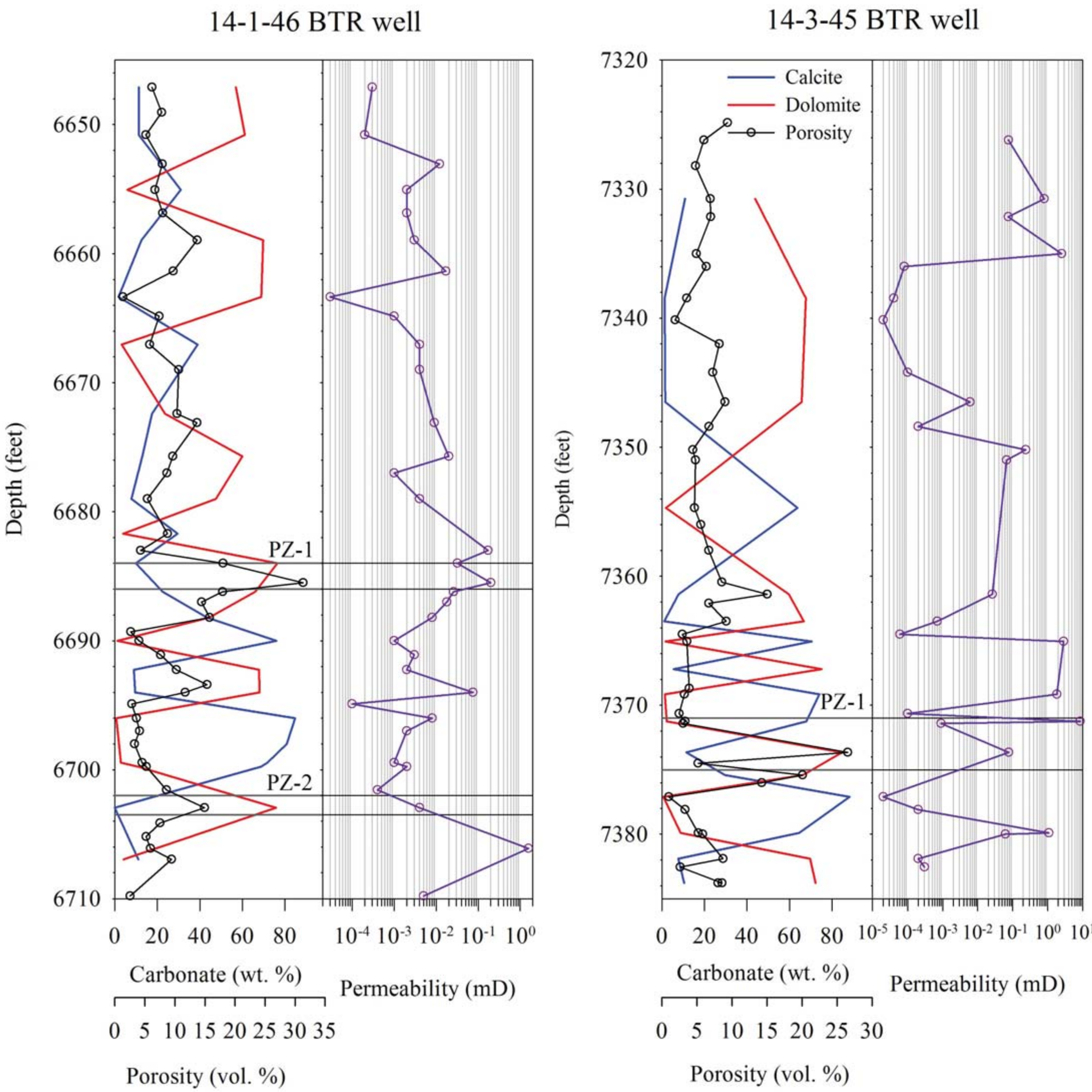

Figure 3. Porosity, permeability, and carbonate mineralogy logs for informal Uteland Butte member cores. mD, millidarcies; vol. %, volume percent; wt. %, weight percent.

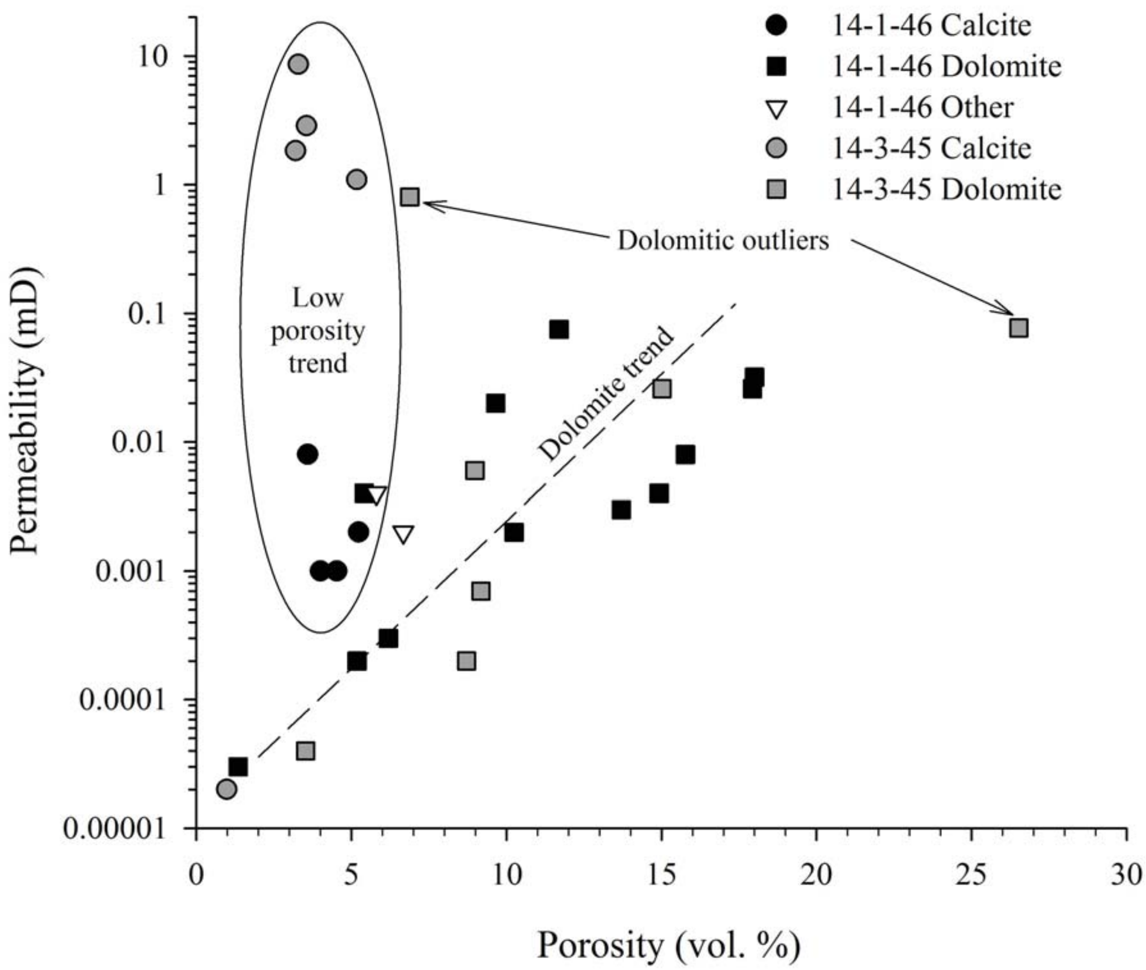

Figure 4. Porosity and permeability data sorted by dominant mineralogy of the sample; the only samples shown are for those depths that included all three measurements. "Other" is the sum of quartz, feldspar, and total clay. mD, millidarcy; vol. %, volume percent void or fluid-filled space.

data. When plotted (Fig. 4), the results indicate two general trends, one with dolomitic samples showing a range of permeability values from 10^{-5} to 0.1 mD and porosity from 1 to 26 %, and calcareous shales showing another range from 10^{-5} to 10 mD, and 1 to 5% porosity. Samples falling into the "other" category (dominated by quartz + feldspar + total clay) plotted in the overlap area between the calcareous and dolomitic trends. All of the high-permeability samples (>0.1 mD, including one dolomitic sample) were from the 14-3-45 BTR well; it is unclear due to the limited sample size if this observation is significant.

The mineralogy of the outcrop samples showed a mix of carbonate and clays, along with quartz and feldspar (Table 1), similar to that observed in the cores. Detailed clay mineralogy showed the common presence of kaolinite, chlorite, and montmorillonite minerals that are generally rare in the saline-brackish phase of the Green River Formation. The presence of these minerals is expected to be related to the particular lake conditions during Uteland Butte time (Dyni, 1976; Yuretich, 1988), but the significance of the mineralogical differences between the freshwater and saline stages of Lake Uinta is currently unclear and requires further study.

Organic Geochemistry

Geochemical logs for the two Uteland Butte member cores are shown in Figure 5 and include XRD mineralogy,

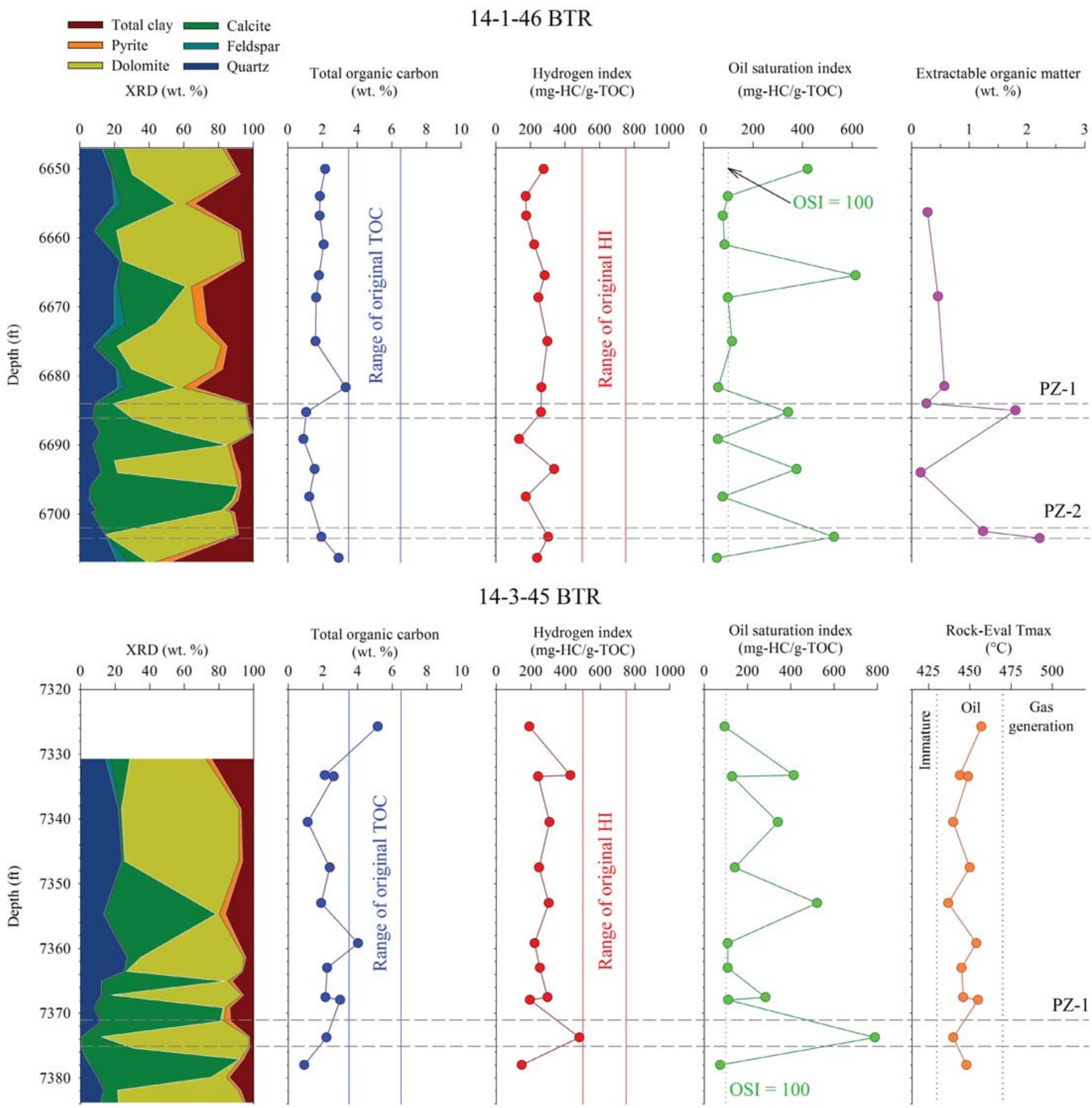

Figure 5. Uteland Butte member core geochemical logs showing quantitative mineralogy (X-ray diffraction, organic-free basis), total organic carbon (TOC) content, Rock-Eval Hydrogen index (HI = S2/TOC×100), Rock-Eval Oil saturation index (OSI = S1/TOC×100), and extractable organic matter content (14-1-46 BTR), and Rock-Eval Tmax (14-3-45 BTR). PZ-1 and PZ-2 are dolomitic intervals targeted for horizontal drilling (see Fig. 2). ft, feet, wt %, weight percent; mg, milligrams.

TABLE 1.

Mineralogy determined by whole-pattern X-ray diffraction and clay separates analysis of thermally immature samples of the informal Uteland Butte member from the White River and Willow Creek–Indian Canyon outcrops. [1]All values are reported as mineral weight percentages on an organic-free basis; [2]illite polytypes; Ca, calcium; Fe, iron; Mg, magnesium; ml, milliliter; no., number.

Sample no.	Quartz[1]	Microcline	Calcite	Aragonite	Mg-Calcite	Dolomite	Pyrite	Gypsum
82614-1-1	21	15	2			7		4
82614-1-2	28	11	7			1		
82614-1-3	20	11	5			16		
82614-1-4	17	8	34			2		
82614-1-5	10	3				71		
82614-1-6	15	6				50		
82614-1-7	24	19				3		2
82614-1-9	14	6	12					1
82614-1-10	24	11	15			2		
82614-1-11	12	1	2			74		
82614-1-13	7	2	85					1
930922-1	8		12	12	58		1	
Sample no.	Kaolinite	Ca-Montmorillonite	Illite 1md[2]	Illite 2m1[2]	Fe-Chlorite	Total Carbonate	Total non-clay	Total clay
82614-1-1	7	17	19	2	7	9	49	52
82614-1-2	11	20	16	1	6	8	47	54
82614-1-3	6	15	19	2	6	21	52	48
82614-1-4	6	12	16	2	5	35	60	40
82614-1-5	3	11		2		71	84	16
82614-1-6	4	13	6	4	3	50	70	30
82614-1-7	7	15	21	3	7	3	48	52
82614-1-9		26	20	11	9	12	33	67
82614-1-10	2	18	21	2	6	17	52	48
82614-1-11		8		3		76	89	11
82614-1-13	1	1	2			85	95	5
930922-1		2	3	2	2	82	90	10

TOC, hydrogen index (HI = S2/TOC×100), oil saturation index (OSI = S1/TOC×100), EOM content (14-1-46 BTR only), and Tmax (14-3-45 BTR only). Data from immature outcrop samples were analyzed to determine the original TOC and HI ranges indicated (Table 2). The immature samples are generally good quality, oil-prone source rocks with TOC contents ranging between ~3 and 6 wt. %, and HI values >500 mg-HC/g-TOC. Based on these initial conditions, the mature core samples retain some residual oil-generating potential and are approaching the end of the oil generation window.

Rock OSI values in both cores were high (~100 mg/g) to very high (>200 mg/g), reflecting excellent oil producibility (Jarvie, 2012). These high-OSI values were consistent with the EOM content for samples from similar depths (up to 2 wt. %). In general, the dolomitic intervals contained around 4 times more EOM than the calcareous beds, consistent with the lower porosity of the calcite-rich samples. Production index (PI = S1/S1+S2) values (Table 2)

TABLE 2.

Total organic carbon (TOC) content and Rock-Eval measured and calculated values for thermally immature samples of the Uteland Butte member from the White River and Willow Creek-Indian Canyon (930922-1) outcrops. HC, hydrocarbons; [1]hydrogen index (HI = S2/TOC×100); [2]oxygen index (OI = S3/TOC×100); [3]oil saturation index (OSI = S1/TOC×100); [4]production index (PI = S1/S1+S2); wt. %, weight percent; mg, milligram; g, gram.

Sample No.	TOC (wt. %)	S1 (mg-HC/g-rock)	S2 (mg-HC/g-rock)	S3 (mg-CO2/g-rock)	Tmax (°C)	HI[1] (mg-HC/g-TOC)	OI[2] (mg-CO2/g-TOC)	OSI[3] (mg-HC/g-TOC)	PI[4]
82614-1-1	3.46	0.86	24.02	1.39	435	694	40	0.25	0.03
82614-1-2	3.77	0.63	27.23	1.49	431	722	40	0.17	0.02
82614-1-3	3.33	0.82	24.95	1.34	437	749	40	0.25	0.03
82614-1-4	2.87	0.74	18.23	1.26	431	635	44	0.26	0.04
82614-1-5	2.25	0.87	15.45	1.12	432	687	50	0.39	0.05
82614-1-6	2.58	0.92	17.02	1.13	438	660	44	0.36	0.05
82614-1-7	2.42	0.68	14.60	1.06	437	603	44	0.28	0.04
82614-1-9	2.40	0.51	14.14	1.37	442	589	57	0.21	0.03
82614-1-10	6.03	0.72	53.83	2.28	441	893	38	0.12	0.01
82614-1-11	1.29	0.39	7.13	1.17	441	553	91	0.30	0.05
82614-1-13	1.77	0.17	11.36	1.25	441	642	71	0.10	0.01
930922-1	5.86	0.65	43.04	2.73	438	734	47	0.11	0.01

were generally 0.3 or higher and followed the trends in OSI. Tmax values were highly variable and ranged between 430 and 457 °C with no consistent trend in either core, and do not appear to provide useful information on the thermal maturity of the source rocks in the Uteland Butte. Vitrinite reflectance measurements, on a very limited number of core samples, consistently had Ro values of approximately 1%, indicating that the Uteland Butte is currently in the oil window. Using an estimated original HI of 680 mg-HC/g-TOC and PI of 0.03 (average values for outcrop samples), the transformation ratio (or fractional conversion to petroleum; Peters et al., 2005, page 99) of the Uteland Butte core samples approaches 80%. This result indicates that the petroleum generation potential of the Uteland Butte source rocks at depth is nearly exhausted.

Thermally immature outcrop samples had the expected low OSI, PI, and Tmax values. HI and oxygen index (OI = S3/TOC×100) values for the outcrop rocks are plotted (Fig. 6, left panel) along with those from the core samples on a pseudo van Krevelen diagram (Espitalié et al., 1977). The results indicate that the outcrop rocks and core samples contain Type II kerogen. However, a plot of S2 vs. TOC (Fig. 6, right panel; Dembicki, 2009) yields a borderline Type I trend that is more consistent with other Green River Formation shales. The lower hydrogen content of the Uteland Butte mudstones is likely an indication of differences in the preservation of organic matter in the freshwater stage of the lake. Elemental ratios were determined on isolated kerogen from one sample (8261-1-10) collected at the White River section and the Willow Creek–Indian Canyon outcrop sample (Ruble, 1996) and H/C ratios were 1.50 and 1.35, respectively, and O/C ratios were less than 0.1. These results indicate that the Uteland Butte member contains a Type I kerogen with similar or lower hydrogen content to other Green River Formation kerogen (H/C ~1.5).

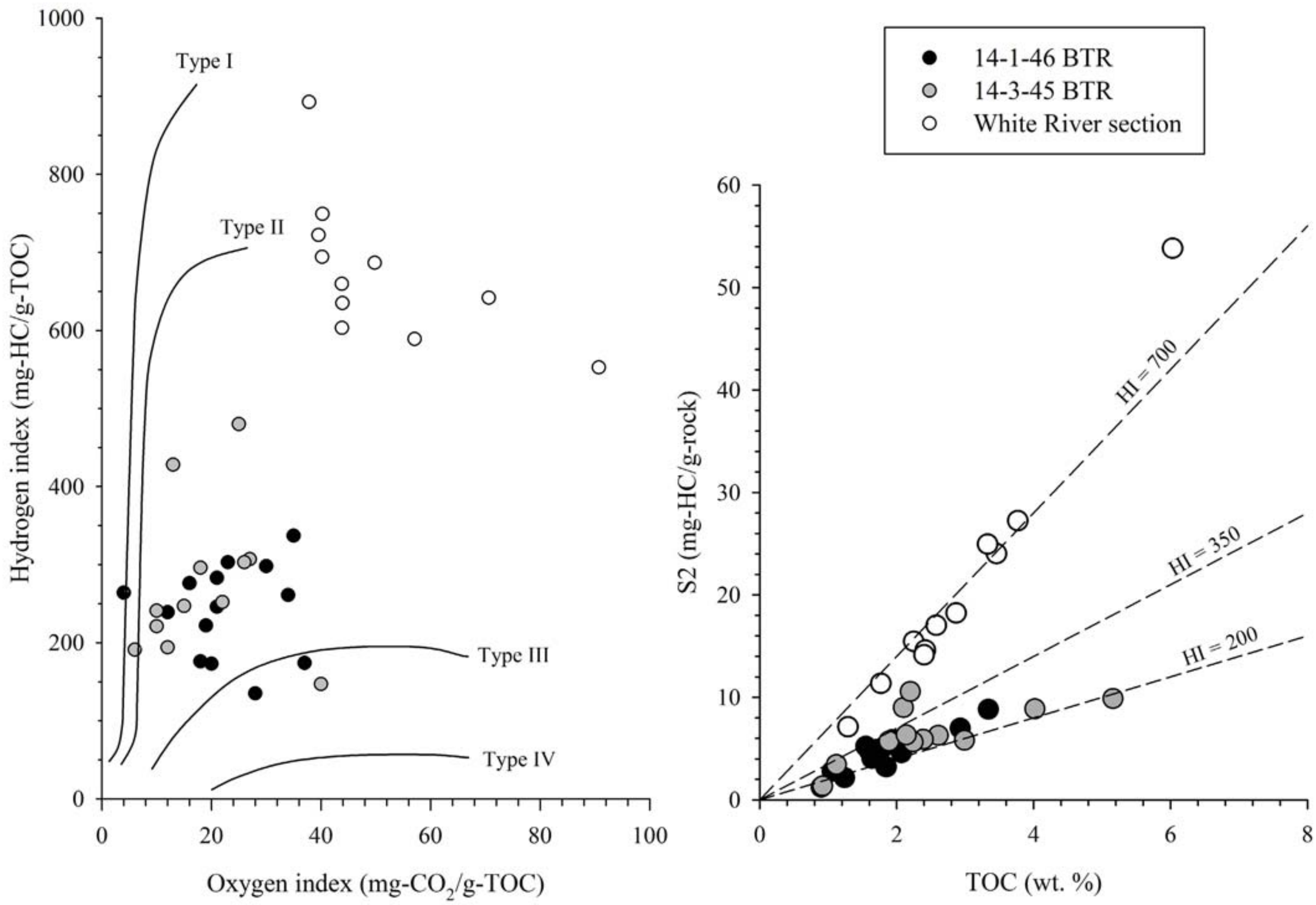

Figure 6. Left plot: pseudo van Krevelen diagram showing Rock-Eval hydrogen index (HI = S2/TOC×100) and oxygen index (OI = S3/TOC×100) data compared with standard kerogen trends. Right plot: Rock-Eval S2 vs. total organic carbon (TOC) content. mg, milligrams; wt. %, weight percent.

CHARACTERIZATION OF OILS AND EXTRACTABLE ORGANIC MATTER

Four oil samples donated by the Bill Barrett Corp. were sourced to the Uteland Butte member based on oil assignments using the respective completion intervals of each well. Oil samples were waxy and ranged from bright yellow to brownish-yellow and black. All Uteland Butte oil samples examined for this study are highly paraffinic, resembling shoe polish at room temperature, with API gravities ranging between 30° and 40°. Table 3 provides a summary of bulk and molecular properties for the Bill Barrett Corp. samples.

The very light isotopic signatures ($\delta^{13}C$ < -30 ‰) of the oils indicate the expected non-marine source. All samples had low sulfur content (≤0.03 wt. %), and high hydrocarbon/polar ratios (>6.4). Pristane (Pr) to phytane (Ph) ratios of the whole-oils and saturates fractions were 1.50 or greater, consistent with a freshwater lacustrine source (Mello et al., 1995). Figure 7 (bottom panel, C) shows a typical Uteland Butte oil saturate fraction trace measured by gas chromatography with a flame ionization detector (GC-FID). Published (Lillis et al., 2003) and unpublished data from a wide range of Uinta Basin oil samples characterized by the USGS Organic Geochemistry Laboratory in Denver were compared with the Uteland Butte oil results. Recognized oil types that were sourced from the Green River Formation in the Uinta Basin include Green River A and Green River B (Lillis et al., 2003). Green River A (GR-A) has been attributed to the "black shale facies," which includes the Uteland Butte member. Green River B (GR-B) has been attributed to the Mahogany zone oil shale, but could also be described as Parachute Creek Member oil so as to include other potential source rocks with similar organic geochemical properties to the Mahogany zone. Another type, Green River "W" (GR-W), is a category including oils that were until recently attributed to reservoirs in the Wasatch Formation, but are now considered to be related to the Uteland Butte oils (Birdwell et al., 2014; Lillis and Cumming, 2014). GR-A oils are the most common Uinta Basin oil type and have high wax contents, carbon preference indices (CPI; Hunt, 1979) < 1.10, and low β-carotane content (Lillis et al., 2003). The GR-B oils typically have higher odd-carbon predominance (CPI > 1.2) and higher β-carotane content than GR-A oils. In general, the Uteland Butte and GR-W oils more closely resemble the GR-A oils, due to their high wax content, low CPIs (~1.0), and minimal β-carotane content. However, comparison of the Pr/n-C_{17} and Ph/n-C_{18} ratios for all of the Uinta Basin lacustrine oils, including the Uteland Butte, showed a consistent trend for oils sourced from various Green River Formation lacustrine facies, indicating a similar organic matter source for Green River Formation oils throughout the lacustrine interval (Fig. 8). The Uteland Butte and GR-W oils consistently had lower Pr/n-C_{17} and Ph/n-C_{18} ratio values than most of the GR-A and GR-B samples, indicating that they are more thermally mature than many of the other Uinta Basin oils (Tissot et al., 1971).

Data on EOM from eight rock samples from the 14-1-46 BTR core are summarized in Table 4 and a plot of the saturate fraction GC-FID trace for two representative samples are shown in Figure 7 (top and middle panels, A and B). Some EOM samples had chromatogram peak distributions that were roughly bimodal (Fig. 7 panel A), with intense peaks between n-C_{13} and n-C_{15} and in the mid C_{20}'s. Other EOM samples had bell-shaped distributions of normal alkanes, with maximum peak intensities in the mid C_{20}'s that were depleted of nearly all hydrocarbons below n-C_{15} (Fig. 7 panel B). A similar observation is reported by Jarvie et al. (2011) in a comparison

TABLE 3.

Bulk and molecular parameters measured for Bill Barrett Corp. oil samples. Gas chromatography parameters determined on saturates fraction. [1]Well information available from the Utah Division of Oil, Gas, and Mining (2015); [2]API standard deviations (stdev.) all ≤ 0.2; [3]Carbon-13 stdev. ≤ 0.11; [4]Carbon preference index (Hunt, 1979); [5]Pristane/phytane ratio; [6]sulfur content stdev. ≤ 0.02 wt. %; [7]ND = not detected. °API, American Petroleum Institute inverse measure of oil density; wt. %, weight percent; ‰, parts per thousand.

Well[1]	Source	API gravity (°)[2]	Saturates (wt. %)	Aromatics (wt. %)	Resins (wt. %)	Asphaltenes (wt. %)	C_{15}- volatiles (wt. %)	Whole oil $\delta^{13}C$ (‰)[3]	Saturates $\delta^{13}C$ (‰)	Aromatics $\delta^{13}C$ (‰)	CPI[4]	Pr/Ph[5]	Pr/ n-C_{17}	Ph/ n-C_{18}	Sulfur (wt. %)[6]
Aurora 4-21d-720	Comingled?	23.0	48.8	17.8	4.4	5.0	24	-31.24	-31.76	-30.76	1.06	1.02	0.83	0.89	0.06
Aurora 5-32	Parachute Creek	21.1	36.4	23.3	24.8	8.0	7.5	-30.87	-32.03	-30.82	1.40	1.17	1.54	2.90	0.29
RU 7-20	Uteland Butte	32.2	64.7	10.9	1.5	10.0	13	-31.43	-31.37	-30.03	1.00	1.56	0.37	0.23	0.03
13H-33-46 BTR	Uteland Butte	33.3	65.2	9.2	1.3	10.2	14.1	-32.41	-32.63	-30.97	1.02	1.58	0.25	0.16	0.03
13H-13-46 BTR	Uteland Butte	37.0	68	5.7	1.3	7.8	17.3	-32.29	-32.43	-30.52	0.99	1.51	0.19	0.13	ND[7]
9H-4-45 BTR	Uteland Butte	39.1	70.4	3.3	0.9	5.8	19.6	-32.36	-32.35	-30.16	0.98	1.60	0.16	0.10	ND

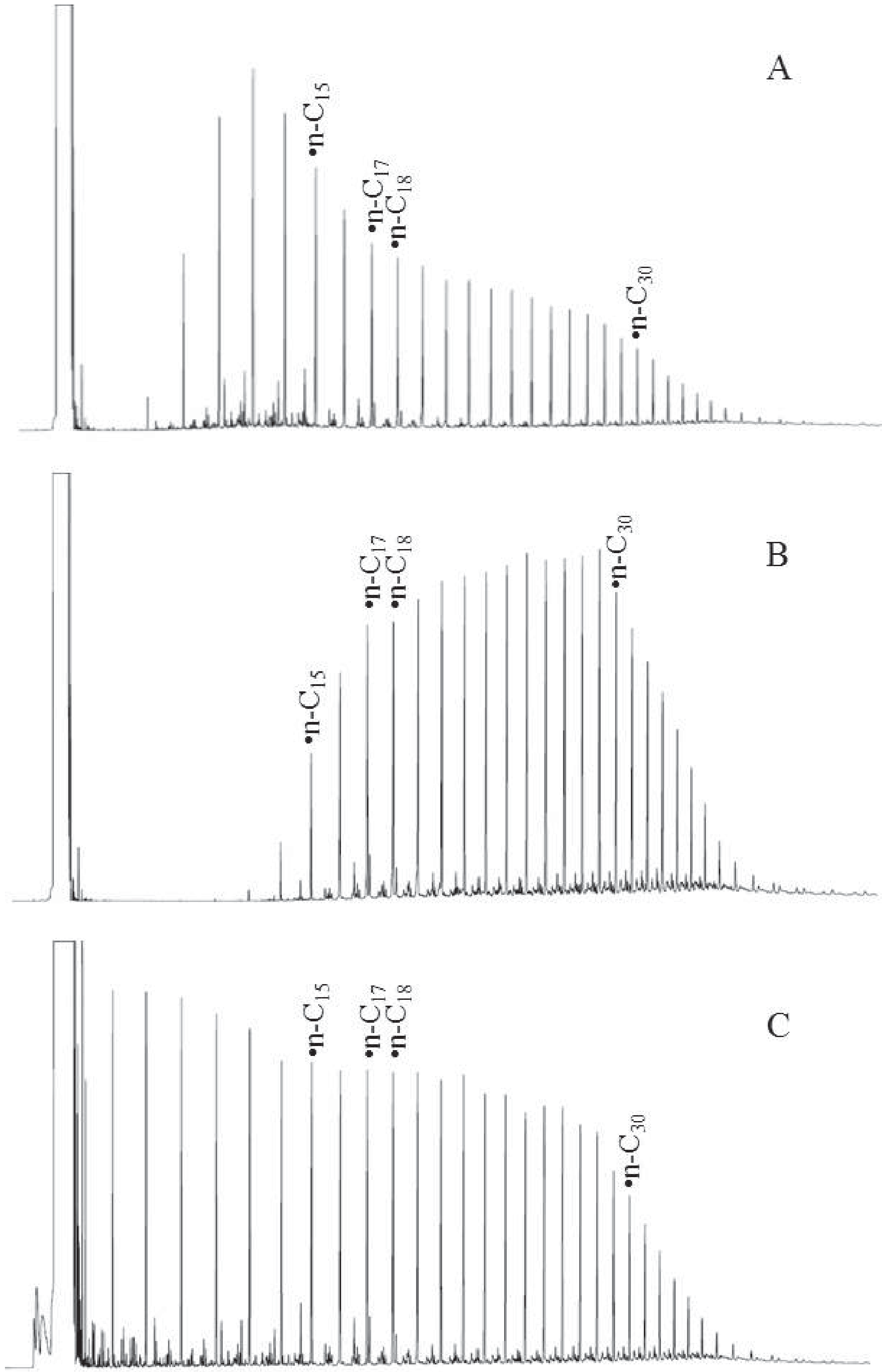

Figure 7. Chromatograms of extractable organic matter (EOM) from the 14-1-46 core (panels A, B) and Uteland Butte member oil from the 9H-4-45 BTR well (panel C). Extractable organic matter (EOM) sample shown in panel A is from a depth of 6,681.5 ft (calcareous shale) and the EOM shown in panel B is from 6,703.5 ft (dolomitic PZ-2; see Figures 2 and 5). Several normal alkanes (n-C) are indicated.

of EOM samples from the low-porosity upper and high-porosity middle members of the Bakken Formation in the Williston Basin. Although the chromatograms show some obvious differences between the EOM samples and Uteland Butte oils, which is attributed to volatilization during core storage (depleted in C_{15-} hydrocarbons), the carbon isotope, SARA, and molecular parameters determined on the EOM samples are consistent with those of the Uteland Butte oils discussed previously, as demonstrated in the plot of Pr/n-C_{17} vs. Ph/n-C_{18} (Fig. 8). The differences in the two EOM chromatograms were related to the mineralogy of the rocks from which they were extracted. Of the eight EOM samples collected, two were from dolomite-rich rocks (about 76 wt. %) and the other six were from rocks with low dolomite content (< 6 wt. %) and high calcite and total clay. The dolomitic samples were also high in porosity (15 – 20 vol. %), contained the highest concentrations of EOM (~2 wt. %) overall, and had bell-shaped distributions in the saturates fraction (and whole-oil, not shown) chromatograms. The non-dolomitic samples had lower porosities (< 9 vol. %) with EOM contents of less than 0.6 wt. % and bimodal distributions in their GC traces. Permeability for all samples examined for EOM content ranged within an order of magnitude (0.002 – 0.032 mD), and due to the limited number of samples, it was unclear if permeability varied systematically with lithofacies among this subset of samples. The higher porosity of the dolomitic samples may explain their greater depletion in light hydrocarbons during core storage.

PRODUCTION HISTORY

The Uteland Butte member is oil productive throughout a large area of the Uinta Basin (i.e., the play is not isolated to any one field, but is nearly basinwide). Until recently the Uteland Butte was not a primary drilling objective (Morgan et al., 2003b). The current focus on Uteland Butte development has targeted thin, regionally extensive dolomite beds with more than 20 percent porosity but low permeability (0.01 – 0.1 mD). These dolomite beds (designated PZ-1, PZ-1′, and PZ-2 along with other unnamed beds by Bill Barrett Corp.; Fig. 2), in particular the PZ-1, are being targeted by horizontal drilling and hydraulic fracturing; the latter of which could connect several dolomitic reservoir beds (Anderson and Roesink, 2013; Vanden Berg et al., 2014). Production data from 84 horizontal wells that produce from the Uteland Butte were extracted from the Utah Division of Oil, Gas, and Mining database (2015). These records were compared with information from individual well files to confirm

TABLE 4.

Bulk and molecular parameters for extractable organic matter (EOM) samples from the 14-1-46 BTR core. Gas chromatography parameters were determined on saturates fraction.

Sample depth (ft)	Lithofacies	EOM (wt. %)	Saturates (wt. %)	Aromatics (wt. %)	Resins (wt. %)	Asphaltenes (wt. %)	Saturates $\delta^{13}C$ (‰)[1]	Aromatics $\delta^{13}C$ (‰)[1]	CPI[2]	Pr/Ph[3]	Pr/n-C_{17}	Ph/n-C_{18}
6668.5	Calcareous shale	0.46%	76.5	9.1	5.8	8.6	-32.17	-30.67	0.98	1.60	0.16	0.12
6681.5	Low carbonate shale	0.57%	74.0	11.4	5.1	9.5	-32.00	-31.07	1.00	1.51	0.14	0.10
6703.5	Shaley dolomite	2.22%	87.4	6.1	2.3	4.3	-32.35	-31.04	0.98	1.44	0.16	0.11
6656.3	Shale (some dol/cal)	0.28%	73.0	12.8	5.6	8.6	-31.34	-30.64	0.98	1.43	0.20	0.15
6684-6686	Dolomite	1.80%	90.6	4.3	1.9	3.2	-31.77	-30.44	1.03	1.22	0.26	0.19
6694	Calcareous shale	0.16%	65.6	15.6	8.4	10.4	-31.79	-30.34	0.99	2.05	0.14	0.08
6702-6703.5	Shaley dolomite	1.24%	83.1	6.9	3.3	6.6	-32.13	-30.90	0.99	1.40	0.19	0.12
6684	Low carbonate shale	0.26%	74.1	13.3	6.7	5.9	-32.80	-30.82	0.97	1.94	0.18	0.13

[1]Carbon-13 standard deviation ≤ 0.72; [2]Carbon preference index (Hunt, 1979); [3]Pristane/phytane ratio.

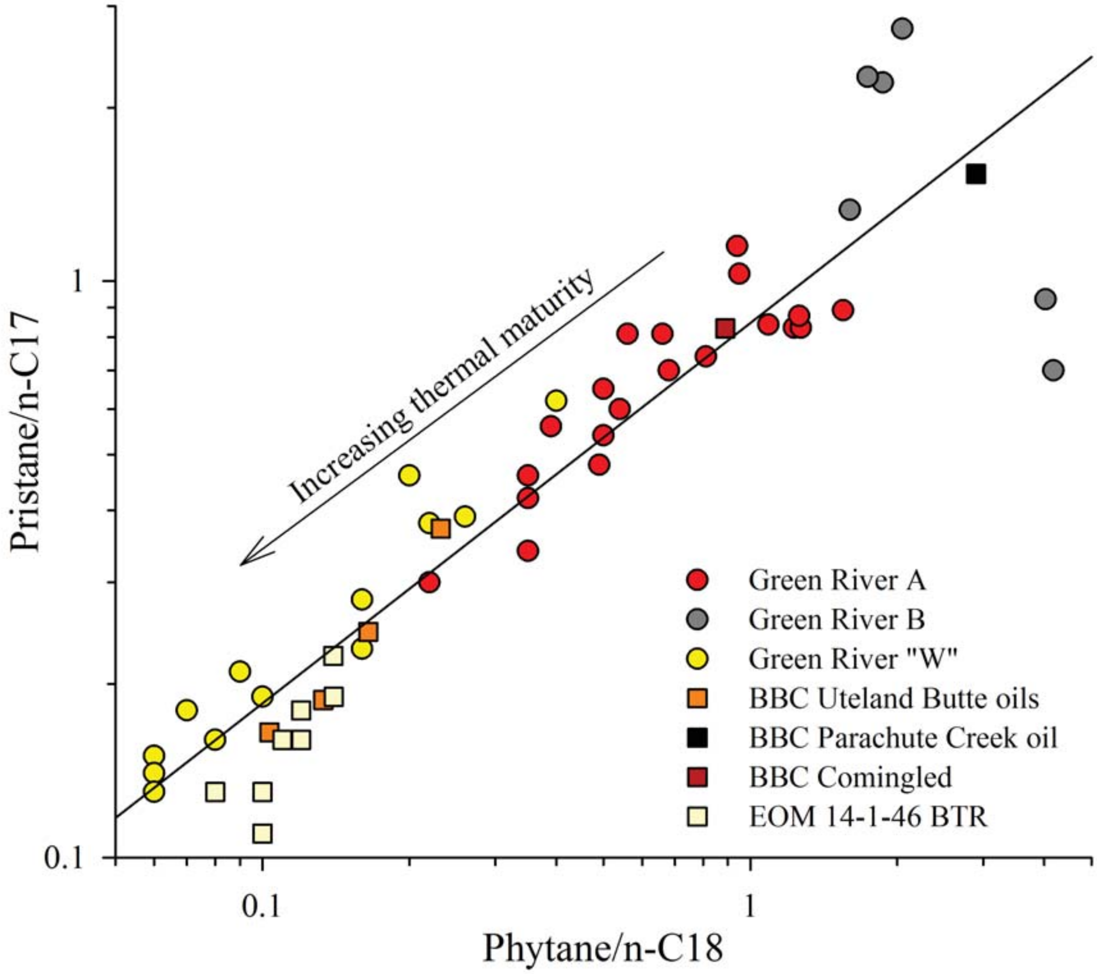

Figure 8. Plot of pristane/n-C_{17} vs. phytane/n-C_{18} for Uinta Basin Green River A and Green River B oil samples (Lillis et al., 2003), Green River “W” oils (previously attributed to Wasatch Formation reservoirs), oils donated by the Bill Barrett Corporation (BBC) from Uteland Butte member (4), Parachute Creek Member (1), and “comingled” oils (1) wells; and extractable organic matter from Uteland Butte core samples (14-1-46 BTR). Scatter in the Green River B samples is due to high variability in n-C_{17} and n-C_{18} content.

that the stratigraphic interval being produced is the Uteland Butte. Data were examined with emphasis on production during the first month (average reporting period 36 days) and first three full months reported as barrels of oil equivalent (BOE), which includes natural gas production (one BOE is equivalent to 5,800 cu. ft of natural gas). Wells were sorted into three categories: (1) forty-two 5,000-ft laterals outside of the overpressured region (“normal-pressured”) shown in Figure 1 (discussed further in a later section); (2) thirty-four 5,000-ft laterals within the overpressured region; and (3) eight extra-long laterals (approximately 11,000 ft) within the overpressured region. Two recently drilled wells of the 84 do not yet have any reported production data.

Histograms showing total production for the first month (sorted by average daily production in BOE) and the first three full months (sorted by total BOE produced from each well) are presented in Figure 9 (top and bottom panels, respectively). Separate distributions for normal-pressured, overpressured, and extra-long lateral wells are shown. The sum of all production for all wells during the first month of operation was 1.14 MMBOE, or about 20% of the total production from the Uteland Butte as of December 2014 (Utah Division of Oil, Gas, and Mining, 2015).

The most common type of producing well was normal-pressured with the first month's production less than 100 and up to 200 BOE/day (n = 32). Among the 5,000-ft laterals in the overpressured area, typical first month's production was between 400 and 800 BOE/day (20 wells). Total production from all wells during their first three full months operating was 1.96 MMBOE; this represents about 35% of all production from the Uteland Butte to date (5.65 MMBOE). All but one of the normal-pressured wells produced less than 20,000 BOE during this timeframe, while 27 of the overpressured wells yielded more than 20,000 and as much as 70,000 BOE (one well). The wells with extra-long laterals in the overpressured area show the greatest initial production by far. All of the wells with 11,000-ft laterals (6 total with data) had first month's production over 1,000 BOE/day and the four with first three months production data all produced over 67,000 BOE during that period, which when combined (503,124 BOE), were more than the sum of all production from the normal-pressured wells during their first three months (342,877 BOE).

Declines in production from Uteland Butte horizontal wells with time-online are typical of unconventional tight-oil plays in that production decreases rapidly when compared to most conventional oil wells. Vanden Berg et al. (2014) compared production rates (BOE/day) for the overpressured and normal-pressured wells with 5,000-ft laterals from the time just after completion to a little more than two years online. A typical normal-pressured well with an initial production rate of about 300 BOE/day had dropped to one-tenth of that after 28 months. An overpressured well, with initial production of around 760 BOE/day, showed a similar decline (to 100 BOE/day) after 32 months. Data for an extra-long lateral, with a timeframe from completion to six-months online, showed a two-thirds reduction in production rate (1,500 to 500 BOE/day)

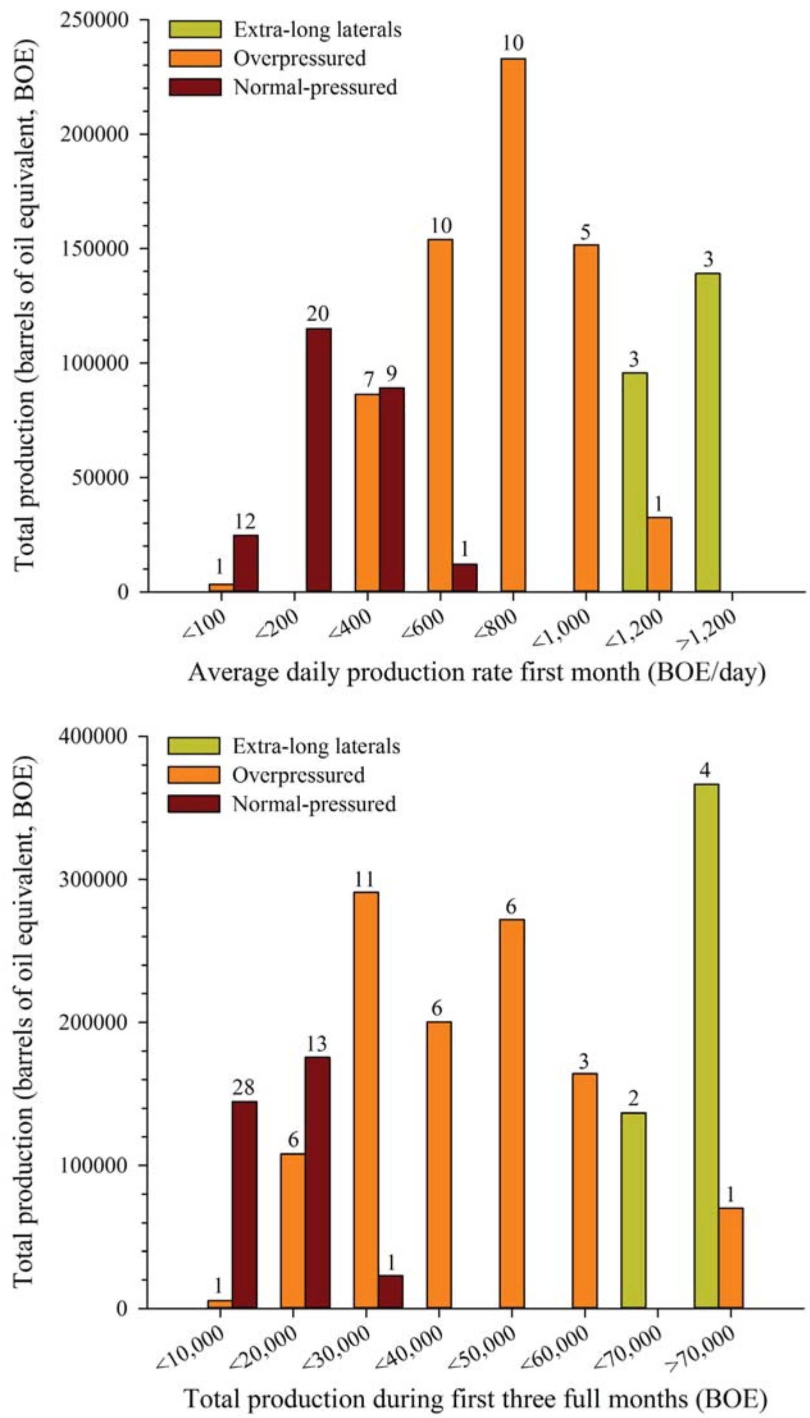

Figure 9. Histograms summarizing first month's average production rate (top, BOE/day) and first three full months of production (bottom, BOE) from normal-pressure (0.433 ft/psi to 0.5 ft/psi), overpressured (greater than 0.5 psi/ft), and extra-long (11,000 ft) lateral wells. Numbers above bars indicate how many wells are represented by each bar. BOE, barrels of oil equivalent; psi, pounds per square inch per foot.

and was consistent with the decline curves for the shorter horizontals wells.

Data on gas-oil (GOR, thousand cubic ft/barrel, MCF/bbl) and oil-water (OWR, barrel/barrel) ratios were also examined for 71 Uteland Butte wells using first 3 full months and first 12 months production data from IHS ENERDEQ (IHS Energy, 2015). In the first three months of production, GOR values were typically around 1 MCF/bbl, with average, median, and maximum values of 1.56, 0.88, and 14.95 MCF/bbl, respectively. Over the first year of production, the values increased slightly, with typical values between 1.25 and 2.25 MCF/bbl, and average, median, and maximum respective values of 2.11, 1.54, and 15.82 MCF/bbl. Correlation of first 3 months and first 12 months GORs showed a moderately high correlation coefficient (R^2 = 0.864) and a slope of 1.18, indicating a slight increase in gas production with increasing production time. Water production varied widely for Uteland Butte wells, with OWR values ranging between 1 and 3 bbl/bbl for most wells for both the first 3 full months and first 12 months of production. Average, median, and maximum OWR were also similar during the two production periods (5.70, 5.98; 2.22, 2.18; 76.05, 85.66 bbl/bbl) and a strong correlation between 3- and 12-month OWRs was observed (R^2 = 0.963) with a near unity slope, indicating little change in relative water production with time online. In general, there was no discernible difference in GOR values between overpressured and normal-pressured wells. However, the normal-pressured wells showed a bimodal distribution of OWRs, with about half ranging between 0.3 and 3 bbl/bbl and the other half varying from 6 to 130 bbl/bbl, while the overall distribution for the overpressured wells was normally distributed between 0.4 and 9.2 bbl/bbl It should be noted that initial water production is expected to be higher in unconventional oil wells due to flow-back waters used during hydraulic fracturing, but there is no evidence for this in the Uteland Butte wells based on trends in the first 3- and 12-month OWR values.

BASINWIDE FACTORS RELATED TO PRODUCTION

Organic Richness

Fischer assay data was generated by the U.S. Bureau of Mines during the 1960s and 1970s on samples of cuttings from drill holes as part of an examination of oil shale resources in the Uinta Basin. In the Uinta Basin Oil Shale database, there were 24 drill holes with Fischer assay data on samples from the Uteland Butte member (Johnson et al., 2010). However, there are a few potential issues with this Fischer assay data because the sampling interval can be 10 ft or more for cuttings used in these analyses, and some thin, organic-rich shale beds may not be detected. Another potential concern with Fischer assay data is that analytical errors in samples with low oil yields may be significant (Stanfield and Frost, 1949) and unlike Rock-Eval, the method does not differentiate between generated oil present in the rock and oil generated during kerogen pyrolysis. Despite these caveats, the Fischer assay results do provide a basinwide dataset that allows for assignment of an approximate extent of the organic-rich rocks in the Uteland Butte member. Figure 1 shows the extent of Uteland Butte samples that exceeded Fischer assay oil yields of one gallon of oil per ton of rock (GPT). Of the 417 Fischer assay samples processed, 257 generated sufficient oil to report oil yield, and of these 67% (n = 172) had yields greater than 1 GPT. Only 3% (8) had yields greater than 5 GPT and the thickest, richest interval based on these data has an oil yield of 3.6 GPT over a thickness of 280 ft. Nearly every well shown on Figure 1 that is producing out of the Uteland Butte member is located within the >1 GPT area.

Overpressure

Abnormal pressure is a common phenomenon in continuous or basin-centered petroleum systems in Rocky Mountain basins (Law and Spencer, 1998). Pressure gradients are determined using pressure measurements with depth and normal formation pressure is defined by the hydrostatic gradient (0.433 psi/ft). Reservoirs in Rocky Mountain basins are considered to be significantly overpressured if the pressure gradient exceeds 0.5 psi/ft (Spencer, 1987). Formations in communication with a regional groundwater system are expected to display normal pressure, unless recharge areas are much higher in elevation than the overall basin. Pressures can exceed the hydrostatic gradient in lithologic units that are isolated or encased by impermeable barriers within subsiding basins where compaction of the lithologic column prevents fluid migration out of the unit. Another mechanism, one that has been invoked to explain overpressure in Rocky Mountain basins, is hydrocarbon generation. Conversion of solid kerogen to oil and gas leads to a net increase in volume of the organic phase (Gies, 1984; Spencer, 1987; Law and Spencer, 1998). Overpressure has been identified as an important factor driving many of the high-production rates for wells in the Uteland Butte horizontal play (Anderson and Roesink, 2013; Vanden Berg et al., 2014).

Downhole pressure within the wellbore can be measured using drillstem tests or from variations in mud weights used during drilling. Drillstem tests do not provide a direct measure of formation pressure, but are considered to be one of the better estimation methods (Holm, 1998). Mud weights are also useful for this purpose, but lack the reliability and precision of drillstem tests for defining overpressure. In this study, we have used data derived from both methods to define overpressured areas within the Uteland Butte member. The reliability of drillstem test data was determined by comparing the initial shut-in pressure with the final shut-in pressure; similar values generally indicate that the test was run long enough to permit equilibration between the well bore and formation pressure.

Drillstem tests from 42 intervals in or near the Uteland Butte were determined to be reliable based on our criterion and within 6 of those intervals the pressure gradients were 0.50 psi/ft or greater defined here as significant overpressure. The mud weights used in five drill holes were added to the drillstem data in defining the overpressured part of the play, and were particularly useful in areas where information from drillstem tests was unavailable. Mud weights used in four of the drill holes indicated significant overpressure; the remaining drill hole was normally pressured. The overpressured area (>0.5 psi/ft) in the Uteland Butte member defined by the drillstem test and mud weight data is shown within the light-pink shaded portion of Figure 1 and is generally comparable to a map of overpressure defined using only mud weight data (Anderson and Roesink, 2013). The majority of drillstem tests within this area indicate significant overpressure, but some do not. The tests within the shaded area that did not indicate overpressure could be due to poorly run tests within an overpressured interval or could reflect that there are some normally pressured zones within a generally overpressured area. Comparison of the production rates plotted in Figure 1 show that the horizontal wells within the overpressured area are the most productive wells in the Uteland Butte, as indicated in previous studies (Anderson and Roesink, 2013; Vanden Berg et al., 2014; Johnson et al., 2015b).

Thermal Maturity

The majority of organic matter identified in the Green River Formation is described as Type I kerogen, which indicates that it is oil-prone with high hydrogen content compared to other kerogen types; this is also true for the Uteland Butte. For Type I kerogen, the onset of oil generation is thought to correspond to a vitrinite reflectance (Ro) of between 0.6 and 0.7%, with oil generation complete between a Ro of 1.2 to 1.3% (Baskin and Peters, 1992; Ruble et al., 2001). Vitrinite measurements on samples rich in Type I kerogen can be difficult to obtain, as the terrestrial-sourced vitrinite maceral will be mixed with and diluted by the more prominent algal organic matter. Therefore, variations in vitrinite reflectance may only indirectly indicate thermal maturity of the largely amorphous Type I kerogen in Green River Formation rocks.

A small number of vitrinite reflectance measurements (n = 11) from within or near the Uteland Butte member were published by Anders et al. (1992). The values in that study generally define an area of high thermal maturity near and just to the south of the basin trough. Isomaturity lines are shown on Figure 1, highlighting regions with Ro values of 0.75%, beyond the onset of oil generation for Type I organic matter, and 1.0% or greater. An incomplete line for values of 0.55% Ro or higher is also plotted, but insufficient data were available to enclose the area representative of this level of thermal maturity. The majority of productive wells are located within the 0.75% Ro line, and the wells with the highest rates of production are within the most mature area (Fig. 1).

The Rock-Eval and vitrinite reflectance data collected on samples from cores 14-1-46 BTR and 14-3-45 BTR were also considered in examining thermal maturity of the Uteland Butte. A limited number of vitrinite measurements (n = 3), available from the Bill Barrett Corp. cores were added to those from Anders et al. (1992) to help determine the variations in thermal maturity. Average Ro values were 0.97% at 6,656.8 ft and 1.00% at 6,706.35 ft in the 14-1-46 BTR core and 0.99% at 7,363 ft in the 14-3-45 BTR core. All were consistent with the Anders et al. (1992) data.

Dolomite Intervals

The total thickness of carbonate beds within the Uteland Butte member has been examined in the subsurface using electric logs and any available Amstrat logs available from the USGS Core Research Center in Denver. Resistant intervals on the electric logs were considered to be carbonate-rich, due to the rarity of sandstones in the Uteland Butte. Figure 10 shows the thickness of the PZ-1 dolomite bed in the Uteland Butte member (numbered isopach) which is one of the primary drilling targets. Figure 2 shows a sample well and core log for one Uteland Butte well with several identifying intervals noted, including the three main dolomite targets (PZ-1, PZ-1′, and PZ-2) and the C- and D-shales, which can be used to locate the interval of the Uteland Butte that contains the dolomite-rich beds. The carbonate map was generated based on core descriptions and well logs and therefore differs somewhat from the Anderson and Roesink (2013) map that was derived solely from log data. The maximum thickness of dolomite-rich beds is about 16 ft in the carbonate-rich area within the thickest part of the Uteland Butte; this is about one-third of the maximum thickness reported previously (Anderson and Roesink, 2013); they indicated that the total thickness of dolomite-rich beds drops off rapidly to the north and this is generally consistent with our map (Fig. 10). This decrease in dolomite-rich thickness was used to help delineate the northern boundary of the Uteland Butte tight-oil play.

The results shown in Figure 10 include all lacustrine rocks containing some carbonate-rich beds and are thicker than the main carbonate-rich interval of the Uteland Butte member isopached by Morgan et al. (2003b). We assumed that all intervals with carbonate content could produce some oil, particularly when fractured along with the main carbonate-rich interval. The thickness of this interval varies from less than 50 ft in the southeast part of the basin, where it consists of a single ostracodal and oolitic limestone, to more than 400 ft thick along the basin trough, where it directly overlies older lacustrine rocks and directly underlies the R-0 zone of the Garden Gulch Member. The Uteland Butte could not be identified with certainty north of the isopached area shown in Figure 1 and therefore the northern limit of the Uteland Butte is not clearly defined. In this area, the Uteland Butte grades into a thick, complex mix of intertonguing facies, including the offshore lacustrine, marginal lacustrine, and alluvial rocks that form the stratigraphic trap for the Altamont-Bluebell field, making it difficult to define a distinct boundary. It is clear from the production data shown in Figure 1 and the PZ-1 thickness isopach in Figure 10 that many of the most productive wells are located where the dolomite-rich beds are present, but all highly productive wells are not necessarily associated with the dolomites.

Assessment Units

Figure 1 outlines the assessment units (AUs) designated by the USGS to be within the Uteland Butte tight-oil play (Johnson et al., 2015a). Two AUs and one “sweet spot” were assigned based on the available geological, geochemical, and production data and are briefly described herein. The Uteland Butte Carbonate Continuous AU lies within the area bounded by the green line on Figure 1 and encompasses much of the deep, central portion of the Uinta Basin. This AU contains most of the wells currently producing from the Uteland Butte member. A sweet spot, containing most of the highest producing wells is included within this AU. The sweet spot is defined by the presence of overpressure (>0.5 psi/ft), coincides with the thickest part of the offshore phase of the Uteland Butte, and includes high levels of organic richness with thermal maturities within the oil window.

The southern margin of the Continuous Carbonate AU is defined by the transition from organic-rich offshore lacustrine carbonate and shale to more marginal sandstone, siltstone, and mudstone of the Uteland Butte Marginal Lacustrine Conventional Oil and Gas AU, outlined by the pink line on Figure 1. The southern contact between the two AUs is gradational in terms of lithofacies, thus the line between them was assigned based on Fischer assay oil-yield data, specifically where the organic richness of the Uteland Butte is less than 1 GPT. At the northern boundary of the Continuous Carbonate AU, it is also gradational into the marginal lithofacies and extends into the northern area of the Marginal Lacustrine AU. This boundary was defined using both the lithofacies map of carbonate thickness and the Fischer assay oil-yield isopachs for 1 and 2 GPT cutoffs. The eastern boundary for the Continuous Carbonate AU was difficult to define due to the limited availability of core or production data. The boundary was placed a few miles from outcrop.

CONCLUSIONS

This paper has summarized the geology and various geochemical and mineralogical properties related to tight-oil production from the continuous resource play in the Uteland Butte member of the Green River Formation in the Uinta Basin. Based on our examination of the Green River Formation basins, only the Uinta Basin possesses the combination of interbedded organic-rich shale and brittle carbonate lithologies at sufficient thermal maturity to have

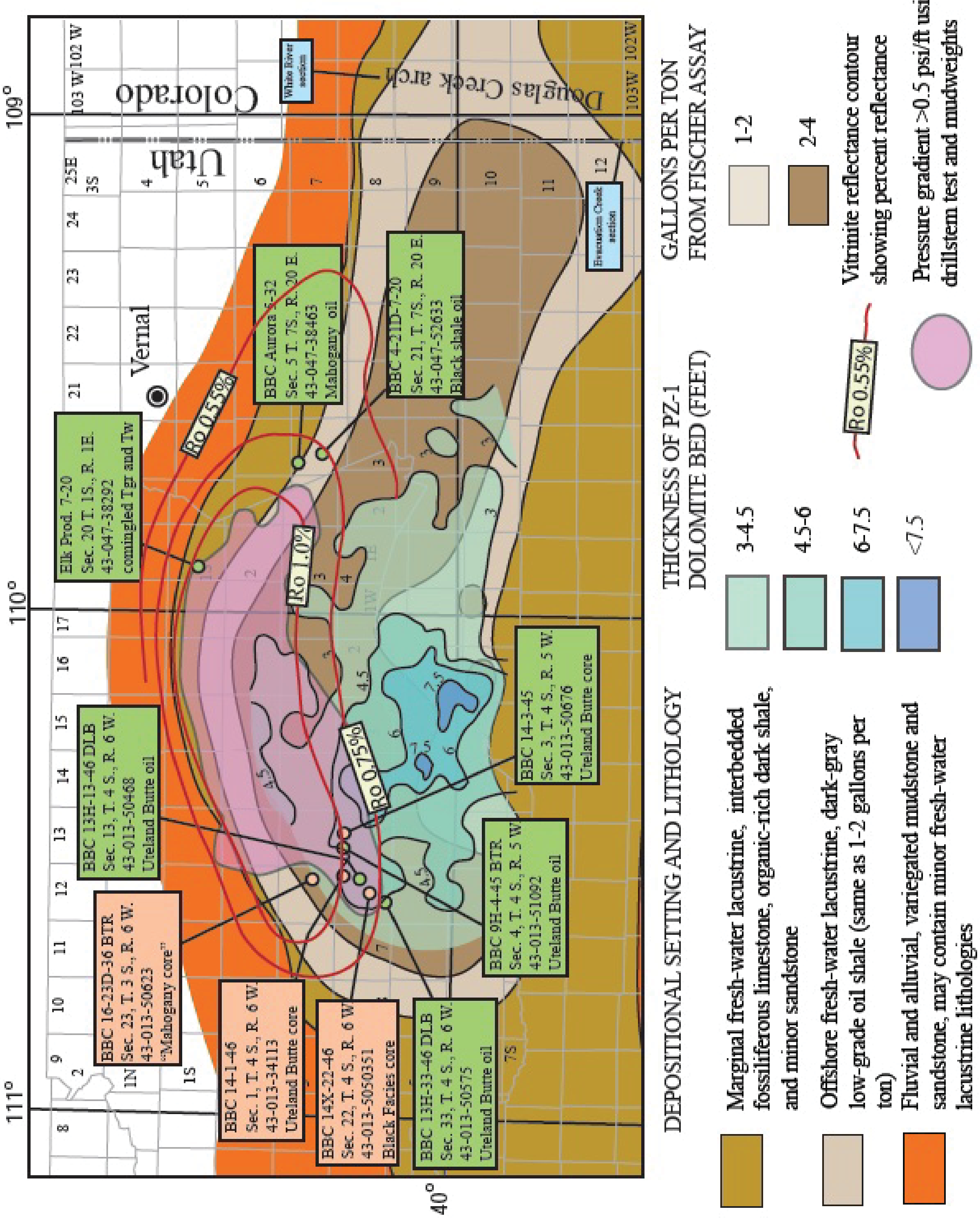

Figure 10. General Uteland Butte member map showing thickness in ft of the PZ-1 bed (numbered isopachs) and locations of cores (salmon-colored boxes), oil wells (green boxes), and outcrops (blue boxes) are also indicated. See Figure 1 for additional legend information.

generated large quantities of oil to produce a viable tight-oil play. The high thermal maturities in the Green River Formation in the Uinta Basin are related to the tremendous subsidence that took place after the main organic-rich interval was deposited; this burial was far greater than in the other Green River basins during the same period.

The organic geochemistry and mineralogy of the Uteland Butte member vary somewhat from that of the overlying saline-brackish oil shale intervals of the Douglas Creek, Garden Gulch, and Parachute Creek Members of the Green River Formation. Lower TOC and HI values in immature samples relative to the overlying oil shales may be related to lower organic productivity or poor preservation in the freshwater lacustrine phase of Lake Uinta when compared to the more saline and alkaline conditions that dominated later. The mineralogy of the Uteland Butte, both in core and outcrop, is also different from other freshwater lacustrine intervals of the Green River Formation in the Piceance and Greater Green River Basins, in that carbonates are common and often the dominant mineral component. The common occurrence of clays, such as kaolinite, montmorillonite, and chlorite, in the Uteland Butte also differentiates it from other stages of Lake Uinta's history, in that the dominant aluminosilicates in later intervals are feldspar minerals and analcime.

The most productive area of the Uteland Butte member is located where the following standard criteria are met: (1) organic-rich based on Fischer assay yields, (2) presence of overpressure, and (3) high thermal maturity. The high-porosity, brittle and dolomite-rich intervals provide targets for horizontal drilling and are potentially important reservoir rocks, but their presence does not appear to be essential for high productivity. The relationship between overpressure and well productivity has been noted previously for Uteland Butte wells (Anderson and Roesink, 2013; Vanden Berg et al., 2014) and based on production data is shown to be the primary driving factor for differences in well performance. Future development in the Uteland Butte member is expected to emphasize the use of extended 11,000-ft laterals that should lead to substantially higher production rates, particularly in the overpressured area of the basin.

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Michael Brownfield is a Scientist Emeritus geologist with the U.S. Geological Survey in Denver, Colorado. He received B.S. and M.S. degrees in geology from the University of Oregon. His research has focused on coal geology, geochemistry, and sedimentology utilizing data from petrographical, mineralogical, and geological analysis of coal and coal-bearing rocks. Mick has worked extensively in both domestic and foreign coal and petroleum systems, with particular focus on regional stratigraphic studies of Cretaceous and Tertiary coal-bearing sequences in northwest Colorado to support resource evaluation. He was a key member of the National Coal Assessment, National Oil and Gas Assessment for the northwestern United States, the 2012 World Petroleum Assessment, and the Green River Formation Oil Shale Assessment. He has been involved in USGS programs designed to provide technical assistance to foreign countries in defining and developing their resources, including Mauritania and Bulgaria and a multiyear project in Armenia, where he served as a consultant to Armenian geologists on coal exploration and resource assessment. Currently he is conducting assessments for the National and Global Assessment of Petroleum Resources Project on basins in Sub-Saharan Africa.