STRATIGRAPHY, DEPOSITIONAL ENVIRONMENT, AND RESERVOIR CHARACTERIZATION OF THE OSAGE-LAYTON SANDSTONE IN NORTH-CENTRAL OKLAHOMA

By

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Major Field: GEOLOGY

Abstract:

The Osage-Layton sandstone is an important oil- and gas-producing reservoir in Oklahoma. Previous studies have concluded that the Osage-Layton sandstone (also known as the Cottage Grove sandstone in central and northwest Oklahoma), was deposited in a fluvial deltaic setting that was sourced from the Ouachita Mountain region of southeastern Oklahoma. Little is known about the sandstone on a localized scale. The purpose of this study was to develop a better understanding of the distribution and depositional environment of the Osage-Layton sandstone from a regional scale and relate it to reservoir characterization of the sandstone on a localized scale. A combination of regional cross-sections, structure, and thickness maps were used to evaluate regional and local structure, depositional environments and sandstone distribution. It was concluded that the general paleo dip at the time of deposition of the Osage-Layton sandstone was north-north westward. Paleo shorelines that trend in a southwest to northeast direction were interpreted from distribution of delta front deposits and localized limestone banks. Core facies from eight wells were described and used to interpret Osage-Layton sandstone depositional environments. Cores from the Garrity #10-24 and Hart #4-24 wells were sampled for thin-section petrography to determine constituents, porosity types, and reservoir quality. The lower Osage-Layton sandstone is interpreted to be a series of stacked channels with thin intervals of flooding and tidal reworking. Between the upper and lower Osage-Layton sandstones is a middle section that is interpreted to be a zone of tidal flat deposits. The upper Osage-Layton sandstone appears to be mostly tidal deposits. Based on these findings, it is concluded that the Osage-Layton sandstone was deposited initially in a deltaic setting that was influenced by both fluvial and tidal processes. Tidal processes dominated upper Osage Layton deposition. In order to fully understand the Osage-Layton sandstone at the field scale, it is necessary to integrate depositional features, constituents, porosity, and reservoir data from core with sandstone distribution patterns, interval thicknesses, and wireline log and core-derived electrofacies to construct a reasonable reservoir model.

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CHAPTER I

INTRODUCTION

Location of Study Area

The Osage-Layton sandstone is an important oil- and gas-producing reservoir in northern Oklahoma. According to DrillingInfo (2018) the Osage-Layton sandstone has produced about 60 million barrels of oil and about 350 billion cubic feet of gas. This study examines regional distribution patterns for the Osage-Layton dispersal system and interprets depositional processes in a smaller area with an extensive dataset.

The study area encompasses a five-by-five township area of approximately 900 square miles and includes townships 22 north to 26 north and ranges 1 east to 5 east within Kay, Noble, Pawnee, and Osage counties in north-central Oklahoma (Figure 1).

Statement of Problem

The purpose of this study was to develop a better understanding of the stratigraphic framework, depositional environment, and controls of reservoir quality for the Osage-Layton sandstone (Figure 2). This research will hopefully encourage future exploration and development opportunities in this and other analogous Pennsylvanian sandstones such as the Tonkawa, Layton, Cleveland, Prue, and Red Fork sandstones.

Previous Investigations/Literature Review

The Oklahoma Geological Survey conducted a series of studies in 1996 and 1997 on what they interpreted as fluvial-dominated deltaic reservoirs. These reservoirs include, in ascending stratigraphic order, the Bartlesville (Andrews, et al., 1997), Red Fork (Andrews, et al., 1997), Skinner and Prue (Andrews, et al., 1996), Peru and Cleveland (Andrews, et al., 1997), Layton and Osage-Layton (Andrews, et al., 1997), and Tonkawa (Andrews, et al., 1997) sandstone plays.

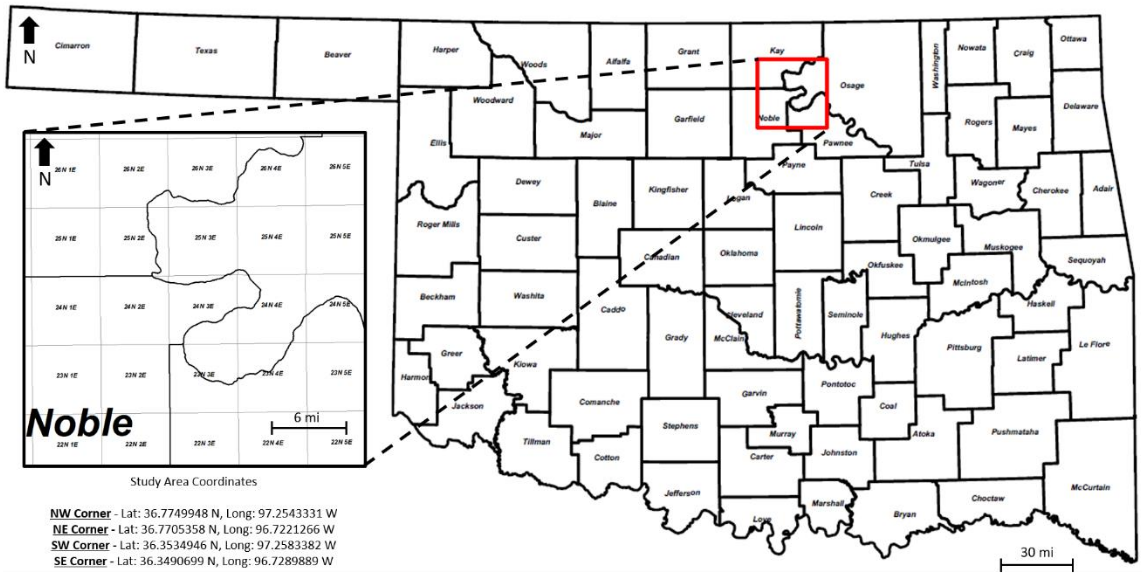

Figure 1: Location of study area (inset) within north-central Oklahoma.

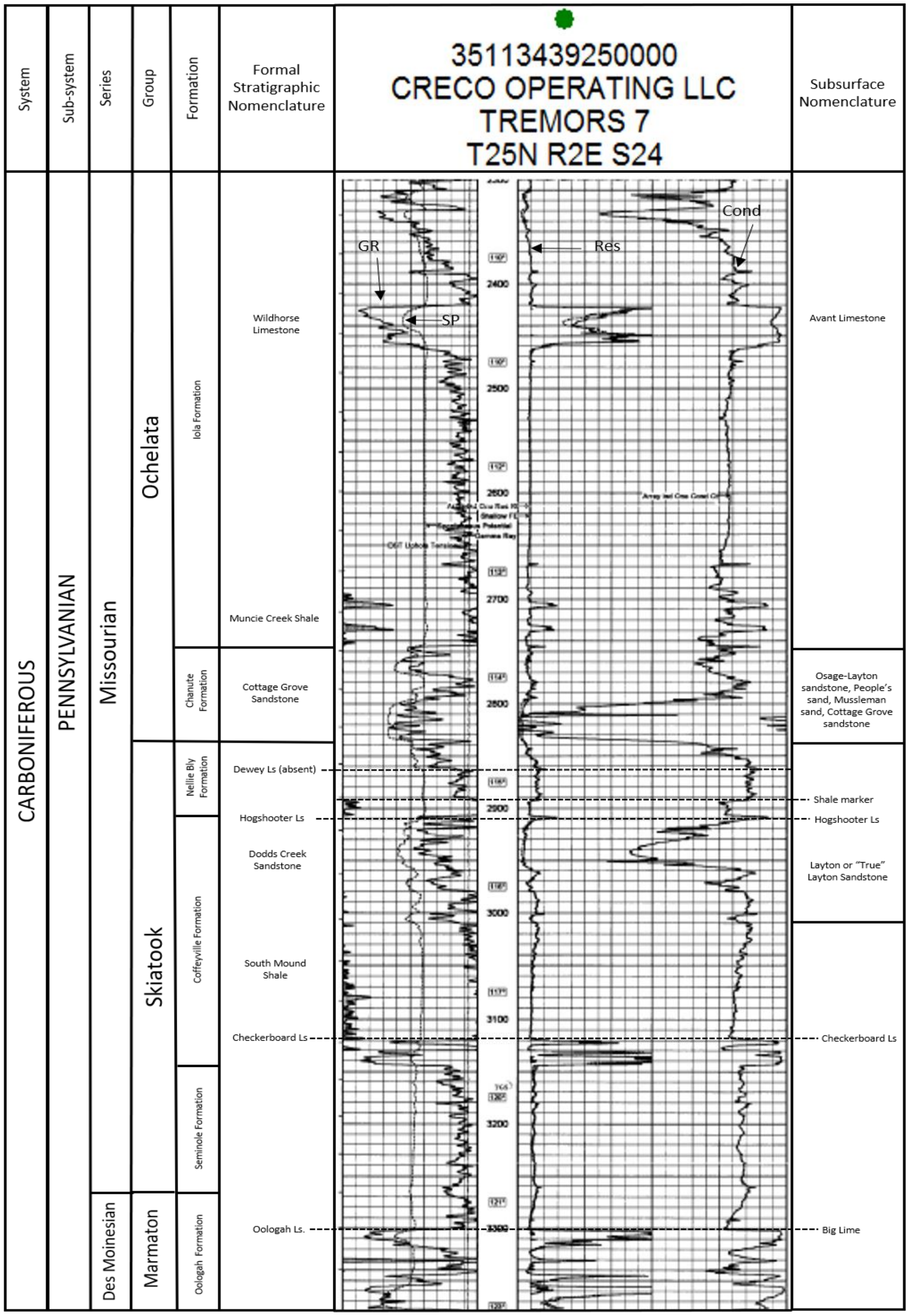

Figure 2: Representative wireline log showing gamma-ray (GR), spontaneous potential (SP), resistivity (Res) and conductivity (Cond) curves for the interval of study from the Checkerboard Limestone up to the Avant Limestone. Outcrop (formal) stratigraphic nomenclature is left of log curves; informal subsurface nomenclature is to the right. Wireline log is from a well drilled in section 24, T.25N., R.2E., Big Bend field area, Osage County, Oklahoma.

Studies of the Osage-Layton using subsurface data include Lalla (1975) who studied the paleogeography at the time of Osage-Layton deposition and concluded that the Osage-Layton sandstone was deposited in a deltaic setting and that the source of the sandstones for both the Layton and Osage-Layton was most likely from the Ouachita Mountains region in southeast Oklahoma. Lalla (1975) interpreted the Osage-Layton as a fluvial-dominated delta with major channel sandstones, distributary sandstones, interdistributary bay deposits, and mouth bars. Other studies include Visher (1996) who applied a sequence stratigraphic framework to the Layton and Cottage Grove (Osage-Layton) depositional systems, Knapp and Yang (1996) who focused on reservoir engineering in the East Lake Carl Blackwell field, Payne County, and Mish (1985) who mapped sandstone distribution and used cores to determine the clay mineralogy of the Layton and Osage-Layton sandstone and concluded that glauconite, illite, and kaolinite were present and that the depositional environments were likely mixed marine and deltaic (Mish, 1985). Studies of the Missourian and Virgilian Series in north-central Oklahoma include Fambrough (1963) who used thickness and distribution of, lithologies in each series to develop a relationship between structural and depositional history and Heckel (2013) who clarified outcrop stratigraphy by constraining lithostratigraphic sections using core shales and conodont biostratigraphy. Additional studies of note are Bross (1960), Oakes (1940), Bennison (1972a, 1972b, 1972c), Towns (1978), Calvin (1965), and Visher and Rennison (1978). Visher and Rennison (1978) proposed all the Coffeyville Formation (“True” Layton interval) was a fluvial-dominated delta that prograded into an epeiric sea (Figure 3).

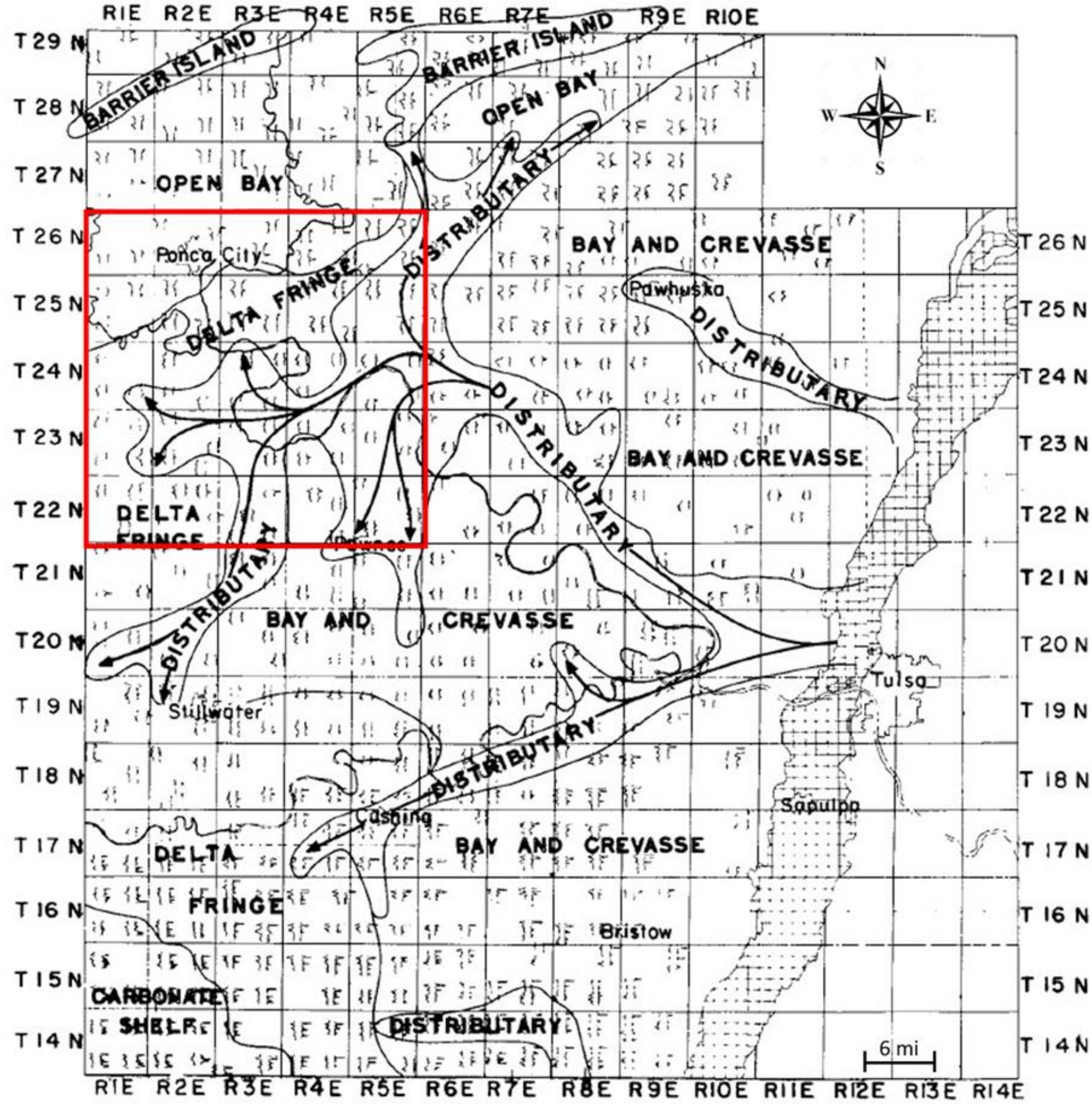

Figure 3: Environmental reconstruction of the Coffeyville Formation ("True" Layton interval) from Visher and Rennison (1978), with the current study area shown by red box.

Methodology

This study begins with a regional-scale analysis of the Osage-Layton sandstone and then focuses on the sandstone at the field scale in the Big Bend West field of eastern Kay and western Osage Counties. Cardinal River Energy provided much of the data used in the study, which included well information, wireline logs, and production data for approximately 10,000 wells. Cores and core samples used for petrographic and mineralogic analysis were provided by the Oklahoma Geological Survey Oklahoma Petroleum Information Center (OPIC).

Approximately 20,000 well logs were used to identify regional stratigraphic surfaces and to determine the geometry and distribution of sandstone bodies. Correlation of the intervals of interest was established by construction of six cross-sections (Plates 1-6) seen on figure 4. Stratigraphic surfaces such as radioactive "core" shales were identified in order to recognize sequence packages that can be correlated across the study area. Figure 2 shows a type log for the area.

Three structure maps were constructed using consistent, transgressive limestones and the top of the main interval of interest. In ascending stratigraphic order, these maps include the Checkerboard Limestone, Hogshooter Limestone, and the Osage-Layton sandstone.

Isopach maps were made for intervals from the top of the Checkerboard Limestone to the top of the Hogshooter Limestone, the top of the Hogshooter Limestone to the top of the "Shale Marker", the top of the "Shale Marker" to the base of the Osage-Layton sandstone, and the base of the Osage-Layton sandstone to the top of the Osage-Layton sandstone to illustrate the thickness and geometry of the main sequences seen in this region. These are indicative of accommodation space and helped to establish paleogeography during deposition and the expected orientation of sediment dispersal systems.

To determine thickness and distribution of the individual Osage-Layton sandstones in locales where the Osage-Layton is productive, isolith maps were constructed. These maps help improve understanding of trapping mechanisms and trends of thicker and better quality reservoir rock (higher porosity and permeability), thereby improving exploration and development strategies.

Access to cores of the Osage-Layton sandstone from 8 wells (Table 1) was provided by the Oklahoma Geological Survey's Oklahoma Petroleum Information (OPIC) Center in Norman, Oklahoma. These cores were examined and described to construct a detailed facies description for the Osage-Layton sandstone and identify depositional features useful in interpreting depositional environments. Cores from the Garrity #10-24 and the Hart #4-24 were sampled for thin-sections. These thin-sections were examined with an Olympus BX 51 petrographic microscope and the results used to determine grain size, pore type and size, and detrital and authigenic minerals. Grain density, porosity and permeability measurements were acquired and used to relate reservoir quality to depositional environment. Core lab analysis reports for the remaining 6 cores, along with several other cores that were not available for viewing, were provided by OPIC and are included in Appendix A.

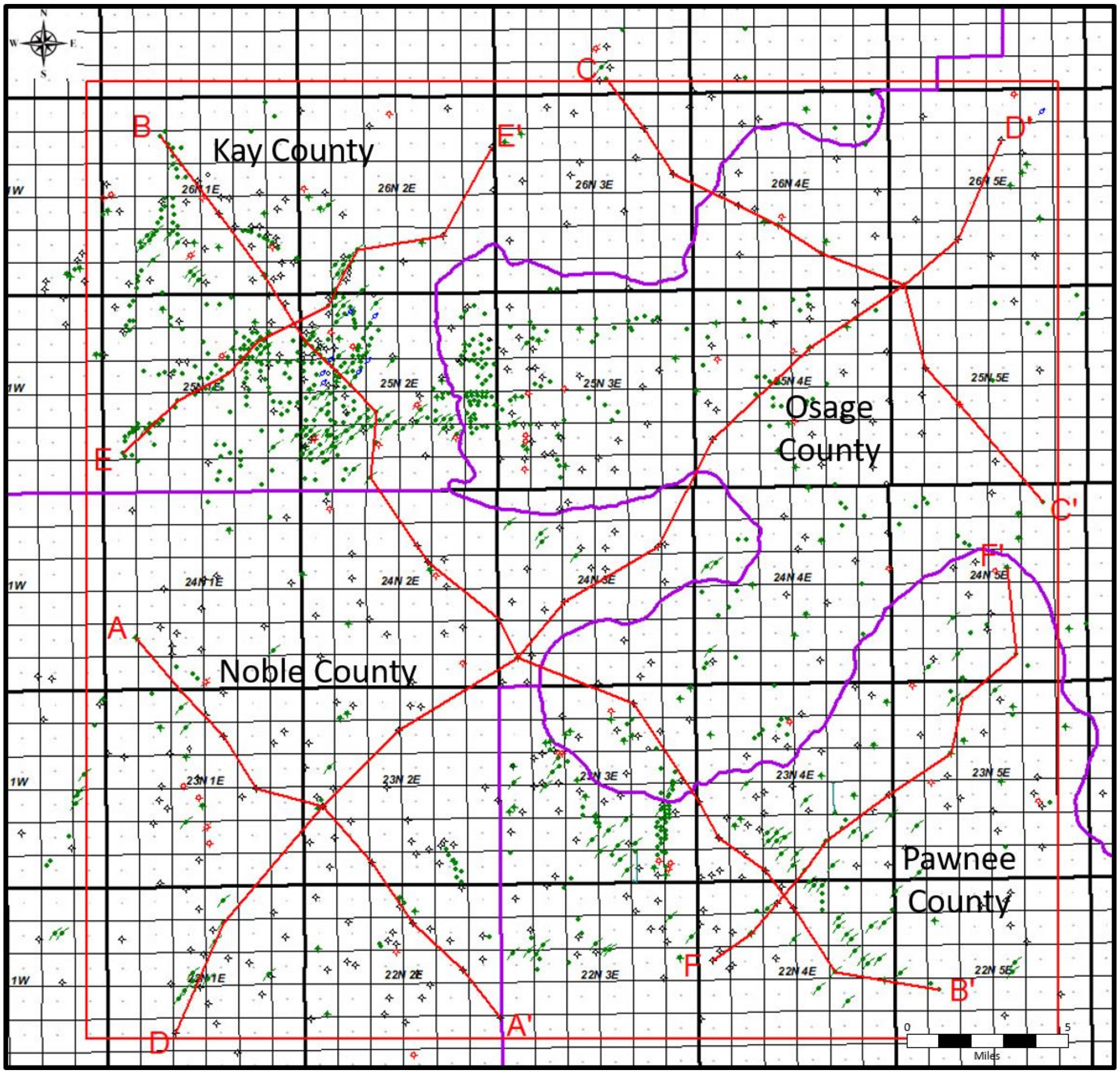

Figure 4: Map of study area with locations of regional cross-sections A-A', B-B', C-C', D-D', E-E', and F-F'.

Table 1: List of wells with cored intervals examined in this study. Core descriptions are located in Appendix A.

Well Name	Location	County	Formation	Cored Interval (feet)
Hart #4-24	Sec 24-25N-2E SE SW NE	Osage	Upper and Lower Osage-Layton	2770-2800 2814-2903
Garrity #10-24H	Sec 24-25N-2E NE SE NW	Osage	Upper Osage-Layton	2840-2870
Secrest #2	Sec 19-25N-3E SW SW SW	Osage	Upper Osage-Layton	2781-2805
Irwin (Osage) #2	Sec 18-25N-3E NE SE NE	Osage	Upper Osage-Layton	2811-2830
Wah-Sah-Po #1	Sec 21-25N-3E SW SW NW	Osage	Upper and Lower Osage-Layton	2785-2861.6
Marchesoni #1	Sec 28-25N-3E SE SW NW	Osage	Lower Osage-Layton	2847-2882.2
Cyril #1A	Sec 29-25N-3E NE SE SE	Osage	Lower Osage-Layton	2805-2830
Nuckols 2	Sec 25-25N-2E SE NW NE	Osage	Upper Osage-Layton	2770-2797

CHAPTER II

STRATIGRAPHIC/TECTONIC FRAMEWORK

Tectonic Framework

The Pennsylvanian sub-period of the Carboniferous Period was a time of intense tectonic activity as Laurentia and Gondwana collided, continuing the formation of the major geologic provinces in Oklahoma. During Middle to Late Pennsylvanian several major cratonic uplifts and subsiding basins were active, forming the geologic provinces recognized today (Figure 5). The area of study is located on the Cherokee Platform, also referred to as the Central Oklahoma Platform (Figure 5). The Cherokee Platform is bordered on the west by the uplift and faulting of the Nemaha Uplift. To the west of the Nemaha Uplift was the subsiding Anadarko Basin that forms the southwest boundary for the Cherokee Platform. Towards the southeast were the Ouachita Mountain uplift and concurrent subsiding foredeep Arkoma Basin. The Ozark uplift at this time was at best a low-relief positive feature, making its contribution to the deposition and distribution of the Osage-Layton interval minimal (Rascoe and Adler, 1983). According to the paleogeographic map of the Southern Midcontinent (Rascoe and Adler, 1983) the major source of sediment during the Missourian and Osage-Layton deposition was the Ouachita Uplift (Figure 6).

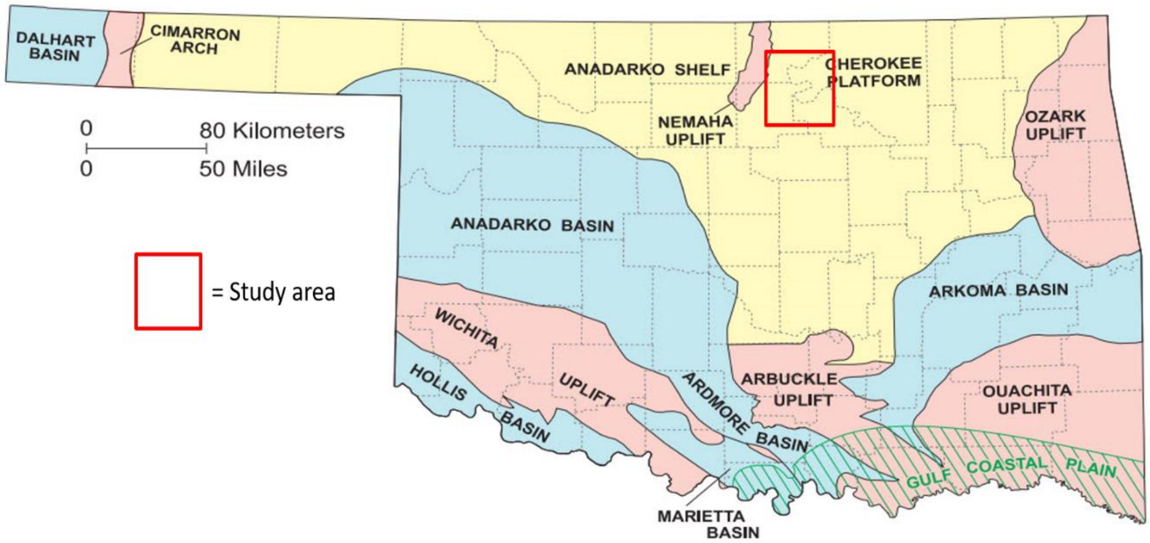

Figure 5: Map of the major geologic provinces of Oklahoma from Johnson (2008). Red box represents study area.

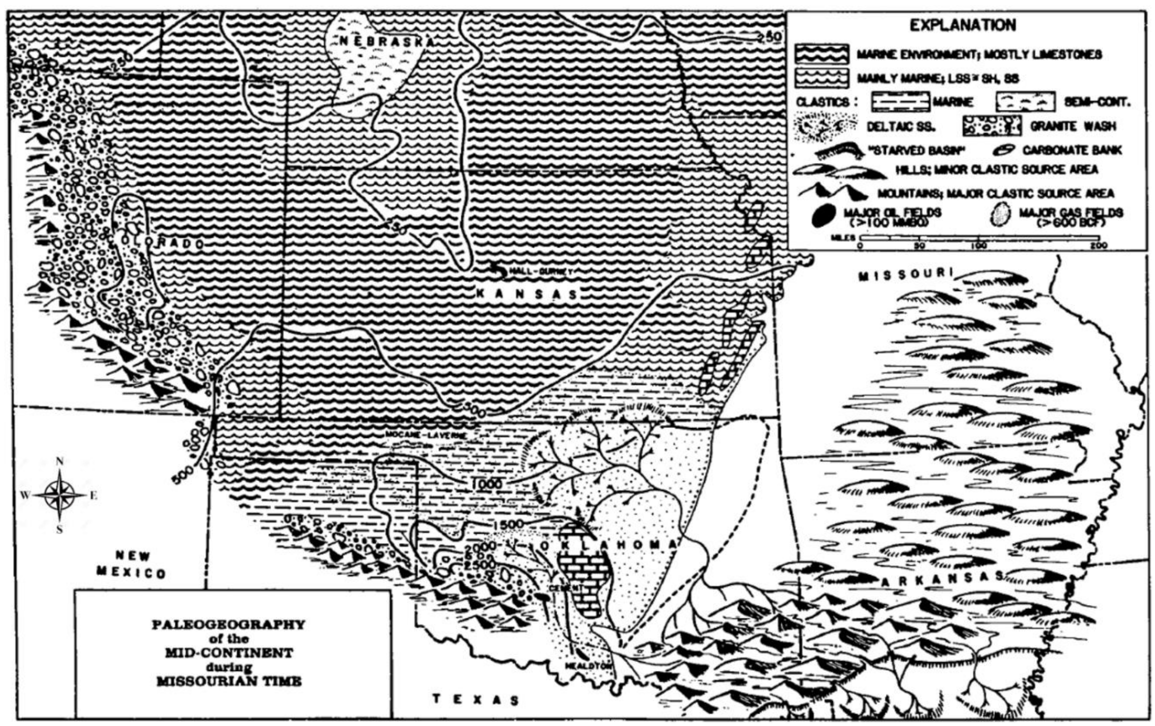

Figure 6: Paleogeographic map of the Southern Midcontinent during Pennsylvanian Missourian time from Rascoe and Adler (1983).

Missourian Series

The lithostratigraphic units that make up the Missourian Series (Figure 2) extend from the base of the Seminole Formation to the base of the Tonkawa sandstone. For the purposes of this study, only those rocks within the Skiatook and Ochelata groups are considered including the Seminole Formation, Coffeyville Formation, Nellie Bly Formation, Chanute Formation, and Iola Formation (Figure 2). The names of subsurface units shown on figure 2 do not conform to standard rules of stratigraphic nomenclature and are meant to aid the reader in recognizing the operational informal terminology utilized by the oil and gas industry in Oklahoma.

The Skiatook Group extends from the top of the Holdenville Shale to the Dewey Limestone. Within the study area (Figure 1), the Dewey Limestone is absent, so the upper boundary of the Skiatook Group is defined as the base of the Osage-Layton sandstone. This group consists of mostly sandstone and shale with important limestones such as the Hogshooter and Checkerboard that are lithostratigraphic marker beds. The commonly recognized sandstones within the Skiatook Group are the Cleveland sandstone, and lower Layton sandstone that is also known to the petroleum industry as the “True” Layton sandstone. The Cleveland sandstone is the oldest rock-stratigraphic unit in the Skiatook Group, but is not discussed in this study. For more information concerning the Cleveland sandstone the following sources are recommended: Krumme and Visher (1972), Bacon (2010) and Cain (2018).

The next distinct lithostratigraphic unit is the Checkerboard Limestone. This transgressive limestone directly overlies the Cleveland sandstone interval and is widely distributed throughout the study area, making it a useful stratigraphic marker bed. As is evident on figure 2, the Checkerboard Limestone has a distinct wireline log signature with Rt (deep resistivity) exceeding 40 ohm-m and gamma-ray measurements mostly between 30 and 45 API units.

The operational term for the shale-sandstone section above the Checkerboard Limestone is the “True” Layton sandstone interval (Figure 2). This interval begins at the top of the Checkerboard Limestone and extends to the base of the Hogshooter Limestone. Based on wireline-log curves, the “True” Layton sandstone interval is mostly shale and sandstone with the occasional thin limestone. Where it is present, the “True” Layton sandstone is typically medium grey to off white, very fine-grained to fine-grained, sub-rounded to sub-angular, and very micaceous (Allen, 2018). Core of the “True” Layton was not available for this study.

Above the “True” Layton sandstone interval lies the Hogshooter Limestone (Figure 2). The Hogshooter is a thin, brown, hard, crystalline, dense (low porosity), sandy limestone with mica, chlorite, and glauconite (Allen, 2018). At less than 5’ thick, the Hogshooter Limestone can be difficult to identify on wireline logs. However, if gamma-ray curves are available, the radioactive shale (Cherryvale Shale, Heckel, 2013) immediately above the Hogshooter Limestone is easily recognized. Therefore, this study focuses on the Osage-Layton sandstone that lies stratigraphically above the “True” Layton sandstone.

CHAPTER III

RESULTS

Wireline-log Based Generalized Stratigraphy of the Osage-Layton Sandstone

At the time of deposition of the Osage-Layton sandstone, the general depositional dip was northwest. According to Lalla (1975), the Osage-Layton sandstone was sourced from the eroding Ouachita Mountains in what is now southeastern Oklahoma with possible minor sourcing from the Ozark Uplift to the east. Lalla (1975) suggests the Osage-Layton sandstone formed as part of a large delta system within the study area and surrounding region. This interpretation of the depositional setting of the Osage-Layton sandstone in northeastern Oklahoma was based principally on wireline log data and core. Lalla (1975) used cross-sections and net sandstone isolith maps to show a distributary system in the outcrop that fanned out into a lower deltaic plain just before reaching the study area (Figure 7).

Within the study area, the Osage-Layton sandstone consists of an upper and lower sandstone. The lower sandstone is most prevalent throughout the region and is typically identified as the lower Osage-Layton sandstone. Other names from scout tickets and mud logs include: “Osage-Layton”, “Layton Massive Sand”, “Main Sand”, and “Main Porosity Sand”. The upper sandstone, typically called the upper Osage-Layton sandstone, is used more locally because it is distinctive in the north and northwestern part of the study area and is absent or very difficult to correlate to the east and southeast. This study attempted to distinguish between the upper and lower Osage-Layton intervals, identify depositional environments from available cores, wireline log electrofacies distribution and sandstone geometry, and evaluate the diagenetic history using thin-section petrography.

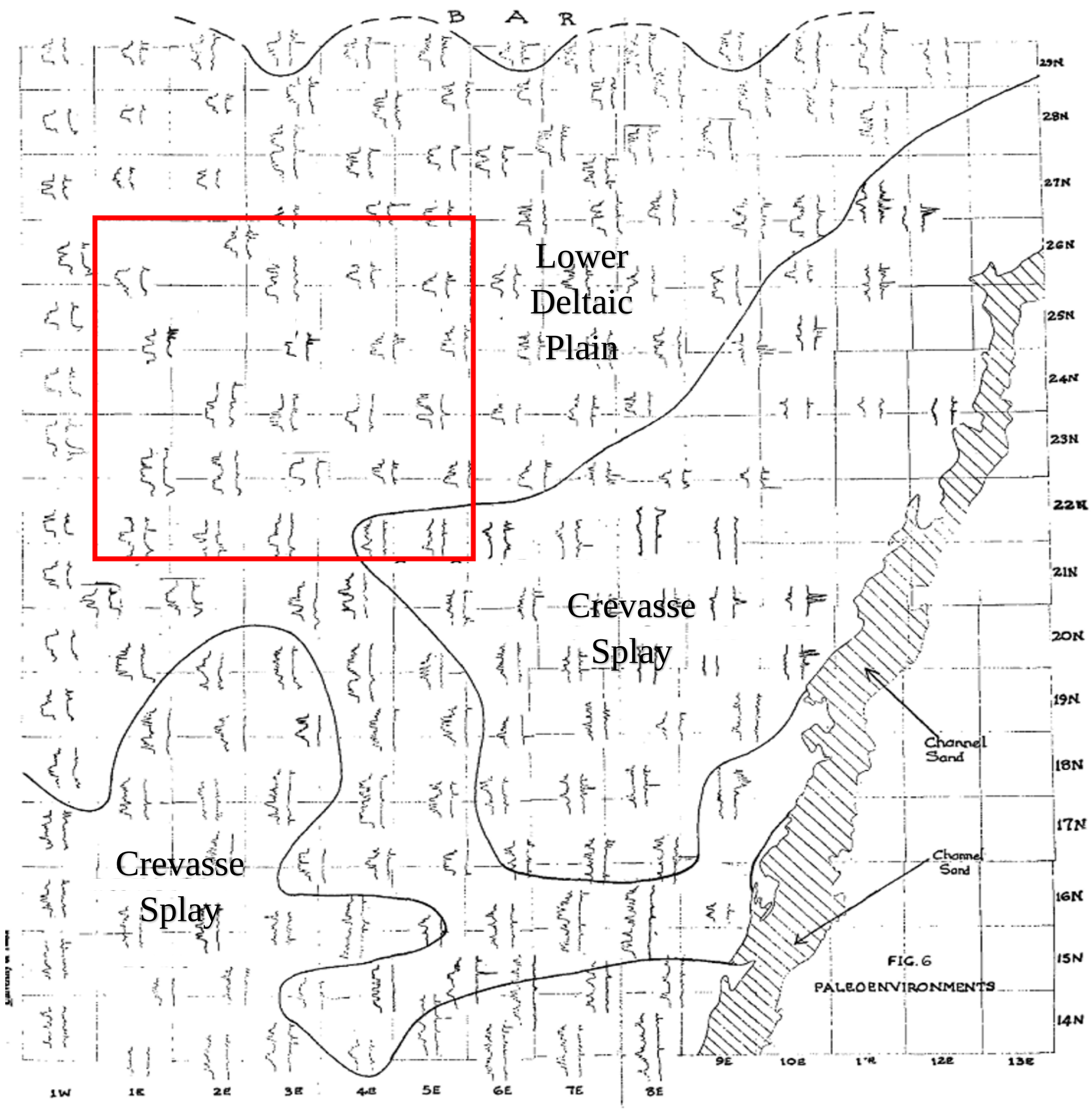

Figure 7: Regional interpretation of depositional environment of the Osage-Layton sandstone of northeastern Oklahoma using wireline log and electrofacies distribution pattern (modified from Lalla (1975)). Red box represents the study area for this thesis.

Core Facies Descriptions

Cores of the Osage-Layton interval were examined and described from 8 wells within a 24 square mile area in T.25N-R.3E and the eastern part of T.25N-R.2E (Figure 8). See Appendix A for core description sheets). Three of those wells, the Hart #4-24, Garrity #10-24H, and the Wah-Sah-Po #1, were near complete and suitable for photography (See Appendices B-D). The cored intervals contain a variety of depositional features and facies including massive to cross-bedded sandstones, interlaminated sandstone and shale, coal, and shale.

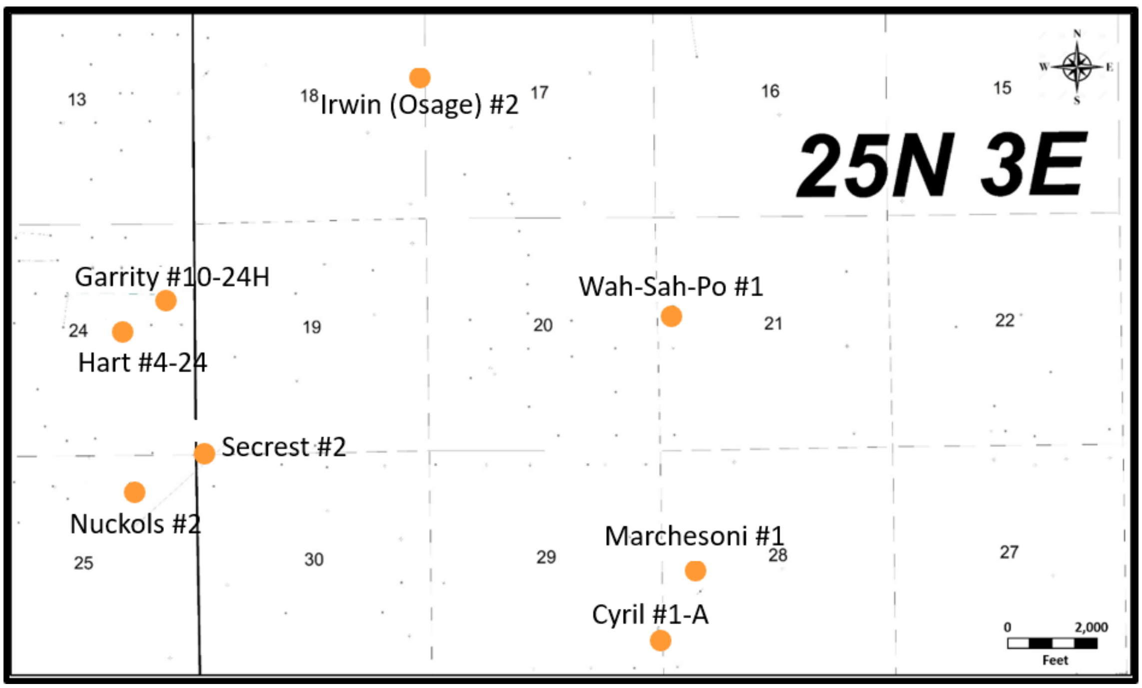

Figure 8: Location of cores examined in T.25N., R.2E. and T.25N., R.3E., Osage County, Oklahoma.

Wah-Sah-Po #1 Core

The Wah-Sah-Po #1 is in the SW SW NW, Section 21, T.25N.-R.3E., Osage County, Oklahoma (Figure 8). The well was drilled by Ceja Corporation in February 1969, and the Osage-Layton interval cored with a 3 ½-inch rotary diamond core bit (See Appendix A). A picture of the log showing the cored interval on the electric log can be seen in figure 9. Full core photographs can be found in Appendix B. From about 2828 feet to the end of the core at 2861 feet is a massive sandstone typically correlated as the lower Osage-Layton, which is a grey to light grey very fine-to-fine grained sandstone. The lower Osage-Layton in the Wah-Sah-Po #1 core contains rip up clasts and climbing ripples near the top, and more small-scale herringbone and planar cross-bedding throughout the rest of the section. At 2826 feet, climbing ripples and wavy bedded features were observed (Figure 10). At 2816.8 feet, there is evidence of herringbone cross-bedding and symmetrical ripple bedded laminae at low angles (about 10-15 degrees). At a depth of 2812 feet, there is a sudden shift in sandstone versus shale. The sandstone to shale ratio almost reverses (Figure 11). The sandstone is less burrowed and slightly larger grain size going from mostly silty to silty and very fine-grained. The shale laminae are much siltier and thinner. At core depth of about 2800 feet, the lithology becomes siltier with wavy and lenticular bedding, vertical and horizontal burrows, and slump features or zones of micro faulting (Figure 12). Dark grey shale is more abundant than lenticular grey sandstone. At core depth 2789 feet, an oxidized zone with calcite nodules, water escape features, burrows, and root traces occur just below the upper Osage-Layton sandstone.

The upper Osage-Layton is described as very fine grained, light grey sandstone with clay rip up clasts (Figure 13), some sideritized. Soft sediment deformation is evident near the base of the sandstone. Marine invertebrate shell fragments identified as brachiopods (2-3 mm in length), occur near the base of the sandstone. No thin sections were sampled from this core.

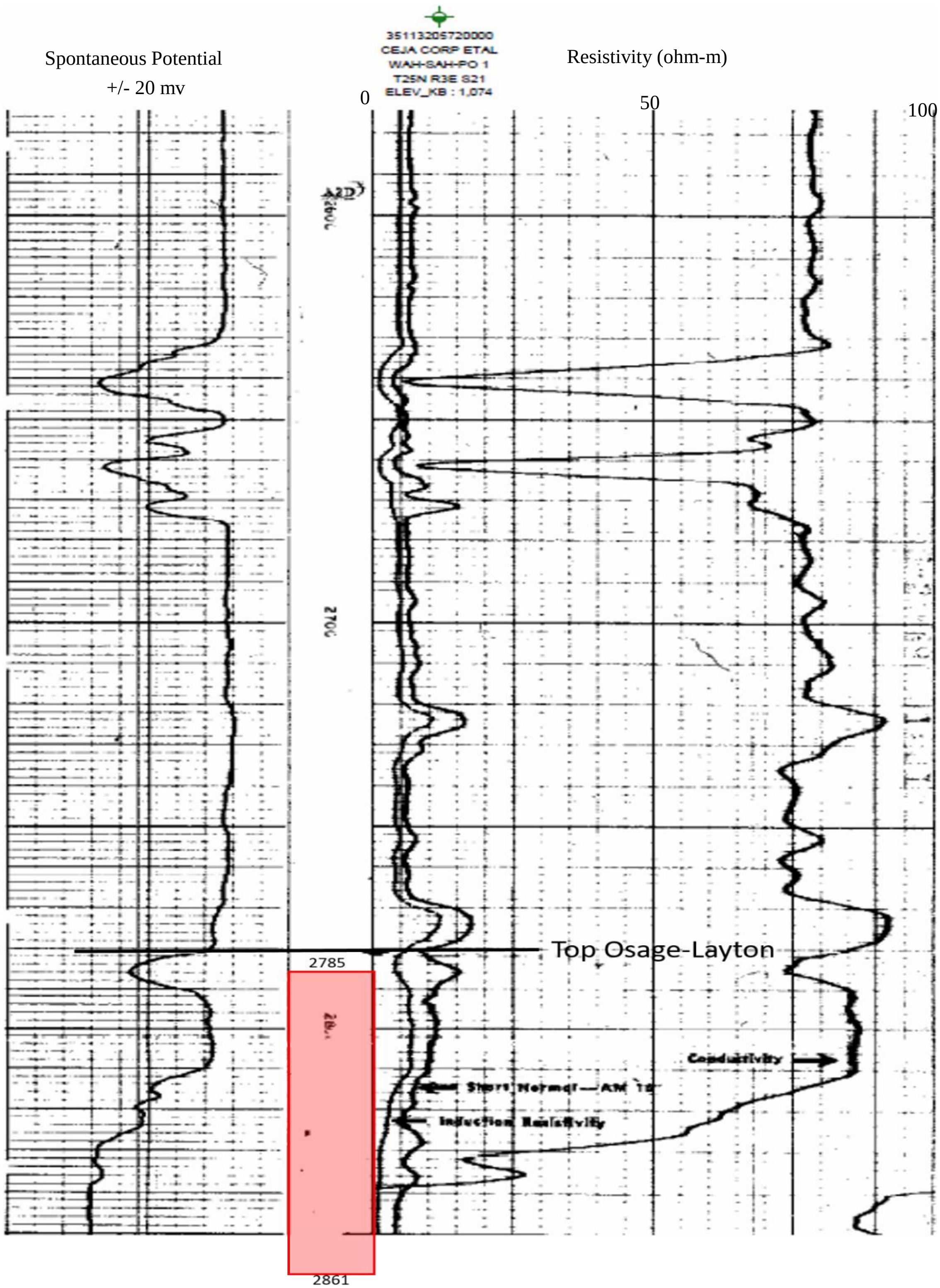

Figure 9: Section of wireline log across the cored interval in the Wah-Sah-Po #1 well with shaded box indicating cored interval. The wireline log did not log to the bottom of the wellbore.

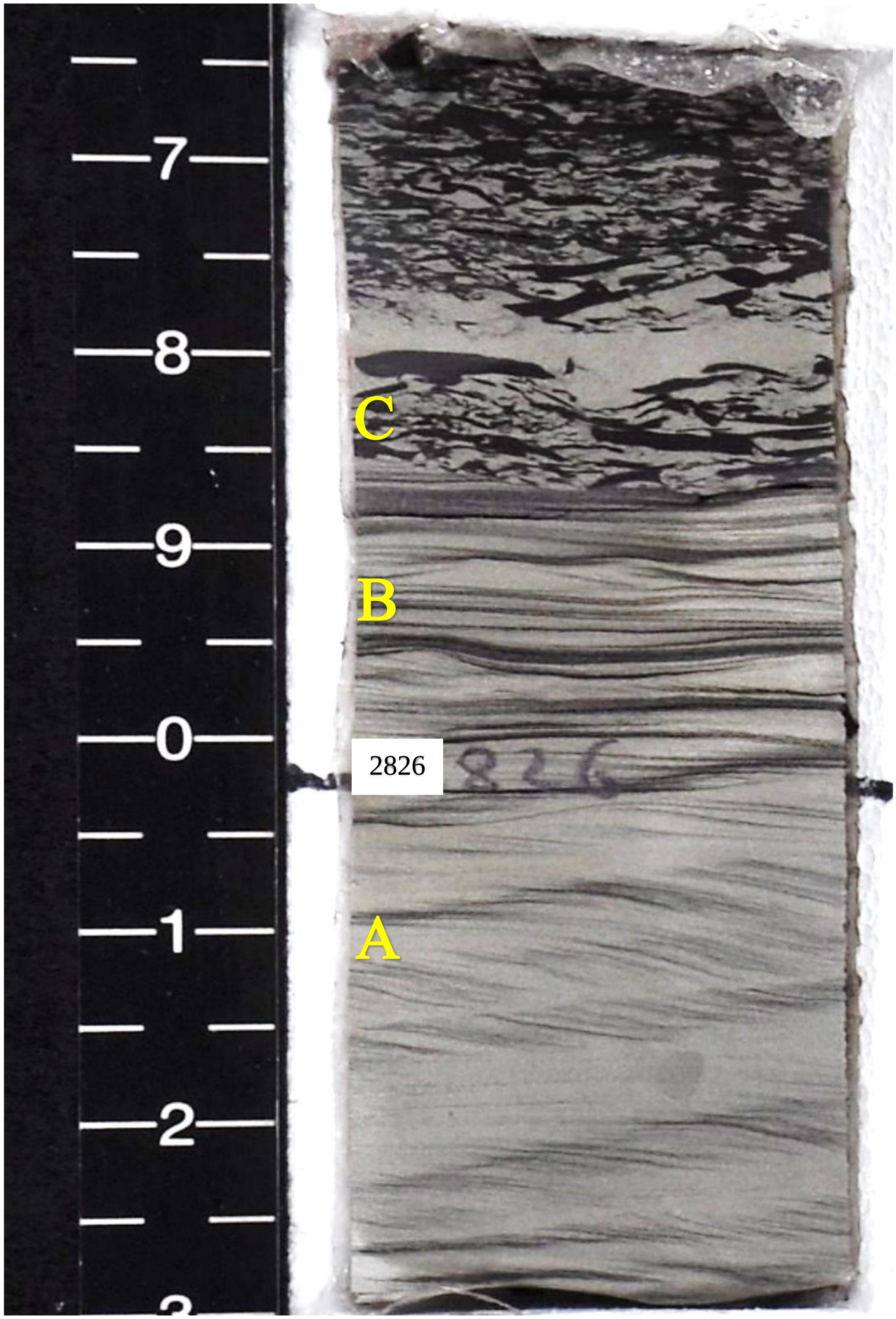

Figure 10: Slabbed core from the Wah-Sah-Po #1 showing an interval of climbing ripples with wavy (A), lenticular bedding (B) above. The top of this slab is a clay clasts rich zone (C) with burrows. Depth 2826 feet. Scale bar indicates tenths of feet.

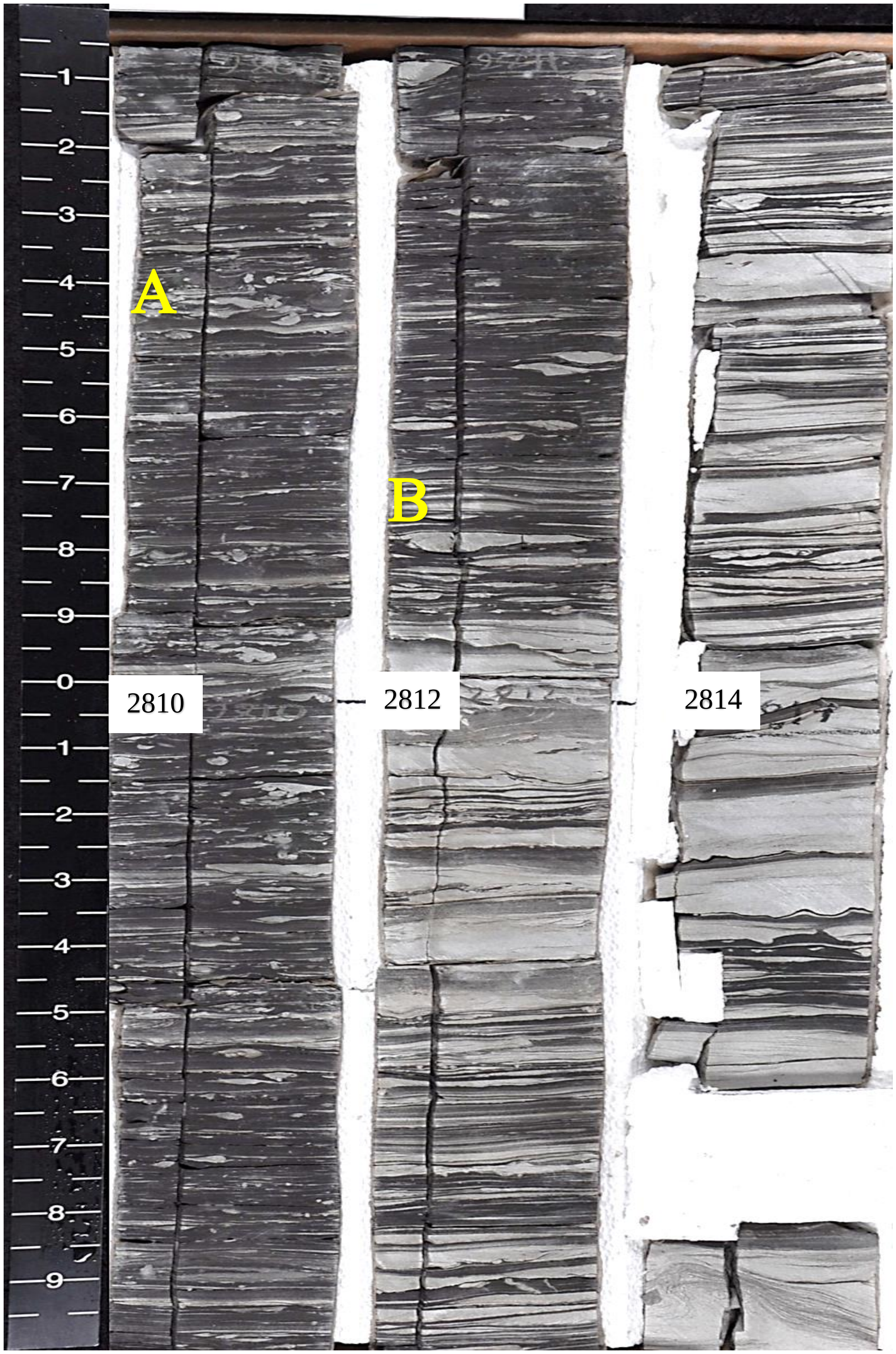

Figure 11: Slabbed core from the Wah-Sah-Po #1 showing an interval of abundant vertical and horizontal burrows (A), wavy lenticular sandstone beds (B), and a sudden change in sandstone to shale ratio around 2811.8 feet. Scale bar indicates tenths of feet.

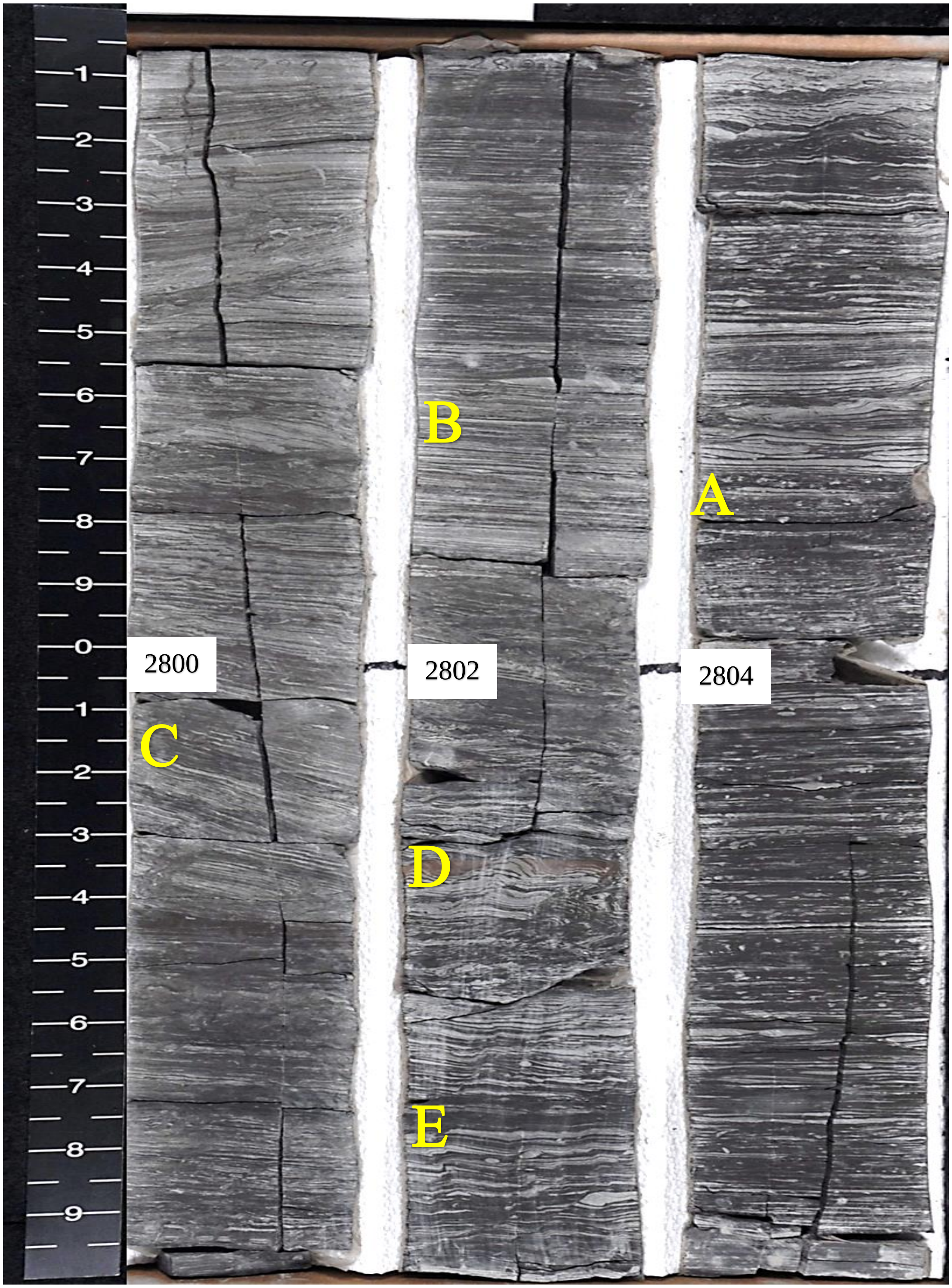

Figure 12: Slabbed core from the Wah-Sah-Po #1 showing an interval of layered burrows (A), alternating thin sand and shale laminae displaying rhythmic deposition (B), dipping/tilted laminae up to 40° (C), water escape features (D), and micro faults/slump features (E). Scale bar indicates tenths of feet.

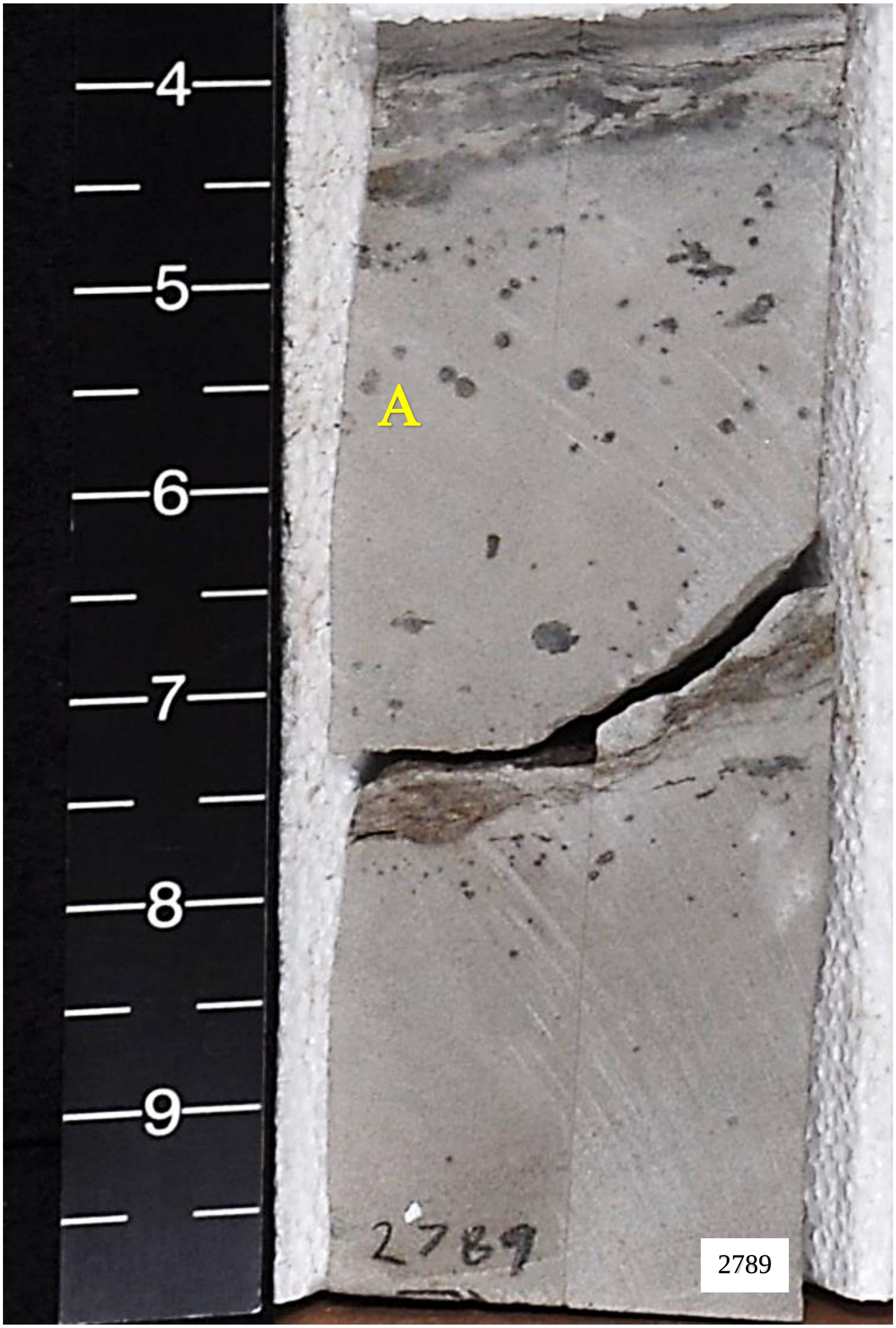

Figure 13: Slabbed core from the Wah-Sah-Po #1 showing clay rip up clasts (A) from 2788.4 to 2788.8 feet. Scale bar numbers indicate tenths of feet.

The Wah-Sah-Po core was sampled for conventional core plugs that were analyzed by Earlougher Engineering. The core report indicated only 2 net feet of permeable Osage-Layton oil-saturated sandstone at cored depth 2829 to 2831 feet. These 2 feet of sandstone had an average permeability of 37 millidarcies and average porosity of 16.6%. The average core oil saturation was 14% and the average core water saturation was 42%. The complete core analysis is in Appendix A.

Hart #4-24 Core

The Hart #4-24, SE SW NE Section 24, T 25 N., R. 2 E., was drilled and cored in the Osage-Layton in August 2014 by Cardinal River Energy. For full core photographs, see Appendix C. When this core was recovered, the light brown staining seen in the upper portion of the core had a very strong odor of oil. Figure 14 shows the open hole wireline log with the cored interval shaded. Plates 7-11 (in pocket) show the core in plain light and ultraviolet light (UV) in order to show oil and gas fluorescence. Top of the lower Osage-Layton interval is 2893 feet. The lower Osage-Layton sandstone is fine to medium grained, cross-bedded at angles of 25° to 30°, interbedded with organic-rich dark shales, and contains rip up clasts up to 1 cm in width (Figure 15). The middle section from about 2893 to 2843.5 feet (Figures 16 and 17) contains abundant sedimentary structures, including hummocky, trough, and planar cross-bedding, flame structures, ripple laminae, and wavy, ripple bedding, and soft sediment deformation. The sandstone in the middle section is very fine grained to silty with sandy shale laminae. The upper Osage-Layton sandstone is from 2840 to 2814 feet. Immediately below the sandstone is a thin coal/dark shale bed (Figure 18). The abrupt contact between the coal/dark shale and overlying sandstone is irregular and indicative of a marked change in energy across the surface. The upper Osage-Layton sandstone consists of interlaminated/interbedded sandstone and shale with soft sediment deformation, medium-grained sandstone above sharp contacts, ripple laminae, clay clasts less than 3 cm in conglomeratic zones, coal at 2821 feet and root traces and burrows in apparent paleosols. A pronounced irregular contact is evident at 2816.7 feet (Figure 19). The sandstone within this interval ranges from silty, very fine to medium grained, and when better porosity is coupled with larger grain size, the sandstone is stained brown with oil (Figures 18 and 19). This sandstone is the reservoir within the Big Bend West field where the Hart #4-24 is located (which will be discussed in more detail further into this study). The uppermost 30 feet of the core consists of radiogenic marine shale above the Osage-Layton sandstone. This dark shale contains marine macroinvertebrate fauna including cephalopods, gastropods, and brachiopods.

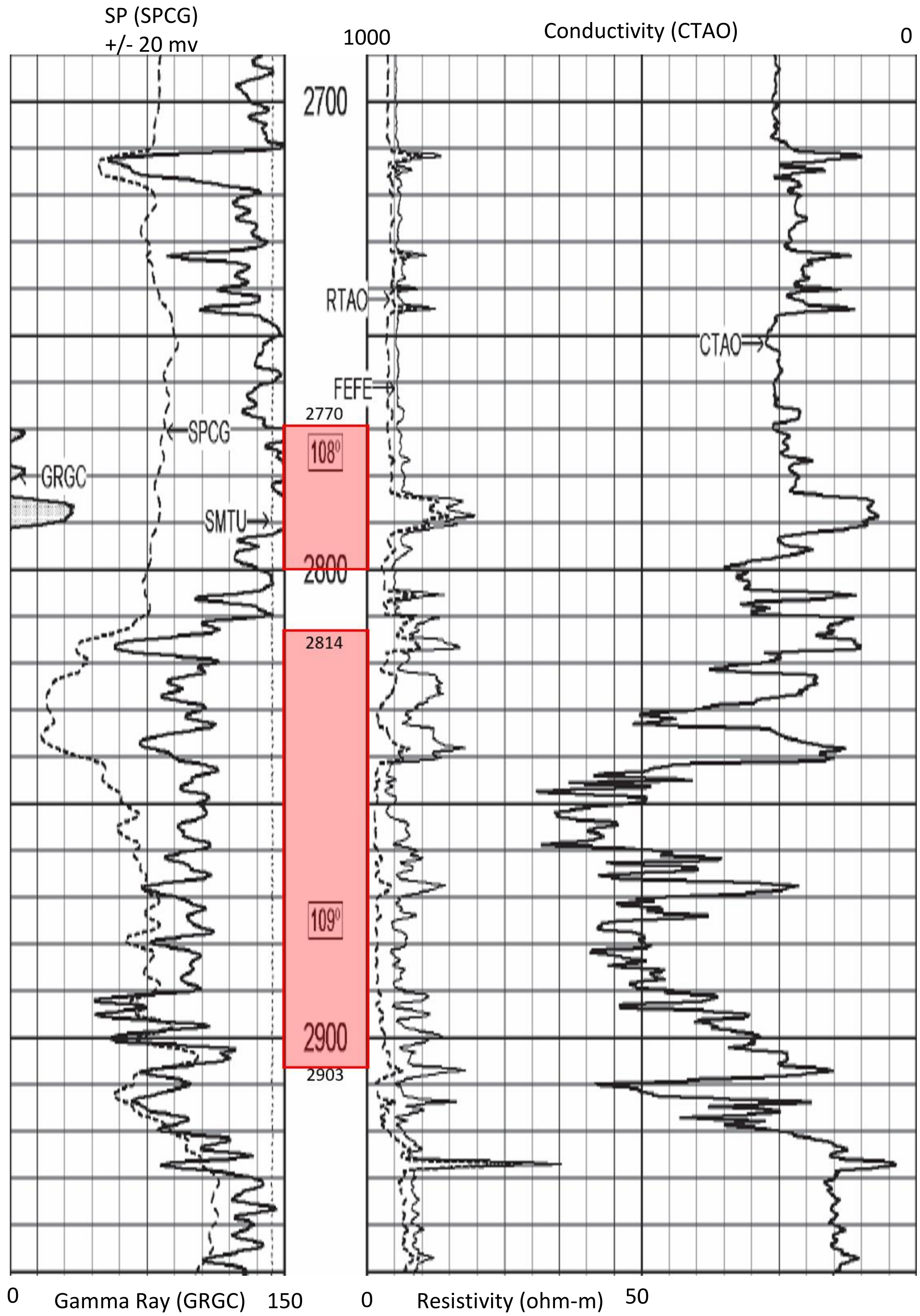

Figure 14: Wireline log across the Osage-Layton interval in the Hart #4-24. Cored interval indicated by shaded box. Log curves are spontaneous potential (SPCG), gamma-ray (GRCG), shallow (FEFE) and deep true resistivity (RTAO), and conductivity (CTAO).

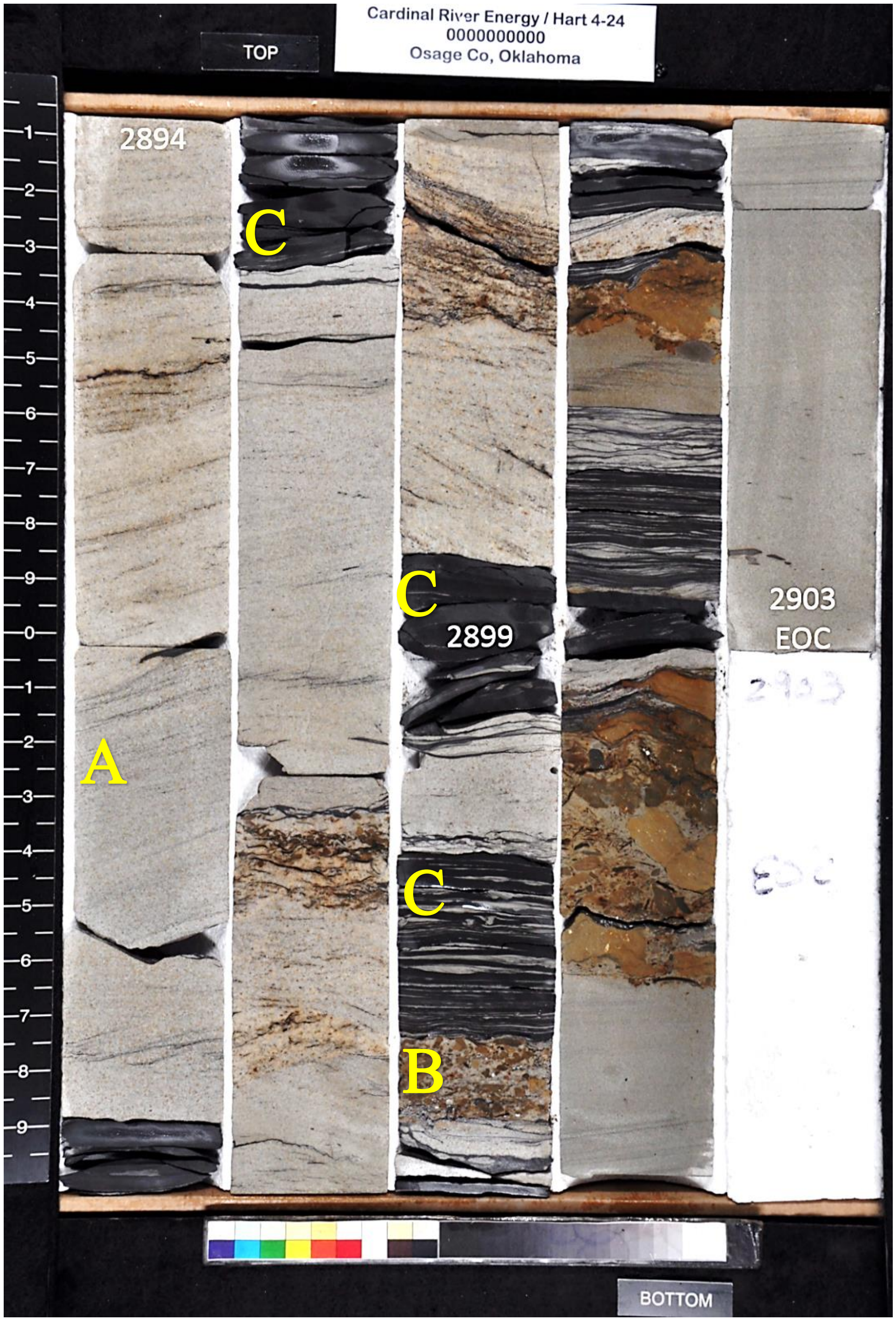

Figure 15: Slabbed core from the Hart #4-24 covering the interval 2904 to 2894 feet. This interval is a series of stacked sandstones with current features including high angle cross bedding (A) and rip up clasts (B). Sandstone bodies are separated by dark shale and interlaminated sandstone and shale (C). Scale bar numbers indicate tenths of feet. EOC: End of core.

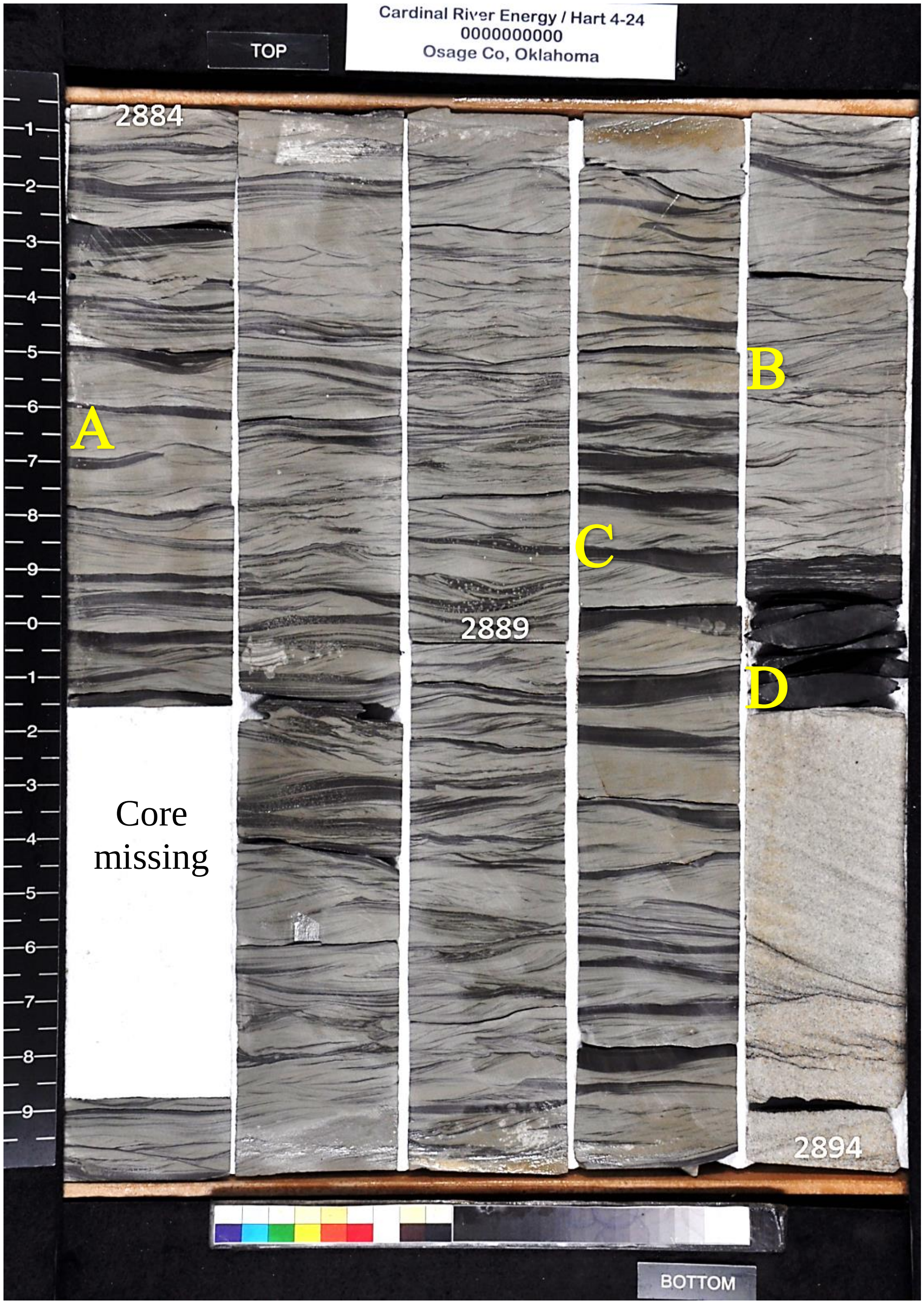

Figure 16: Slabbed core from the Hart #4-24 covering the interval from 2894 to 2884 feet. Wavy ripple bedding (A), hummocky cross bedding (B), and climbing ripples (C) are evident. At 2893 feet, dark shale is in sharp contact with fine to medium-grained sandstone (D). Scale bar numbers indicate tenths of feet.

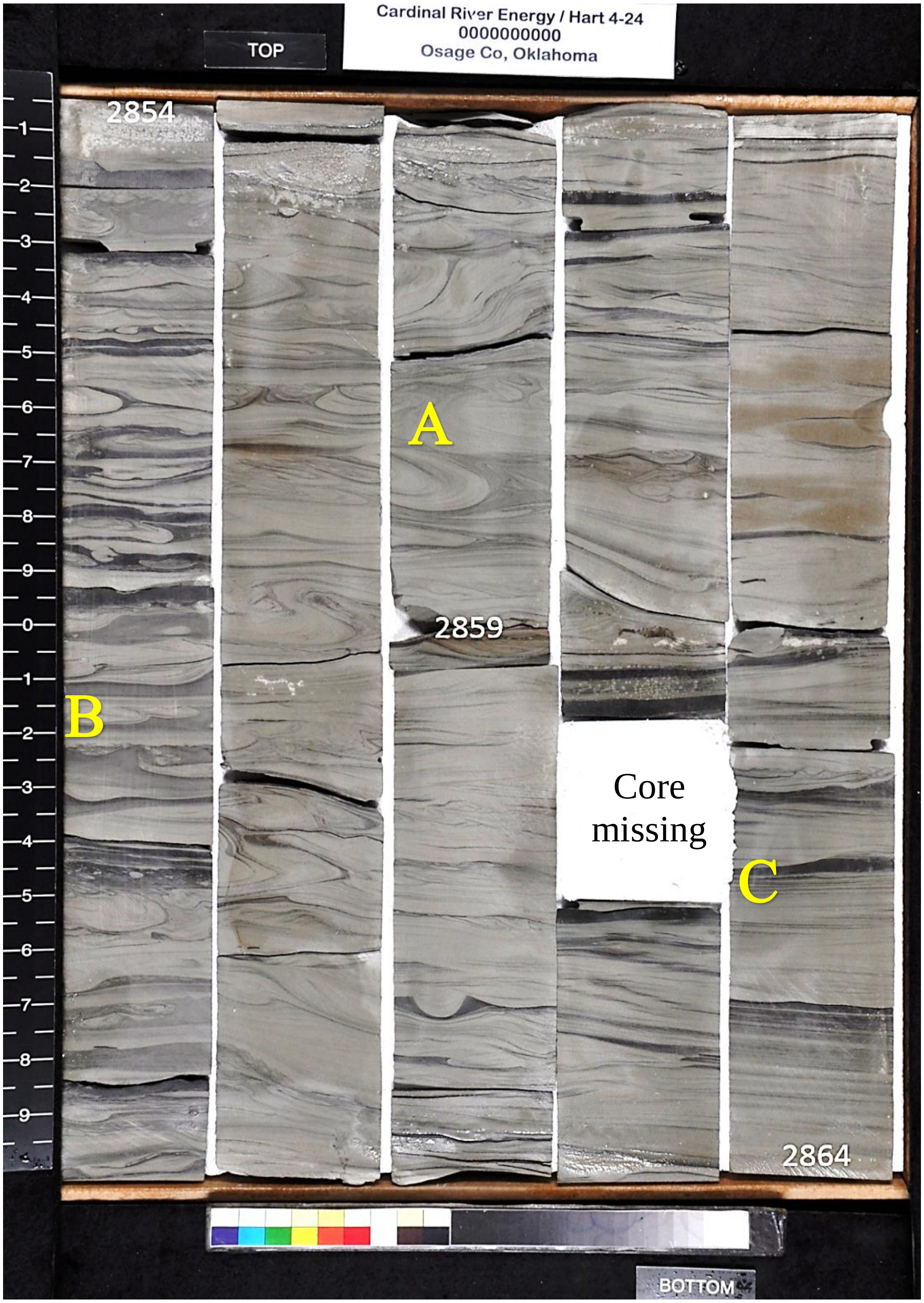

Figure 17: Slabbed core from the Hart #4-24 covering the interval 2864 to 2854 feet. Soft sediment deformation (A) disrupts and contorts bedding. Ball and pillow structures (B) are evident. Distinct hummocky cross bedding (C) is evident at 2863.6 and 2859.2 feet. Scale bar numbers indicate tenths of feet.

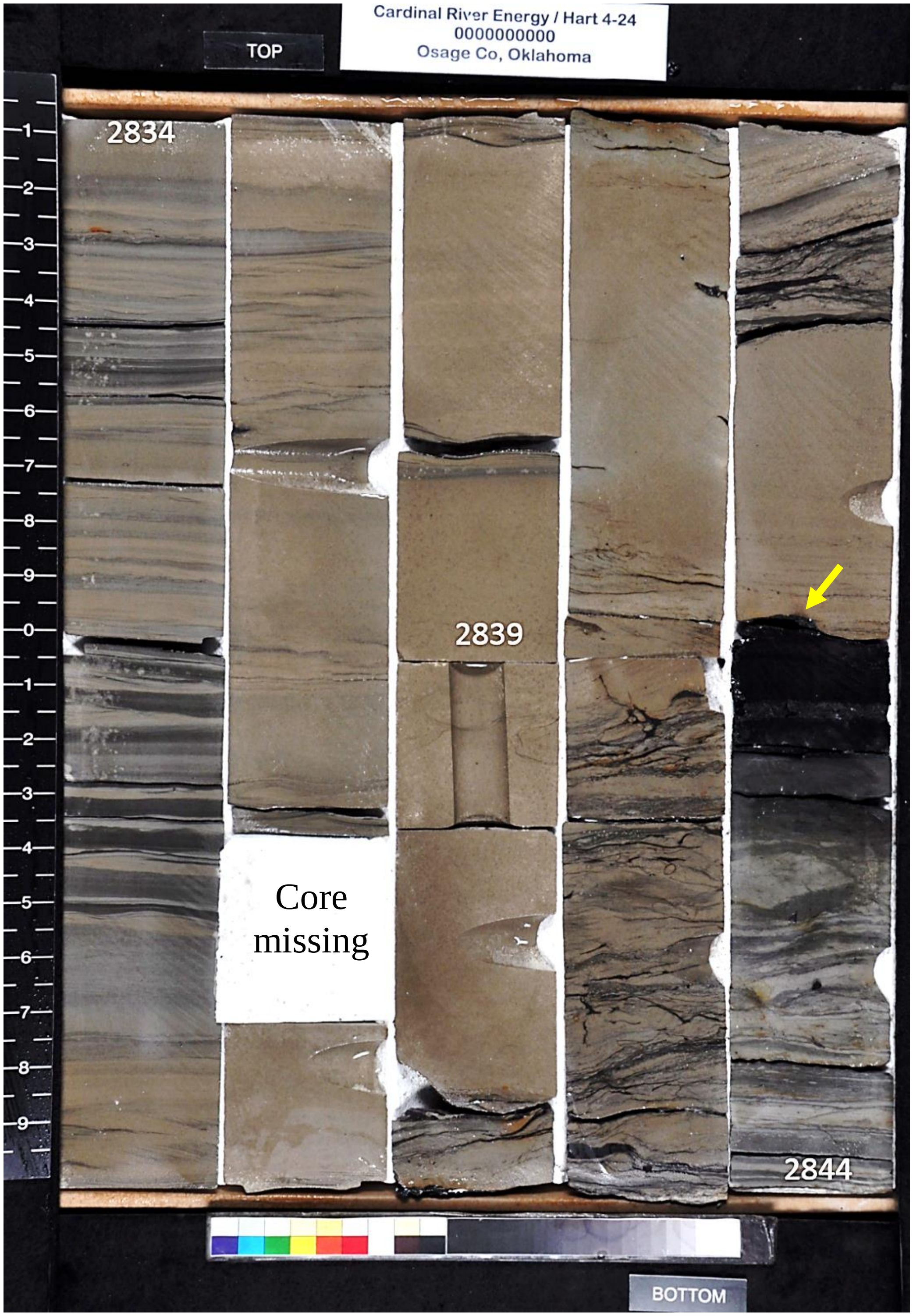

Figure 18: Slabbed core from the Hart #4-24 covering the interval 2844 to 2834 feet. The brown color is oil staining. At 2843 feet, (yellow arrow) is a sharp irregular contact between sandstone and the underlying coal/dark shale. Scale bar numbers indicate tenths of feet.

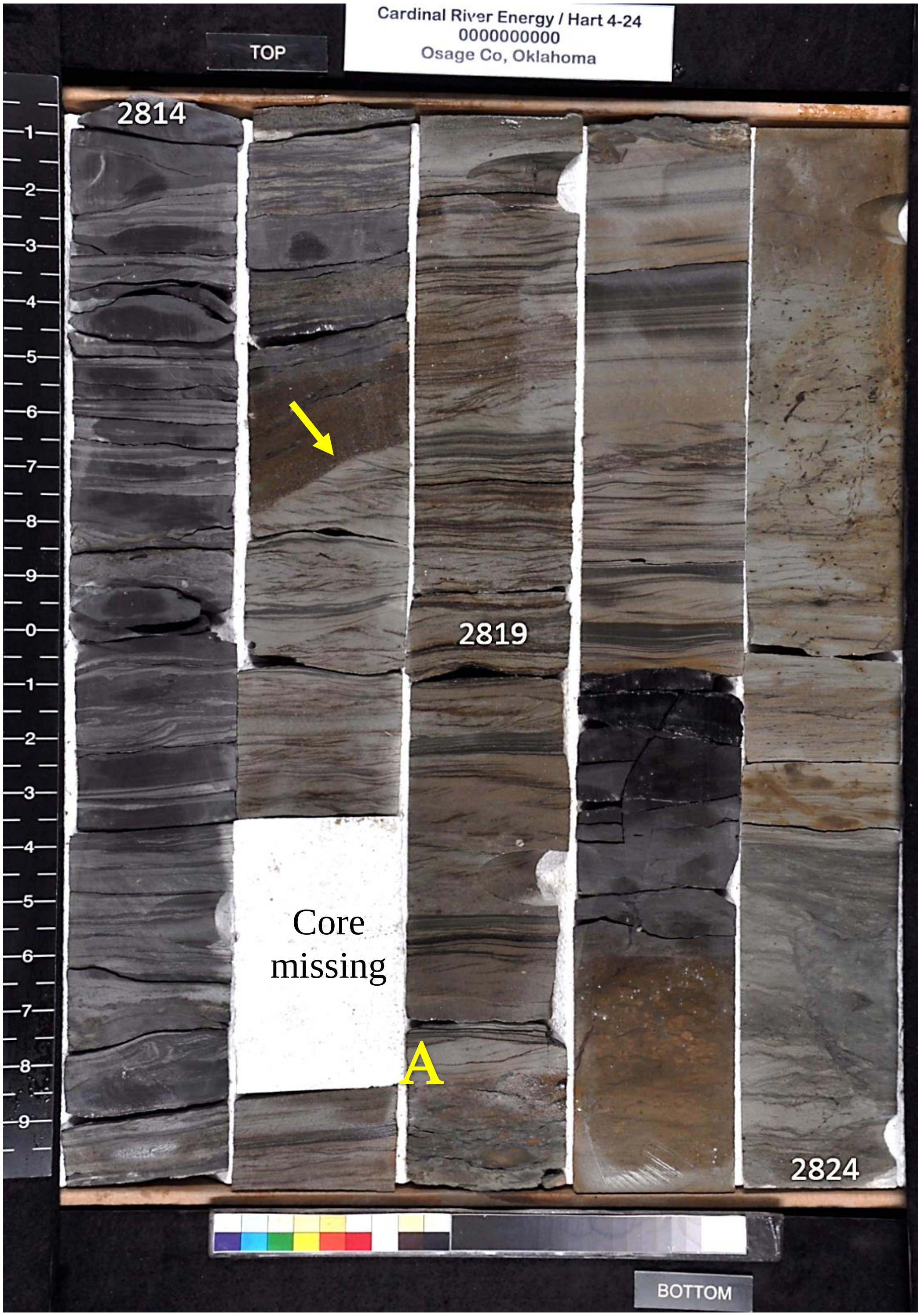

Figure 19: Slabbed core from the Hart #4-24 covering depth 2824 to 2814 feet. Notice the sharp irregular contact at 2816.7 feet (yellow arrow). At 2819.8 are possible siderite nodules (A). The brown color is the result of oil staining. Scale bar numbers indicate tenths of feet.

Garrity #10-24H Core

Cardinal River Energy drilled the Garrity #10-24H pilot hole in the NE SE NE Section 24, T.25N.-R.2E. in 2010 and cored and open hole logged the well before completing it as a horizontal well in the upper Osage-Layton sandstone. Thirty feet of core was recovered. Full core photographs can be found in Appendix D. Figure 20 shows the open hole log for the Garrity #10-24H and the cored interval. Conventional core plugs were taken every foot between 2850.8 to 2843.5 feet. From the base of the core at 2870.4 to 2866.5 feet is interlaminated silty and very fine-grained sandstone with grey shales. Wavy beds and lenticular sandy beds were also observed. Rubbly zone at 2864 to 2865 and 2866 to 2866.5 feet (Figure 21), disrupt laminated intervals. In the upper and middle parts of the interval are burrows and clay clasts, some possibly siderite. Macrofauna are rare with only a gastropod identified at 2866.2 feet. From core depth 2866.5 to 2857.4 feet is an interval of grey shale, with little sandstone, that is very friable. A prominent rubbly zone is apparent from 2860 to 2857.4 feet. At core depth 2857.4 to 2857.2 feet is a thin coal bed (Figure 22) that is in sharp contact with the base of the principal upper Osage-Layton sandstone.

The upper Osage-Layton sandstone is very fine-grained with light brown color attributed to oil stain. Bedding in the sandstone is difficult to see given the very thin nature of some planar bedding and the overall very fine grained, sometimes silty, nature of sandstone bodies. The upper part effervesced on contact with HCl, indicating calcite cement. The main part of the sandstone, from 2857 to 2844 feet, consists of sandstone separated by thin intervals of very silty shale laminae. Muscovite mica is abundant along shale bedding planes. Near the top of the core from 2844 to 2840 feet, soft sediment deformation was observed with clay clasts (Figure 23).

The reservoir in the Garrity #10-24H core is the upper Osage-Layton sandstone from 2857.2 to 2844 feet. According to the core analysis, average porosity for this sandstone is about

17% with an average permeability of 3 millidarcies. Average oil saturation was 27% with an average water saturation of 43%.

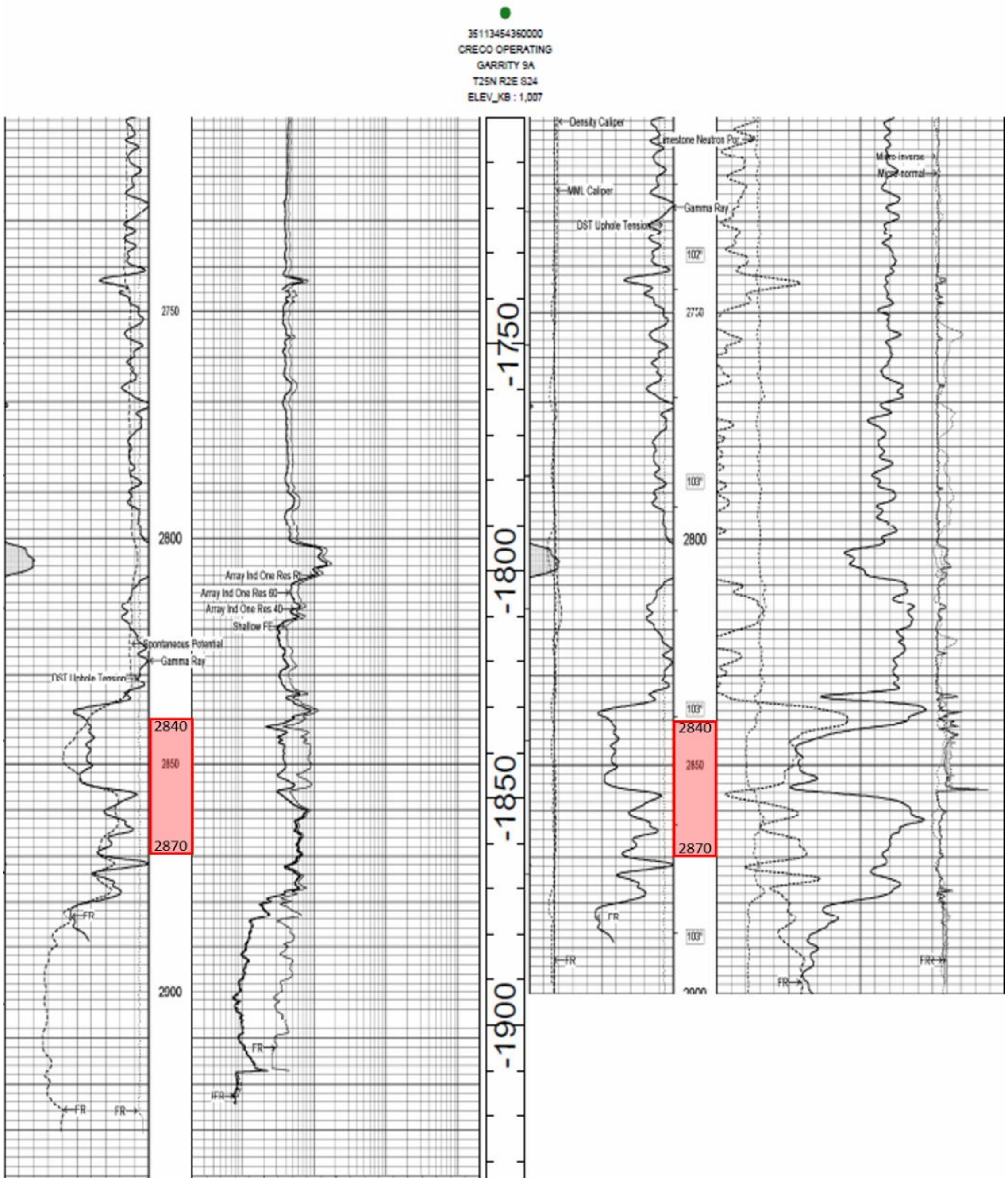

Figure 20: Wireline log for the Garrity #10-24H showing the interval cored. Gamma-ray, spontaneous potential (SP), resistivity curve (left track). Gammy-ray, photoelectric (PE), porosity (Neutron-Density) curve and micro-resistivity curves to right of subsea value track.

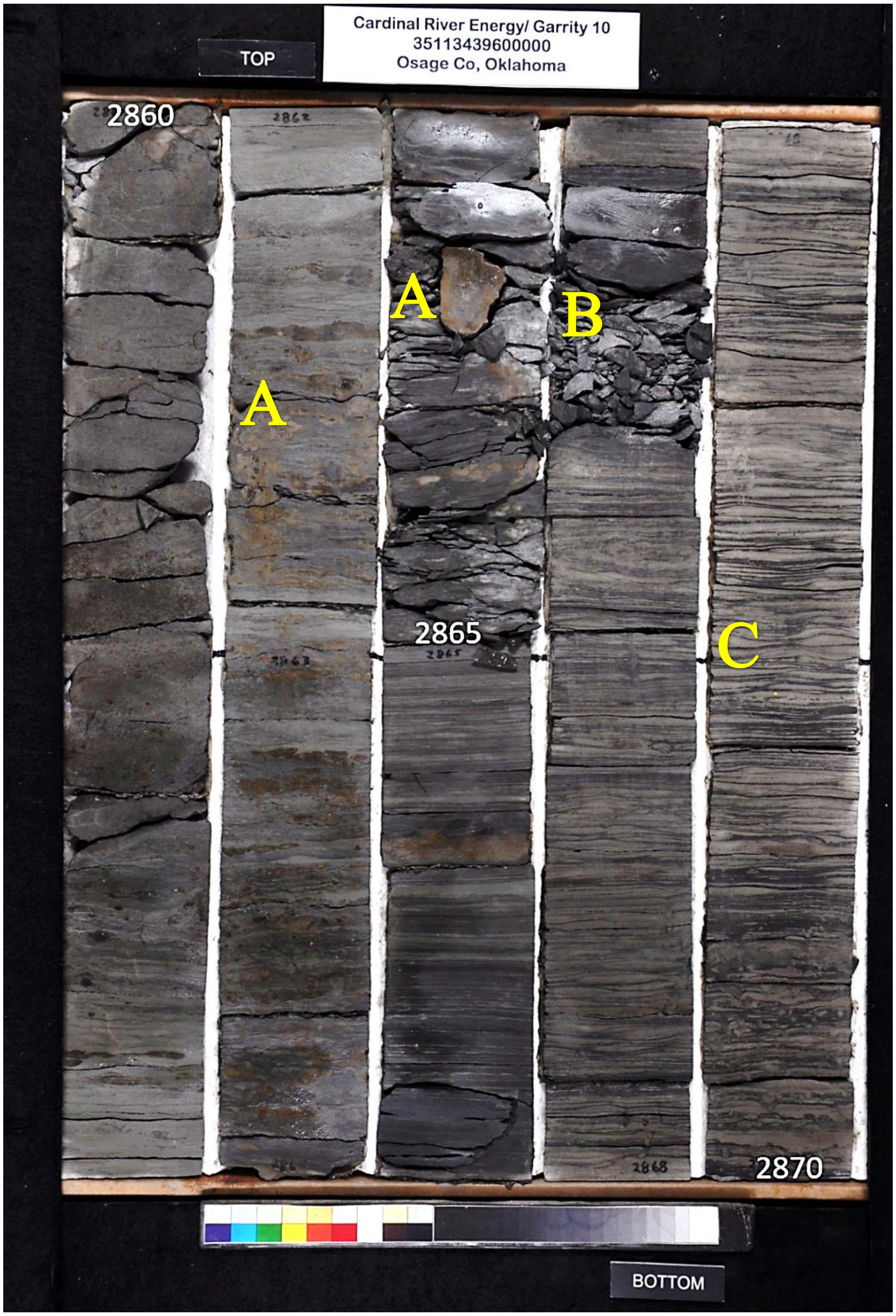

Figure 21: Slabbed core, Garrity #10-24H, depth 2870 to 2860 feet. Burrows, clay clasts, and siderite nodules (A) are evident. Zones of rubble shale (B) could be interpreted as exposure surfaces/paleosols. Sand content increases from 2870 to 2867 feet in rhythmic wavy beds and lenticular sandstones (C).

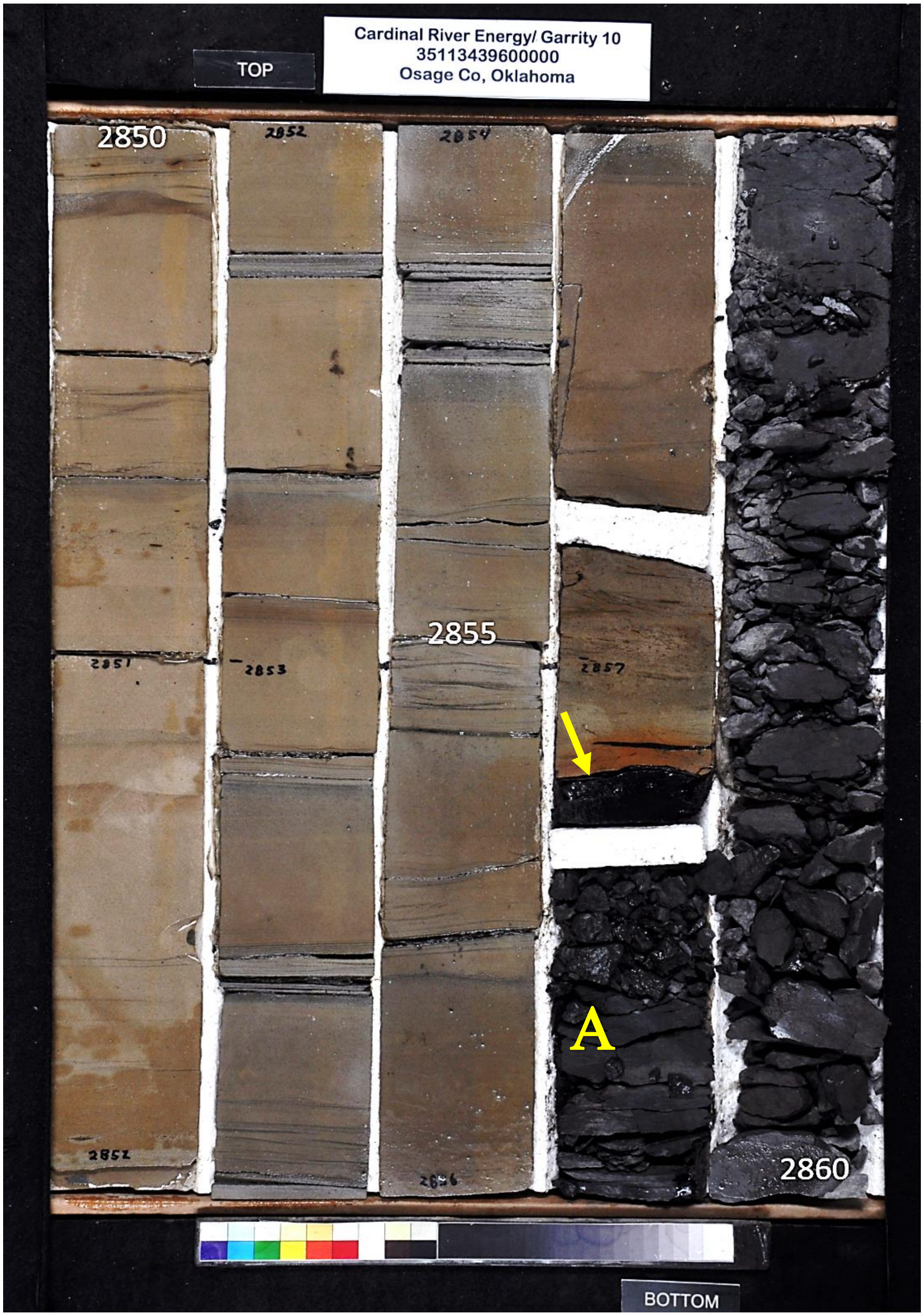

Figure 22: Slabbed core from the Garrity #10-24H covering depth 2860 to 2850 feet. Sharp contact at 2857.2 feet (yellow arrow) with coal fragments included in sandstone above and a relatively thin bed of coal beneath. Below the coal is a rubbly zone typical of underclays and paleosols (A).

Figure 23: Slabbed core from the Garrity #10-24H. Clay rich zones with soft sediment deformation towards the top of the section grading into a cleaner sandstone. Soft sediment deformation evident at 2848.8 feet (yellow arrow).

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Composition

Lower Osage-Layton

The lower Osage-Layton sandstone has been described through drill cuttings as being a fine to medium grained massive sandstone. It is typically grey to light grey and moderately to well sorted. It is mostly clean sandstone with only minor shale laminae and little clay content based on examination of cuttings and thin-sections. The lower Osage-Layton within the study area primarily exhibits a thick, blocky SP log signature with a sharp lower contact and a sharp to gradually fining upward upper contact.

Thin sections of the lower Osage-Layton interval were studied in the Hart #4-24 (Figures 24, 24a, 24b, 24c, 24d, and 24e). Dominant detrital constituents observed were inclusion-rich quartz grains (Figure 24a), intact and weathered feldspars (Figure 24e), and deformed muscovite. In addition, trace amounts of zircon, and tourmaline were observed. Authigenic clays identified were kaolinite filling pore spaces (Figures 24a, 24d, and 24e), and illite-smectite (Figure 24b). Other diagenetic constituents observed were pyrite, abundant quartz overgrowths (Figures 24a, 24c, 24d, and 24e), mixed calcite-dolomite cement, siderite, and chloritized biotite (Figures 24a, 24c, and 24e).

Upper Osage-Layton

The upper Osage-Layton sandstone is typically silty to very fine grained, clay rich, light brown sandstone with a mix of calcite and dolomite cement. This sandstone is much thinner than the lower Osage-Layton and often exhibits a fining-upward SP curve signature indicative of waning energy typical of fluvial processes.

Thin sections of the upper Osage-Layton interval were studied in the Hart #4-24 (Figures 25, 25a, 26, 26a, 26b, and 26e) and the Garrity #10-24H (Figures 27, 27a, 27b, and 27c).

Principal detrital constituents observed were quartz grains (Figures 25a, 26a, 26b, and 26c), muscovite (Figures 25a, 26a, and 26b), and feldspars. Authigenic clays observed were illite (Figure 26b, 29b, 29c) and pore filling kaolinite. Other diagenetic constituents observed were mixed dolomite-calcite cement (Figures 25a, 26e, 28a, 29b, and 29c) with dolomite being more abundant, and abundant pyrite (Figure 25a, 27a, 28a, 29a, 29b, and 29c). A sample collected at 2850.8 in the Garrity #10-24H core for XRD analysis was determined to be 72% quartz, 14% plagioclase, 2% k-feldspar, 4% ankerite, 1% pyrite, 6% illite, 1% chlorite, and trace % kaolinite. Point count analysis from 4 thin sections (depths 2840.4, 2898.6, 2901.3, and 2902.3 feet) of the Hart #4-24 plots the Osage-Layton sandstone as a sublitharenite (Folk, 1974) (see Appendix E).

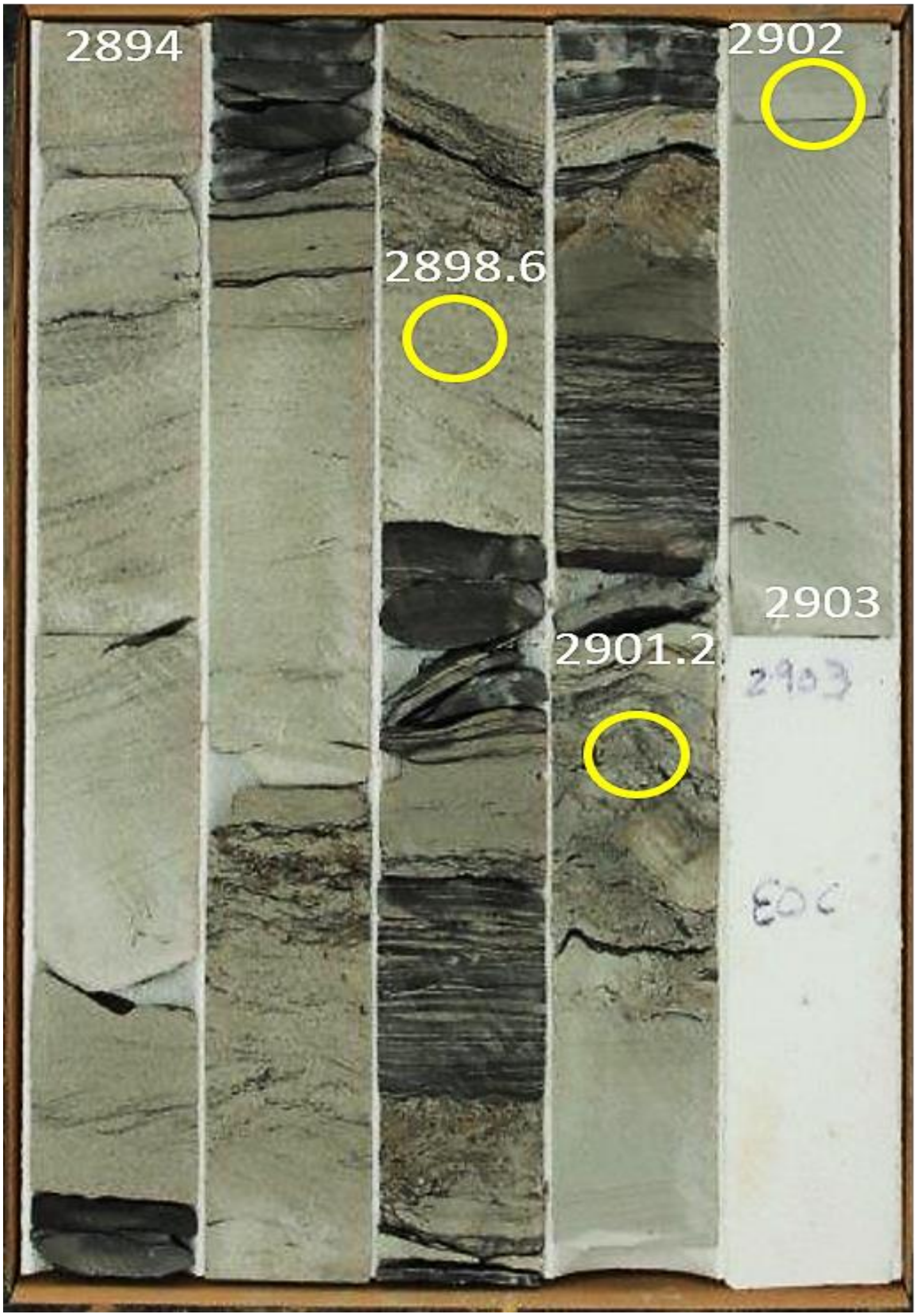

Figure 24: Photograph of Hart #4-24 core from 2894 to 2904 feet, lower Osage-Layton sandstone. Yellow circles indicate locations of samples for thin sections. Thin section photomicrographs follow as figures 24a – 24e. EOC: End of core. Sampled intervals include cross-stratified, massive and soft-sediment deformed sandstone at 2898.6, 2901.2, and 2902 feet, respectively. Interlaminated zones were not sampled.

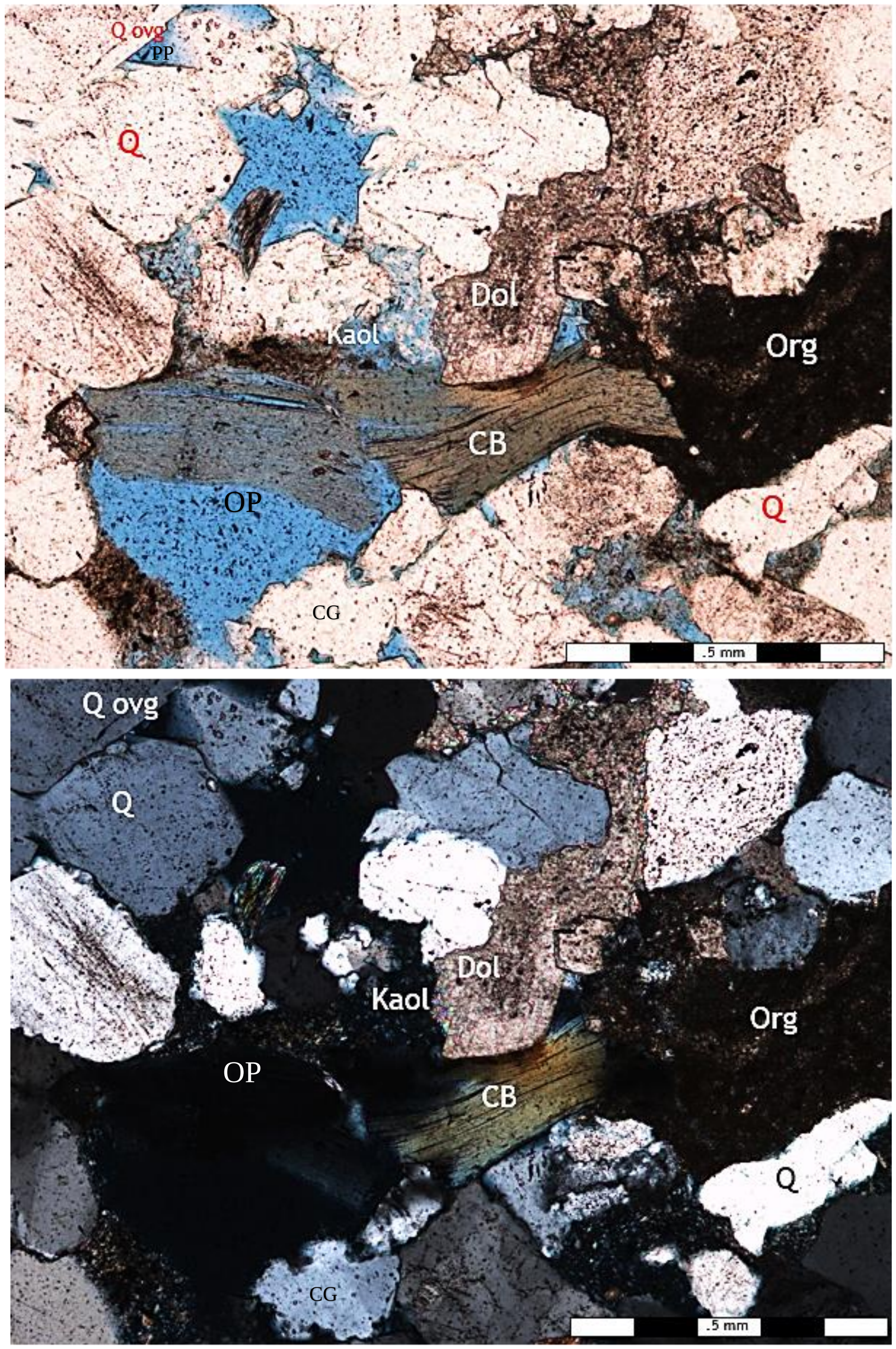

Figure 24a: Thin section photomicrograph of the cross stratified lower Osage-Layton sandstone. Detrital constituents include quartz (Q) and chloritized biotite (CB). Authigenic constituents include quartz overgrowths (Qovg), dolomite cement (Dol) and kaolinite with micro-porosity (Kaol). Other features include oversized pores (OP), corroded grains (CG) and primary porosity (PP). Dark mass along right margin of image is believed to be organic matter (Org). Hart #4-24, depth 2898.6 feet. Top: 5x plane-polarized light (PPL) Bottom: 5x cross-polarized light (CPL). See Appendix E for point counts and ternary diagram.

Figure 24b: Thin section photomicrograph of the soft-sediment deformed lower Osage-Layton sandstone. Detrital constituents include quartz (Q) and muscovite (M). Dark streaks are believed to be organic matter. Hart #4-24, depth 2901.2 feet. Top: 5x (PPL) Bottom: 5x (CPL). See Appendix E for point counts and ternary diagram.

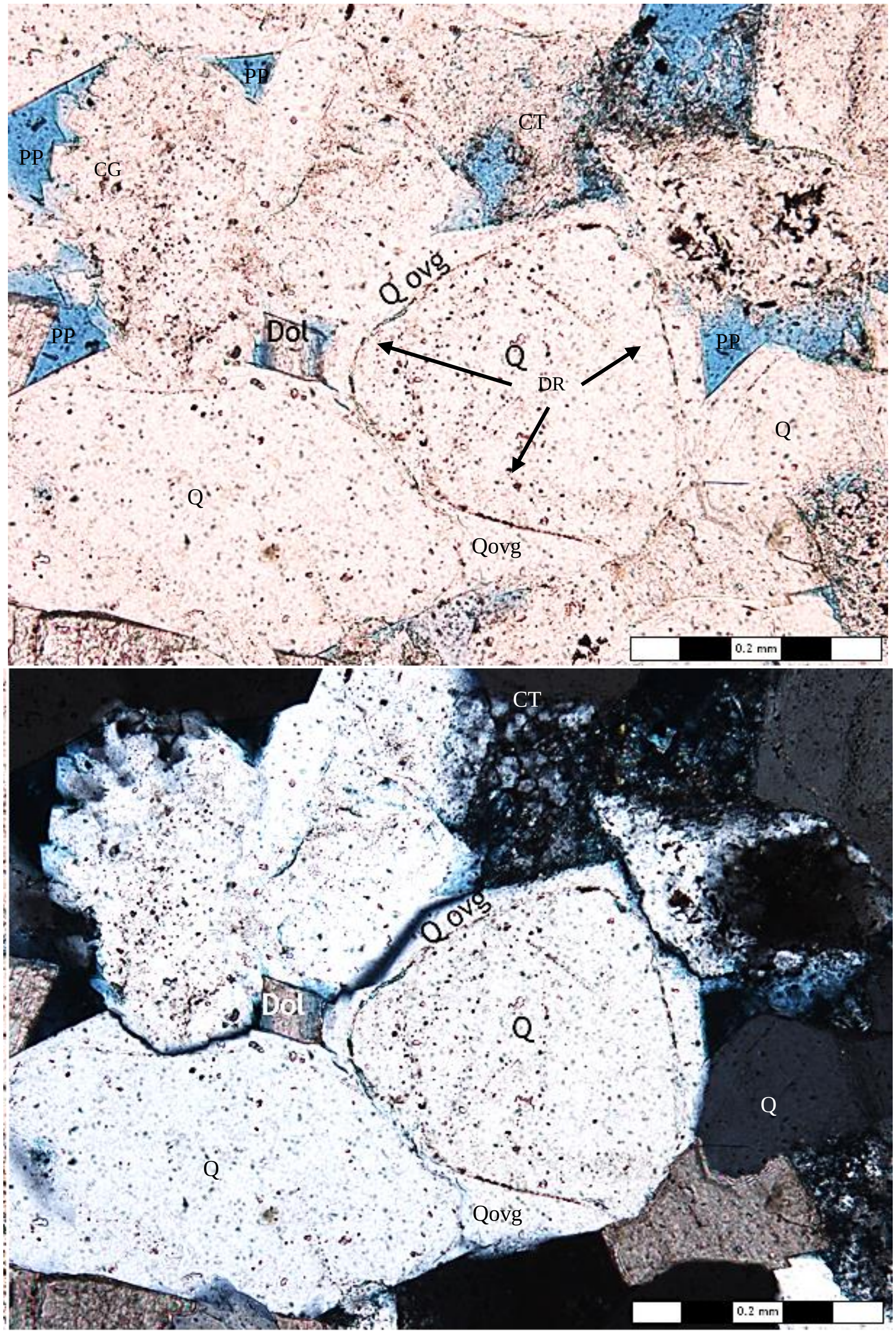

Figure 24c: Thin-section photomicrograph of cross stratified lower Osage-Layton sandstone. Framework grains include quartz (Q), and chert (CT) with micro-porosity. Other features include quartz overgrowths (Qovg) with dust rims (DR), dolomite cement (Dol), corroded grains (CG), and primary porosity (PP). Hart #4-24, depth 2898.6 feet. Top: 10x PPL. Bottom: 10x CPL. See Appendix E for point counts and ternary diagram.

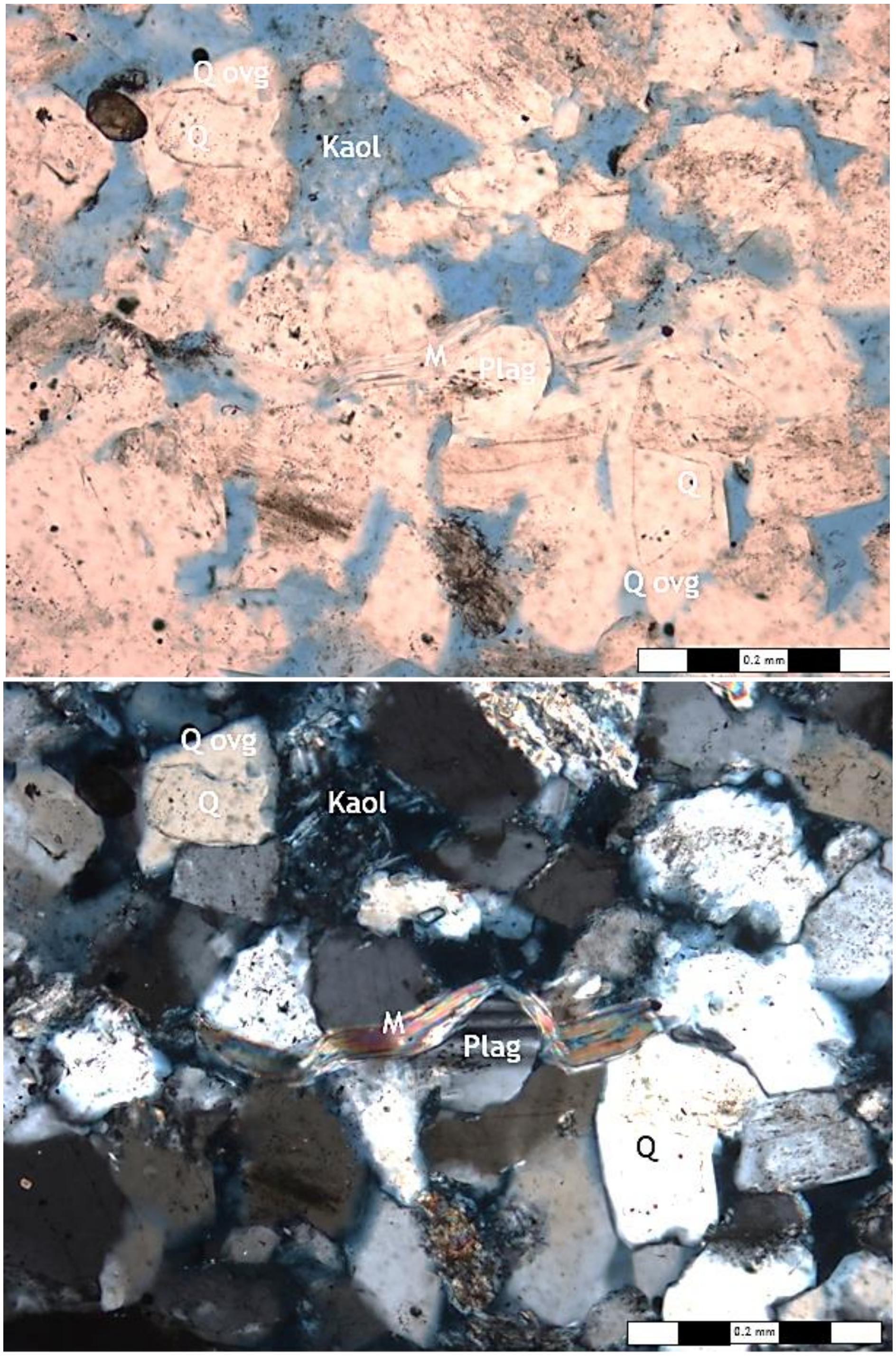

Figure 24d: Thin-section photomicrograph of massive lower Osage-Layton sandstone. Framework grains include quartz (Q), plagioclase (Plag), and deformed muscovite (M). Authigenic constituents include quartz overgrowths (Qovg), and kaolinite (Kaol). Hart #4-24, depth 2902 feet. Top: 10x PPL. Bottom: 10x CPL. See Appendix E for point counts and ternary diagram.

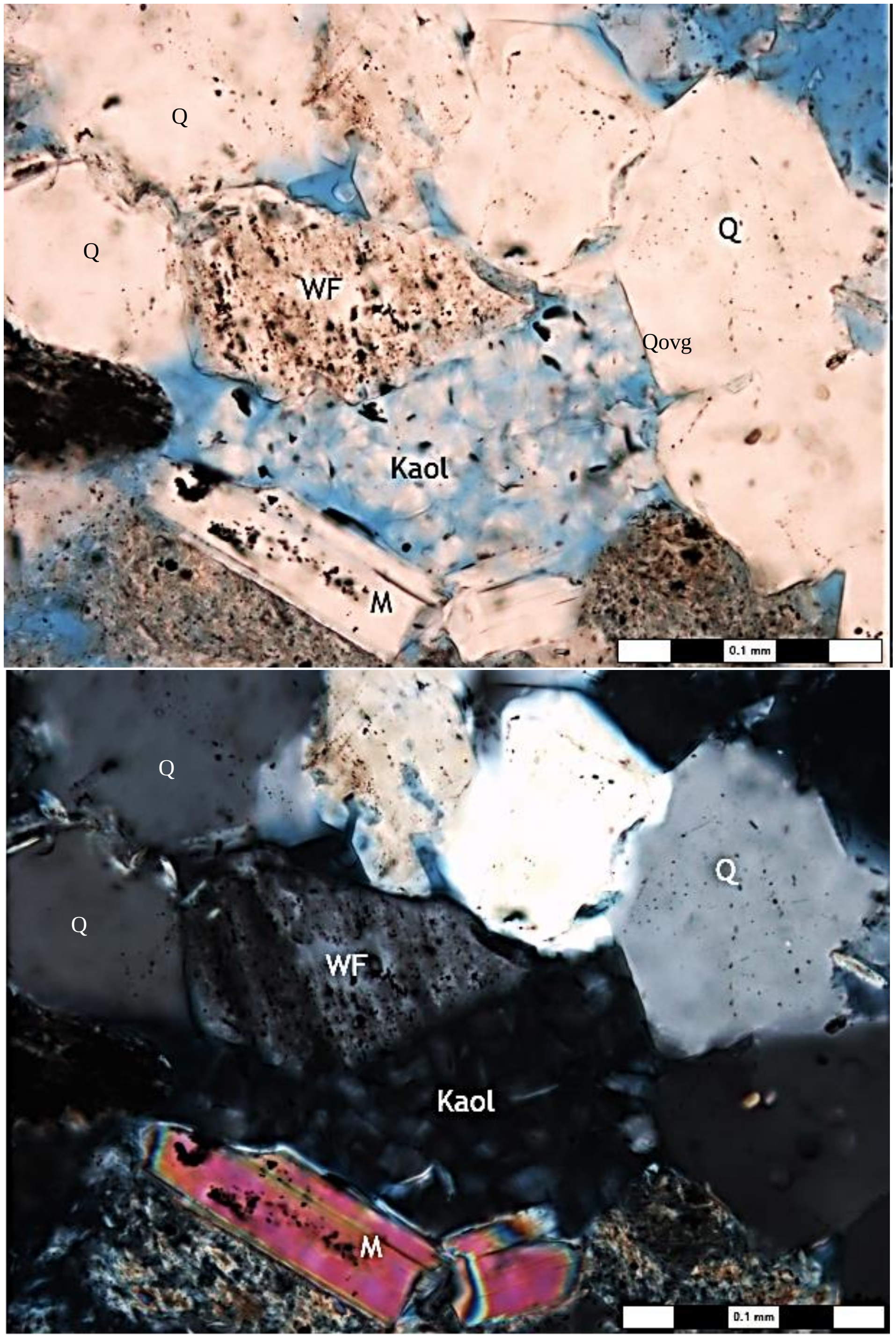

Figure 24e: Thin-section photomicrograph of massive lower Osage-Layton sandstone. Framework grains include quartz (Q), deformed muscovite (M) and a partially dissolved feldspar (WF). Authigenic constituents include quartz overgrowths (Qovg), and kaolinite (Kaol) with micro-porosity. Hart #4-24, depth 2902 feet. Top: 10x PPL. Bottom: 10x CPL. See Appendix E for point counts and ternary diagram.

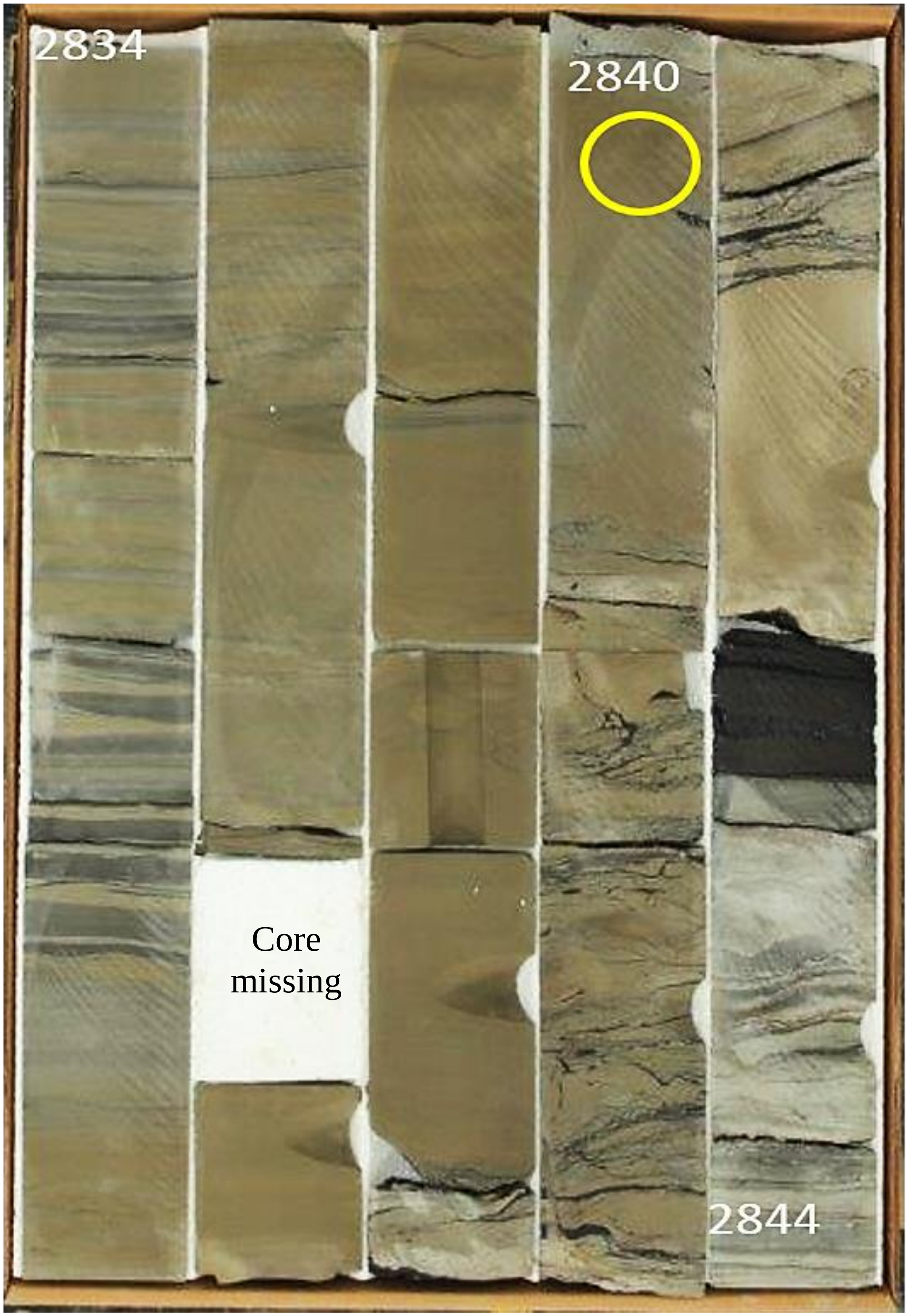

Figure 25: Core photograph of upper Osage-Layton sandstone in Hart #4-24 core. Yellow circle indicates location of sample for thin section. Sandstone is oil stained. Photomicrograph of thin section follows in Figure 25a.

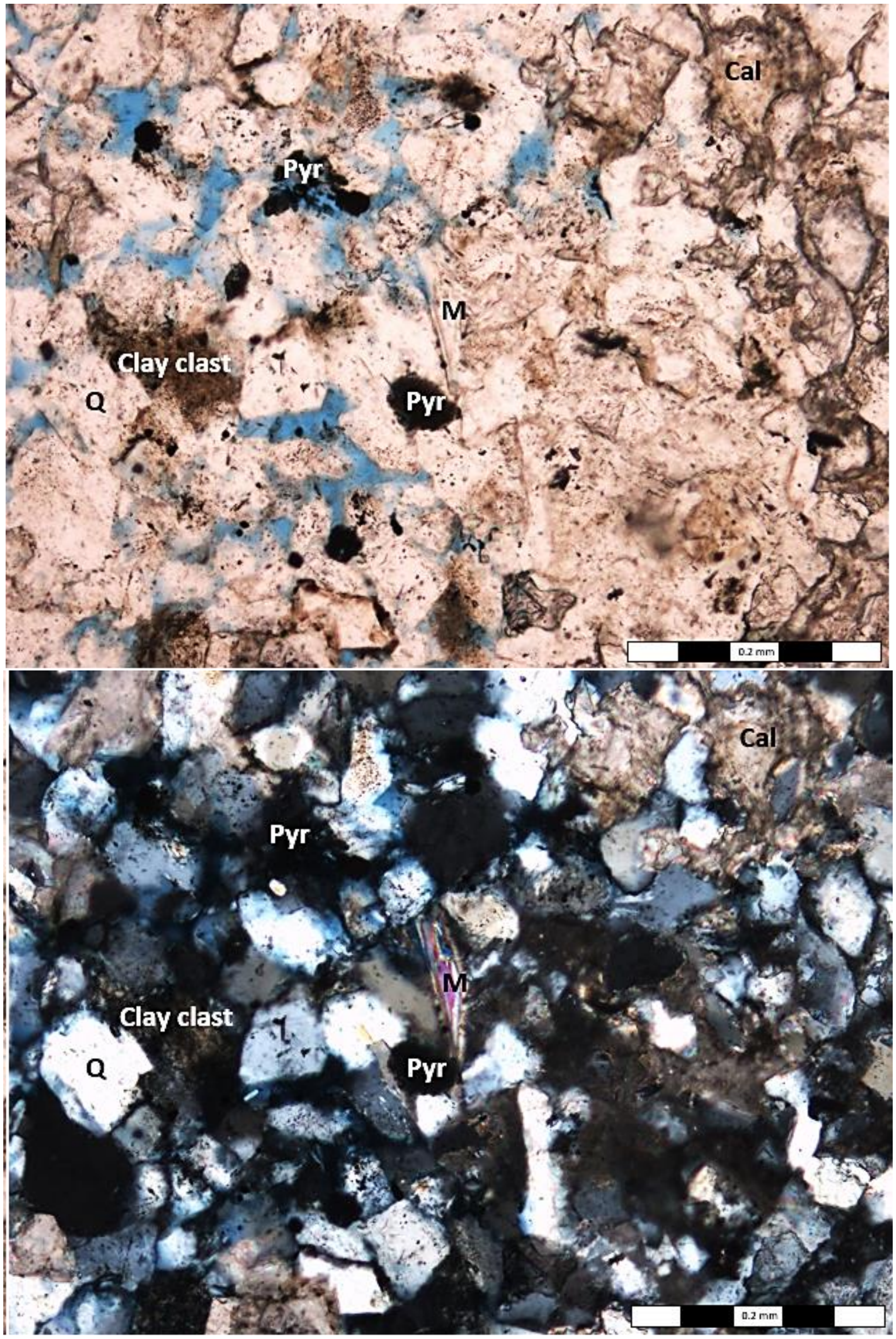

Figure 25a: Thin-section photomicrographs of upper Osage-Layton sandstone. Dominant detrital constituents include quartz (Q) and muscovite (M). Cements include calcite (Cal) and pyrite (Pyr). Hart #4-24 core. Depth 2840.4 feet. Top: 10x PPL. Bottom: 10x CPL. See Appendix E for point counts and ternary diagram.

Figure 26: Photograph of section of upper Osage-Layton sandstone, Hart #4-24 core. Yellow circle indicates location of thin-section photomicrographs shown in figures 26a – 26c. Sample is of contact between fine-grained sandstone above and silty, very fine-grained sandstone below.

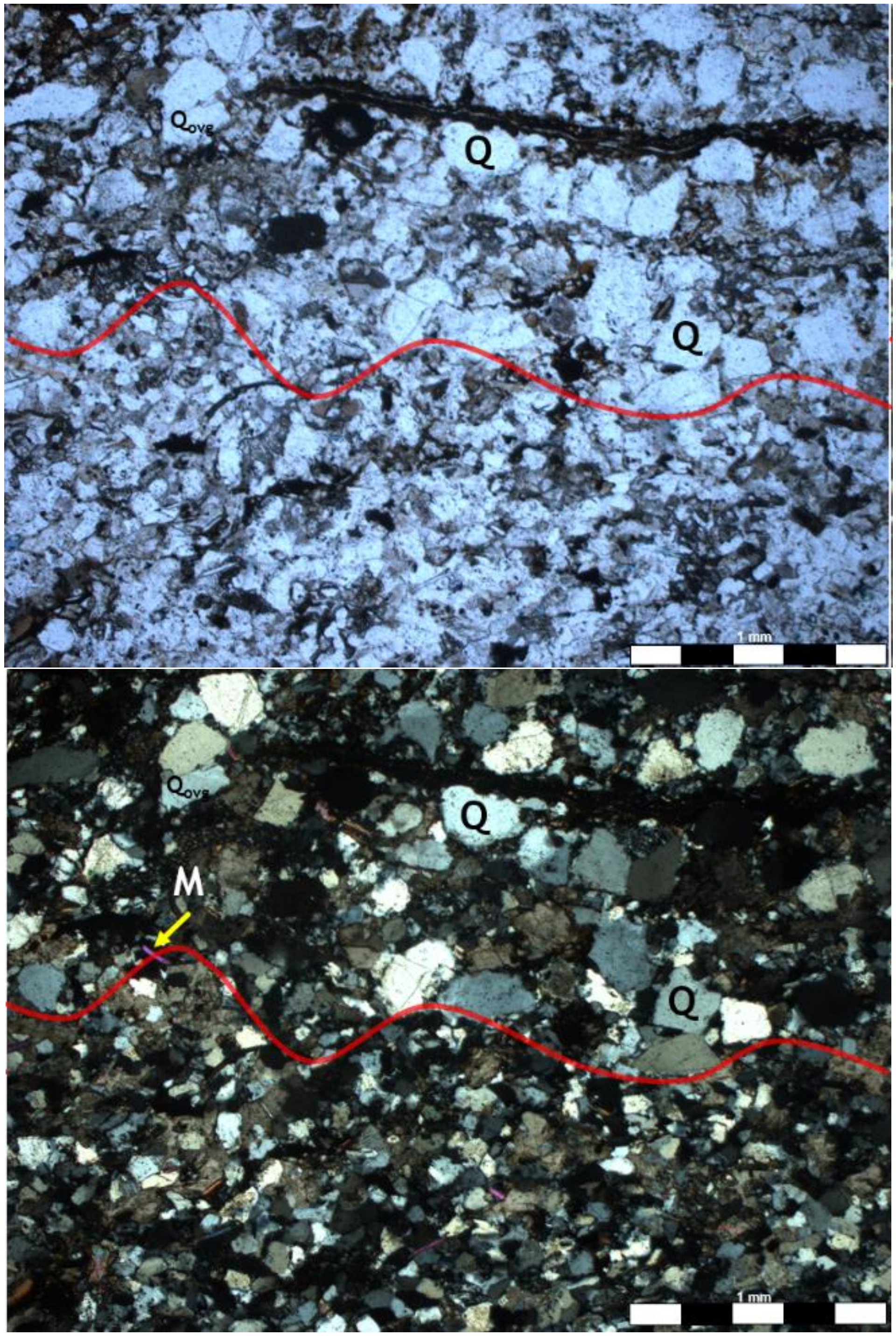

Figure 26a: Thin-section photomicrograph showing contact between fine-grained sandstone and very fine-grained sandstone. Red line marks boundary. Quartz (Q) and muscovite (M). Hart #4-24 core. Depth 2816.65 feet. Top: 2x PPL. Bottom: 2x CPL.

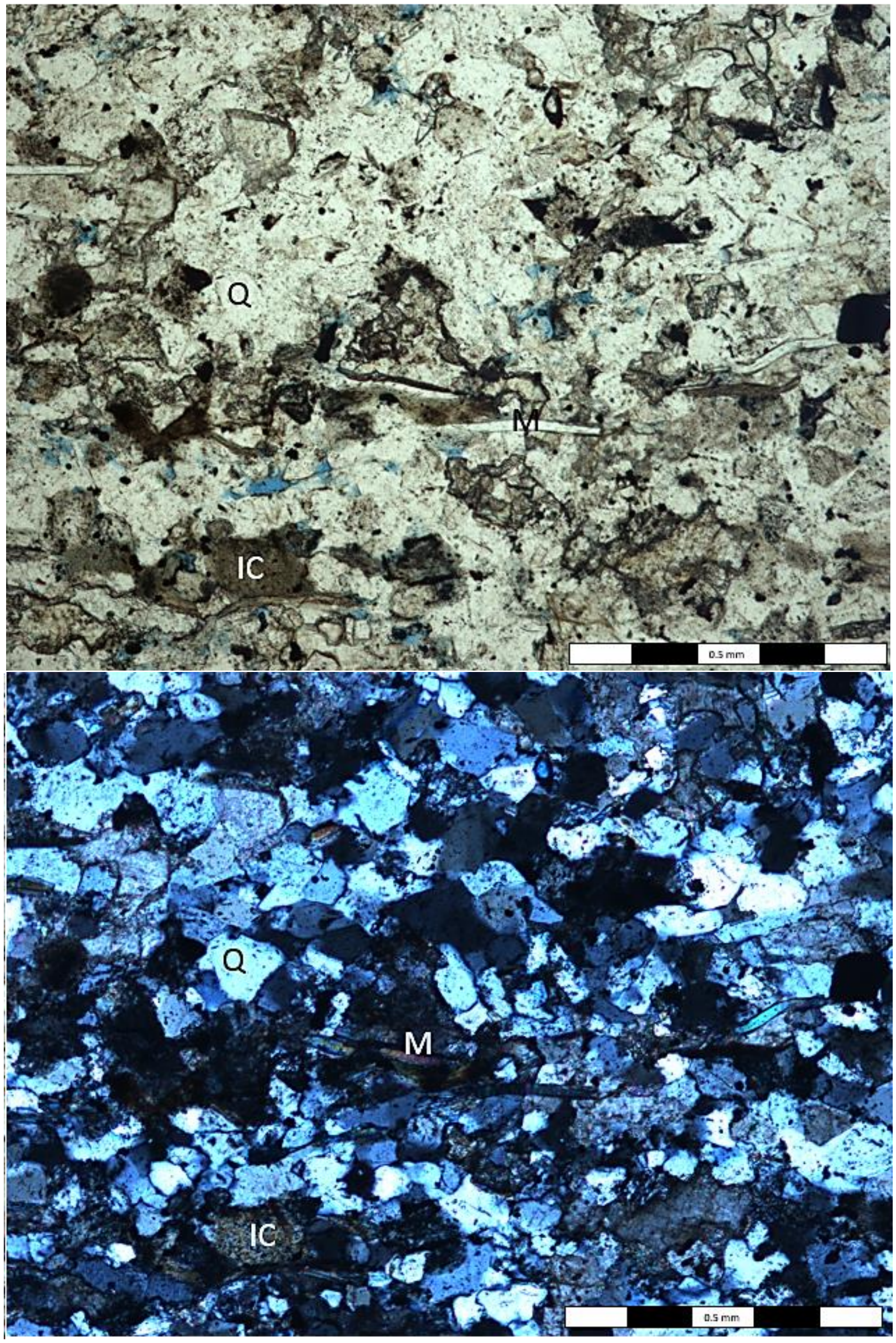

Figure 26b: Thin-section photomicrographs of upper Osage-Layton sandstone. Dominant detrital constituents include inclusion-rich quartz (Q) and muscovite (M). Other features include illitic clay clasts (IC). Hart #4-24 core. Depth 2816.65 feet. Top: 5x PPL. Bottom: 5x CPL.

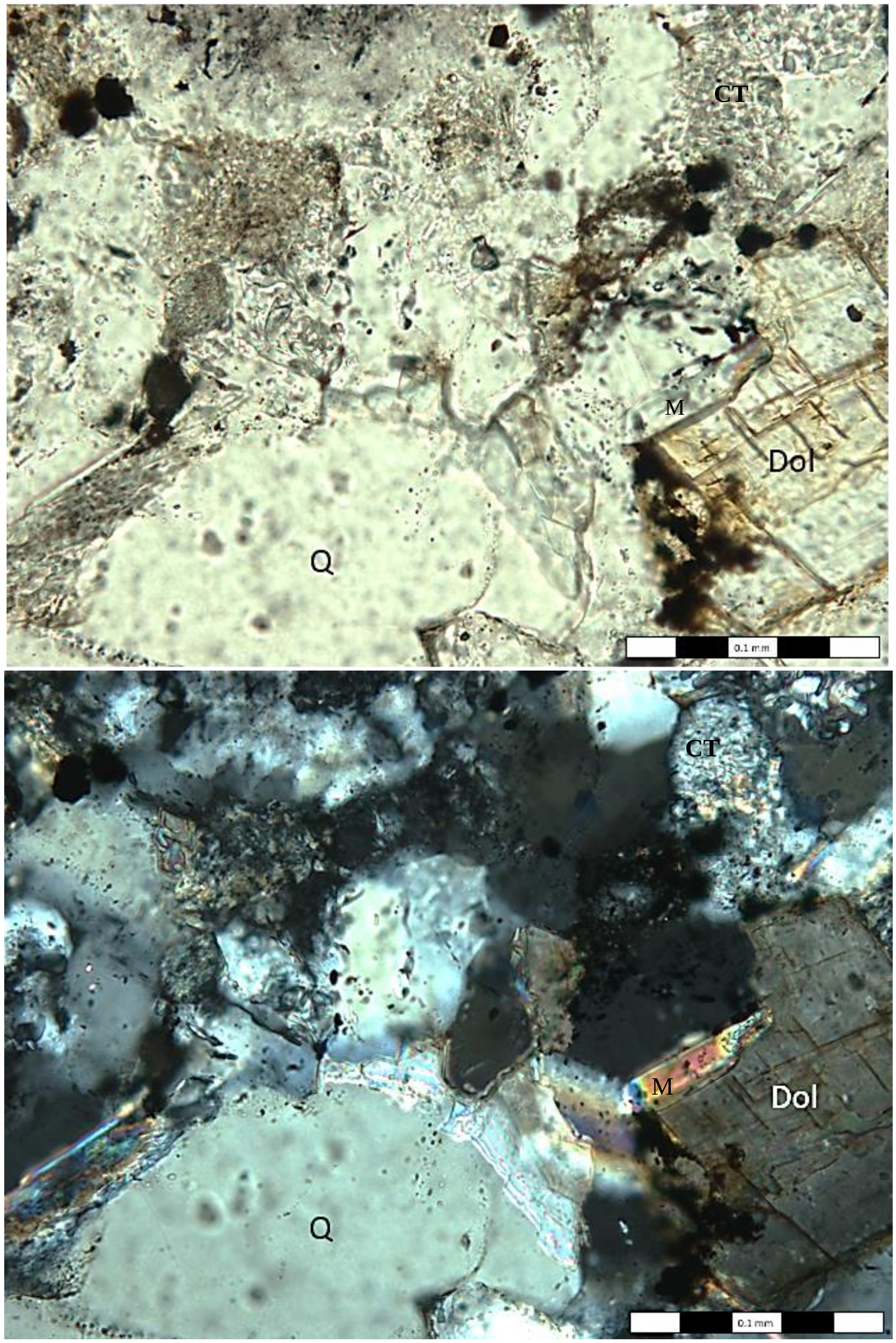

Figure 26c: Thin-section photomicrographs of upper Osage-Layton sandstone. Dominant detrital constituents include quartz (Q), chert (CT), and muscovite (M). Cements include dolomite (Dol). Hart #4-24 core. Depth 2816.65 feet. Top: 20x PPL. Bottom: 20x CPL.

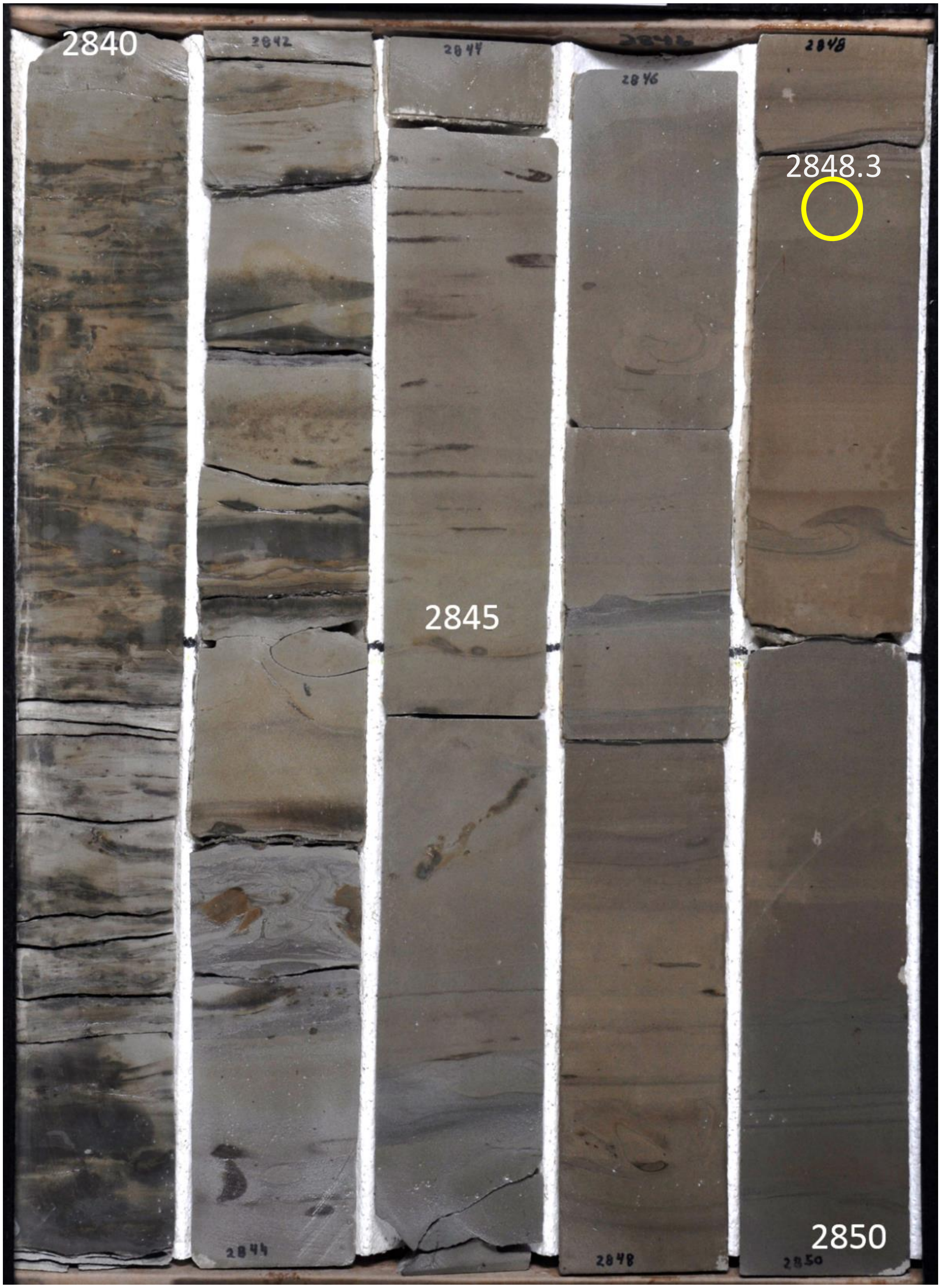

Figure 27: Core photograph from Garrity #10-24H showing location of thin-section (yellow circle) in massive sandstone. Thin section photomicrograph is shown in figure 27a.

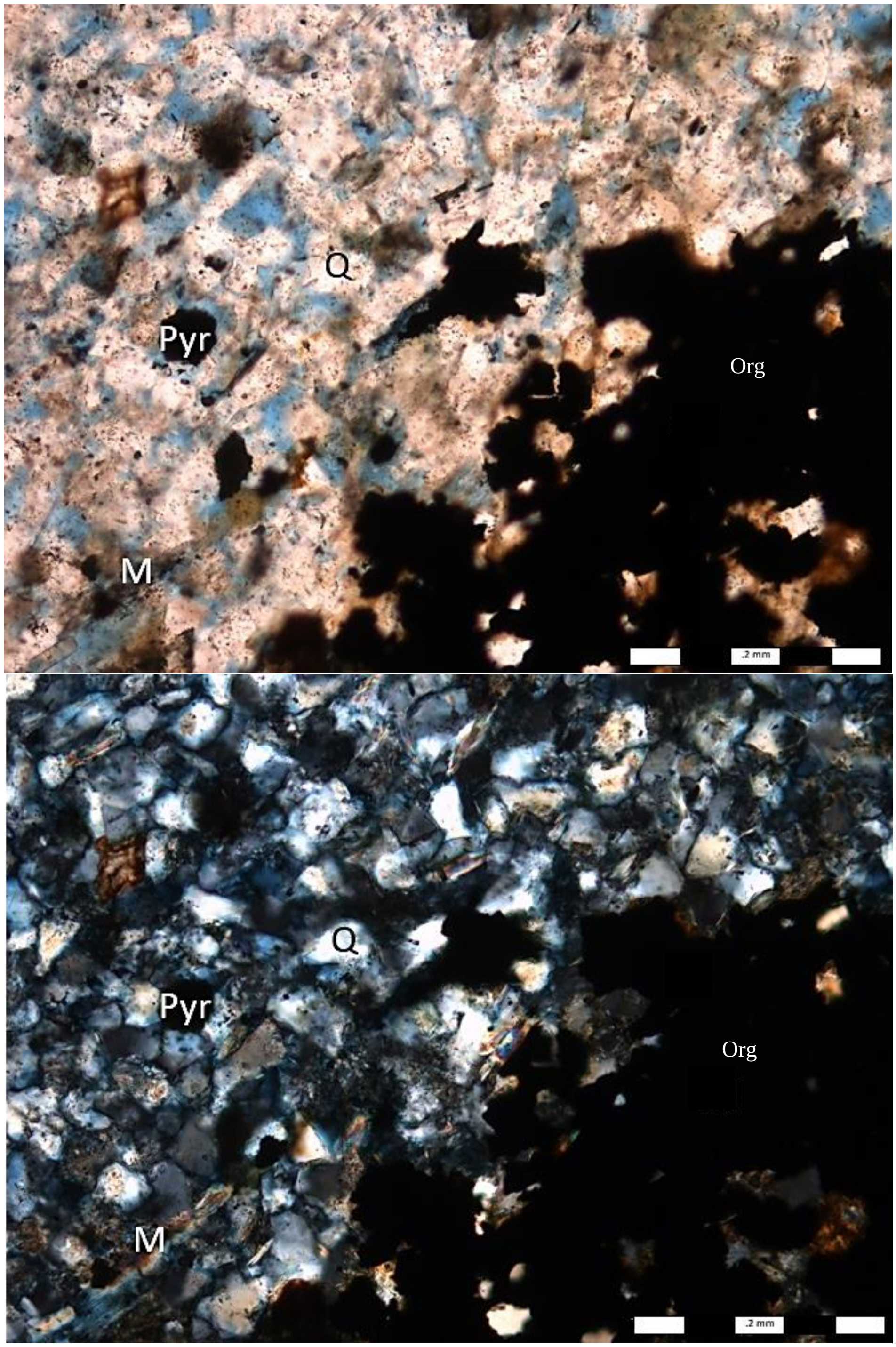

Figure 27a: Thin-section photomicrographs of massive upper Osage-Layton sandstone. Detrital constituents include quartz (Q) and muscovite (M). Other features include pyrite (Pyr). Dark mass along right margin of image is believed to be organic matter (Org). Porosity (blue) is mainly secondary. Garrity #10-24H core. Depth 2848.3 feet. Left: 10x PPL. Right: 10x CPL

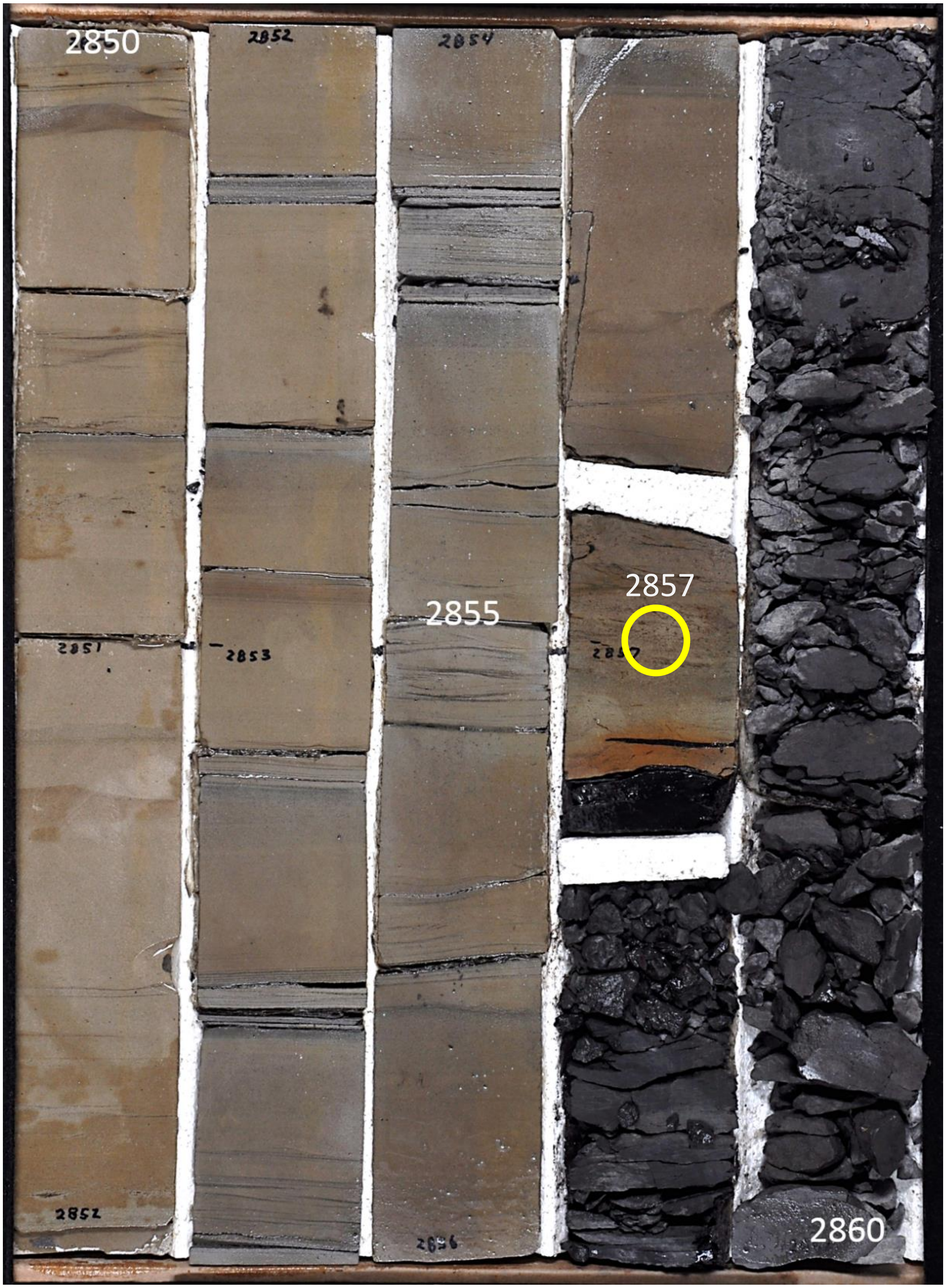

Figure 28: Core photograph from Garrity #10-24H showing location of thin-section (yellow circle) in massive to mostly horizontally bedded sandstone. Thin section photomicrograph is shown in figure 28a.

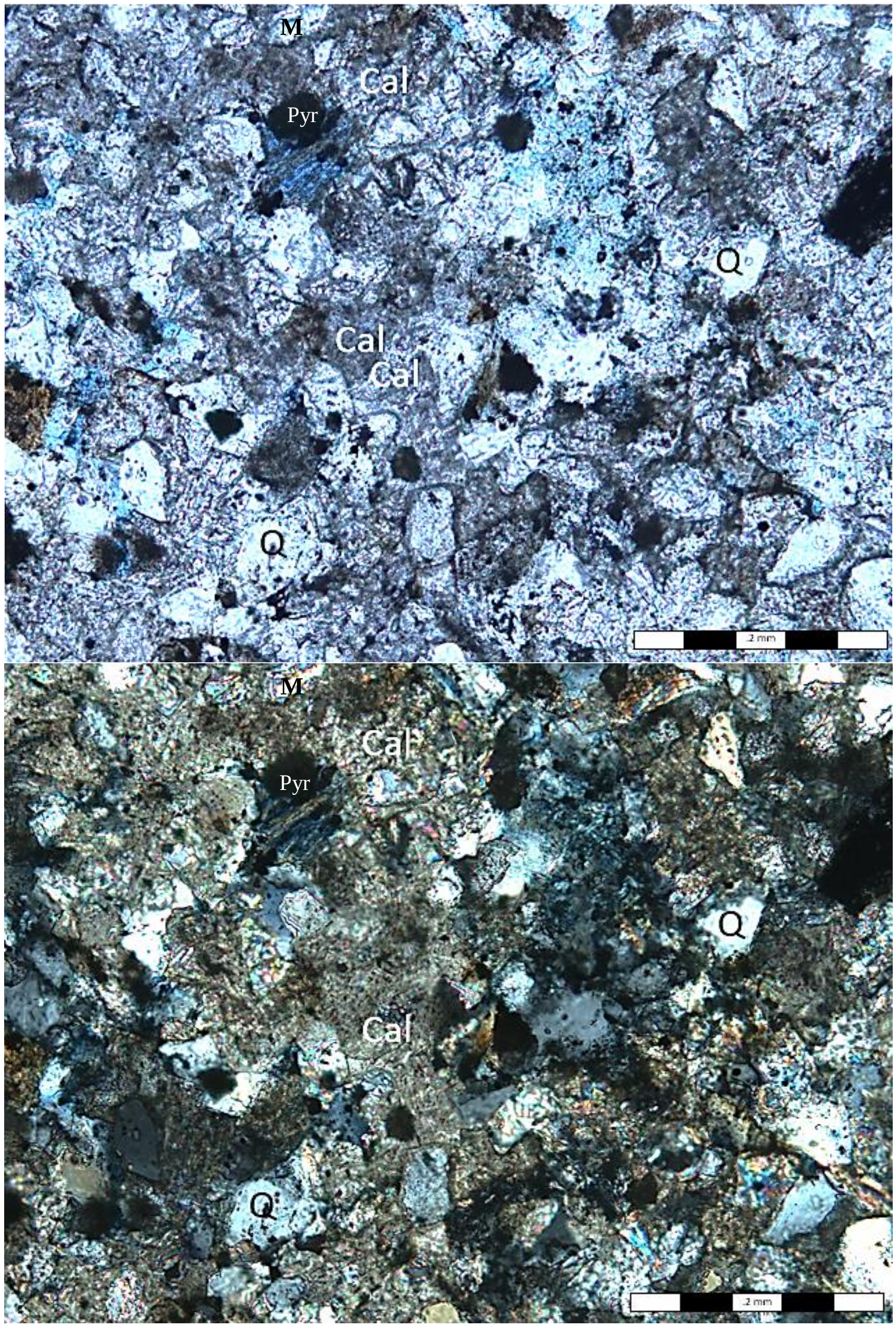

Figure 28a: Thin-section photomicrographs of upper Osage-Layton sandstone. Detrital constituents include quartz (Q) and muscovite (M). Cements include calcite (Cal) and pyrite (Pyr). Garrity #10-24H core. Depth 2857 feet. Left: 10x PPL. Right: 10x CPL

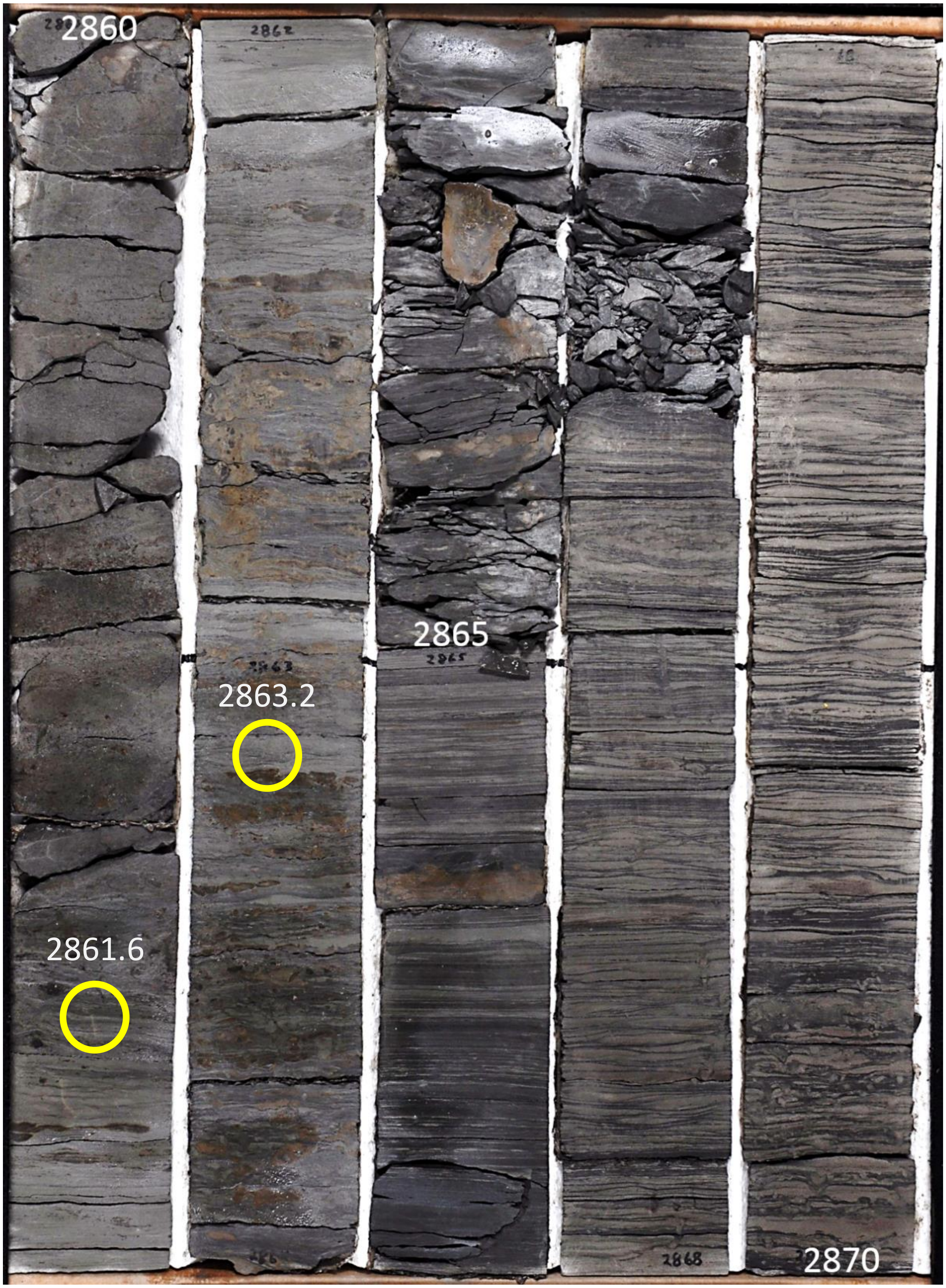

Figure 29: Core photograph from Garrity #10-24H showing locations of thin-sections (yellow circles) from silty zones. Note rhythmic and burrowed bedding. Thin section photomicrographs are shown in figures 29a – 29c.

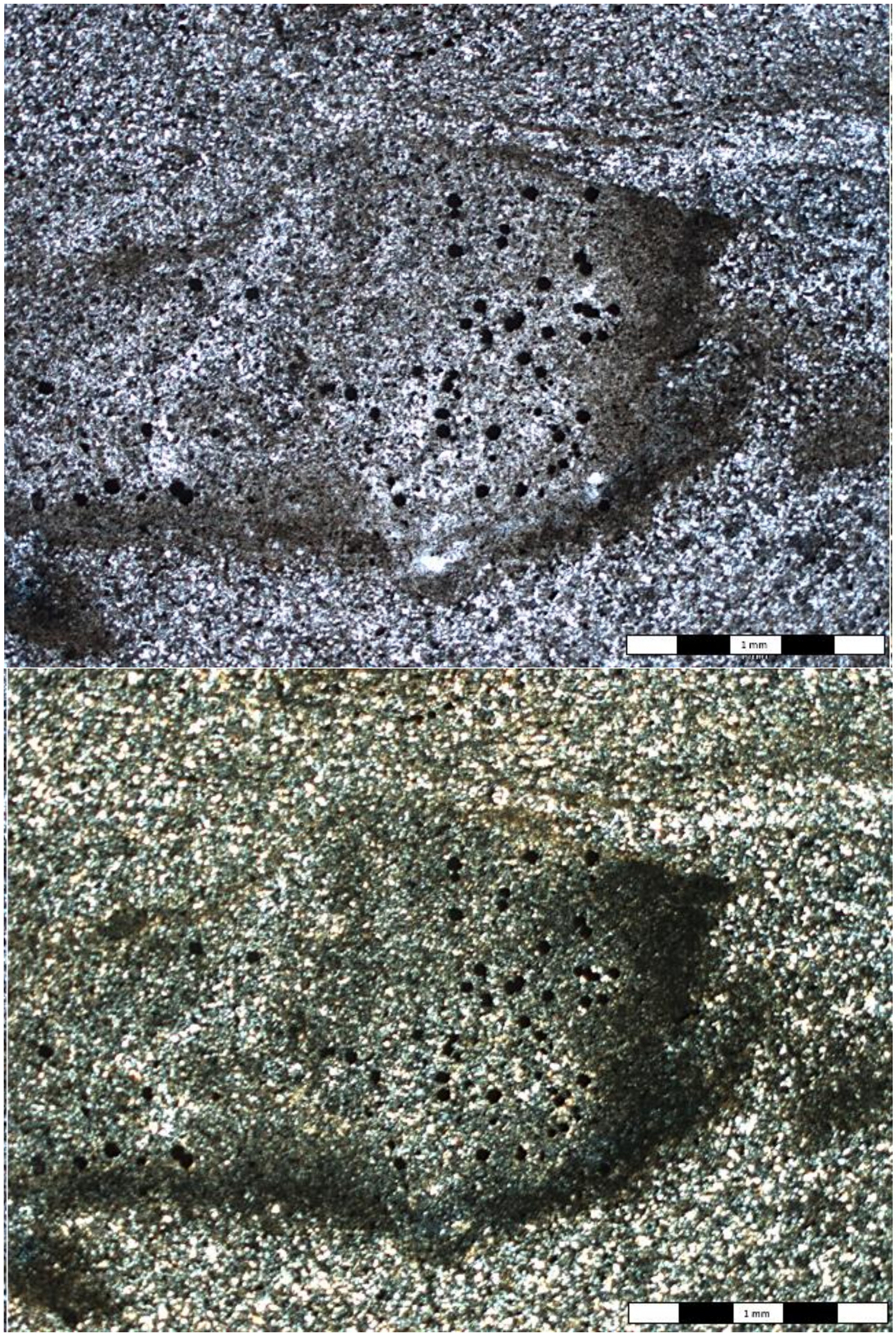

Figure 29a: Thin-section photomicrographs of siltstone in the upper Osage-Layton sandstone interval showing soft sediment deformation and pyrite (black spots). Garrity #10-24H core. Depth 2861.6 feet. Left: 2x PPL. Right: 2x CPL

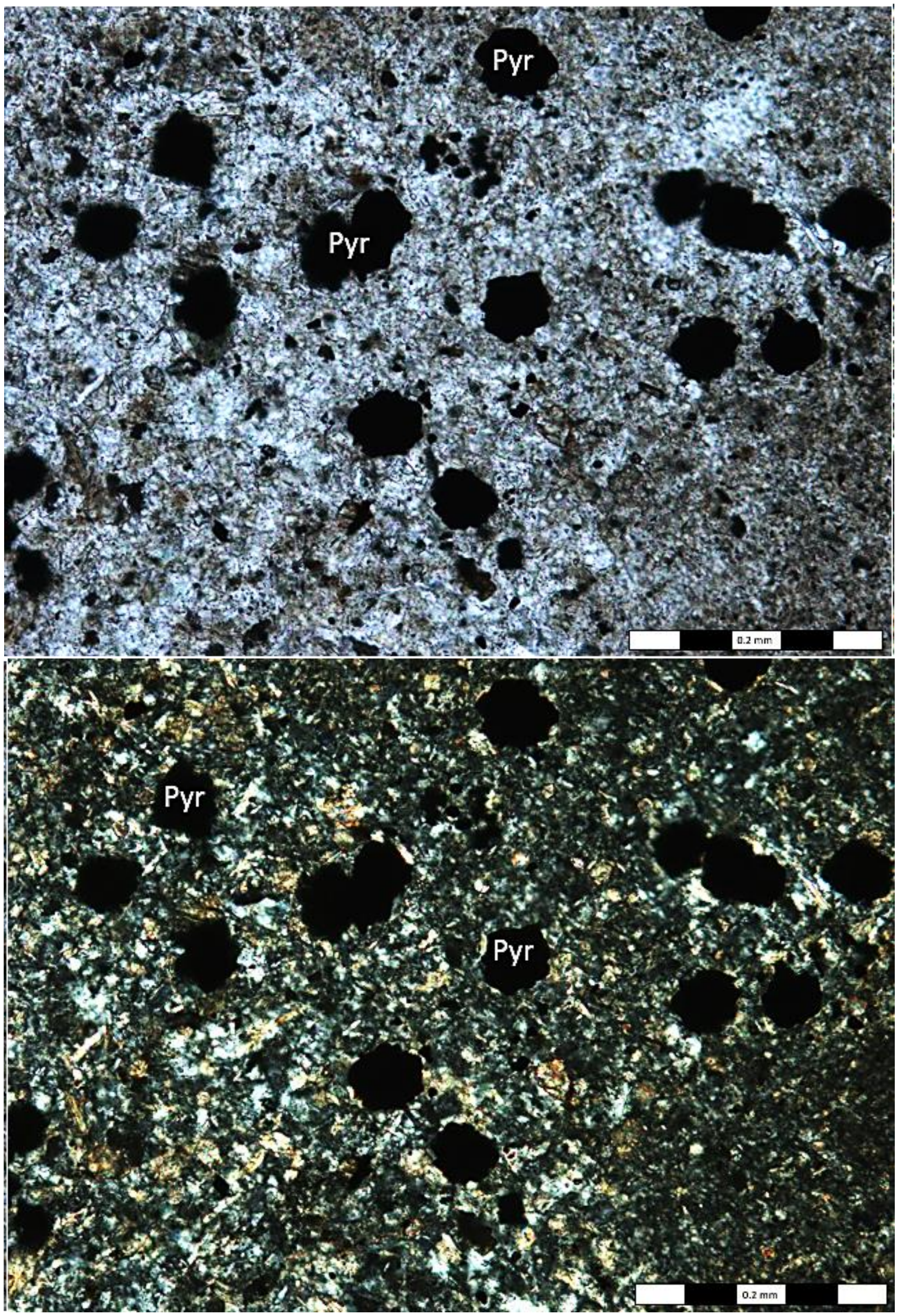

Figure 29b: Thin-section photomicrographs of siltstone in the upper Osage-Layton sandstone interval. Features include pyrite (Pyr). Garrity #10-24H. Depth 2861.6 feet. Left: 10x PPL. Right: 10x CPL.

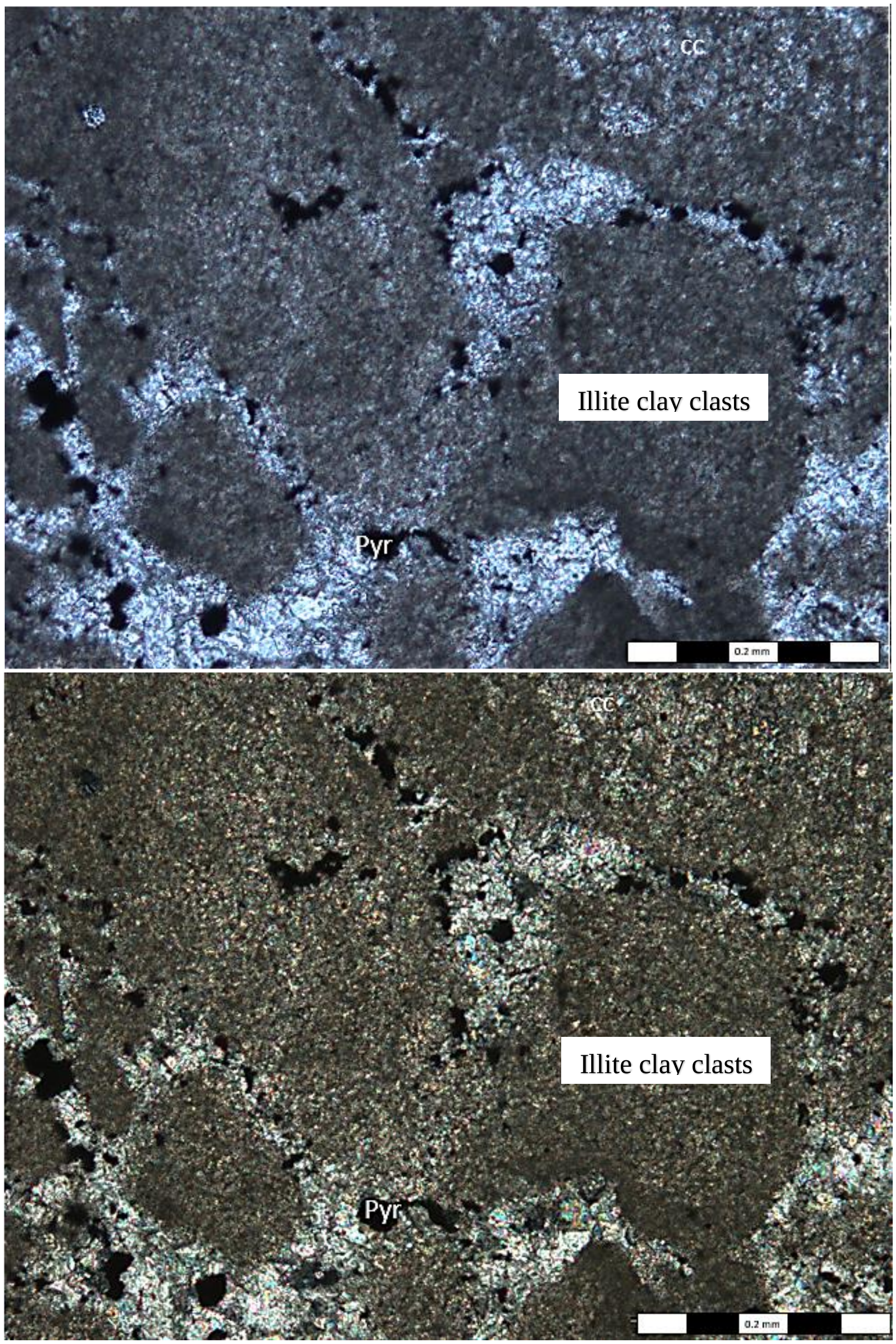

Figure 29c: Thin-section photomicrographs of siltstone in upper Osage-Layton sandstone interval. Features include pyrite (Pyr) around larger illite clay clasts. Garrity #10-24H. Depth 2863.2 feet. Left: 10x PPL. Right: 10x CPL.

Regional and Localized Mapping

Based on generated interval isopach maps, the general paleo dip at the time of deposition was north-north westward. Structure maps of the Checkerboard Limestone (Figure 30), Hogshooter Limestone (Figure 31), and Osage-Layton sandstone (Figure 32) show current monoclinal dip to the southwest with several larger faulted structures in the western part of the study area that are associated with the Nemaha Uplift.

The isopach of the interval between the Checkerboard Limestone to the Big Limestone shows trends of thick intervals in the northern and eastern portion of the study area (Figure 33). The isopach of the Hogshooter Limestone to the Checkerboard Limestone interval indicates a consistent thickening to the southeast and a quick thinning in the northwest portion of the study area (Figure 34). Moving up the stratigraphic column, the “Shale Marker” to Hogshooter Limestone interval isopach indicates counter trends compared to the previous interval isopach (Figure 35). Where thicker “True” Layton sandstone interval is mapped, the superjacent “hot” marine shale is thinner and as a result is thickest in the northwestern portion of the study area (Figure 35). The isopach of the base of the Osage-Layton to the “Shale Marker” shows a general thinning to the east and thickening as you move westward (Figure 36). The isopach for the top of the Osage-Layton to the base of the Osage-Layton shows a general thickening to the southeast (Figure 37). There are anomalous thicks and thins and a southwest to northeast trend of thinning in the southeastern part of the study area. The Osage-Layton interval can be divided into and upper and lower sandstone throughout most of the northwestern and northeastern portions of the study area. Towards the south and southeast, distinct separation begins to become increasingly difficult to identify and correlation tenuous. Therefore, an overall Osage-Layton net sandstone map was constructed to show general trends and geometries of the thicker sandstones (Figure 38).

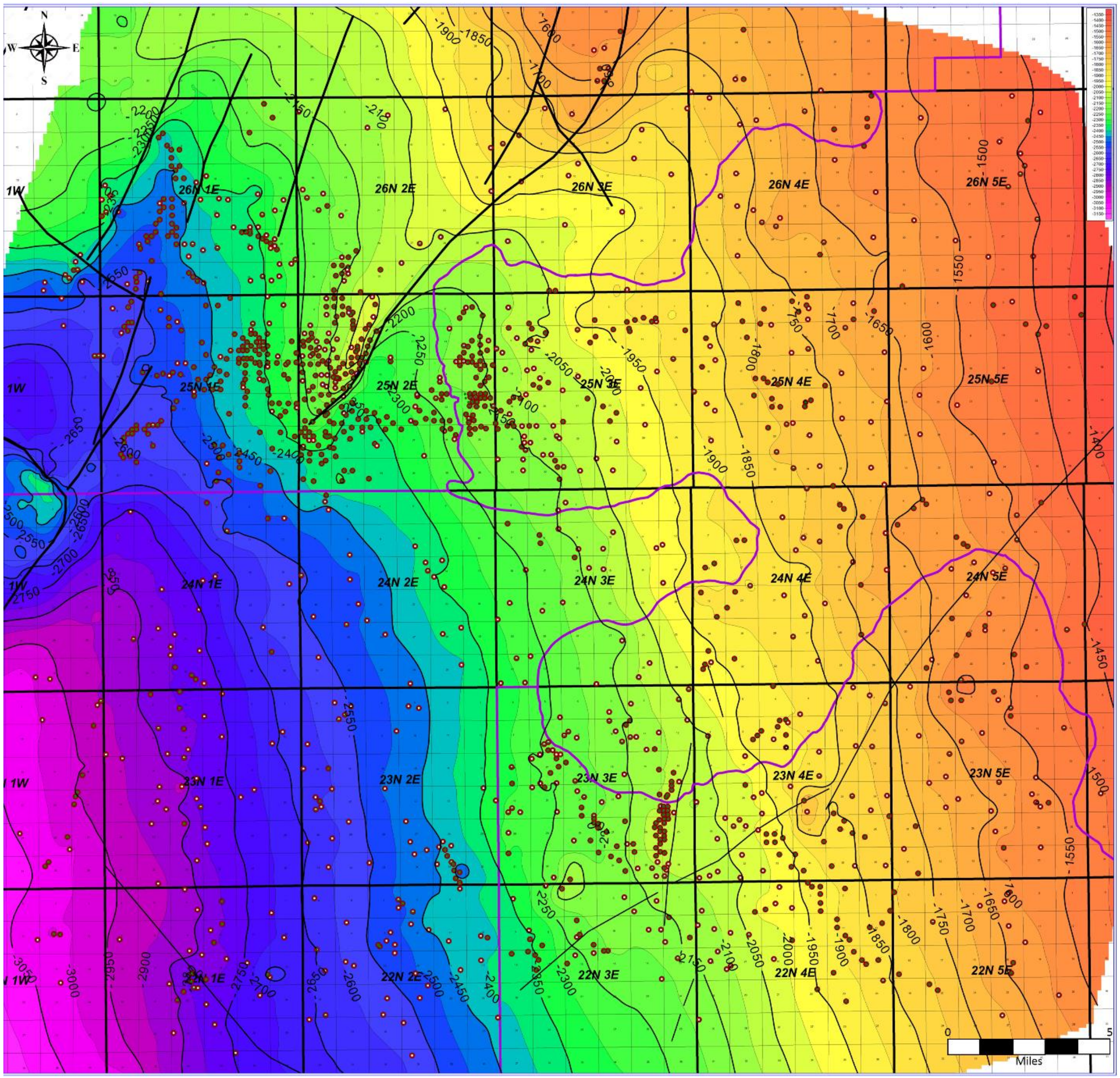

Figure 30: Regional Checkerboard Limestone structure map. Contour interval is 50 feet. Faults shown are from the Oklahoma Geological Survey (OGS) statewide fault shapefile, with some evident in contour patterns and others not. Some faults may be deeper or shallower than the contour map and may not show evidence of faulting through regional mapping. Subsea contour values range from -1350 feet in the northeast to -3100 feet in the southwest. Warm colors represent shallower areas, cooler colors represent deeper areas.

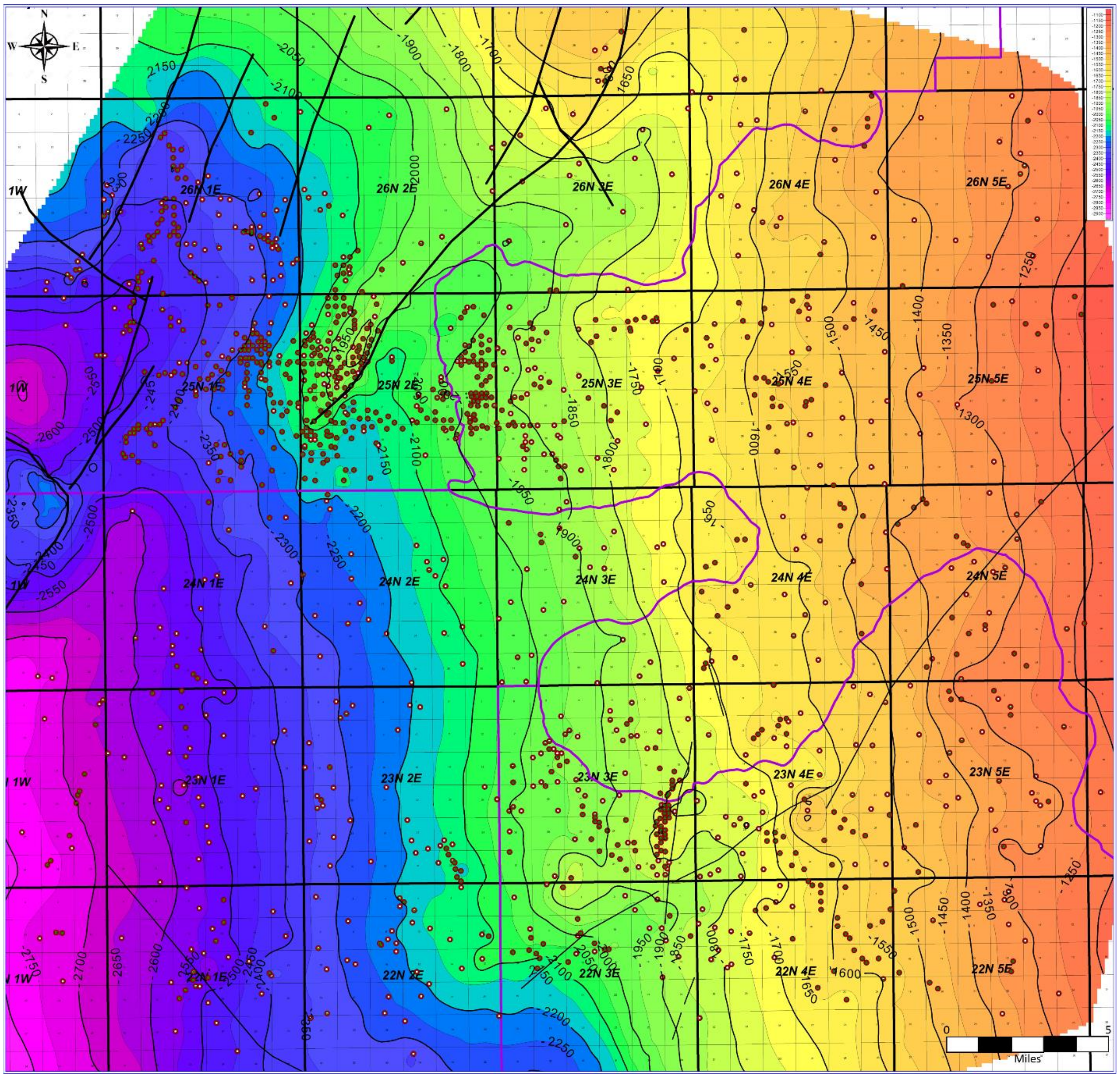

Figure 31: Regional Hogshooter Limestone structure map. Contour interval is 50 feet. Faults shown are from the Oklahoma Geological Survey (OGS) statewide fault shapefile, with some evident in contour patterns and others not. Some faults may be deeper or shallower than the contour map and may not show evidence of faulting through regional mapping. Subsea contour values range from -1150 feet in the east to -2700 feet in the west. Warm colors represent shallower areas, cooler colors represent deeper areas.

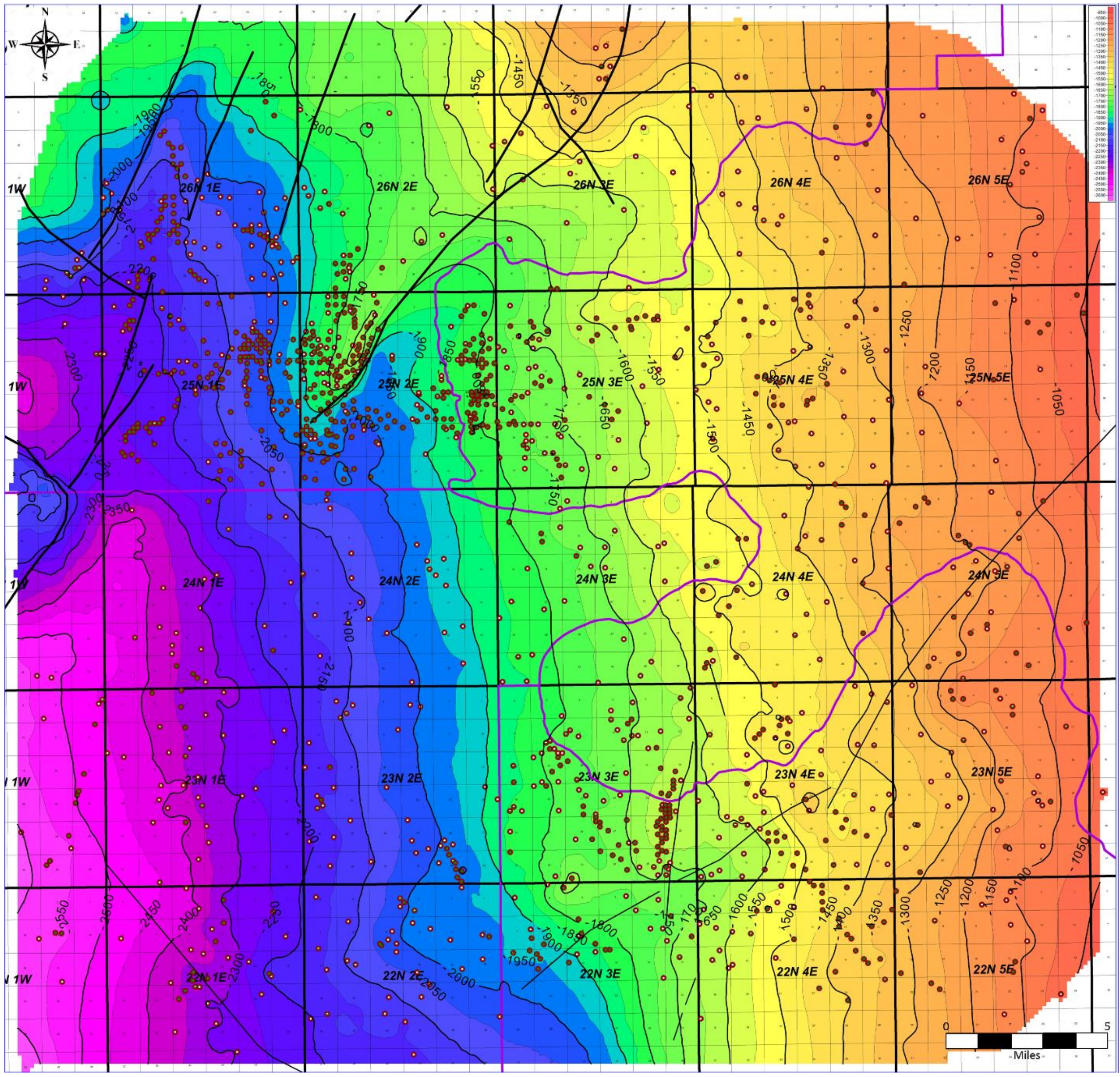

Figure 32: Regional Osage-Layton structure map Contour interval is 50 feet Faults shown are from the Oklahoma Geological Survey (OGS) statewide fault shapefile. Some faults may be deeper or shallower than the contoured interval. Subsea contour values range from -1000 feet in the east to -2600 feet in the west-southwest. Warm colors represent shallower areas, cooler colors represent deeper areas.

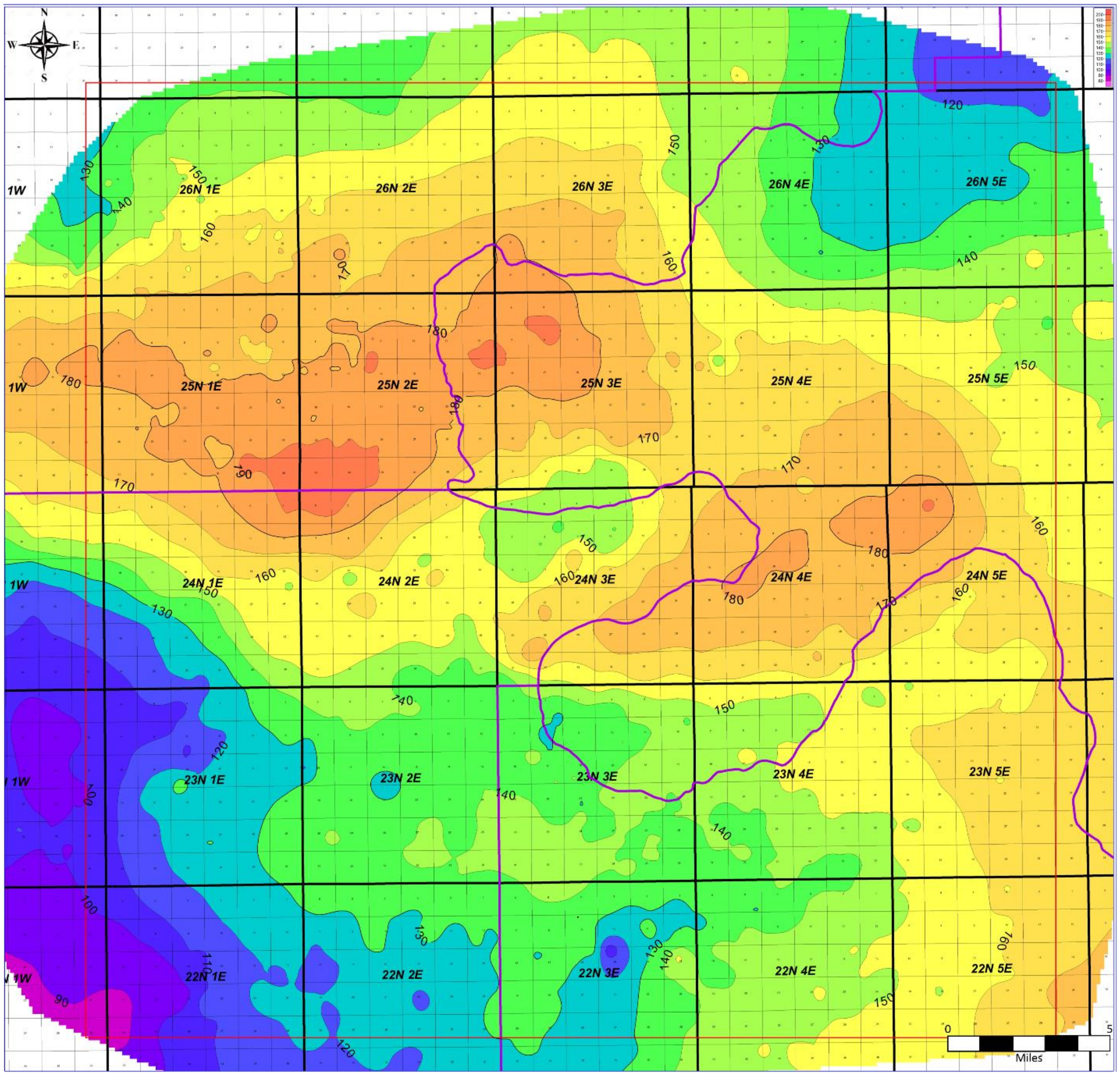

Figure 33: Checkerboard Limestone to Big Lime interval isopach. Contour interval is 10 feet. Warm colors represent thicks, cooler colors represent thinner intervals. Thicknesses range from 90 to 190 feet. Thicker values are in the center, whereas thinnest are in southwest and northeast parts of study area.

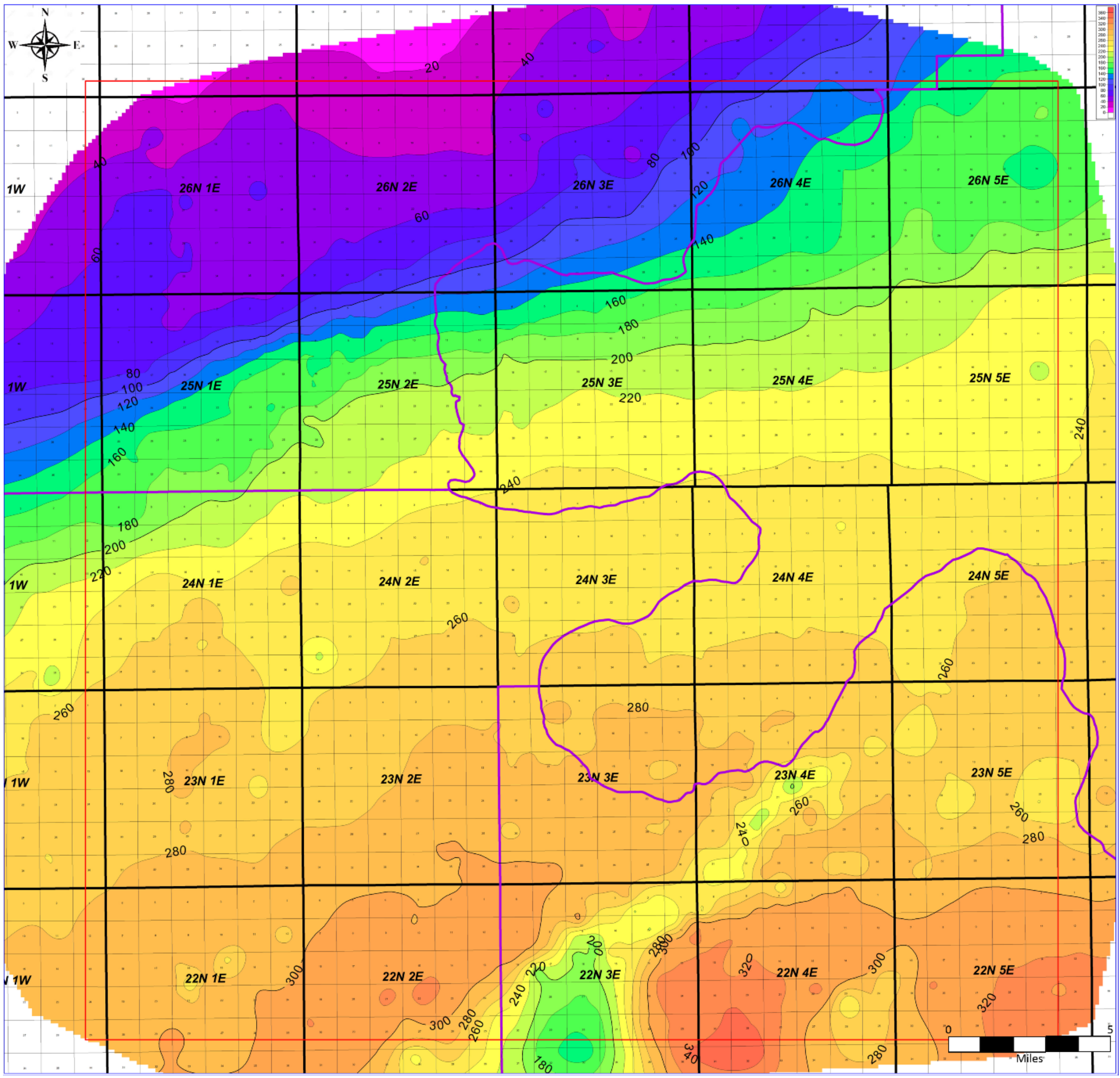

Figure 34: Hogshooter Limestone to Checkerboard Limestone interval isopach. Contour interval is 20 feet. Warm colors represent thicker interval, cooler colors represent thinner intervals. Thicknesses range from 20 feet in the northwest to 340 feet in the southeast.

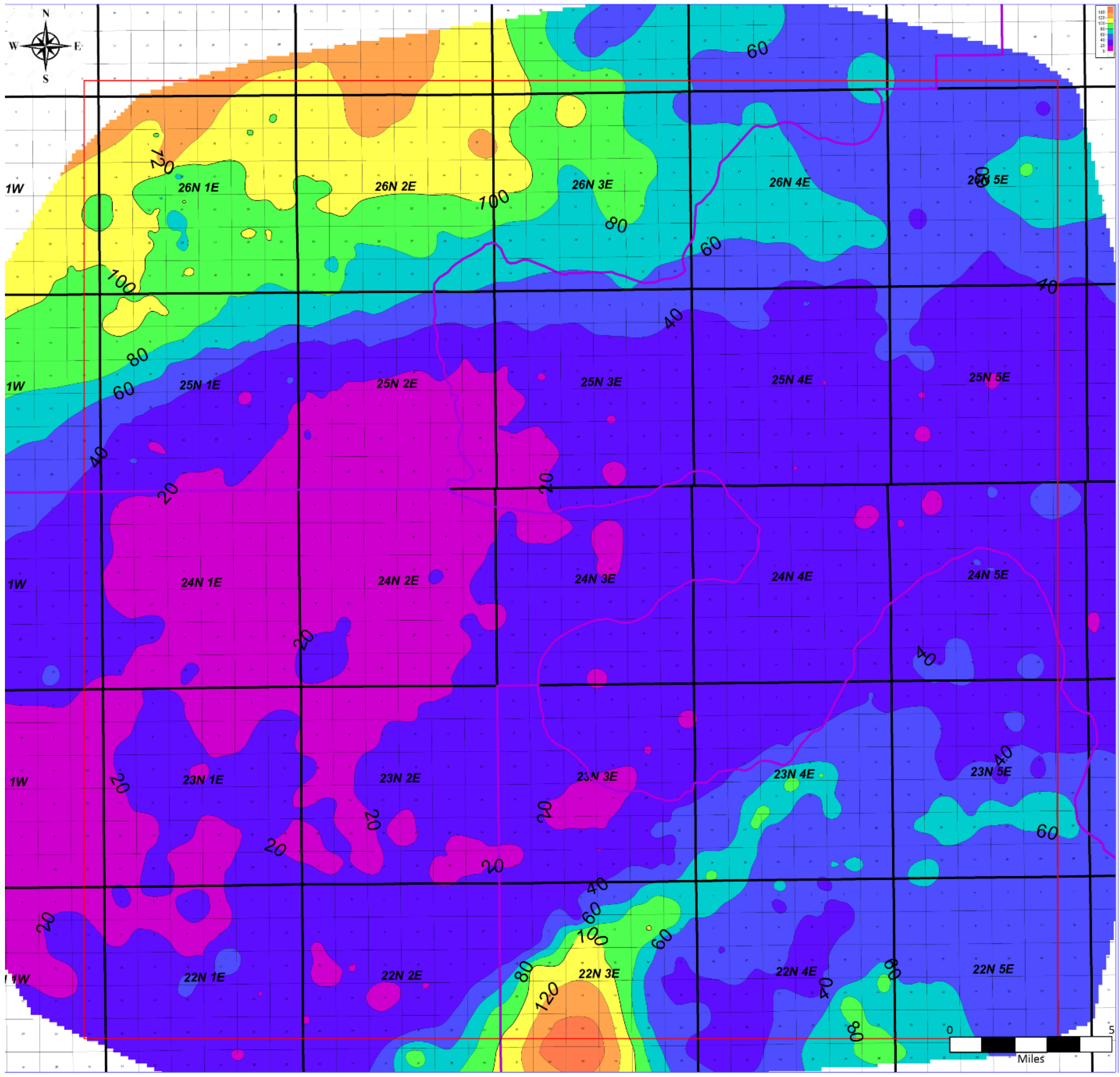

Figure 35: Thickness of the interval between top of "Shale Marker" and Hogshooter Limestone (See regional cross-section A-A' for "Shale Marker" identification, Plate 1). Contour interval is 20 feet. The thin areas from the Hogshooter Limestone to Checkerboard Limestone interval isopach correspond to thicker accumulation of the overlying shale section. Warm colors represent thicker intervals, cooler colors represent thinner intervals.

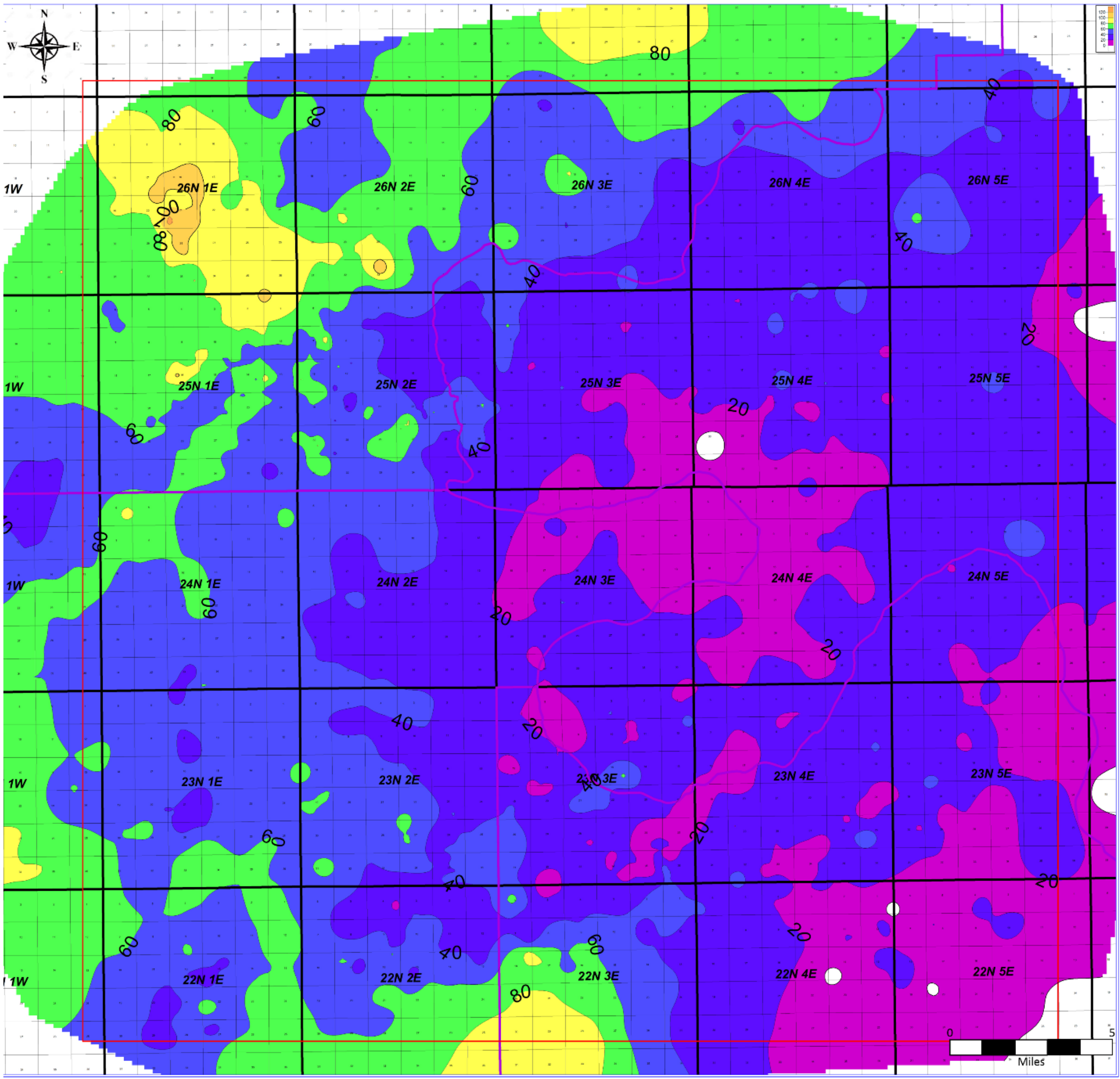

Figure 36: Thickness of the interval between the base of the Osage-Layton sandstone and the "Shale Marker" (see Plate 1). Contour interval is 20 feet. This interval is represented by a distinct coarsening-upward sequence. Southwest to northeast trends are evident. Thicker intervals in northwest corner of study area is normal to the other trends. Warm colors represent thicker interval, cooler colors represent thinner intervals.

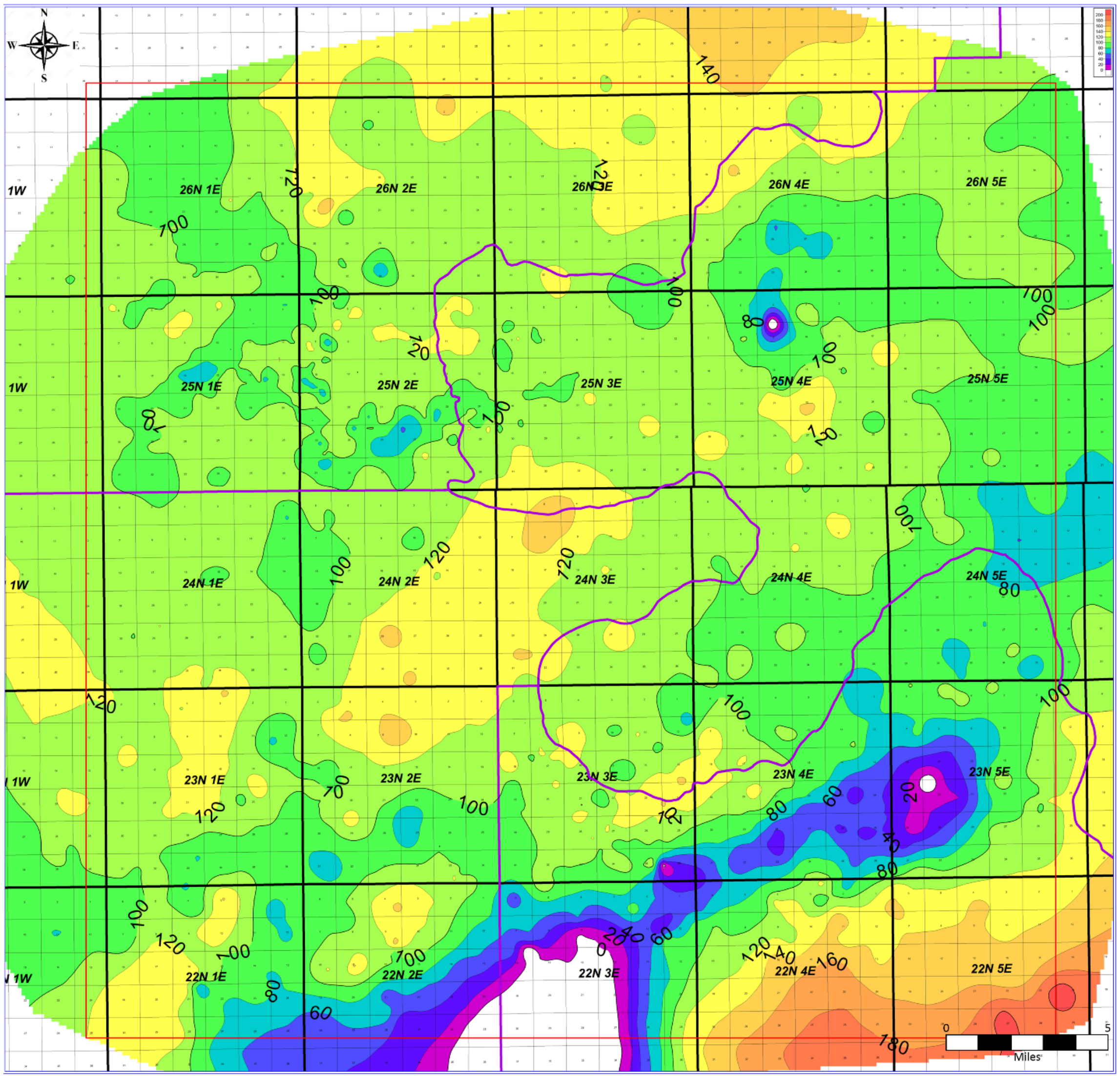

Figure 37: Map showing thickness of the interval between the top of the Osage-Layton interval to the base (Figure 2) (see Plate 1). Contour interval is 20 feet. Prominent trend of thinner interval is evident in the southern portion of the study area.

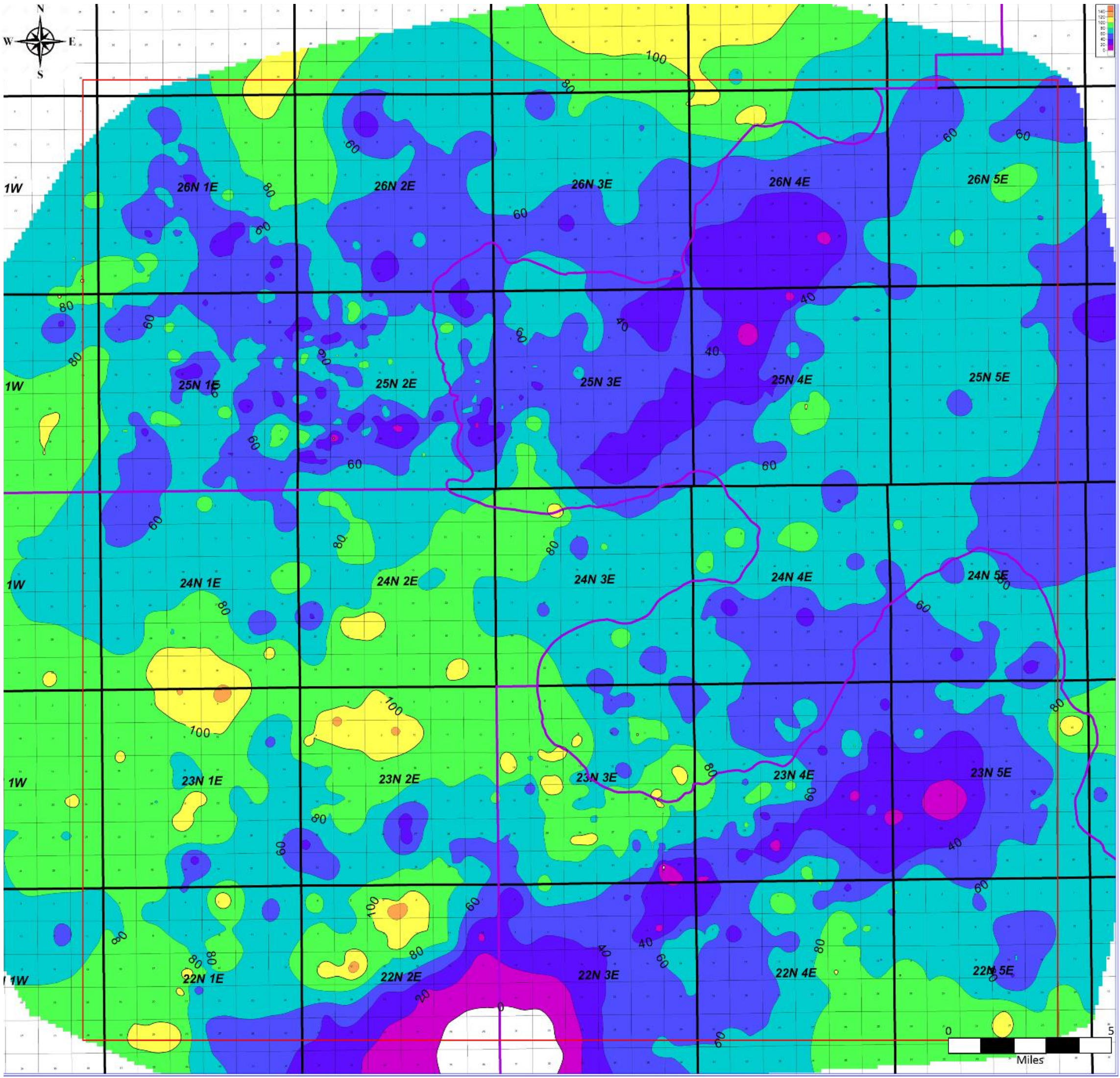

Figure 38: Osage-Layton net sandstone map. Contour interval is 20 feet. Notice the general southeast to west-northwest trend of the thicker net sandstone areas.

CHAPTER IV

PETROLEUM GEOLOGY: BIG BEND WEST FIELD, OSAGE AND KAY COUNTY, OK

General Info

In 2010, Cardinal River Energy acquired 800 acres to drill and develop the upper portion of the Osage-Layton sandstone in Osage County, Oklahoma (Figure 39). Sixteen wells were successfully drilled and completed in the upper Osage-Layton sandstone for years 2010 to 2015. Due to the success of these wells, another roughly 700 acres was acquired to the west across the Arkansas River in Kay County, Oklahoma. To date, four wells were successfully drilled and completed on this new acreage with a potential for 14 additional vertical and directional locations (red stars on field maps). Overall, the field contains approximately 720 acres of productive leasehold. To interpret sandstone distribution patterns and examine the relationship between oil and gas production and structure, a series of maps were constructed at both regional and local scales.

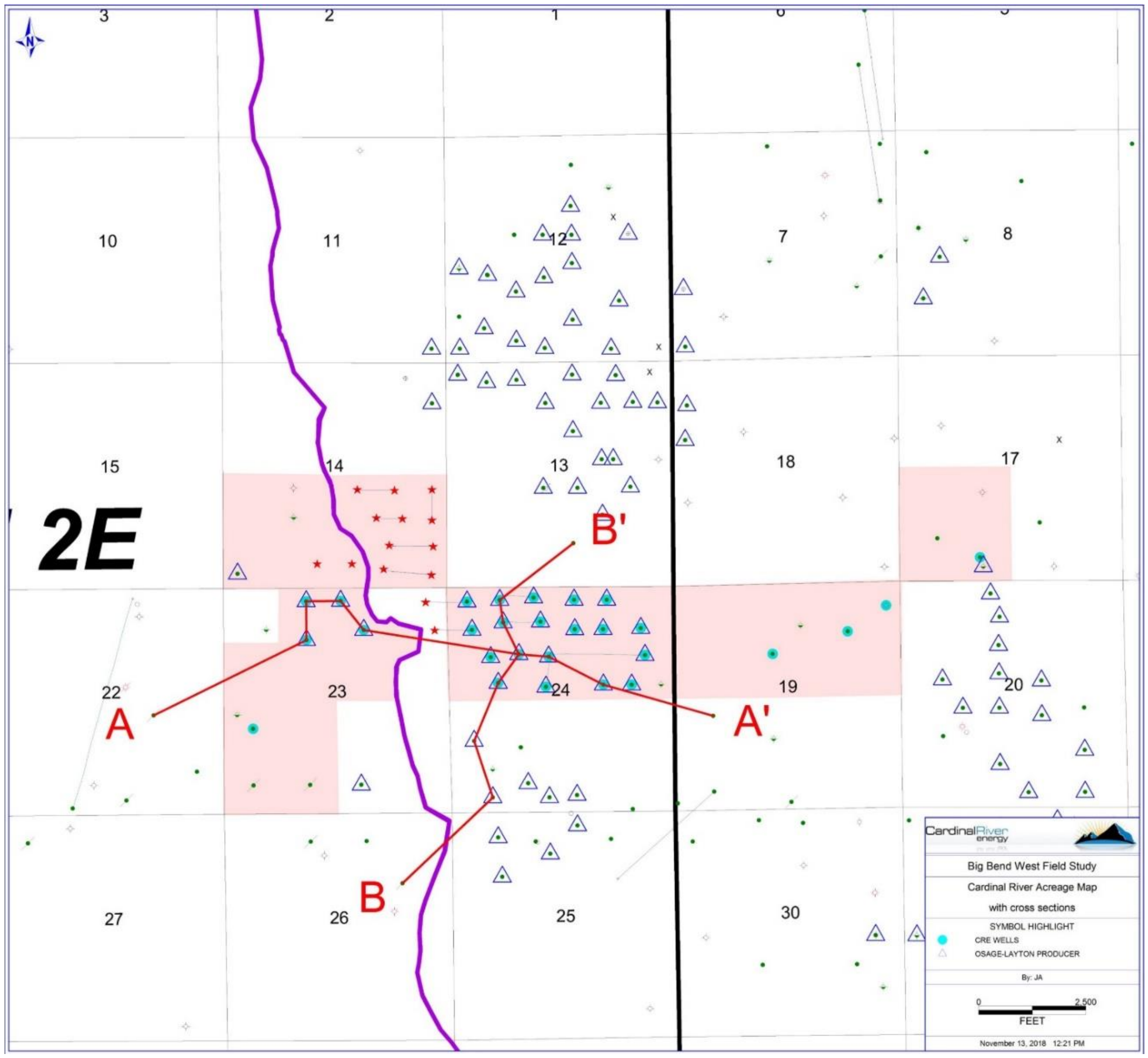

Figure 39: Map of Cardinal River Energy's leasehold and locations of field cross-sections A to A' and B to B' (Plates 12-15). The acreage to the east of the township line (sections 17 and 19) were not used to calculate OOIP. The blue triangles identify wells producing from the Osage-Layton reservoir. The field along the east side of the map is a lower Osage-Layton field that was not evaluated.

Structure

The structure of the Osage-Layton interval exhibits monoclinal dip to the southwest (Figure 40). There are no major structures present, but low relief structural noses enable the stratigraphy to entrap hydrocarbons. Just outside of the mapped area lies the large Ponca City field anticlinal structure. Plates 12-15 show structural and stratigraphic cross-sections A-A' and B-B' through the Big Bend West field area.

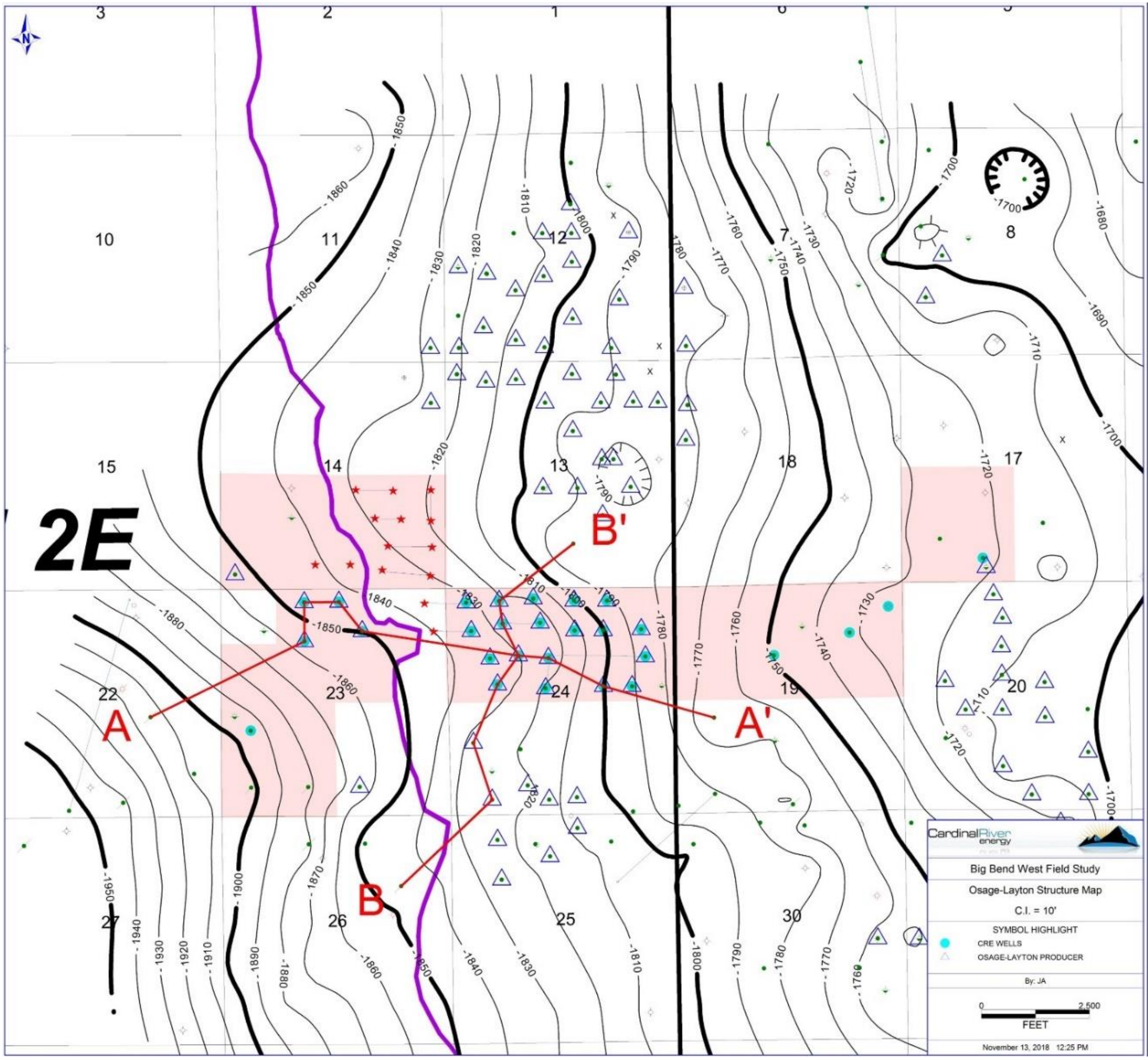

Figure 40: Osage-Layton structure map. Contour interval is 10 feet. Red shaded areas represent Cardinal River Energy leasehold. Blue triangles are wells producing from the Osage-Layton reservoir and the light blue dots represent Cardinal River Energy operating wells.

Net Sandstone

Figure 41 is the upper Osage-Layton net sandstone map using gamma-ray and spontaneous potential curves for sandstone versus shale (with a cutoff of 50% sandstone) and calculated porosity using a cutoff of greater than or equal to 10 percent. The formula used for the porosity calculation is as follows:

$$PorBD = (\rho_{ma} - \rho_b)/(\rho_{ma} - \rho_f)$$

Where,

PorBD = Calculated porosity using Bulk Density

ρ_{ma} = matrix density, 2.68 g/cm^3

ρ_b = bulk density, from wireline log curve (g/cm^3)

ρ_f = fluid density, 1.0 g/cm^3

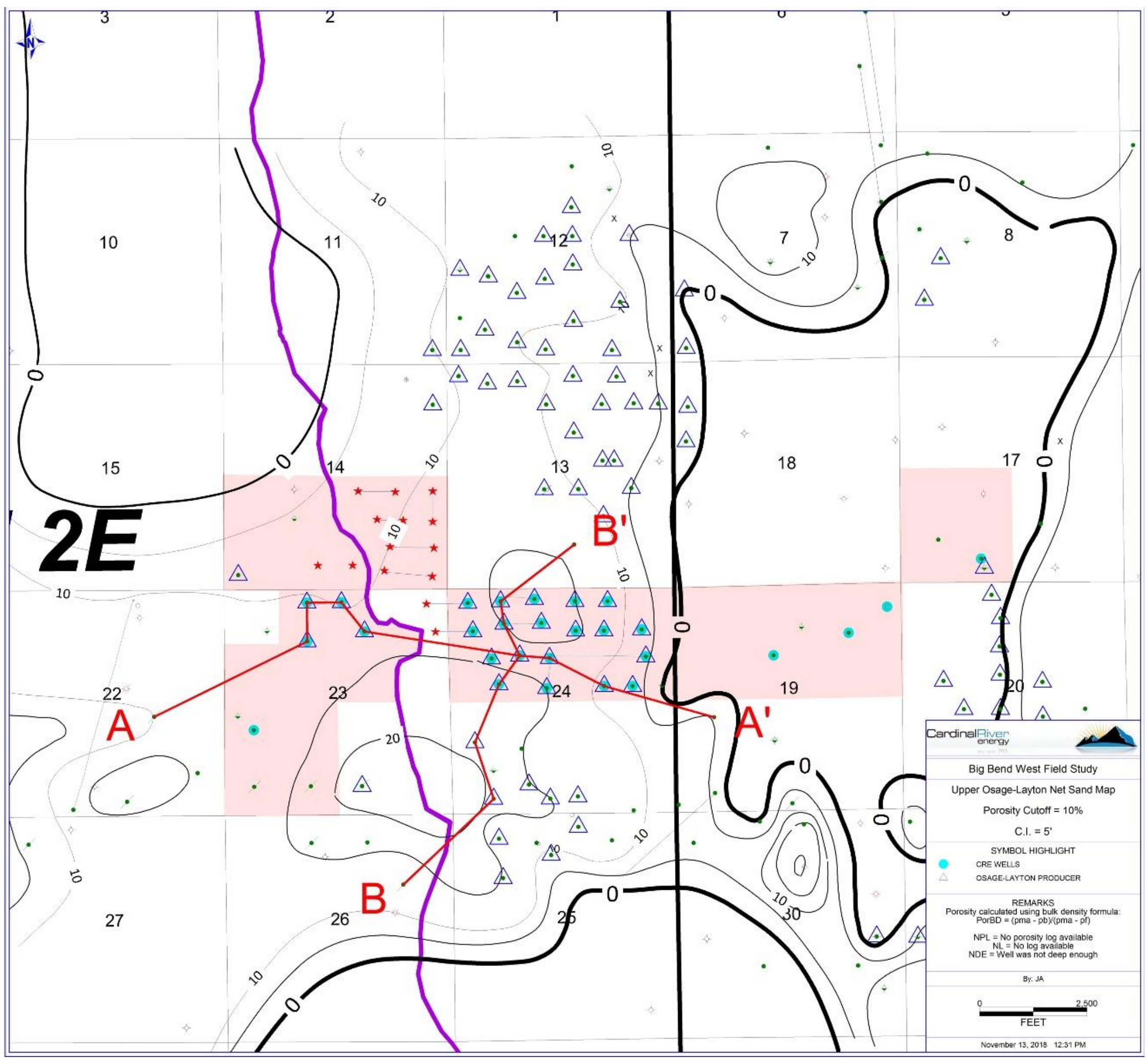

Figure 41: Upper Osage-Layton net sandstone isopach map. Contour interval is 5 feet.

Water Saturation

Water saturation (S_w) for the Osage-Layton sandstone is sensitive to clay content of the rock. Using a normal Archie equation to calculate water saturation will generate values that are typically 15% to 20% too high. This high calculated value is confirmed by production data for wells within the Big Bend West field. Original water saturation calculations based on normal Archie values are actually 55 to 65%. After thin section analysis and clay content (sometimes 30% to 40%) was confirmed, water saturations were recalibrated and updated. The orginal Archie equation for water saturation calculation follows:

$$S_w = \left[\frac{a \times R_w}{\Phi^m \times R_t}\right]^{1/n}$$

Where,

S_w = water saturation

a = tortuosity constant, normally 1 except for most sandstones in Oklahoma use 0.81.

n = saturation exponent, normally a vaule of 2.0

R_w = formation water resisitivity at formatino temperature

Φ = porosity, calculated using the bulk density equation from above

m = cementation exponent, normally 2 for carbonates and 1.8 for most sandstones in Oklahoma

R_t = true formation resisitivity

For exploration and development within the Big Bend West Field, values of 2.0 for n, .035 for R_w, and 0.81 for a, and 1.7 for m are used. Using this method, water saturation values were reduced about 15% to 20% to a more reasonable number comparable to what is seen in production data. Figure 42 is a water saturation map overlaid on the net sandstone isopach map. When compared to the Osage-Layton structural map, the water saturation does not follow the structural contours. This suggests that the reservoir has minor structure influence and is mostly stratigraphic.

The Osage-Layton is a low resisitivity pay, with productive reservoirs producing as low as 2 ohms-meters. Interstitual clay in the sandstone causes water saturation readings to be too high due to the level of clay bound water. Fortunately, this water tends to be irreducible water. Bulk volume water calculations are consistently low (around 4% to 5%) and do not change drastically indicating the water in the formation is mostly irreducible.

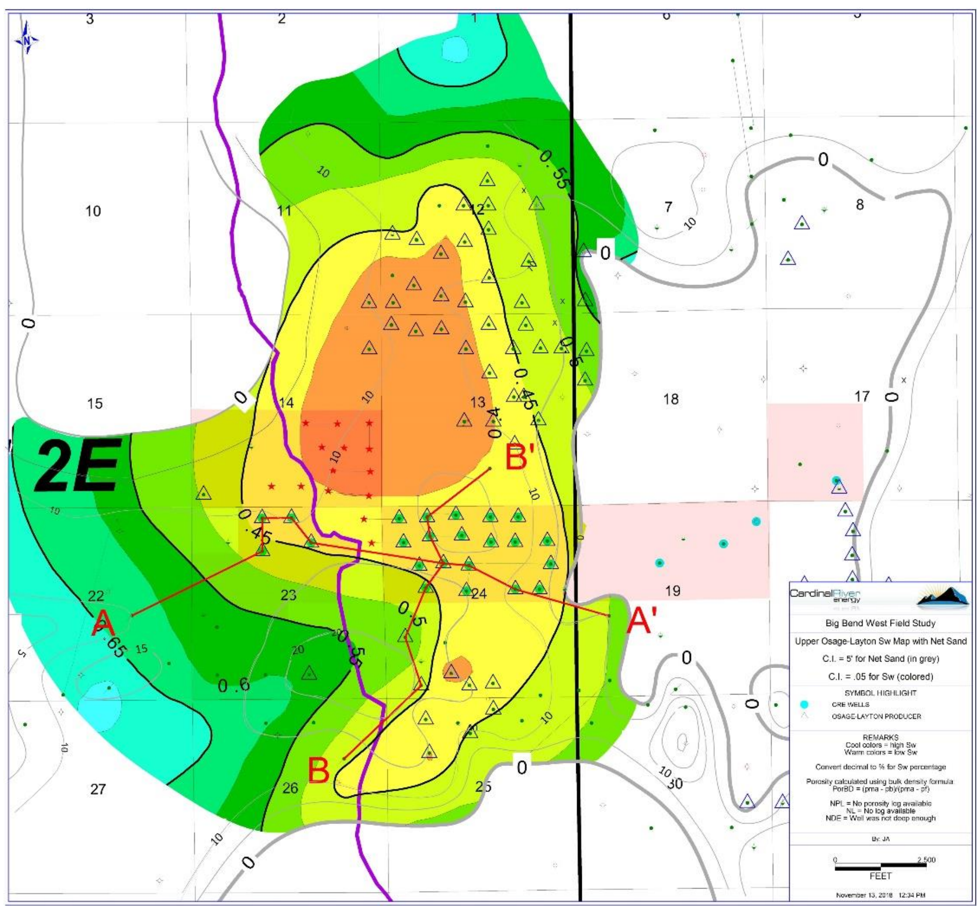

Figure 42: Water saturation map (colored) with values in decimals overlain on the net sandstone isopach map (grey contours). Contour interval is 5 feet for the net sandstone map and .05 for the water saturation map. Warm colors represent low water saturations and cool colors represent higher water saturations.

Volumetrics

OOIP and recoverable reserves were calculated using the following formulas:

$$N = \frac{(7758.4 \times A \times H \times \Phi \times S_o)}{B_o}$$

$$Recoverable\ Reserves = N \times RF$$

Where,

Constants:

N = Original oil in place (OOIP) in Stock Tank Barrels (STB)

Φ = Average calculated porosity (decimal)

S_o = Oil saturation (decimal)

B_o = Formation volume factor (reservoir barrel/STB)

RF = Recovery factor

Variables:

A = Average area (acres)

H = Average thickness of reservoir (feet)

To obtain a more accurate OOIP and recoverable reserves esitmates, the net sandstone isopach was divided into five foot intervals, each having its own area and thickness of oil saturation. These isopach intervals were applied across Cardinal River Energy's acreage leasehold to provide a reasonal estimate of reservoir thickness (H) used to calculate OOIP. Values used are: 1.2 for B_o, 16% for RF, 18% for Φ, and 53 % for S_o. Figure 43 is a table of values showing the net sandstone isopach intervals used to calculate OOIP of 4,561,183 STB of oil and and estimated ultimate recovery (EUR) of 729,789 STB of oil using a recovery factor of 16%.

Cardinal River Energy Big Bend West Field Volumetrics			
Isopach Interval	Area (A) (acres)	Avg. Thickness (H) (feet)	OOIP (STB)
0-5	79	2.5	121,817
5-10	254	7.5	1,174,990
10-15	296	12.5	2,282,133
15-20	91	17.5	982,243
		Total OOIP (STB)	4,561,183
		After RF	729,789

$$OOIP\ (STB) = \frac{(7758.4 * A * H * \Phi * S_o)}{B_o}$$

Where,

$B_o = 1.2$

RF = 16%

Avg. $\Phi = 18\%$

Avg $S_o = 53\%$

A = Area (acres)

H = Thickness (feet)

Figure 43: Estimates of original oil in place (OOIP) for the upper Osage-Layton reservoir in Big Bend West field. All values provided by Cardinal River Energy.

CHAPTER V

DISCUSSION AND INTERPRETATION

The Osage-Layton sandstone is interpreted to have been deposited in a deltaic setting that was influenced by both fluvial and tidal processes. The lower Osage-Layton sandstone was more proximal and appears to be more fluvial, but core through the entire sandstone is not available. Based on the available core, tidal influence dominated the middle section of the Osage-Layton and sedimentary structures and distribution for the upper Osage-Layton sandstone support its deposition in an environment such as a tidal flat that experienced tidal processes. The generalized paleo dip at the time of Osage-Layton deposition was very gradual basinward, which was to the northwest. Before deposition of the Hogshooter Limestone, paleo dip was southeast toward the Arkoma Basin. However, by the time of Osage-Layton deposition the elevation of the Ouachita Mountains and filling of the Arkoma Basin caused a shift toward a northern depocenter (Rascoe and Adler, 1983).

The interval isopach of the Checkerboard Limestone to the Big limestone (Figure 33), exhibits thickness patterns that differ from Figures 34 and 36, but can be attributed to thickening and thinning of the Marmaton Group carbonate and/or thicker Cleveland sandstone. Thinner areas are attributed to differential compaction around thick Cleveland sandstone and/or carbonate buildup in the Marmaton Group. Although focus was not on the "True" Layton sandstone, the interval isopach of the Hogshooter Limestone to the Checkerboard Limestone (Figure 34) is interpreted to show the source for the "True" Layton sandstone as coming from the southeast, the

Ouachita Orogeny. In the northwestern part of the study area, rapid thinning into a more gradual thinning is attributed to the edge of coarser siliciclastic deposition and evidence of a small depocenter. A net sandstone map was not included in this study, but there is no significant "True" Layton sandstone deposited in the proposed depocenter.

Deposition of the shale above the Hogshooter Limestone appears to complement Hogshooter Limestone to Checkerboard Limestone thickness. The shale thickens in the depocenter along the northern boundary of the study area and in the southwestern quadrant of T.25N, R.3E. (Figure 35). The anomalous thin trend in the southeast part of the study area that trends southwest to northeast follows a fault on the Oklahoma Geological Survey fault map and as such is proposed to be the result of active regional strike-slip faulting.

The stratigraphic interval between the top of the "Shale Marker" to the base of the Osage-Layton sandstone exhibits a coarsening upward geometry (Figure 2) typical of a prograding delta front environment. After deposition of the Hogshooter Limestone and the overlying shale, the Pennsylvanian Sea began to regress as a result of increased sediment supply, subsidence or both. Reworking of the coarsening upward interval resulted in the northeast to southwest trends evident on (Figure 36). The thicker area in T.26N, R.1E is believed to be associated with thicker distributary channels as it is oriented normal to the southwest to northeast trend interpreted to represent the paleoshoreline.

The thickness of the Osage-Layton sandstone (Figure 37) shows the distribution of cleaner sandstone above the coarsening upward interval (Figure 2). Anomalous thicks and thins are attributed to differential compaction of shaley areas and paleostructure. The southwest to northeast trend thinning in the southern part of the study area is interpreted as a paleohigh related to uplift. This feature is evident on all thickness maps (Figures 33-37) and aligns with a fault zone (Figures 31 and 32). Interestingly, this thinner trend attributed to a paleohigh becomes a low area with thicker sediment accumulation following Hogshooter deposition. The area was apparently positive doing Osage-Layton deposition as sandstone thins or is absent over the trend.

The Osage-Layton sandstone (Figure 2) can be divided into an upper and lower sandstone throughout most of the northern part of the study area. Elsewhere these become increasingly difficult to separate. Therefore, an overall Osage-Layton net sandstone map was constructed to show general trends or sandstone (Figure 38).

The lower Osage-Layton is interpreted to represent a distributary channel system. Across most of the study area the lower sandstone has blocky or fining upward wireline curve geometry. Thicker accumulations of sandstones within this interval may represent stacked channels. In some parts of the study area, the lower Osage-Layton is thinner and exhibits a coarsening upward log character indicative of a delta front environment or distributary mouth bar.

From core, the lower Osage-Layton sandstone exhibits sedimentary features typical of fluvial and tidal environments. For example, from the Hart #4-24 core, the lower Osage-Layton sandstone consisted of alternating sections of cross-bedded sandstone, organic-rich interbedded dark shales, rhythmically bedded interlaminated zones, and sandstone with rip up clasts up to 1 cm in width (Figure 15: Appendix C). This pattern is interpreted as stacked channels with intervening zones of tidally influenced mud and silt deposits. The lower Osage-Layton sandstone in the Wah-Sah-Po #1 is mostly horizontally bedded to massive with rhythmic patterns in sandstone and interbedded sections (Appendix B).

The middle section that separates the lower from the upper Osage-Layton sandstone is interpreted to be a zone of tidal reworking. This interval in the Garrity #10-24H, Wah-Sah-Po #1, and Hart #4-24 cores is dominated by abundant hummocky cross-bedding, climbing ripples/wavy bedding, soft sediment deformation, and numerous thin, lenticular sandstones with alternating thin shale laminae. Figures 16 and 17 show a few examples of these features. The thin interbedded/interlaminated nature of these features are indications that the zone was influenced by rhythmic processes, typical of tidal environments.

The upper Osage-Layton sandstone is more prevalent in the northeastern and northwestern portions of the study area. It appears to be reworked by channelized flow (Figures 18 and 19) and rhythmic tidal currents. The lack of unidirectional cross bedding may indicate sandstones are related to tidal channels rather than strictly fluvial channels. The sandstone/interbedded shale interval with burrowing may represent a bay fill environment that generates the serrated wireline log signature (Figure 2).

In the Garrity #10-24H core, the upper Osage-Layton sandstone had a distinct erosional contact at the base of the principal sandstone that cut into the underlying coal (Figure 22). This is interpreted as channel erosion of the coal. Small woody/coal fragments incorporated into overlying sandstone are believed to represent erosion of underlying coal and transportation along the channel.

The evidence from mapping and core examination supports the interpretation that the Osage-Layton sandstone was deposited as part of a prograding tidally influenced delta. This differs from the interpretation of Lalla (1975), Visher (1996), and Visher and Rennison (1978), who indicated the Osage-Layton distribution represents a “classic” Mississippian-type birds foot delta with well-defined distributary channels. Total (gross) and net sandstone patterns fail to show well defined channelization. Instead, sandstone intervals contain thin stacked channels with intervening interbedded/interlaminated sandstone and shale that is burrowed and rhythmically bedded, suggesting important tidal influence on depositional processes. The lower Osage-Layton sandstone may represent more inland part of the delta where tidal processes had minor influence on the distributary systems. However, the cores from the northwestern part of the study area indicate significant tidal influence on what appears to be a very low gradient sediment dispersal system. The upper Osage-Layton sandstone was deposited in a more distal part of the system such as a tidal flat, where the primary mode of channelization and sandstone distribution was from tidal processes.

Modern Analog

A modern analog for the lower Osage-Layton delta best fits the Mahakam Delta in Indonesia on the east coast of Borneo (Figures 44). Figure 45 shows an illustrated diagram of the Mahakam Delta overlain upon a map of the study area at similar scale to compare the Mahakam Delta and the Osage-Layton dispersal system. Allen and Chambers (1998) characterized the Mahakam Delta as a mixed fluvial and tide-dominated delta lying in a low energy marine environment with a fan-shaped morphology. The Mahakam Delta began developing at the end of the Holocene transgression about 5000 years ago (Caratini and Tissot, 1988). The delta exhibits a gentle slope of about .06 m/km (Husein and Lambiase, 2005). According to Allen and Chambers (1988), the modern delta formed during low wave energy, low to medium tide ranges, and a large fluvial discharge. Husein and Lambiase (2005) concluded that further landward, fluvial processes were the dominant bedload transport patterns whereas these processes decreased and tidal processes increased and became the dominant bedload transport pattern seaward. The Osage-Layton delta system is similar in that higher energy bedload transport seen in upper flow regime fluvial environments is the dominant process landward (southeastern part of study area), whereas moving seaward (central and northwestern part of study area), lower energy bedload transport evident in lower flow regimes becomes the dominant process.

Figure 44: Google Earth satellite image of the Mahakam Delta, Indonesia. Imagery date: 12/30/2016.

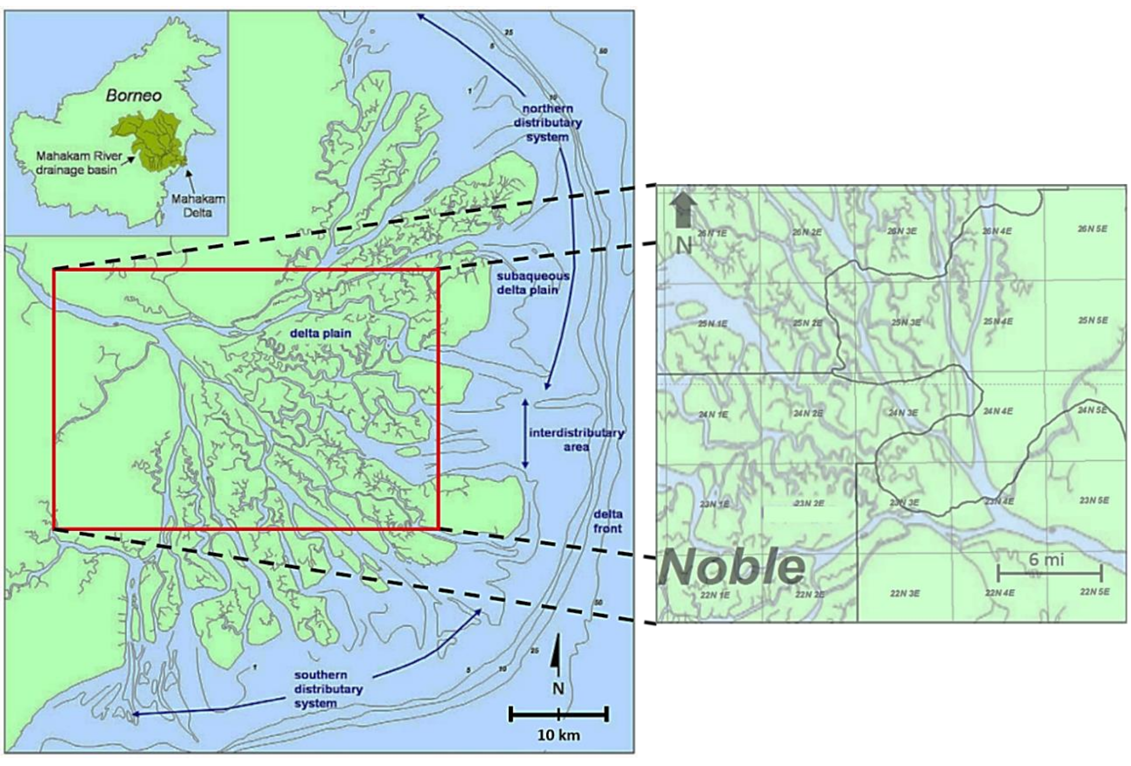

Figure 45: Illustration of the Mahakam Delta system in Borneo, Indonesia (left) with portion of illustration rotated 180° and overlain upon a map of the study area (right) to show a representation of the interpreted depositional environment for the Osage-Layton delta system. (Mahakam Delta illustration from Husein and Lambiase (2005)).

The lower Osage-Layton sandstone is characterized by fine to medium-grained sandstone with high angle cross-bedding and little to no bioturbation. Inland of the cored areas, the lower Osage-Layton sandstone interval could be similar to what Husein and Lambiase (2005) described as occupying the distal reaches of the main distributaries, but proximal enough that tidal processes exerted less influence on the environment, except in the case of an abnormal rise in sea level.

As mentioned before, the upper Osage-Layton sandstone became increasingly difficult to correlate moving landward (southeast). The upper Osage-Layton sandstone was identified mainly within the northern and northwestern parts of the study area and consisted of silty, very fine to fine-grained sandstone with high clay content and rhythmically bedded interstratified shale laminae with thin silty sandstone lenses and bioturbation. This is similar to what Husein and Lambiase (2005) observed in the sand and mud facies of the intertidal areas in the vicinity of channel mouths within the Mahakam Delta. Increased tidal influences are represented by the increased interlaminated shale and sandstone lenses with hummocky cross-bedding, wavy, ripple beds, soft sediment deformation, and the abundant bioturbation.

The Osage-Layton sandstone interval is similar in some ways to stratigraphic successions seen in the Mahakam Delta in that it exhibits an overall fining upward sequence that begins with channel fill with less tidal influence, tidally dominated estuary or tidal flats near shoreline sands of distal, tidally influenced distributaries and channel mouths, and offshore marine shale. Figure 46 shows an example of a typical Mahakam Delta composite stratigraphic succession. Tidal influence increases upward across the Osage Layton and contributes to the depositional heterogeneity evident in cores compartmentalization of reservoirs.

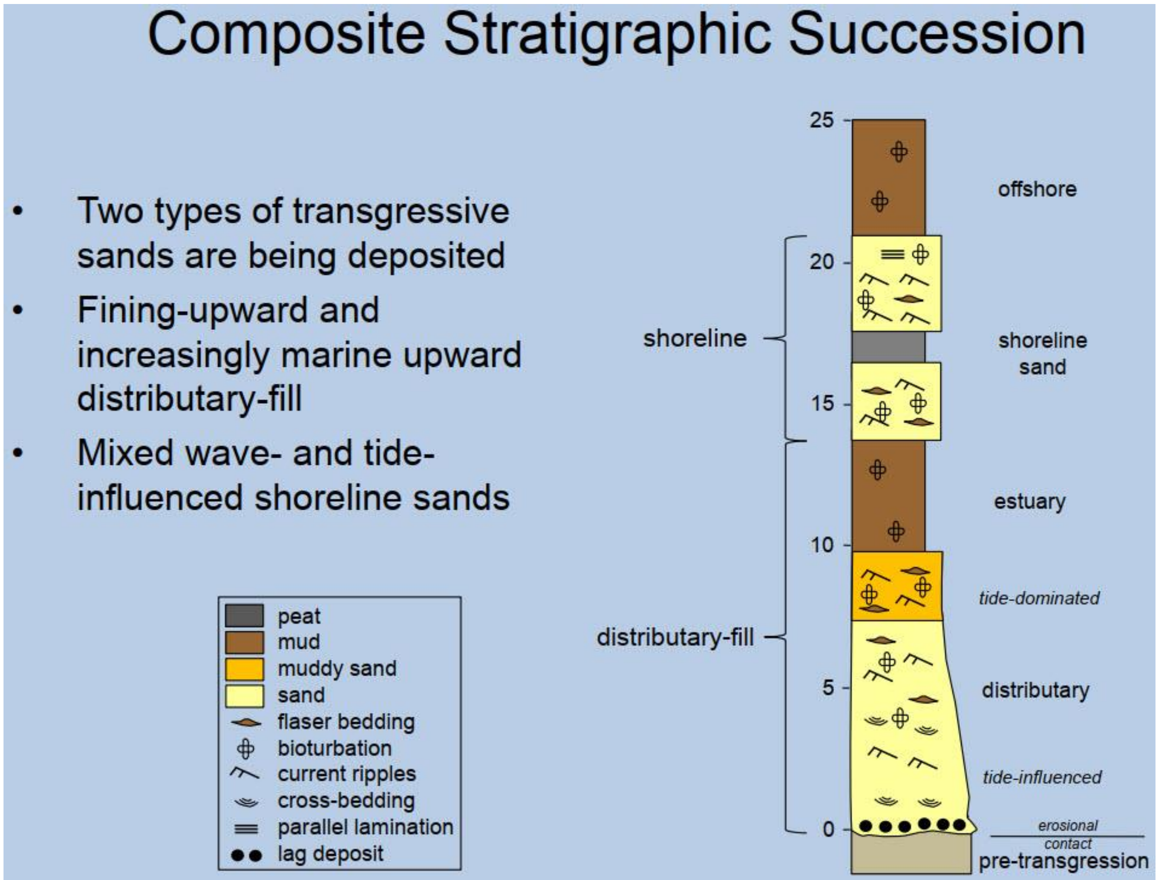

Figure 46: Composite stratigraphic succession of the Mahakam Delta, Indonesia, from Lambiase and Husein (2015).

CHAPTER V

CONCLUSIONS

Principal conclusions of this study are as follows:

1. The Osage-Layton sandstone is interpreted to have been deposited in a deltaic setting that was influenced by both fluvial and tidal conditions.

2. The generalized paleodip at the time of deposition was in a north-north westward trend. The dip was very gradual and minor changes in sea level would have regional impact.

3. Fluvial-deltaic environments with minor tidal reworking were most likely concentrated in the southern, and southeastern portion of the study area. Tidal dominated deltaic environments were most likely concentrated in the northern and northwestern parts of the study area.

4. The upper Osage-Layton sandstone is more prevalent in the northeastern and northwestern portions of the study area. It is believed to represent a series of alternating stacked channels and tidally influenced mud dominated interbedded/interlaminated zones. Channels within the upper Osage-Layton lack distinct unimodal cross stratification and could have formed in a tidal flat environment

5. Detrital constituents in the Osage-Layton are dominantly quartz, feldspars, and muscovite. Authigenic components include kaolinite and calcite, dolomite, and mixed calcite-dolomite cements. Pyrite is common.

6. The lower Osage-Layton is interpreted to have been more fluvially influenced and may represent channel fill.

7. Due to potential permeability barriers such as shale laminae and streaks of porous and non-porous sandstone, enhanced oil recovery projects need to be implemented only after detailed mapping because reworking by a combination of fluvial and tidal processes, distinct and defined sandstone trends are difficult to delineate.

8. In order to fully understand the Osage-Layton sandstone at the field scale, integration of core and mapping data is recommended. Core is essential to interpreting depositional processes and rock composition, whereas mapping of core-calibrated electrofacies offers the best method of delineating reservoirs and seals.

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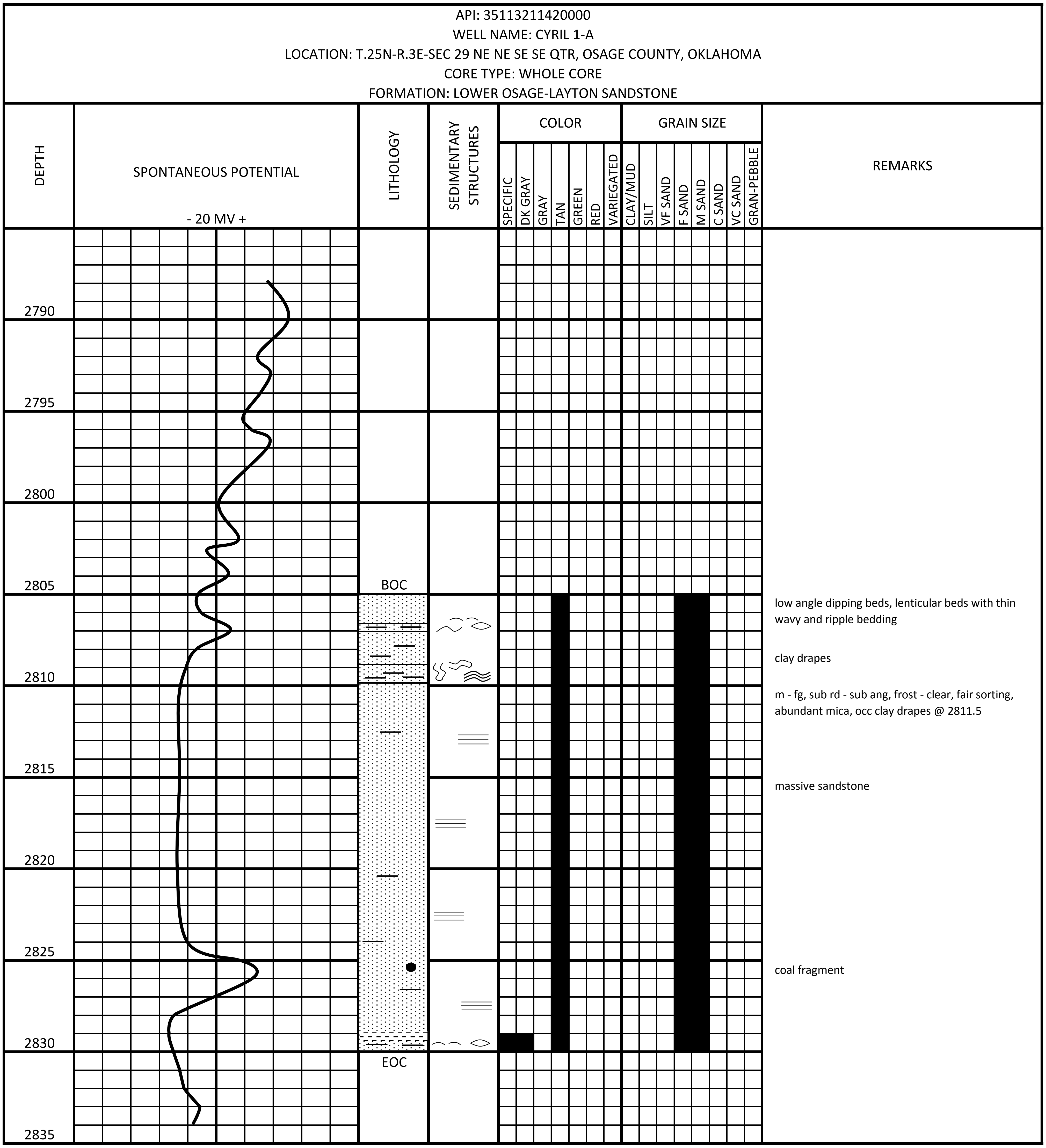
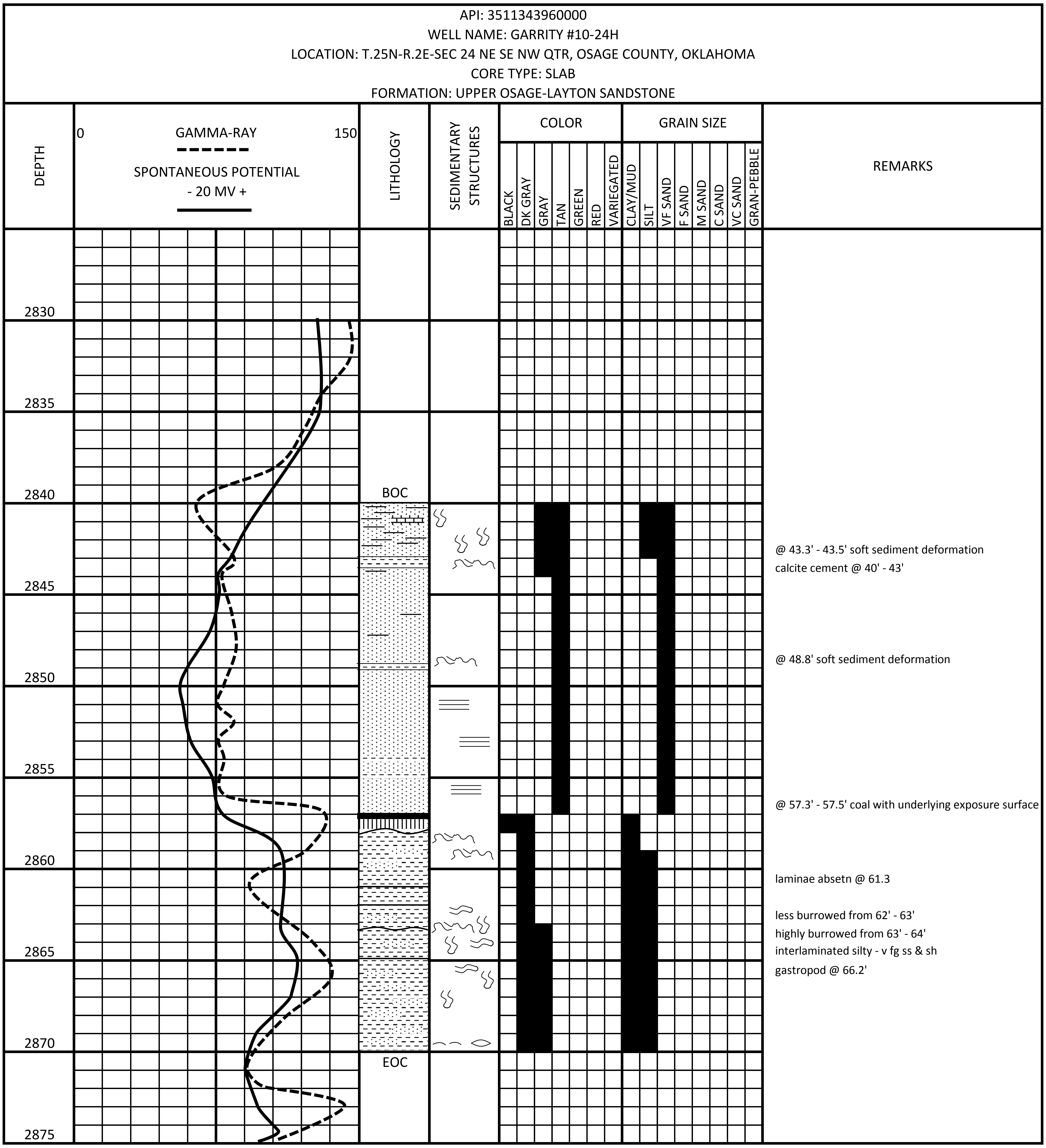
APPENDICES

APPENDIX A

CORE DESCRIPTIONS AND LAB ANALYSIS



Cyril #1-A Core Description Page 1



Garrity #10-24H Core Description Page 2

STIM-LAB, Inc.

Company: Cardinal River Energy
Well: Garrity #10-24H
Location: Osage County, OK
SEC. 24, T25N-R2E

Date: 10/28/2010
Files: SL9061
Analyst(s): DM

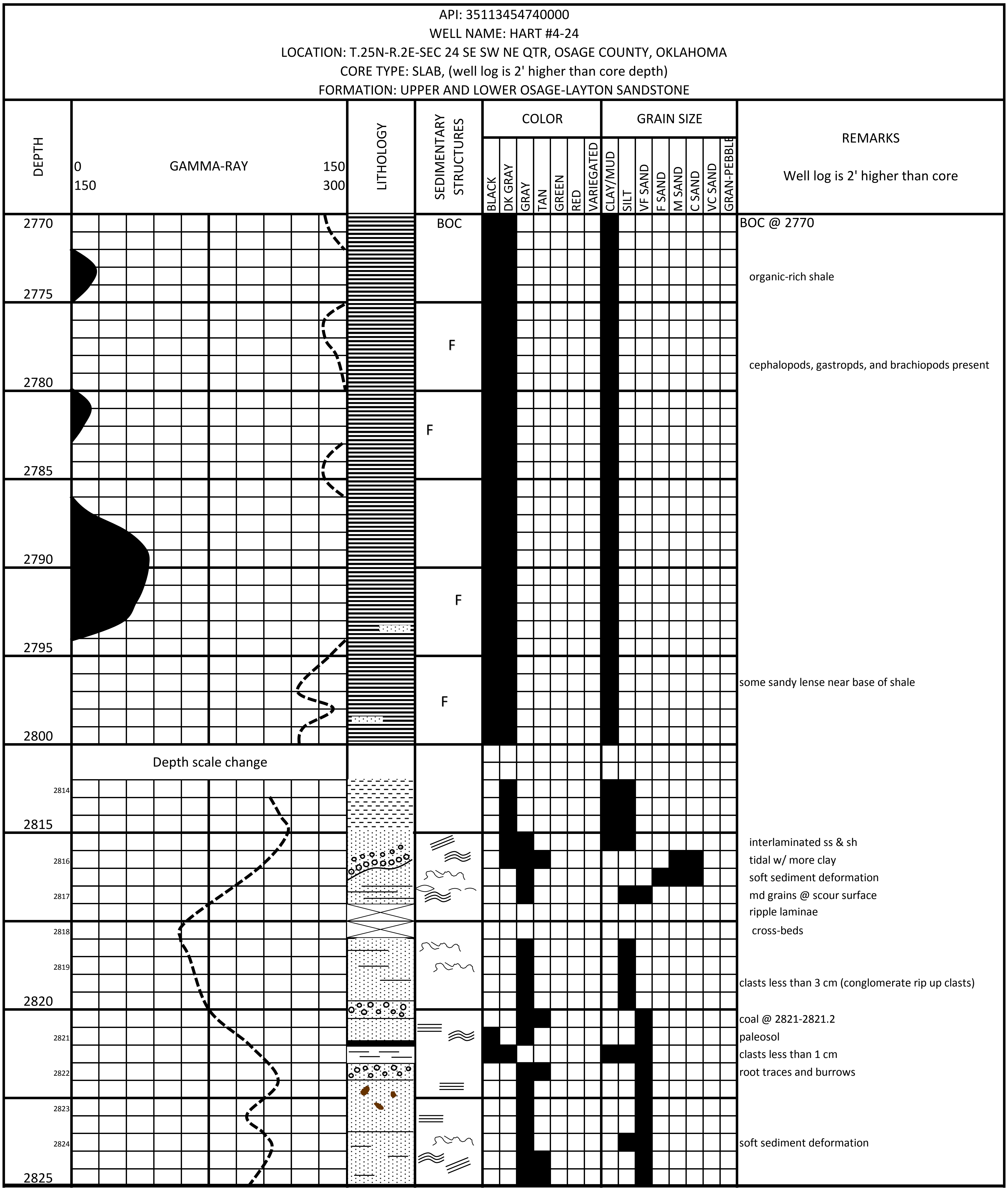
STIM-LAB
CMS-300 CORE ANALYSIS DATA

Sample Number	Depth (ft)	Net Confining Stress (psig)	Porosity (%)	Permeability Kair (mD)	Permeability Klinkenberg (mD)	SATURATION (PORE VOLUME) OIL %	SATURATION (PORE VOLUME) WATER %	Grain Density g/cm3	Lithology
1	2843.5	890	9.2	0.018	0.009	19.9	79.0	2.72	Sd vfg vshy w/lam vslty pyr bioturb stks yl flu
2	2844.5	890	17.5	2.12	1.59	22.5	41.9	2.68	Sd vfg shy w/thn lam vslty pyr bioturb ev yl flu
3	2845.5	890	16.7	2.21	1.66	23.5	44.8	2.67	Sd vfg shy w/thn lam vslty pyr bioturb ev yl flu
4	2846.5	890	17.3	2.82	2.16	26.5	43.6	2.66	Sd vfg shy w/thn lam vslty spyr bioturb ev yl flu
5	2847.5	890	18.1	3.87	3.03	31.9	40.5	2.67	Sd vfg shy vslty spyr bioturb ev yl flu
6	2848.5	890	17.1	2.39	1.81	21.2	44.6	2.67	Sd vfg shy vslty spyr ev yl flu
7	2849.5	890	17.9	3.35	2.61	30.4	40.6	2.66	Sd vfg shy vslty spyr bioturb ev yl flu
8	2850.5	890	16.8	3.43	2.72	26.9	44.6	2.67	Sd vfg shy w/thn lam vslty pyr bioturb ev yl flu
9	2851.5	890	18.0	6.46	5.33	36.8	35.8	2.67	Sd vfg shy w/thn lam vslty pyr bioturb ev yl flu
10	2852.5	890	18.1	5.22	4.22	32.3	39.0	2.67	Sd vfg shy vslty spyr bioturb ev yl flu
11	2853.5	890	16.0	2.37	1.82	28.0	42.9	2.67	Sd vfg shy w/thn lam vslty spyr bioturb ev yl flu
12	2854.5	890	15.6	0.900	0.687	23.4	50.3	2.67	Sd vfg shy vslty pyr bioturb ev yl flu
13	2855.6	890	16.3	1.06	0.741	20.6	47.9	2.68	Sd vfg shy vslty spyr bioturb ev yl flu
14	2856.4	890	18.2	3.47	2.74	24.6	41.2	2.67	Sd vfg shy vslty spyr bioturb ev yl flu
15V	2850.0	890	16.4	0.105	0.073	25.1	46.5	2.68	Sd vfg shy vslty pyr bioturb ev yl flu
16	2850.8	890	16.4	7.58	6.42	N/A	N/A	2.65	Sd vfg shy vslty pyr bioturb ev yl flu

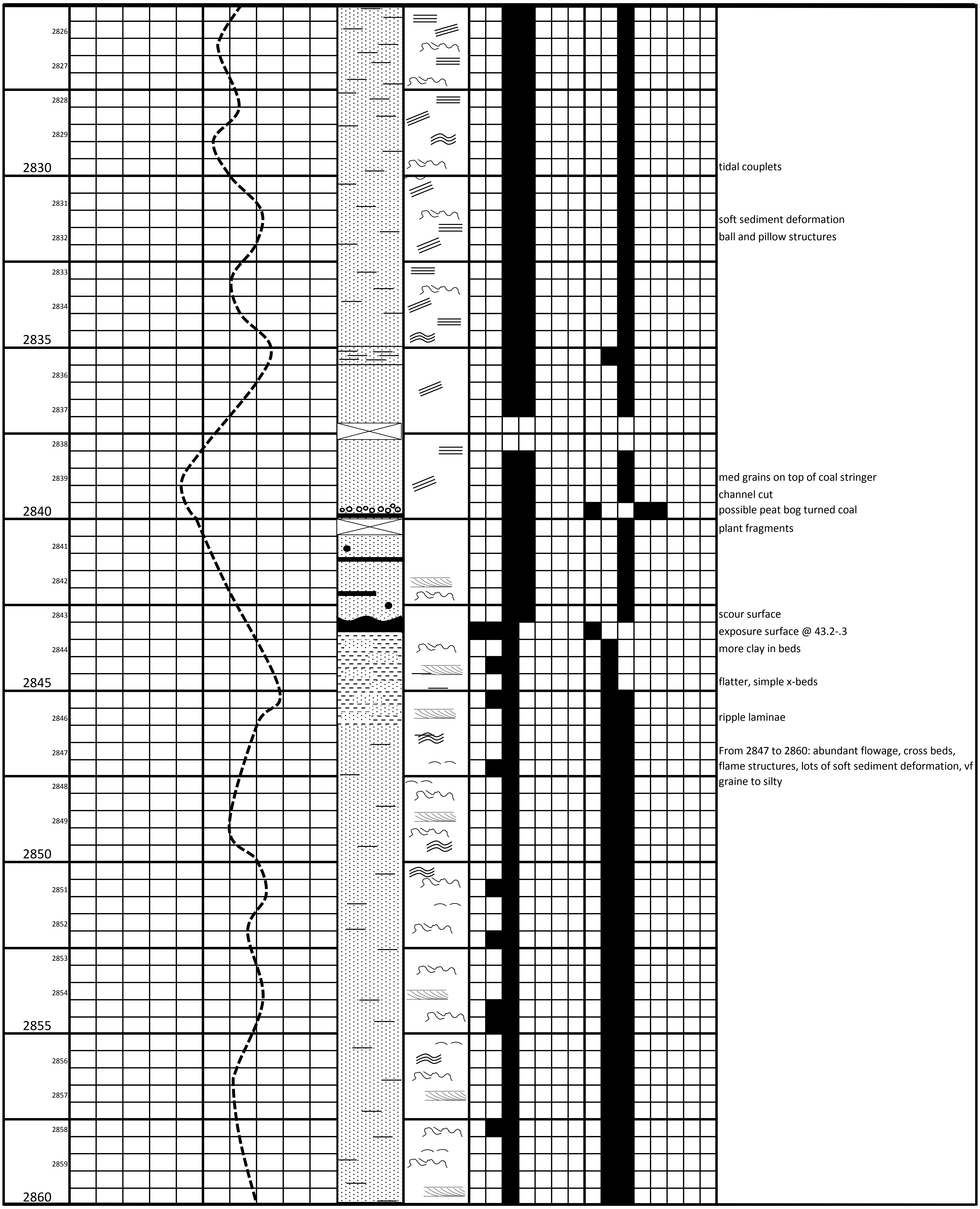
CARDINAL RIVER
GARRITY NO. 10-24H WELL
SL9061

CARDINAL RIVER
GARRITY NO. 10-24H WELL
TABLE OF RESULTS

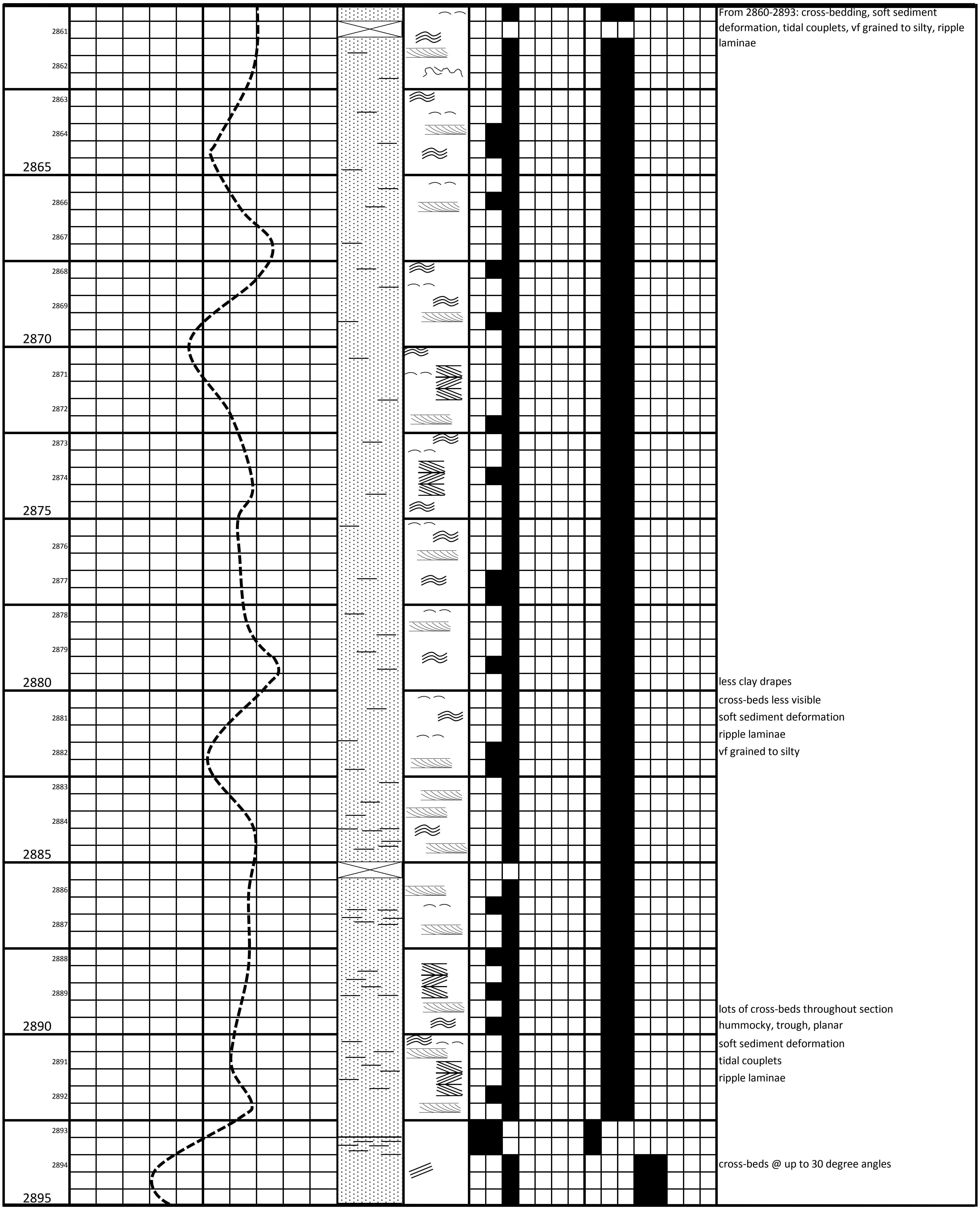
Depth (ft.)	Quartz %	Plagioclase %	K-feldspar %	Ankerite %	Pyrite %	Total Clays %	Illite %	Chlorite %	Kaolinite %
2850.8	72	14	2	4	1	7	6	1	trace



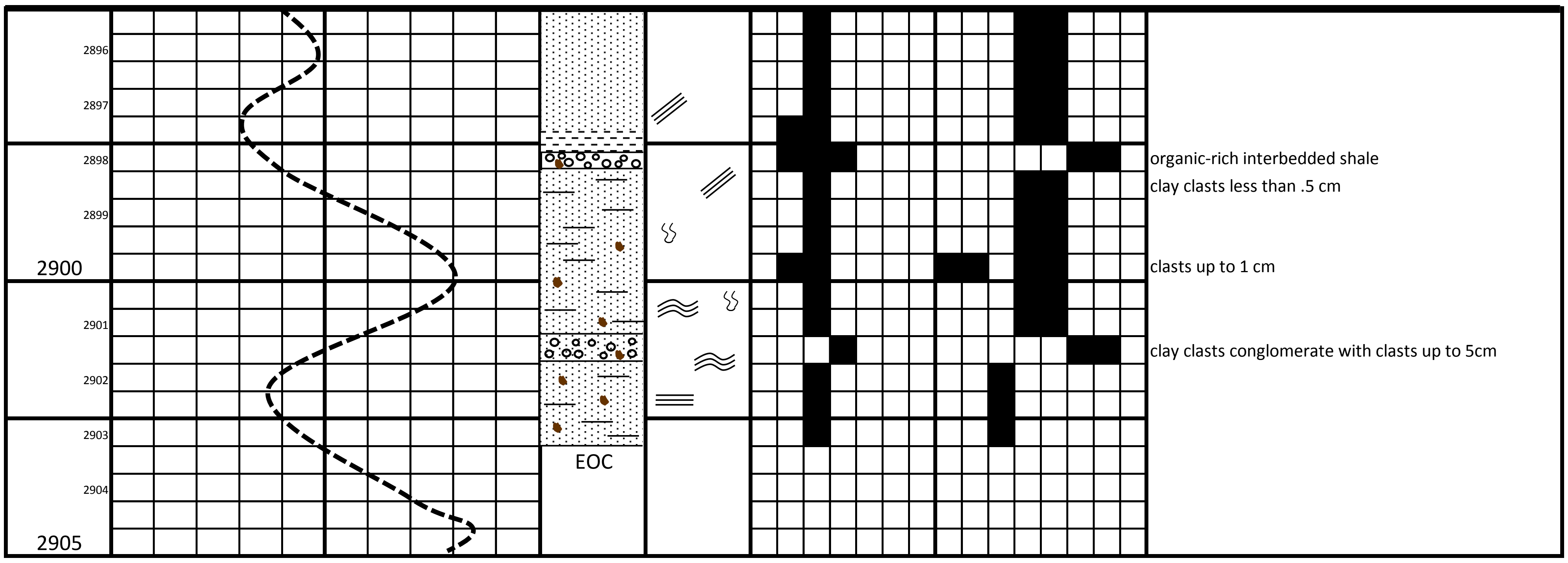
Hart #4-24 Core Description Page 1



Hart #4-24 Core Description Page 2



Hart #4-24 Core Description Page 3



Hart #4-24 Core Description Page 4

STIM-LAB, Inc.

Company: Cardinal River Energy
Well: Hart # 4-24
Location: Osage County, Oklahoma
SEC. 24, T25N-R2E

Date: 9/5/2014
Files: SL 11349
Analyst(s): Deane Miller

STIM-LAB
CMS-300 CORE ANALYSIS DATA

Sample Number	Depth (ft)	Net Confining Stress (psig)	Porosity (%)	Permeability Kair (mD)	Permeability Klinkenberg (mD)	b psi	Beta ft(-1)	Alpha microns	Saturation Oil (% Pore Volume)	Saturation Water (% Pore Volume)	Grain Density g/cm3	Lithology
1A*	2831.1	880	15.28	0.037	0.013	5.54E+01	7.46E+13	2.90E+03	N/A	N/A	2.668	Sst, tn, vfg, mnr dol, phos
2A*	2833.35	880	16.04	0.110	0.051	3.06E+01	6.42E+12	1.05E+03	N/A	N/A	2.673	Sst, tn, vfg, mnr dol, phos
3A*	2839.0	880	18.24	2.54	1.86	2.21E+01	2.36E+09	1.40E+01	N/A	N/A	2.644	Sst, tn, vfg, mnr dol, mnr cl, org, phos
?? 1	2815.6	880	4.80	0.056	0.036	1.46E+01	1.28E+12	1.45E+02	13.6	74.5	2.708	Sd, gry, f gr, sl calc, lam, 0% flu poor cut
2	2818.1	880	7.51	0.088	0.058	1.37E+01	5.86E+11	1.10E+02	4.3	62.1	2.701	Sd, gry, f gr, sl dol, lam, 0% flu poor cut
3	2819.5	880	5.79	0.016	0.008	3.09E+01	2.91E+12	7.38E+01	14.6	39.2	2.739	Sd, gry, f gr, sl dol, lam, 50% yel flu
4	2822.2	880	5.39	0.002	0.0004	1.89E+02	6.37E+16	7.90E+04	7.4	85.4	2.794	Sd, gry, vf gr, sl dol, 0% flu poor cut
5	2823.9	880	10.92	0.020	0.009	3.66E+01	1.45E+13	4.29E+02	6.7	66.7	2.722	Sd, gry, vf-slt gr, lam, 0% flu poor cut
6	2825.7	880	14.93	0.693	0.495	9.18E+00	9.08E+10	1.44E+02	13.3	29.3	2.676	Sd, lt tn, vf gr, 100% yel flu
7	2828.7	880	16.46	1.94	1.48	1.92E+01	3.09E+10	1.47E+02	19.4	31.9	2.677	Sd, lt tn, vf gr, 100% yel flu
8	2830.8	880	15.46	1.78	1.37	1.84E+01	4.72E+10	2.08E+02	18.4	30.7	2.687	Sd, lt tn, vf gr, 100% yel flu
9	2832.8	880	16.02	0.356	0.208	1.73E+01	3.45E+10	2.28E+01	8.7	40.0	2.675	Sd, lt tn, vf gr, 80% yel flu
10	2836.6	880	16.64	1.03	0.699	3.05E+01	2.47E+11	5.46E+02	12.4	35.3	2.676	Sd, lt tn, vf gr, 100% yel flu
11	2837.7	880	17.85	2.95	2.30	1.68E+01	8.93E+09	6.65E+01	18.5	21.5	2.691	Sd, lt tn, vf gr, 100% yel flu
12	2839.6	880	17.67	3.26	2.55	1.65E+01	2.73E+09	2.23E+01	20.5	32.0	2.672	Sd, lt tn, vf gr, 100% yel flu
13	2841.5	880	14.81	0.839	0.593	2.69E+01	2.12E+11	4.06E+02	11.5	34.2	2.651	Sd, lt tn, vf gr, lam, 90% yel flu
14	2842.7	880	16.66	5.54	4.70	1.02E+01	6.94E+08	1.05E+01	9.7	23.9	2.672	Sd, lt tn, vf gr, 100% yel flu
15	2843.6	880	12.41	0.187	0.094	2.56E+01	3.20E+10	9.69E+00	4.9	56.2	2.745	Sd, gry, vf-slt gr, lam, 0% flu poor cut
16	2862.5	880	13.12	1.42	1.08	1.93E+01	1.10E+11	3.86E+02	9.8	35.4	2.686	Sd, lt tn, vf-f gr, lam, 80% yel flu
17	2870.3	880	11.43	1.20	0.92	1.90E+01	7.27E+10	2.14E+02	10.4	33.8	2.692	Sd, lt gry, f-med gr, lam, 90% yel flu

A* = Vertical plugs

Petroleum Services Division

Source Rock Analyses

Leco TOC, Rock-Eval-2 and Maturity Testing

Hart #4-24
Osage County, Oklahoma

Cardinal River Energy

September 11, 2014

218 Higgins Street
Humble, TX 77338
832.644.1184

GEOMARK RESEARCH, LTD.

9748 Whithorn Drive
Houston, TX 77095
281.856.9333

SOURCE ROCK ANALYSES

GEOMARK RESEARCH, LTD.

Cardinal River Energy — **Hart #4-24, Osage County, Oklahoma**

Sample ID: Project / Sample ID	Rock ID	Well	County	State	Formation Name	Upper Depth (ft)	Lower Depth (ft)	Median Depth (ft)	Sample Type
RCOR-140831-001		Hart #4-24	Osage	OK			2,770.00	2,770.00	
RCOR-140831-002		Hart #4-24	Osage	OK			2,780.00	2,780.00	
RCOR-140831-003		Hart #4-24	Osage	OK			2,790.00	2,790.00	

Project / Sample ID	Source Rock Analyses: Percent Carbonate (wt%)	Leco TOC (wt%)	Rock-Eval-2 S1 (mg HC/g)	Rock-Eval-2 S2 (mg HC/g)	Rock-Eval-2 S3 (mg CO2/g)	Rock-Eval-2 Tmax (°C)	Measured %Ro (Vitrinite Refl.)	Calculated %Ro (RE TMAX)	Hydrogen Index (S2x100/TOC)	Oxygen Index (S3x100/TOC)	S2/S3 Conc. (mg HC/mg CO2)	S1/TOC Norm. Oil Content	Production Index (S1/(S1+S2))	Experimental Notations
RCOR-140831-001		1.34	0.28	1.12	0.41	446		0.87	84	31	3	21	0.20	
RCOR-140831-002		1.28	0.39	1.27	0.41	450		0.94	99	32	3	30	0.23	
RCOR-140831-003		6.50	3.01	14.82	0.59	442		0.80	228	9	25	46	0.17	Low Temp S2 Shoulder

S1 = amount of free hydrocarbons in sample

S2 = amount of hydrocarbons generated through thermal cracking
- provides the quantity of hydrocarbons that the rock has the potential to produce through diagenesis.

S3 = amount of CO_2 (mg of CO_2/g of rock) - reflects the amount of oxygen in the oxidation step.

Tmax = temp. @ which maximum rate of generation of hydrocarbons occurs

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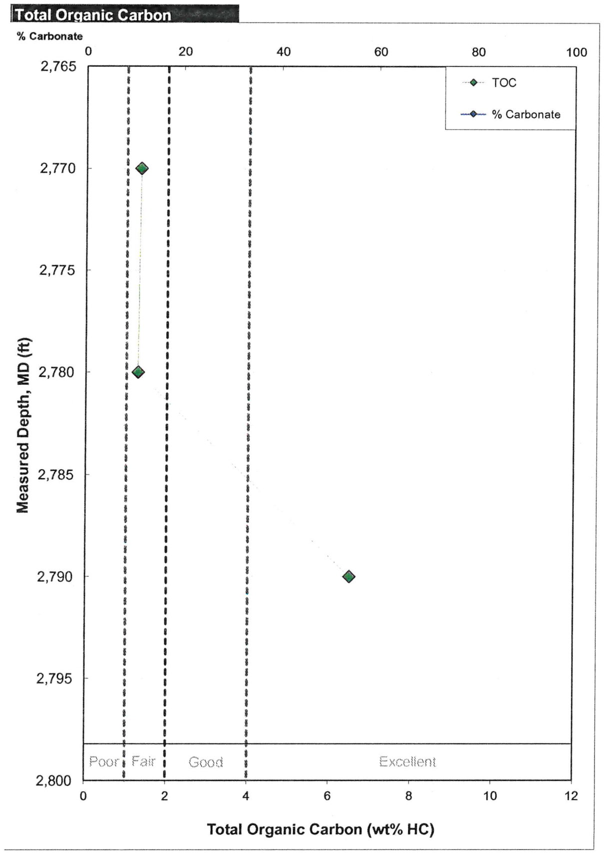
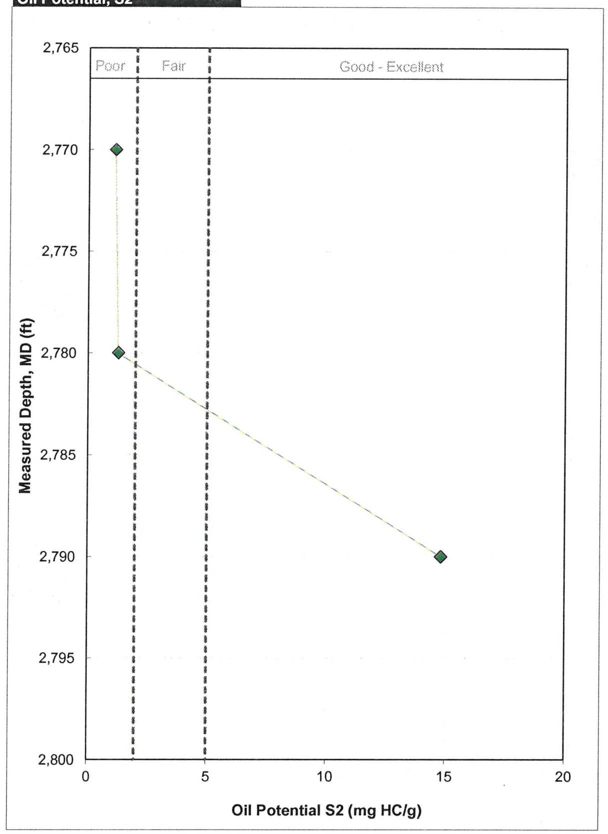
SOURCE ROCK ANALYSES
GEOMARK RESEARCH, LTD.

Cardinal River Energy | **Hart #4-24, Osage County, Oklahoma**

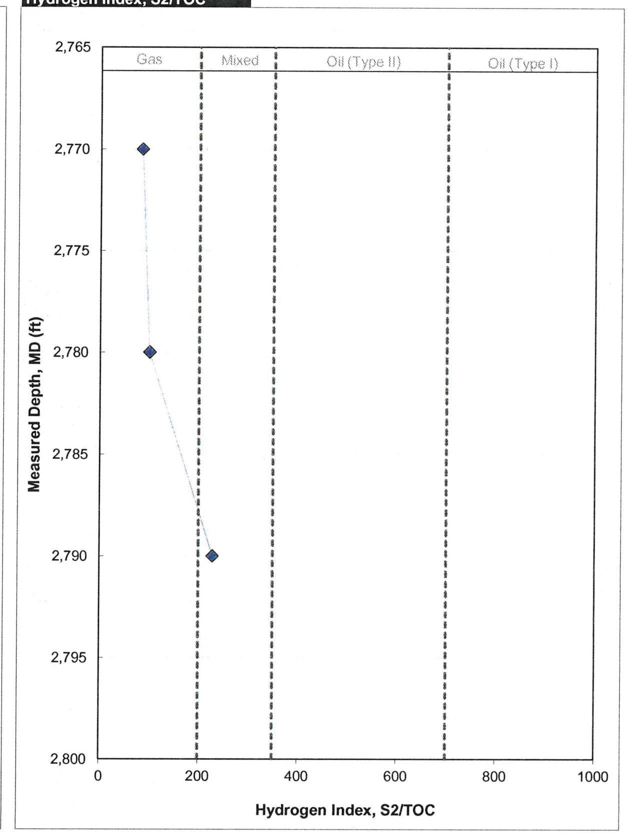
Total Organic Carbon



Oil Potential, S2



Hydrogen Index, S2/TOC

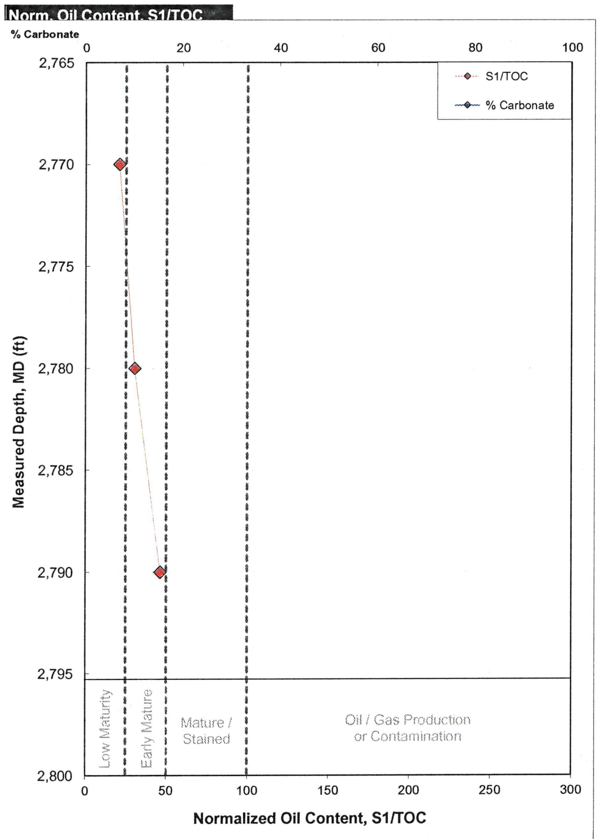


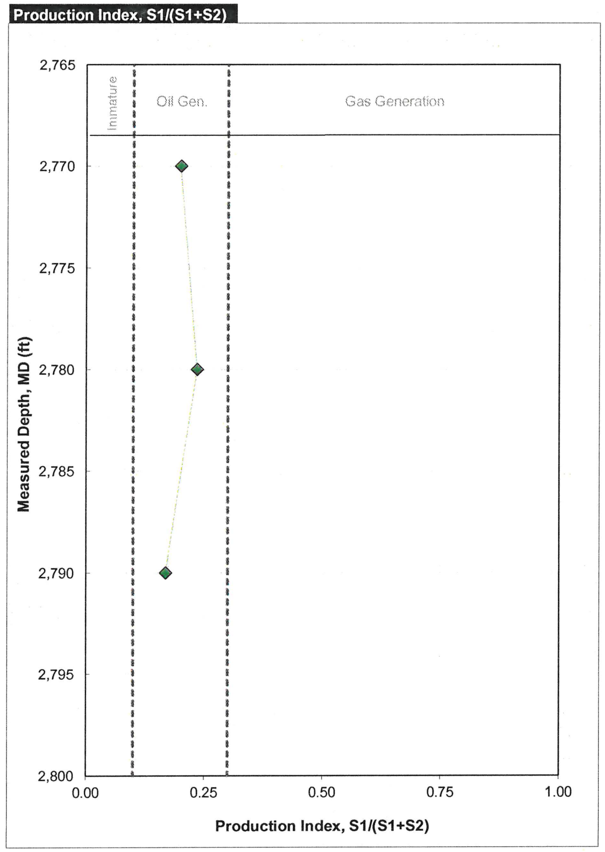
102

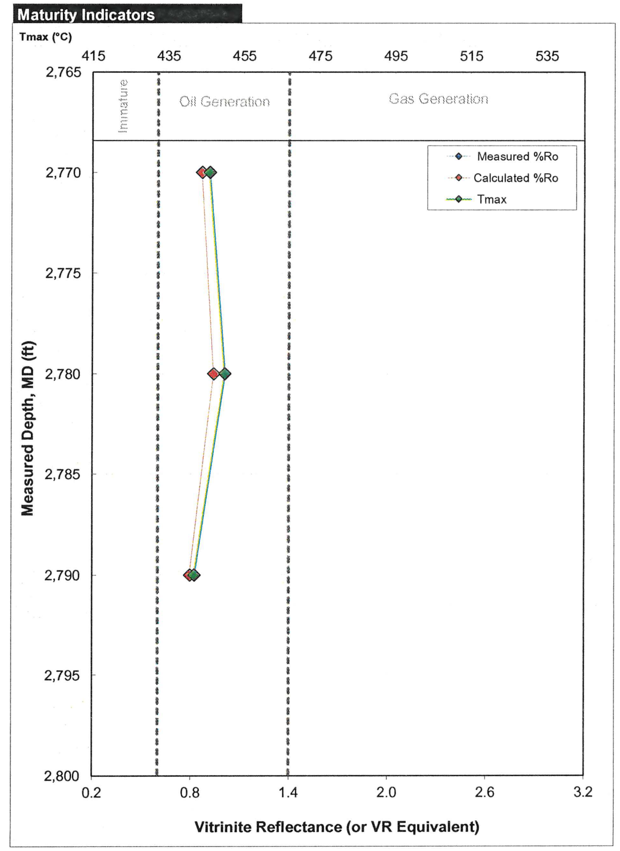
SOURCE ROCK ANALYSES

GEOMARK RESEARCH, LTD.

Cardinal River Energy | **Hart #4-24, Osage County, Oklahoma**







GeoMark Source Rock Services
218 Higgins Street
Humble, TX 77338

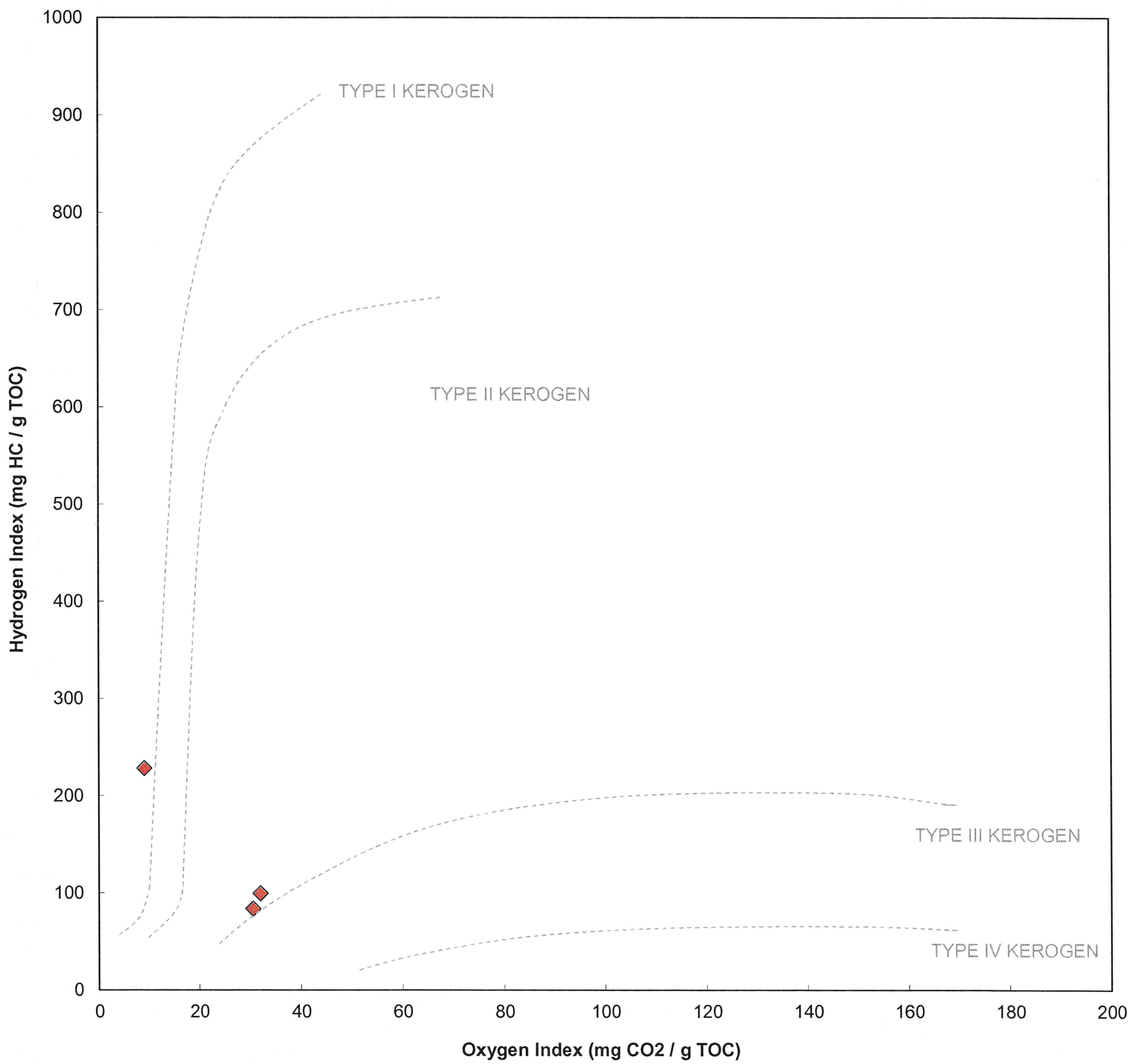
(832) 644.1184
info@ geomarkresearch.com
September 11, 2014

SOURCE ROCK ANALYSES

GeoMark Research, Ltd.

Cardinal River Energy **Hart #4-24, Osage County, Oklahoma**

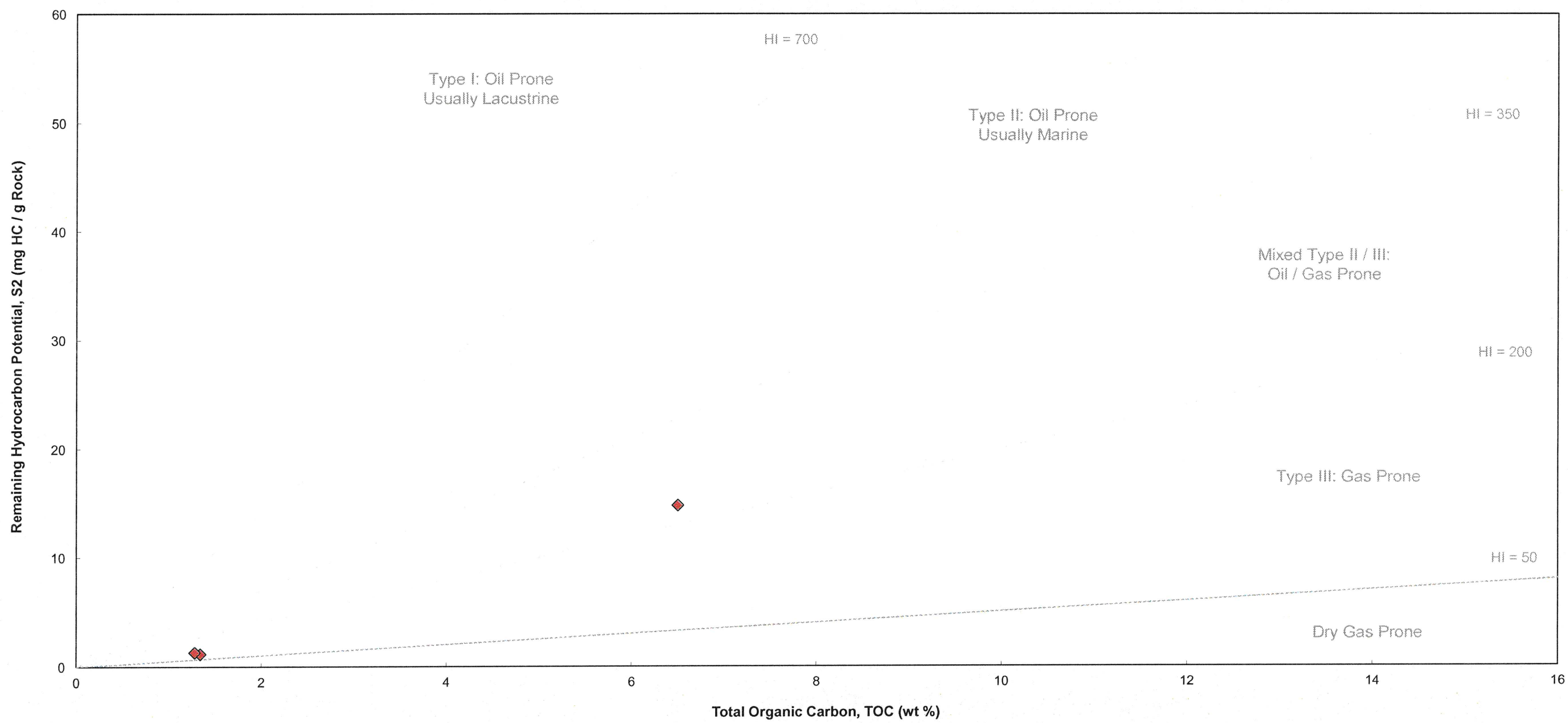
Pseudo Van Krevelen Plot



SOURCE ROCK ANALYSES
GEOMARK RESEARCH, LTD.

Cardinal River Energy	Hart #4-24, Osage County, Oklahoma

Kerogen Quality Plot



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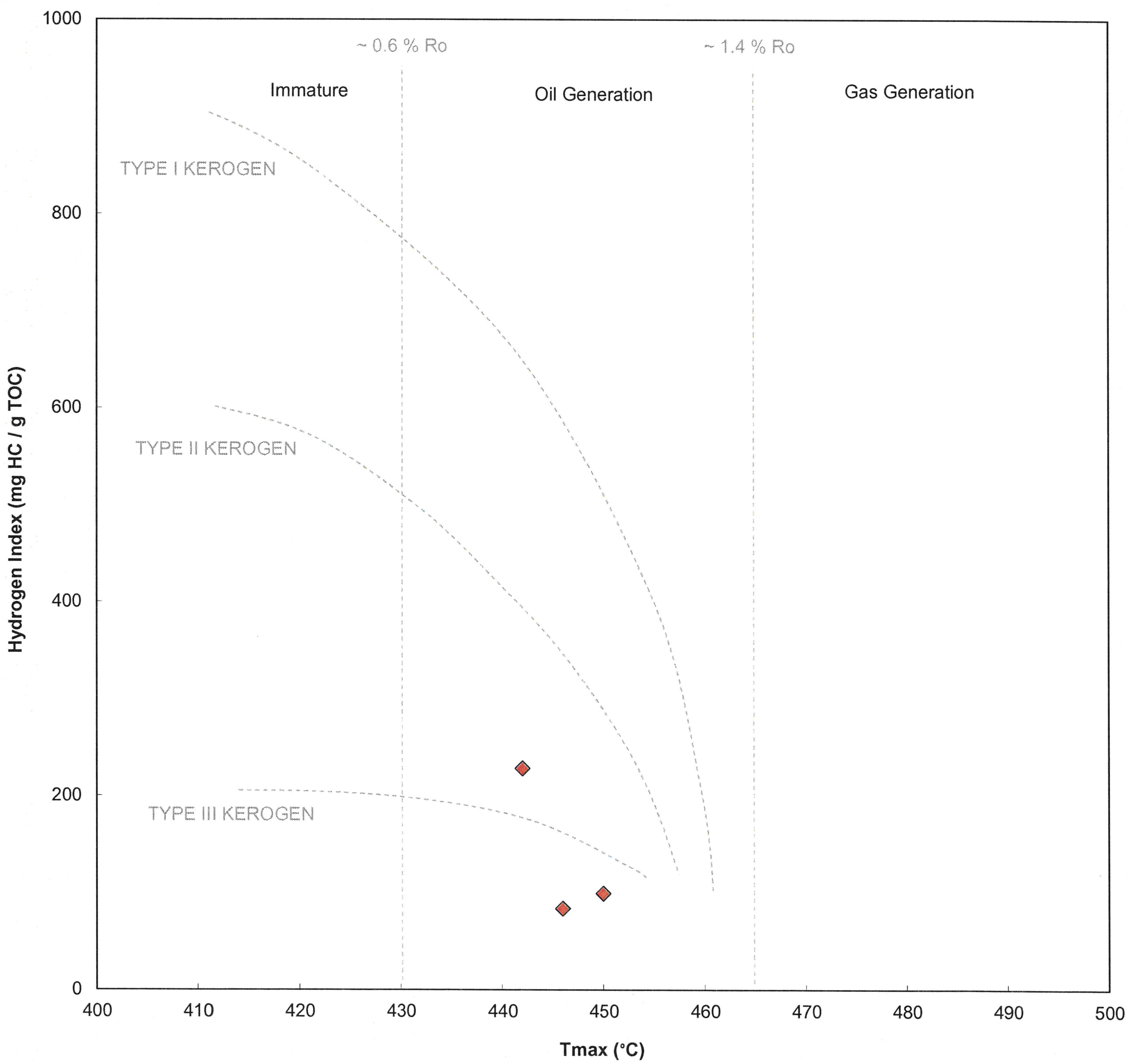
September 11, 2014

SOURCE ROCK ANALYSES

GEOMARK RESEARCH, LTD.

Cardinal River Energy | **Hart #4-24, Osage County, Oklahoma**

Kerogen Type and Maturity



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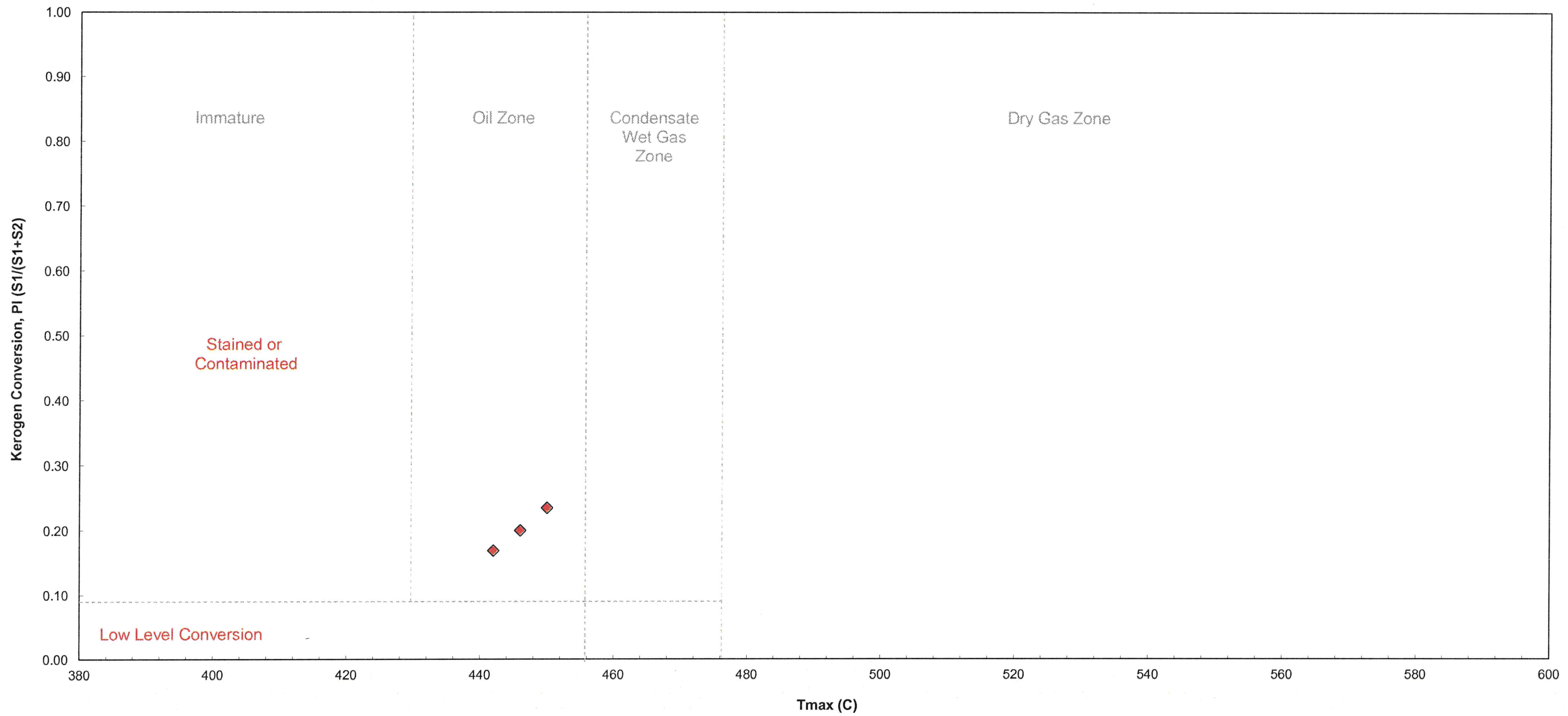
September 11, 2014

SOURCE ROCK ANALYSES
GEOMARK RESEARCH, LTD.

Cardinal River Energy | **Hart #4-24, Osage County, Oklahoma**

Kerogen Quality Plot



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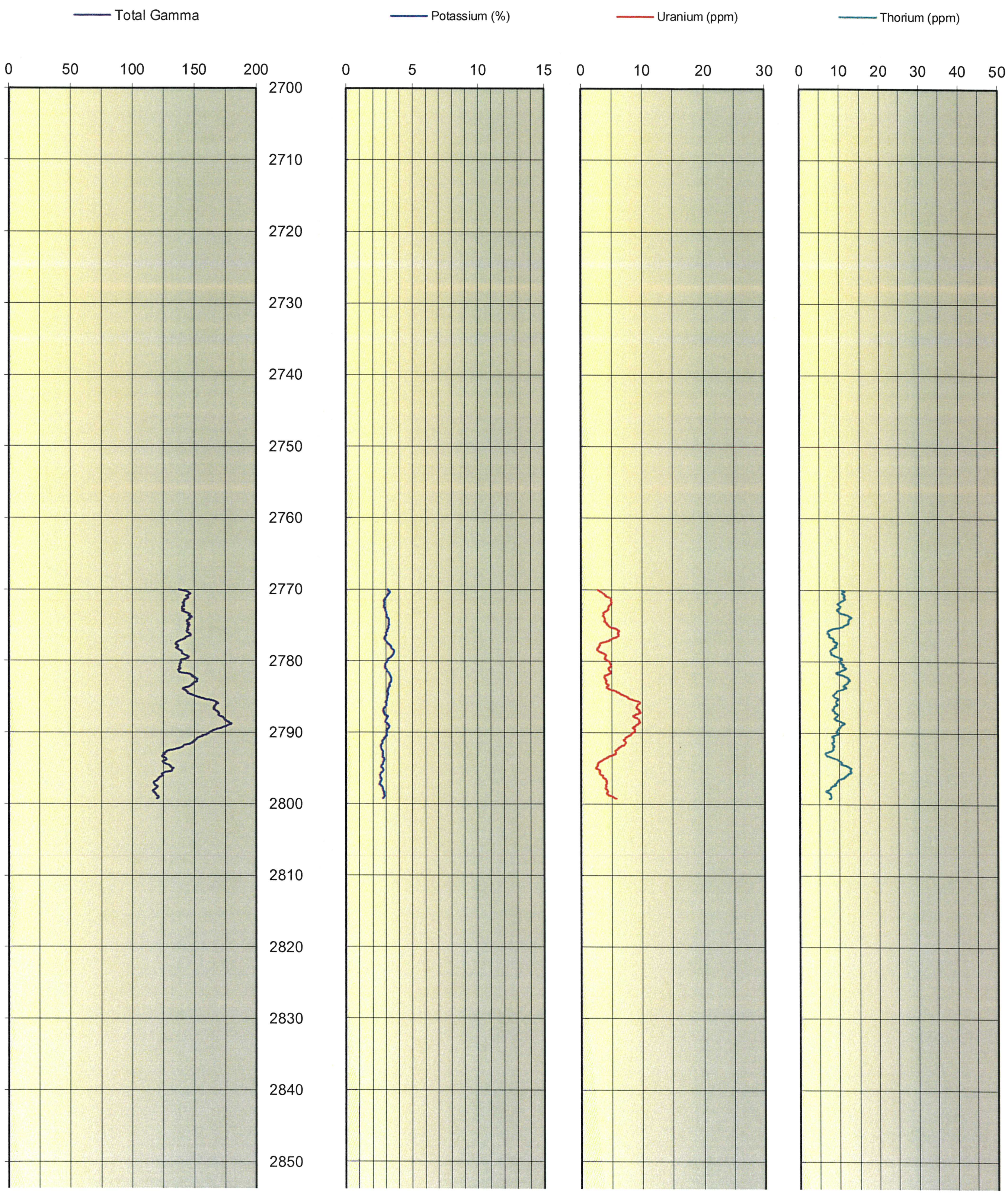
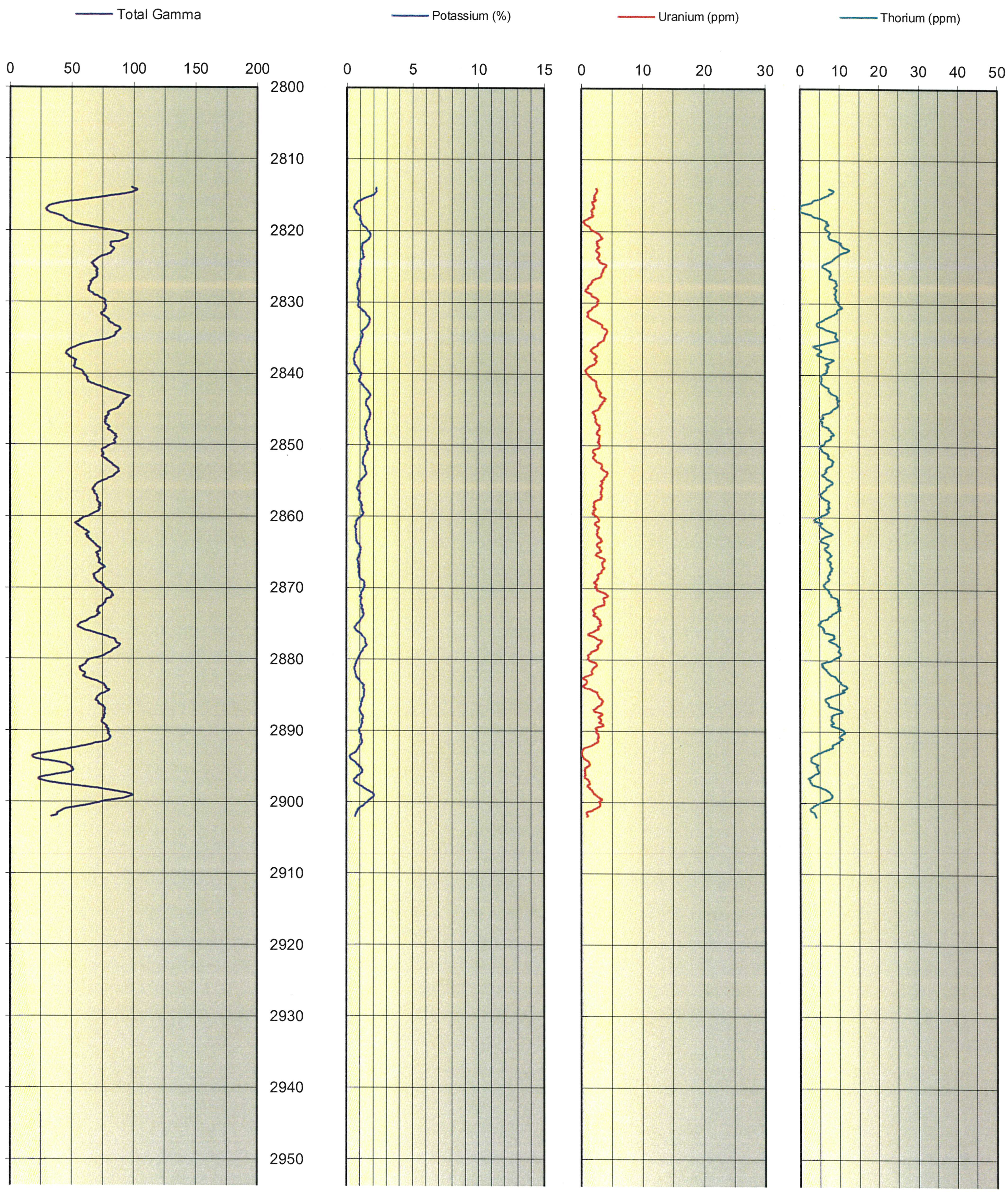
218 Higgins Street
Humble, TX 77338

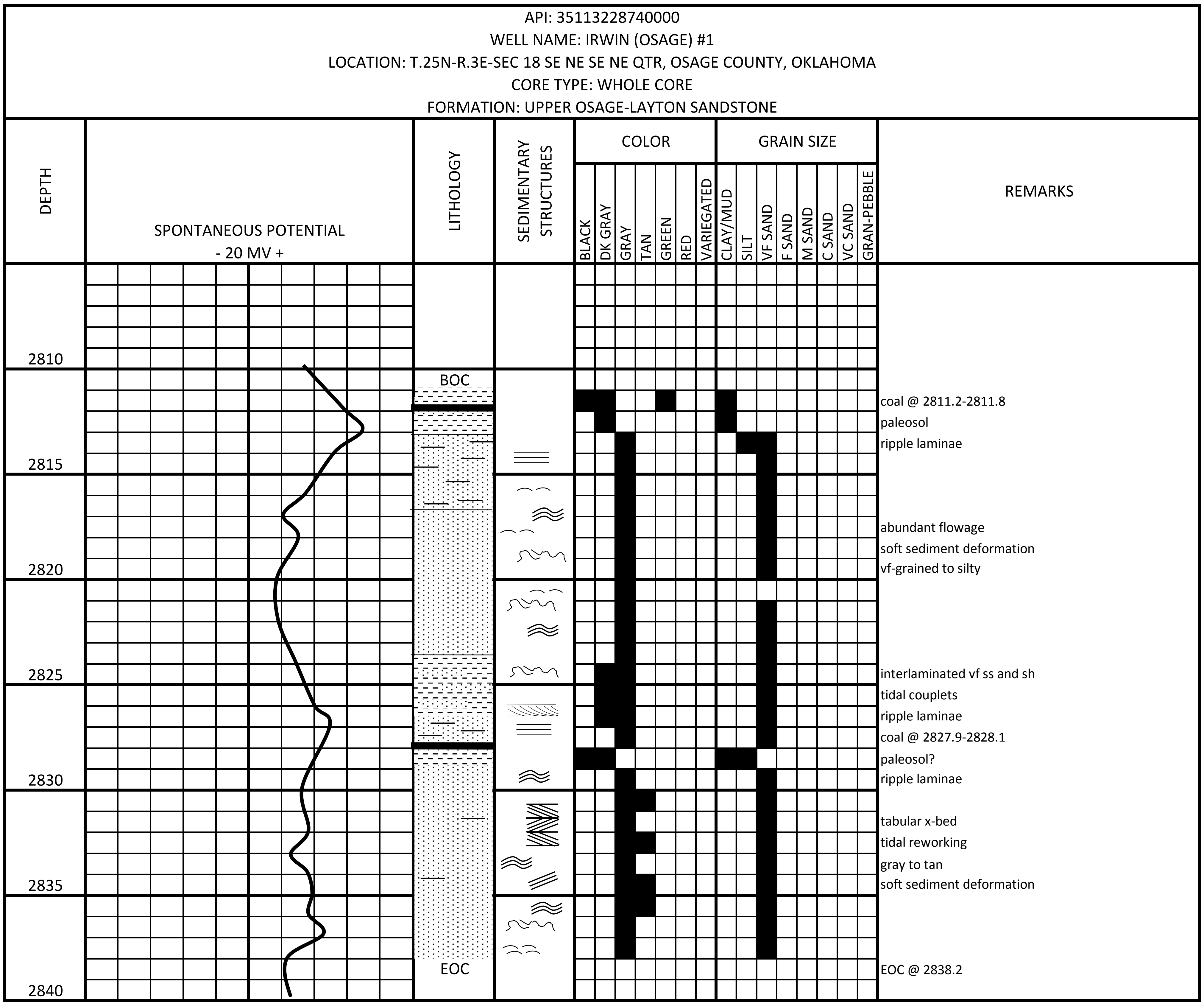
(832) 644.1184
info@ geomarkresearch.com
September 11, 2014

Cardinal River Energy
Hart # 4-24
Osage County, Oklahoma
Spectral Core Gamma
Scale 5" = 100'

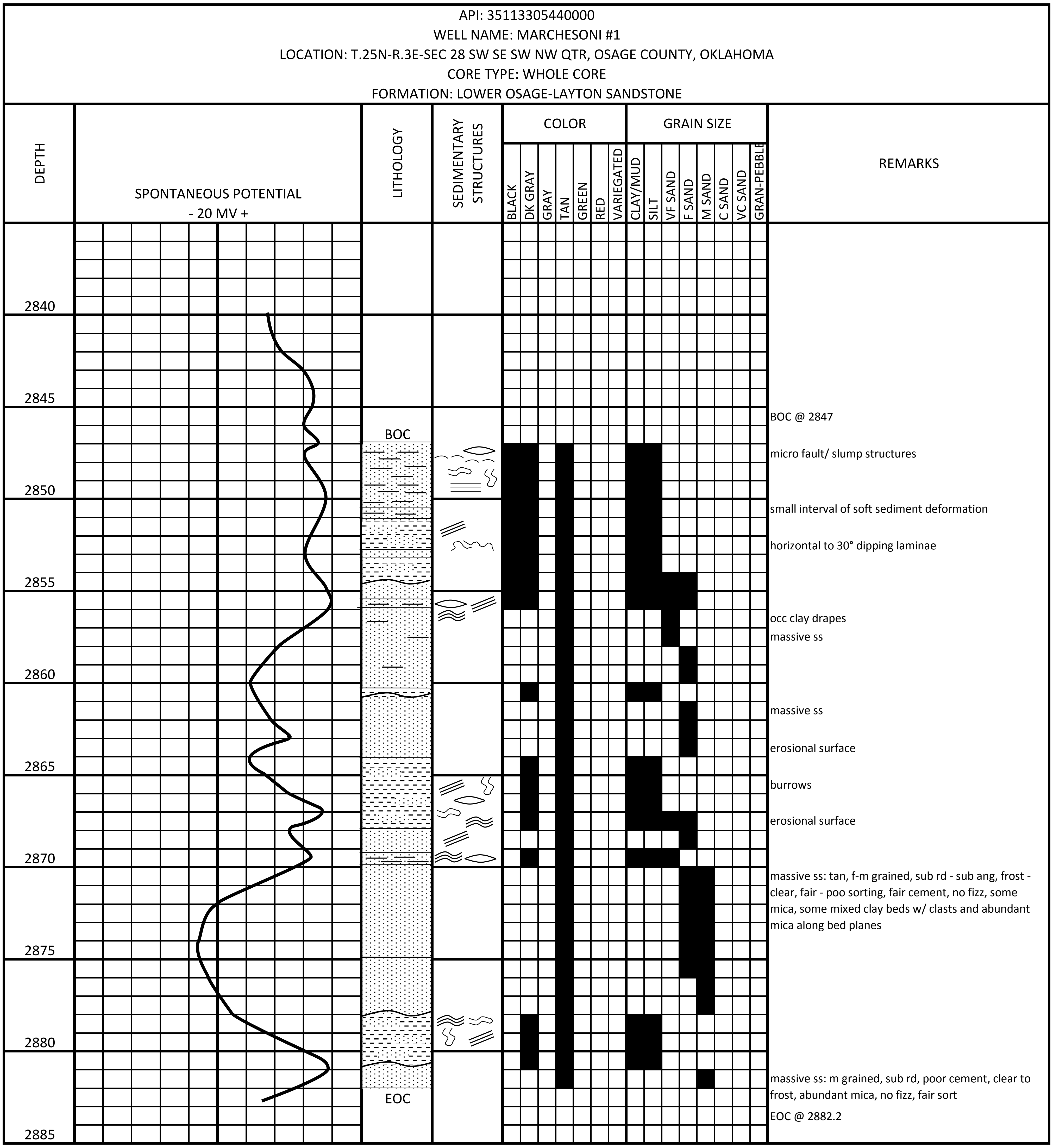


Cardinal River Energy
Hart # 4-24
Osage County, Oklahoma
Spectral Core Gamma
Scale 5" = 100'

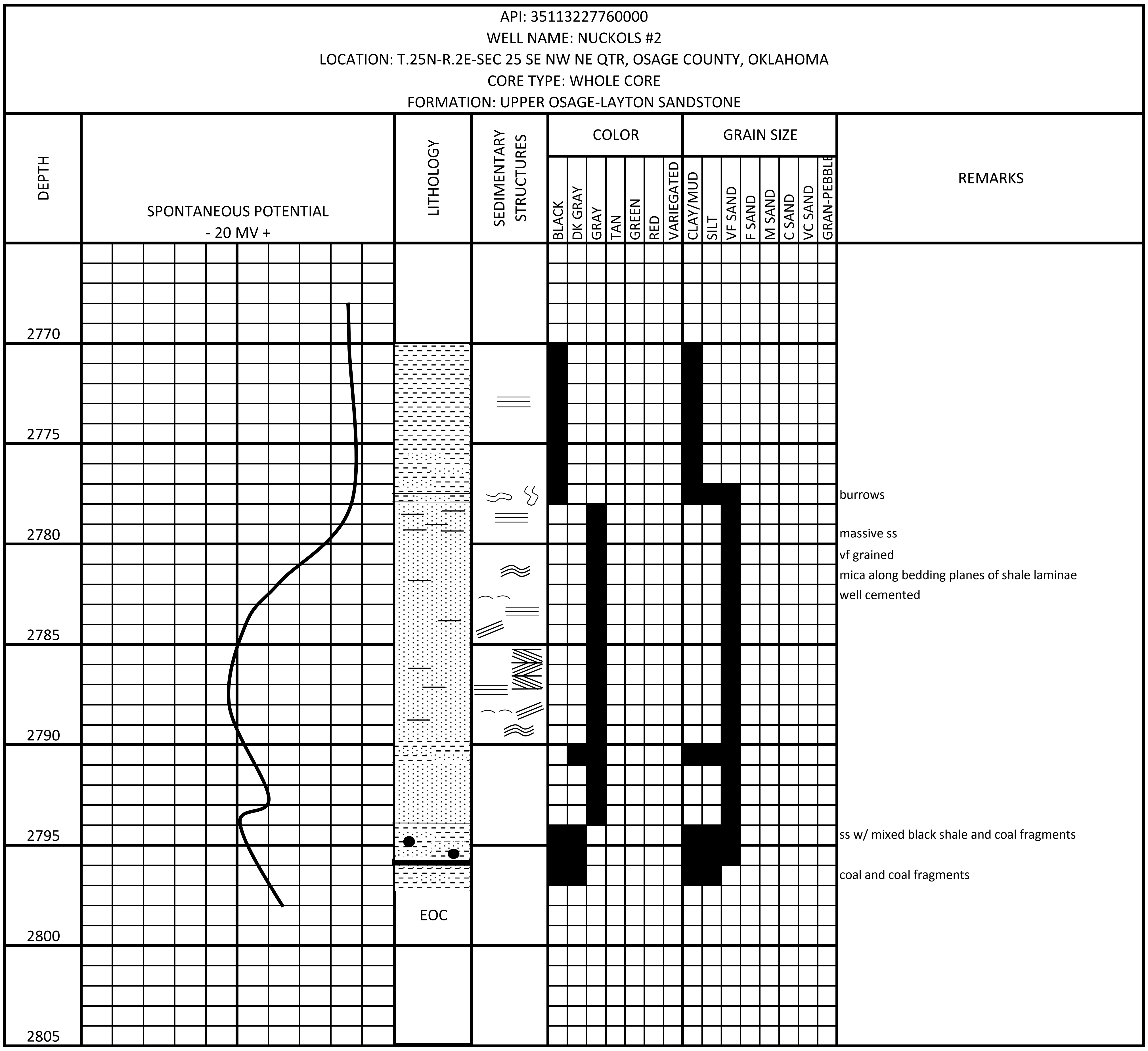




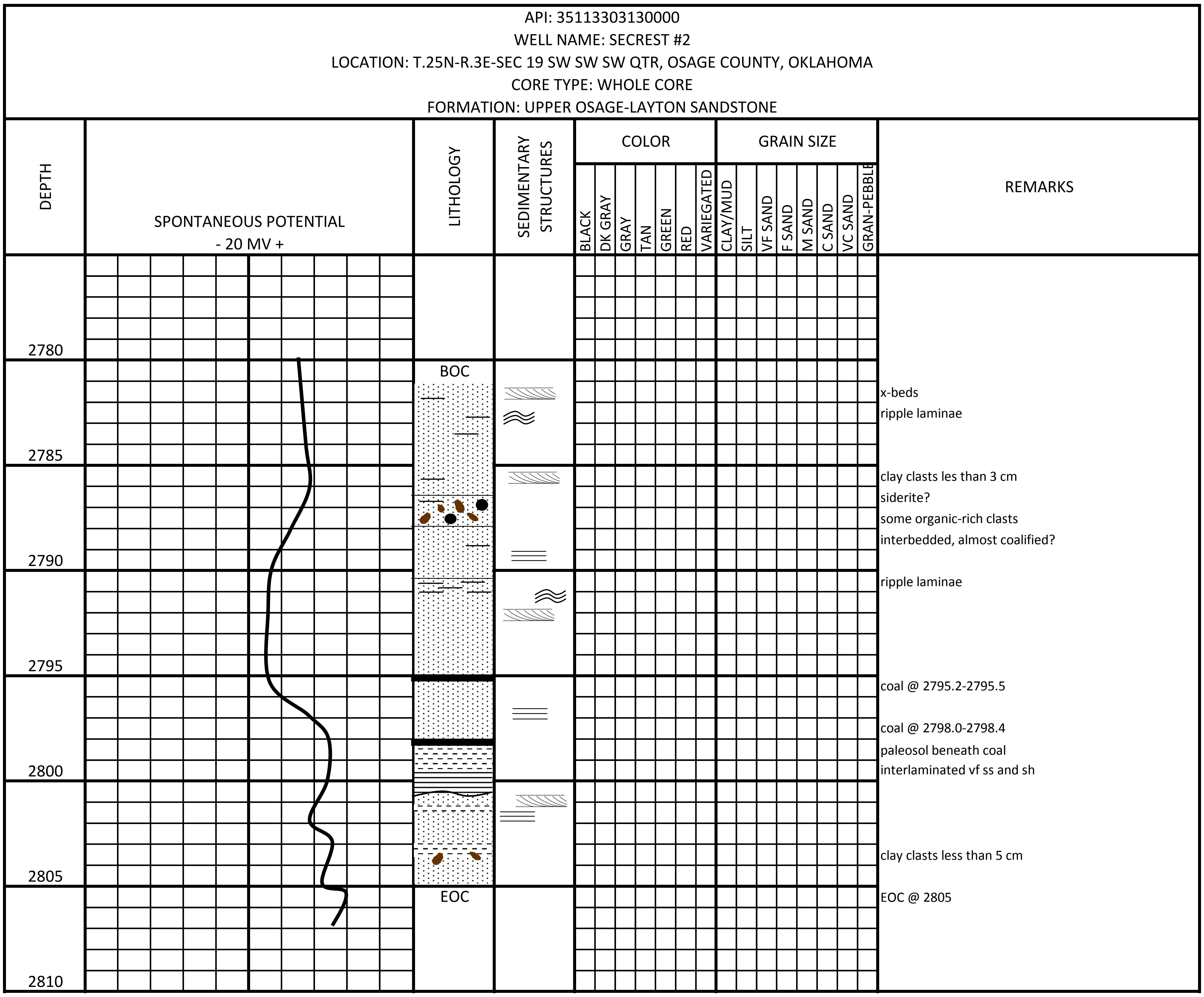
Irwin (Osage) #1 Core Description



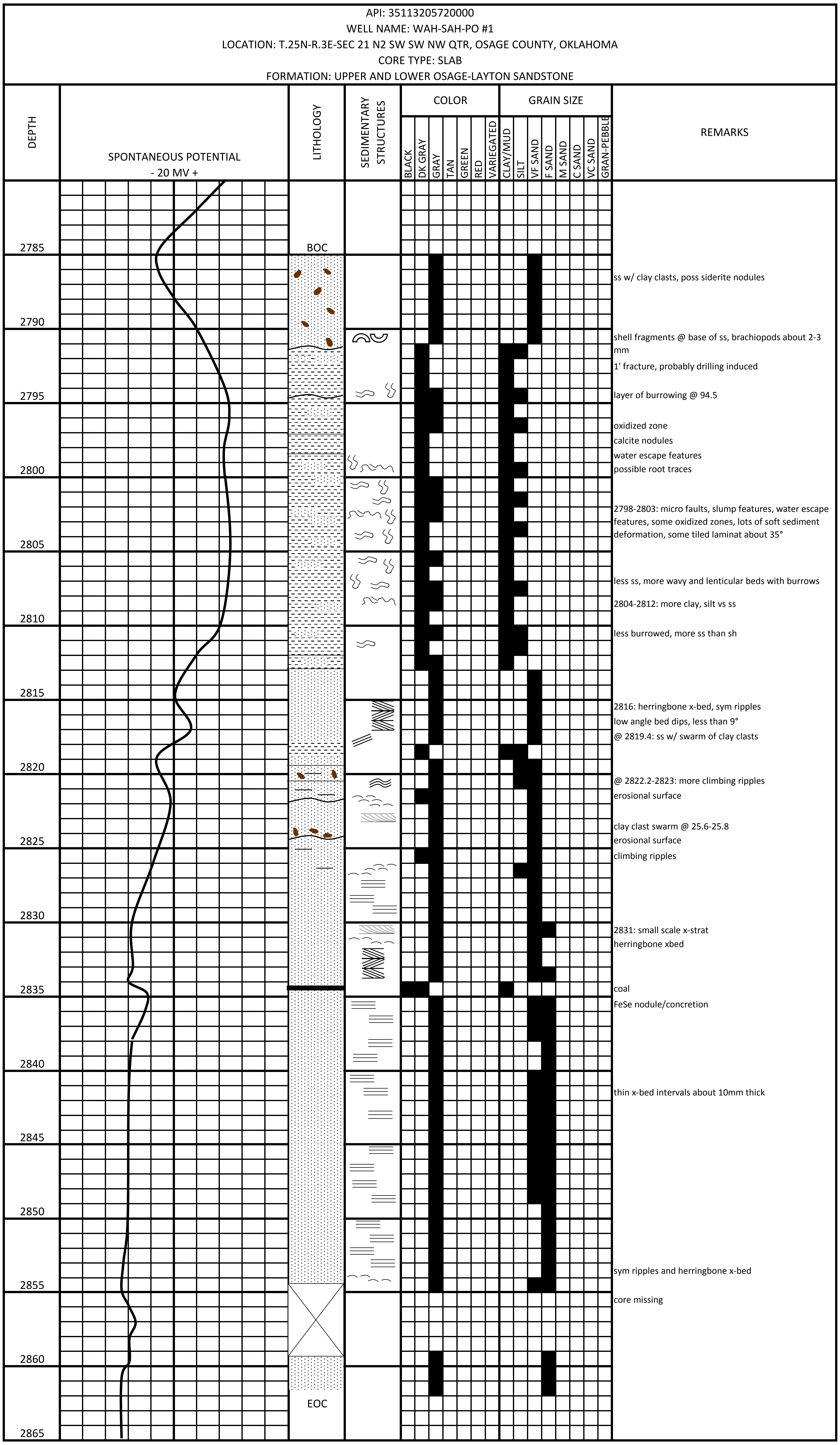
Marchesoni #1 Core Description



Nuckols #2 Core Description



Secrest #2 Core Description

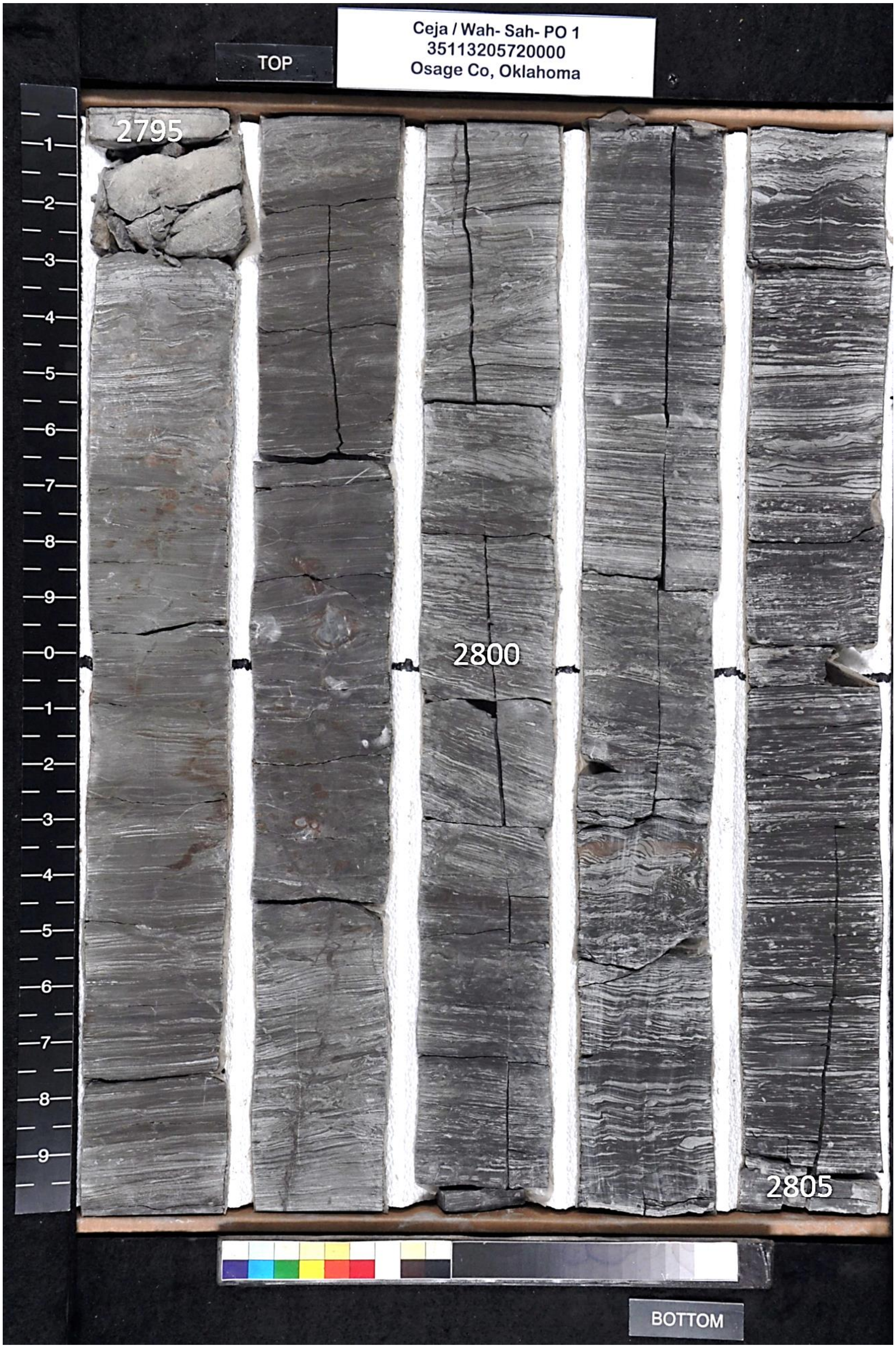


Wah-Sah-Po #1 Core Description

APPENDIX B

WAH-SAH-PO #1 CORE PHOTOGRAPHS


Ceja / Wah- Sah- PO 1
35113205720000
Osage Co, Oklahoma
TOP
2785
2790
2795
BOTTOM



Ceja / Wah- Sah- PO 1
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Osage Co, Oklahoma
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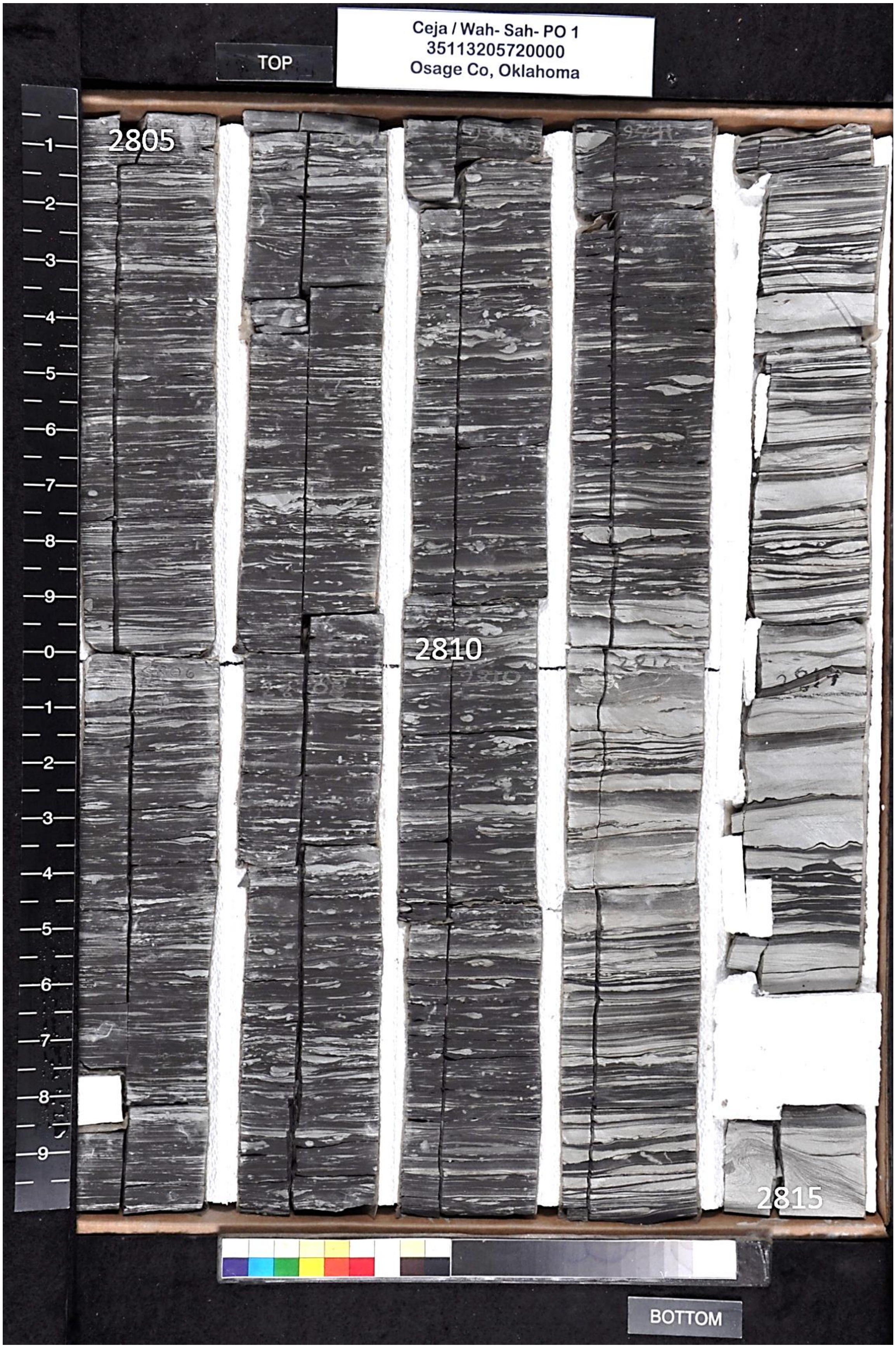
2800
2805
BOTTOM


Ceja / Wah- Sah- PO 1
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Osage Co, Oklahoma
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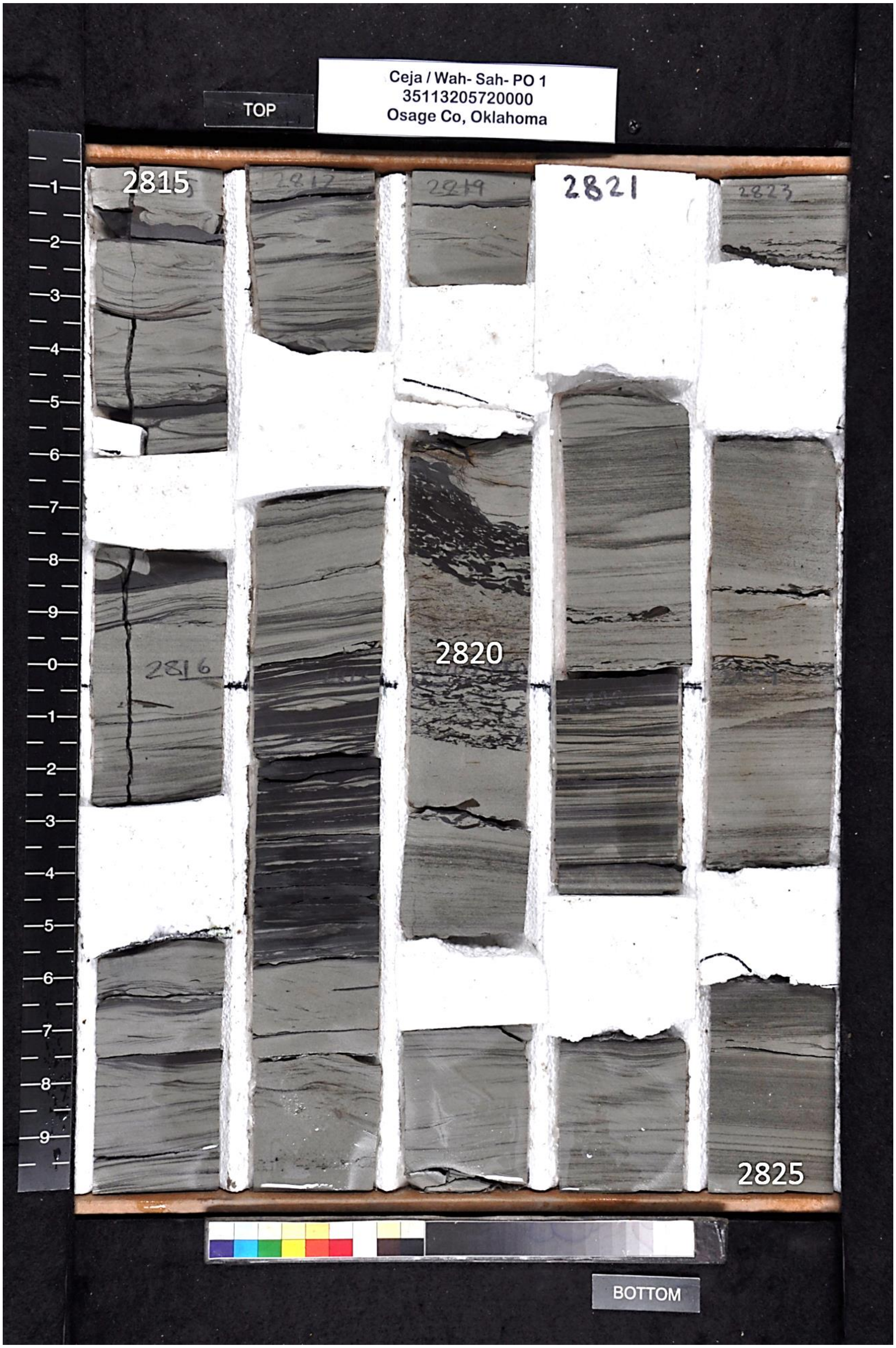
Ceja / Wah- Sah- PO 1
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Osage Co, Oklahoma
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Ceja / Wah- Sah- PO 1
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Osage Co, Oklahoma
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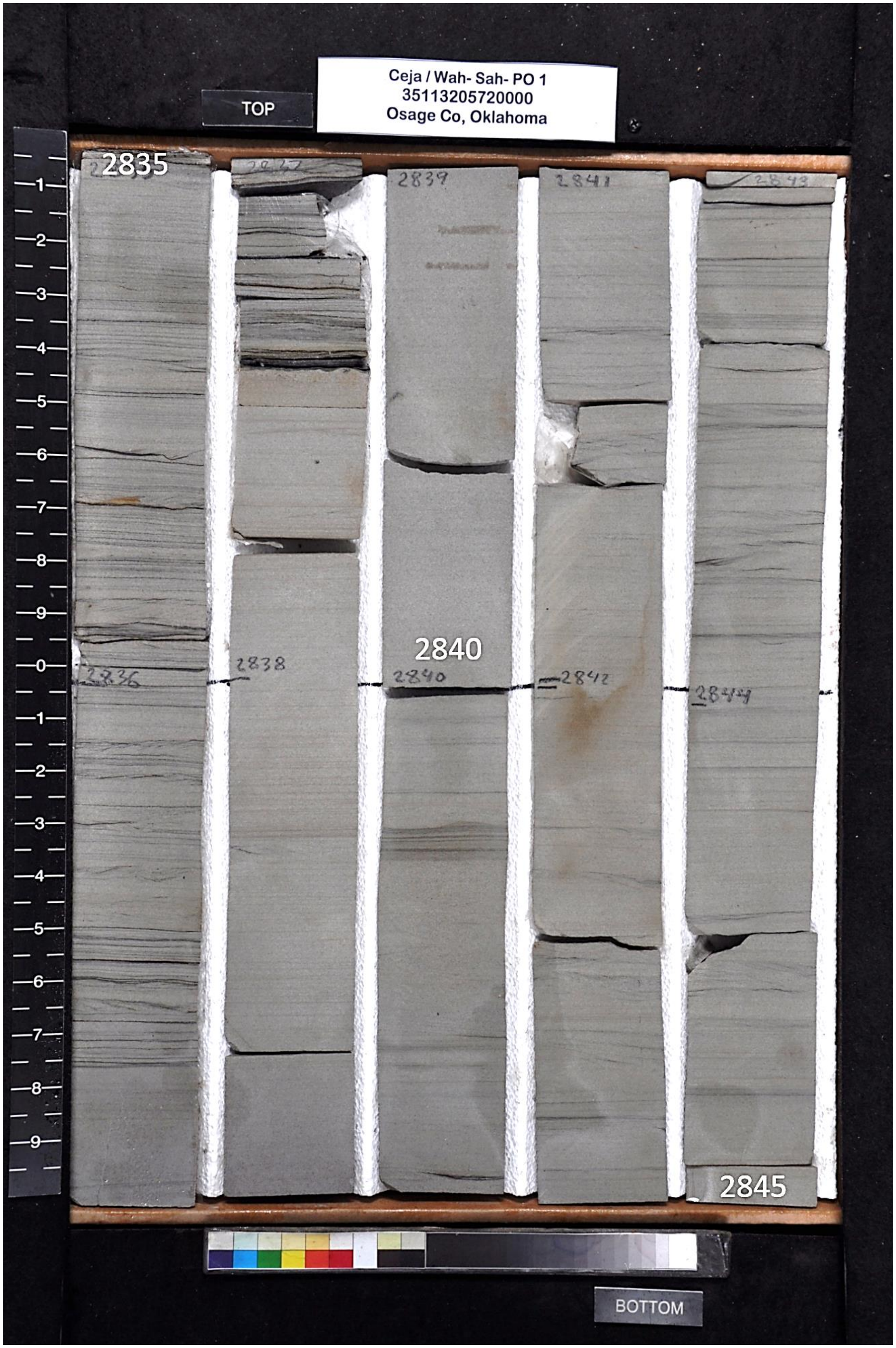
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Ceja / Wah- Sah- PO 1
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Osage Co, Oklahoma
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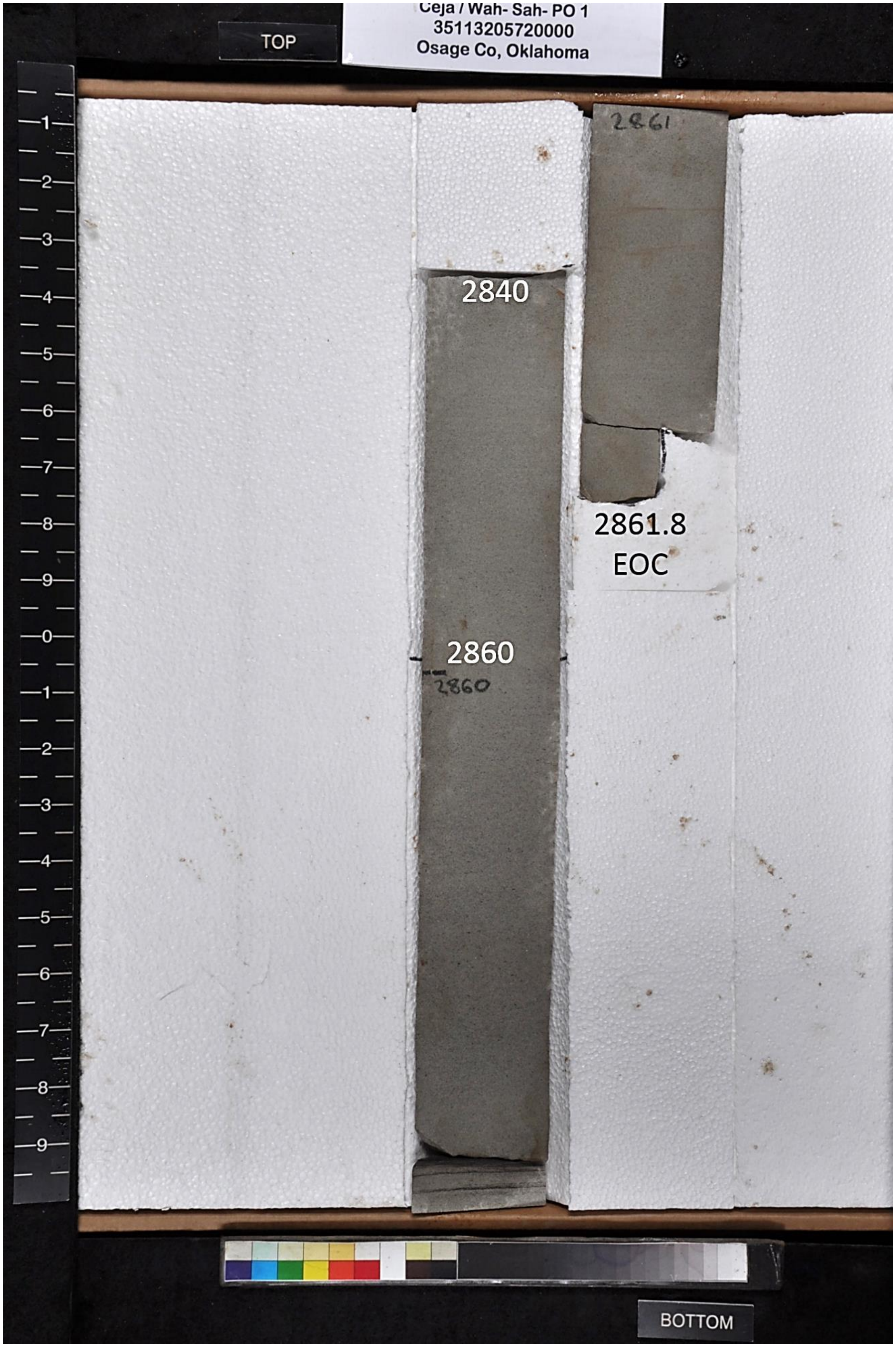
Ceja / Wah- Sah- PO 1
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Osage Co, Oklahoma
TOP
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2861.8
EOC
2860
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APPENDIX C

HART #4-24 CORE PHOTOGRAPHS


Cardinal River Energy / Hart 4-24
0000000000
Osage Co, Oklahoma
TOP
2814
2819
2824
BOTTOM


Cardinal River Energy / Hart 4-24
0000000000
Osage Co, Oklahoma
TOP
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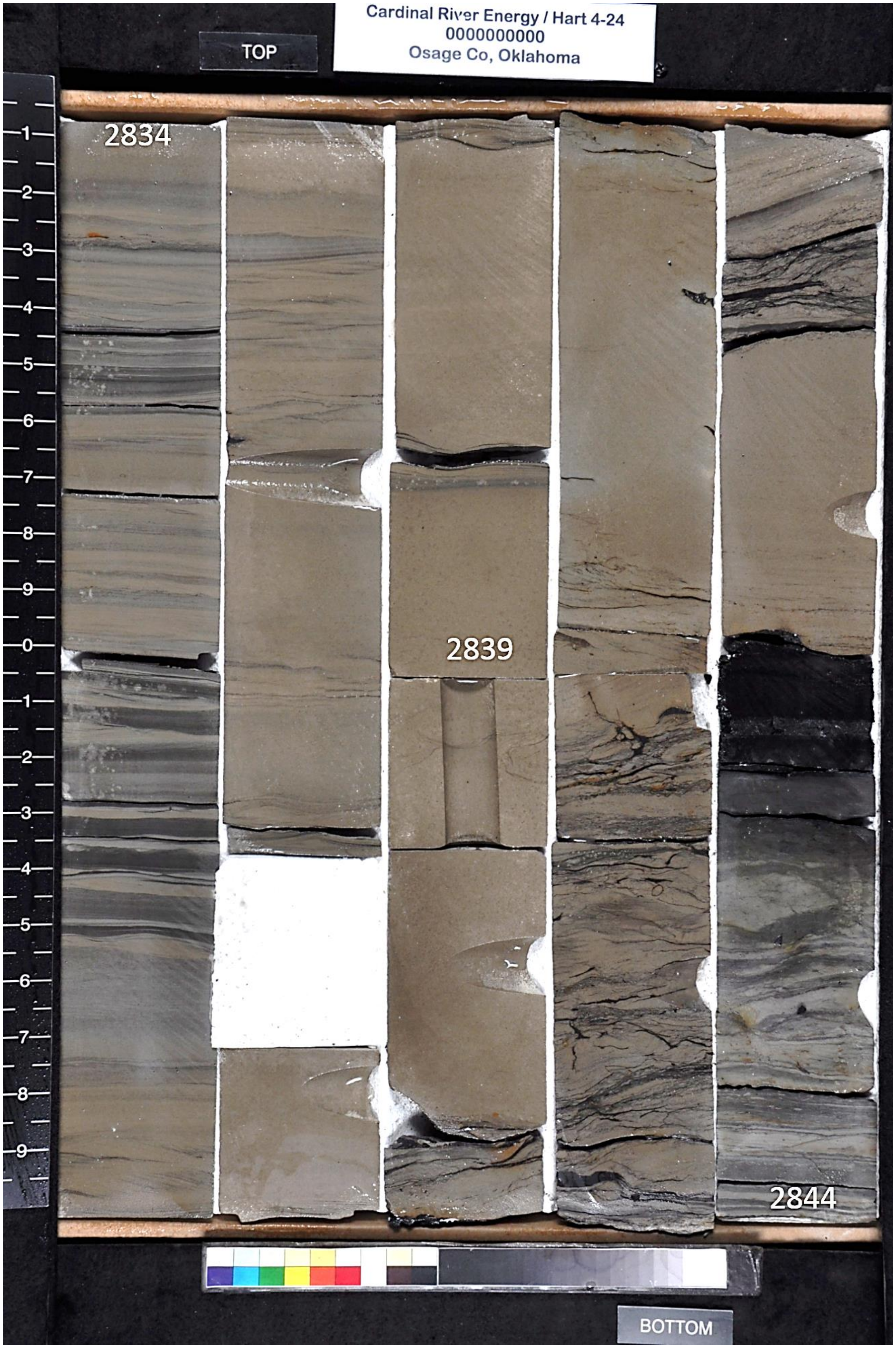
2834
BOTTOM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Cardinal River Energy / Hart 4-24
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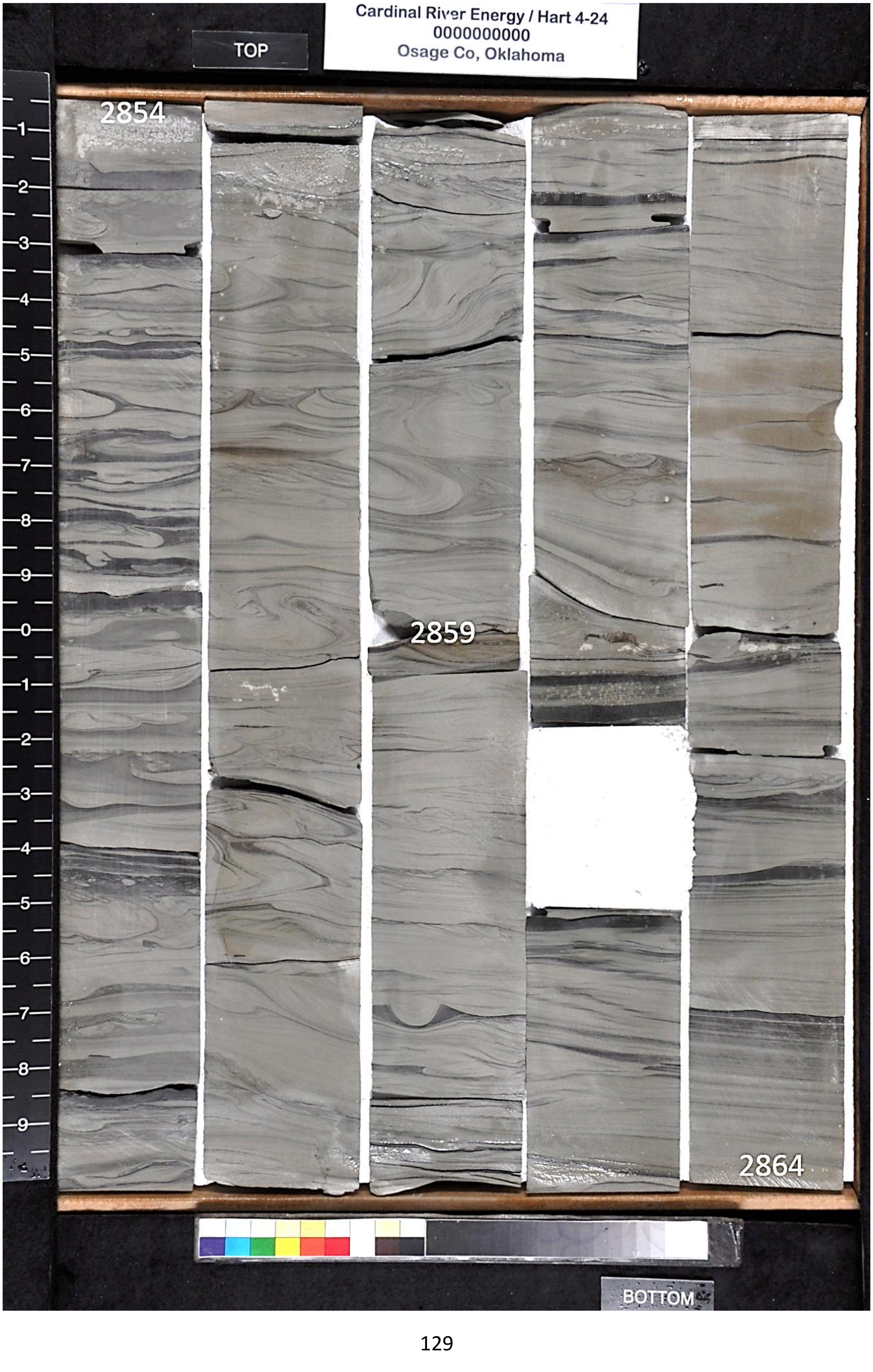
Cardinal River Energy / Hart 4-24
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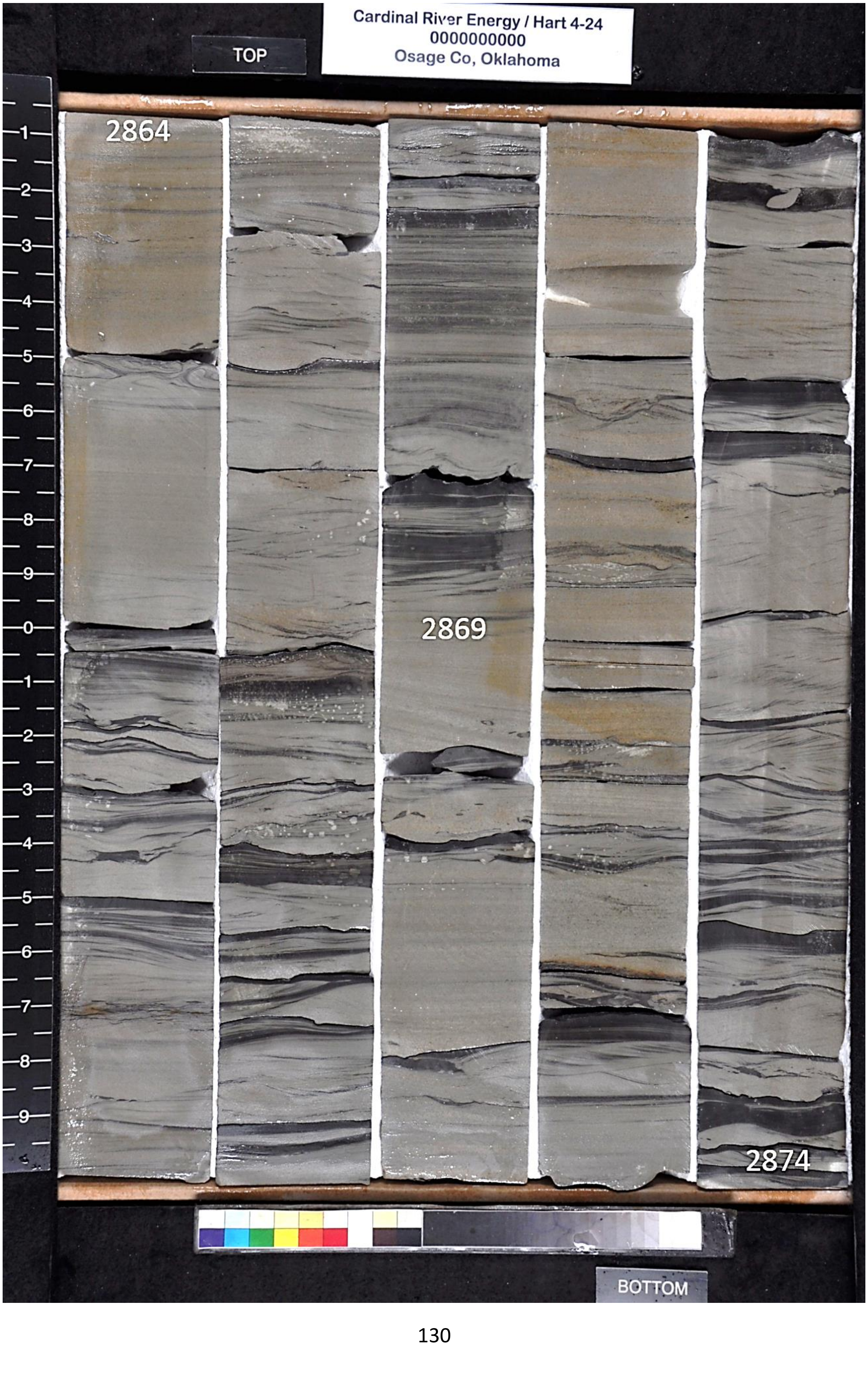
Cardinal River Energy / Hart 4-24
0000000000
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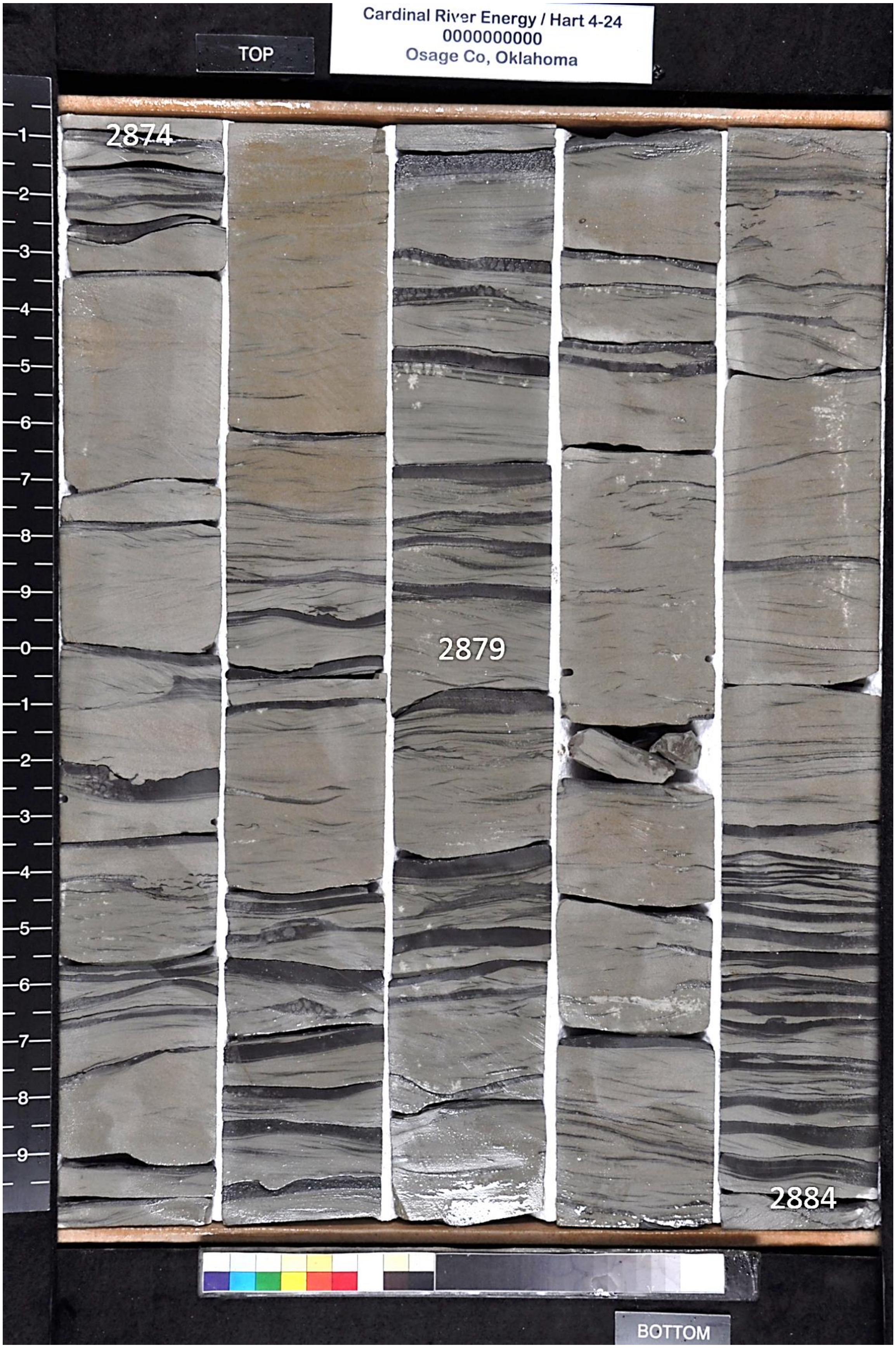
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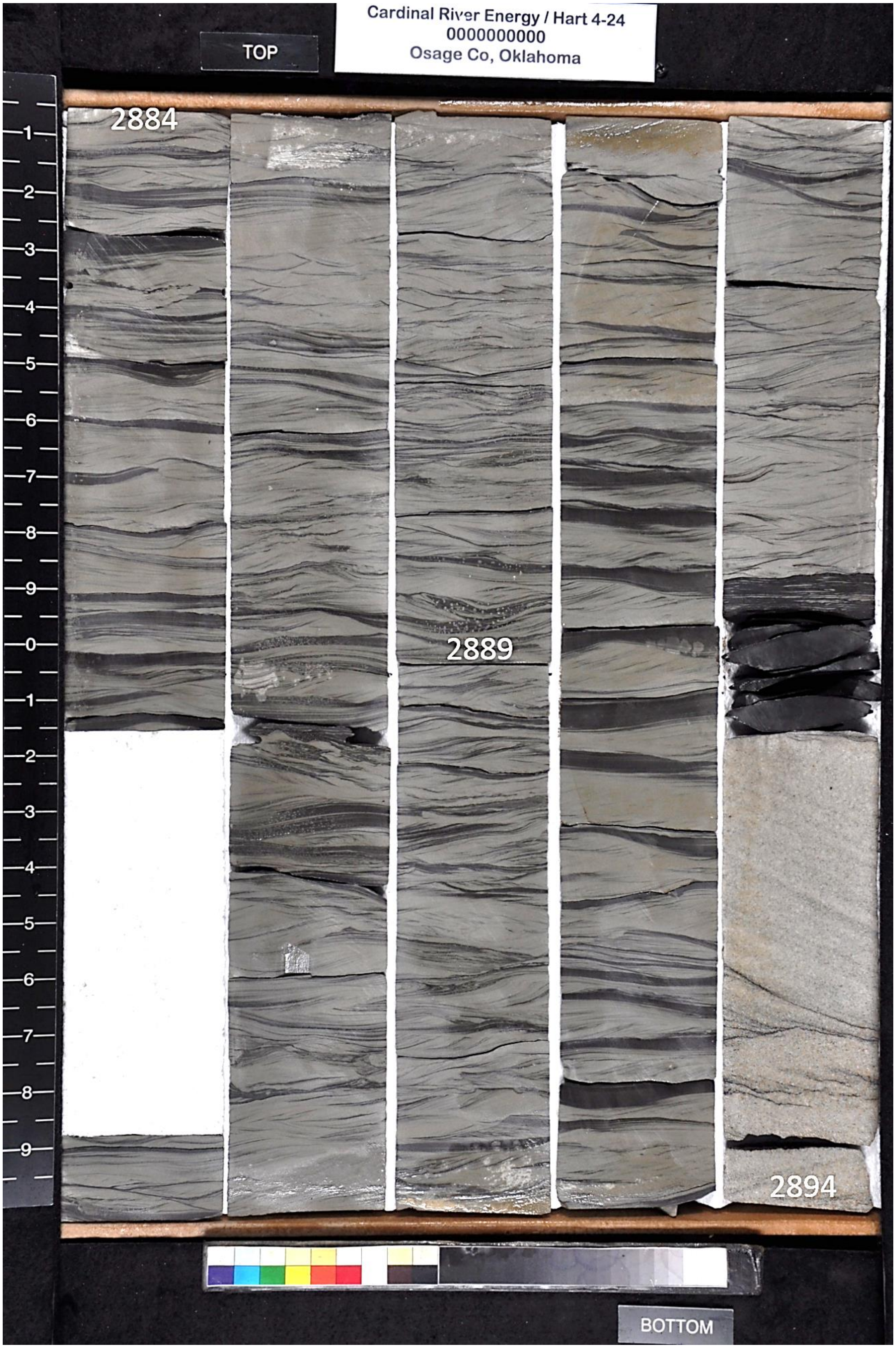
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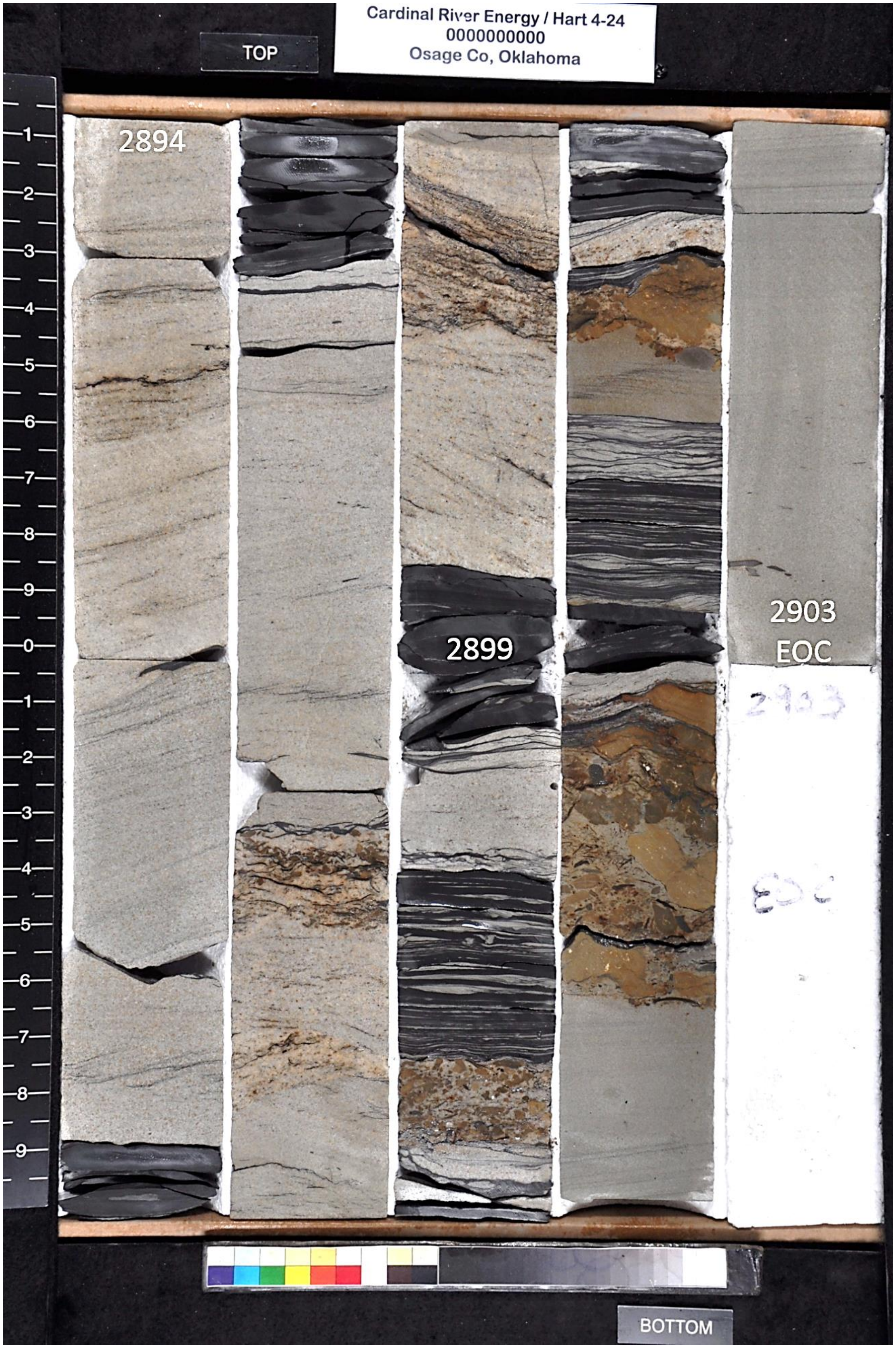

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Osage Co, Oklahoma
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2894
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2903
EOC
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APPENDIX D

GARRITY #10-24H CORE PHOTOGRAPHS


Cardinal River Energy/ Garrity 10
35113439600000
Osage Co, Oklahoma
TOP
2840
2845
2850
BOTTOM


Cardinal River Energy/ Garrity 10
35113439600000
Osage Co, Oklahoma
TOP
2850
2852
2854
2855
2857
2860
BOTTOM


Cardinal River Energy/ Garrity 10
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Osage Co, Oklahoma
TOP
2860
2865
2870
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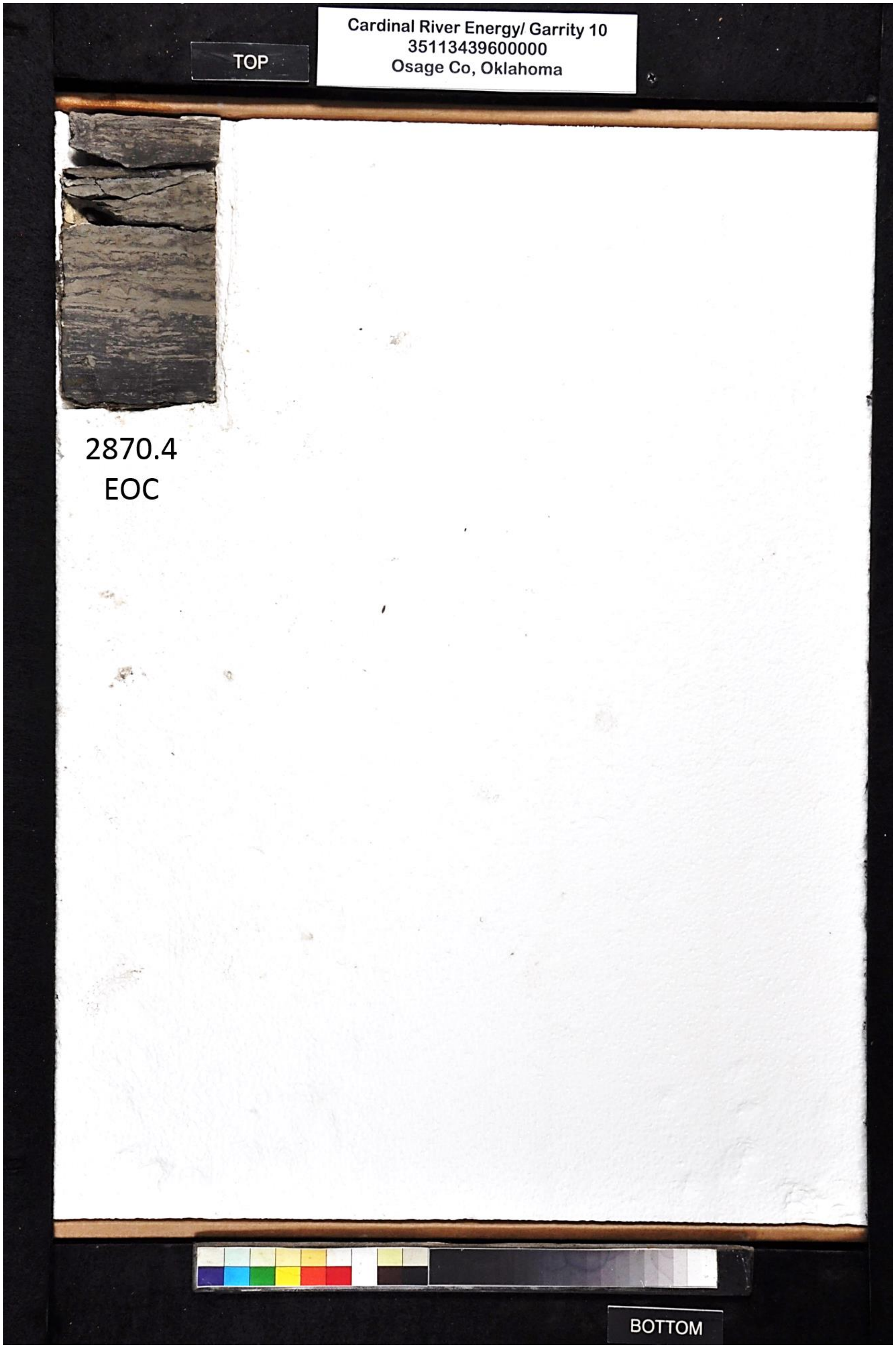
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Osage Co, Oklahoma
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2870.4
EOC
BOTTOM

APPENDIX E

POINT COUNTS AND TERNARY DIAGRAM FOR HART #4-24

THIN SECTION DEPTHS: 2840.4, 2898.6, 2901.3, 2902.3 FEET

SANDSTONE PETROGRAPHY and DIAGENESIS

THIN SECTION NUMBER: Hart 4-24 2840.4 PETROGRAPHER: JA
LOCATION: DATE: 12/5/17

I. Detrital Constituents	%	Size mm	Remarks
1. QUARTZ			
A. Monocrystalline	36	.02-.08 mm	
B. Polycrystalline			
C.			
2. FELDSPAR			
A. Microcline			
B. Orthoclase			
C. Sanidine			
D. Plagioclase	4	.08-.06	weathered/partially dissolved
E.			
3. ROCK FRAGMENTS			
A. Shale			
B. Chert	2		
C. Sandstone			
D. Carbonate			
E. Siltstone			
F. Metamorphic	4		
G. Plutonic			
H. Volcanic			
I.			
J.			
4. OTHER GRAINS			
A. Glauconite			
B. Shell Fragments			
1.			
2.			
3.			
C. Phosphate			
D. Muscovite	tr	.1mm	
E. Biotite			
F. Pyrite	2	.06 mm	grains/framboids; possibly from hydrocarbon migration
G. Hematite			
H. Zircon	tr	.02 mm	
I. Rutile			
J. tourmaline	1	.06-.08 mm	

II. Detrital Matrix	%	Size	Remarks
1. Clayey			
2. Silty			
3. Limy			
4. Other			

III. Diagenetic Constituents	%	Size	Remarks
1. Cement			
A. Quartz			
1. Overgrowth	2		Syntaxial
2.			
B. Opal			
C. Chalcedony			
D. Feldspar			
E. Carbonate			
1. Calcite	17		
2. Dolomite	22		
3. Siderite			
F. Hematite			
G. Limonite			
H. Phosphate			
I. Gypsum			
J. Anhydrite			
K. Barite			
L. Pyrite			
M.			
2. Authigenic Clays			
A. Kaolinite-Dickite	1		pore filling
B. Illite			
C. Smectite			
D. Chlorite			
E. Mixed-layered			
F.			
3. Others			
A. Zeolites			
B.			

IV. Porosity	%	Size	Remarks
	9		
1. Primary	30		
2. Secondary	70		
A. Moldic			
B. Oversized			✓
C. Micro (Intragrain)			✓
3. Micro (Interclay)	tr		

V. Classification

1. Name sublitharenite
2. Plot on attached page

VI. Texture

1. Sphericity sub rd - sub ang . more sub rd
2. Sorting poor - mod
3. Maturity
4.

VII. Description

very fine grained sub rd - sub ang sublitharenite

Ford 4-24 2840.4

Point Counting Table

Qtz	Poly Quartz	Plag	Micro	Ortho	Gran RF	Sed RF	Met RF	Matrix P-Mat	Chert		SiO_2	Calcite (Cement)	Dol (Cement)	Kaol	pyrite	Por ϕ	tourmaline
25		weathered 10					6					9	7			3	
28		4										10	18				
24		2										9	15		4	6	
27												10	12			7	4
20							3		7			11	14			5	
23							2					7	10	4	3	11	

MATRIX: ____ %	NORM.
Q: 127	79 %
F: 16	10 %
R: 18	11 %
161	100 %

SANDSTONE PETROGRAPHY and DIAGENESIS

THIN SECTION NUMBER: Hart 4-24 2898.6 PETROGRAPHER: VA
LOCATION: DATE: 12/5/17

I. Detrital Constituents	%	Size mm	Remarks
1. QUARTZ			
A. Monocrystalline	56	.1-.26mm	sub rd - sub ang
B. Polycrystalline	tr	.08mm	
C.			
2. FELDSPAR			
A. Microcline			
B. Orthoclase			
C. Sanidine			
D. Plagioclase	4	.18-.26mm	some partially dissolved
E.			
3. ROCK FRAGMENTS			
A. Shale			
B. Chert	3	.06mm	
C. Sandstone			
D. Carbonate			
E. Siltstone			
F. Metamorphic		.1-.3mm	SMRF
G. Plutonic			
H. Volcanic			
I.			
J.			
4. OTHER GRAINS			
A. Glauconite			
B. Shell Fragments			
1.			
2.			
3.			
C. Phosphate			
D. Muscovite	2	varied	
E. Biotite	2	.06-.12mm	Chloritized biotite
F. Pyrite	3		
G. Hematite			
H. Zircon			
I. Rutile			
J. Organics	2		

II. Detrital Matrix	%	Size	Remarks
1. Clayey			
2. Silty			
3. Limy			
4. Other			

III. Diagenetic Constituents	%	Size	Remarks
1. Cement			
A. Quartz	2		
1. Overgrowth		.1-.26mm	Some almost completely surrounding quartz grains
2.			
B. Opal			
C. Chalcedony			
D. Feldspar			
E. Carbonate			mixed but mostly dol
1. Calcite	3		
2. Dolomite	10		
3. Siderite			
F. Hematite			
G. Limonite			
H. Phosphate			
I. Gypsum			
J. Anhydrite			
K. Barite			
L. Pyrite			bands / pyrite cement between grains
M.			
2. Authigenic Clays			
A. Kaolinite-Dickite	7		
B. Illite	tr		illite coating few quartz grains
C. Smectite			
D. Chlorite			
E. Mixed-layered			
F.			
3. Others			
A. Zeolites			
B.			

IV. Porosity	%	Size	Remarks
	6		Mostly secondary
1. Primary	35		
2. Secondary	60	varied	
A. Moldic			
B. Oversized			
C. Micro (Intragrain)			
3. Micro (Interclay)	5		between Kaolinite booklets

V. Classification

1. Name Quartzarenite
2. Plot on attached page

VI. Texture

1. Sphericity sub rd - sub ang
2. Sorting poor - mod
3. Maturity Immature
4.

VII. Description

fine to very fine grained sub rd - sub ang quartzarenite. Poorly to moderately sorted

Hart 4-24 2898.6

Point Counting Table

w/ micro φ (→ muscovite) Cement (over Calcite/Dol) chloritized (→ biotite)

Qtz	Poly Quartz	Plag	Micro	Ortho	Gran RF	Sed RF	Met RF	Matrix P-Mat	Chert	muscovite	SiO_2	Calcite	Dol	Kaol	pyrite	Por φ	biotite	Qtz. Org.	orga
35												3	16					6	
38									9					4		6			3
32		dissolved 13													9	3			3
33												2	8	6		7		4	
38												4	6	10				2	
27										8			5	4	3	7	6		

MATRIX: ______ %

		NORM.
Q:	203	90 %
F:	13	6
R:	9	4
	225	100 %

SANDSTONE PETROGRAPHY and DIAGENESIS

THIN SECTION NUMBER: Hart 4-24 2901.3 A PETROGRAPHER: Justin
LOCATION: DATE: 12/5/17

I. Detrital Constituents	%	Size mm	Remarks
1. QUARTZ			
A. Monocrystalline	31	.06-.24mm	snb-rd to sub-ang w/some ang
B. Polycrystalline	tr		dirty
C.			
2. FELDSPAR			
A. Microcline			
B. Orthoclase			
C. Sanidine			
D. Plagioclase	4		
E.			
3. ROCK FRAGMENTS			
A. Shale			
B. Chert			
C. Sandstone			
D. Carbonate			
E. Siltstone			
F. Metamorphic	5		SMRF
G. Plutonic			
H. Volcanic			
I.			
J.			
4. OTHER GRAINS			
A. Glauconite			
B. Shell Fragments			
1.			
2.			
3.			
C. Phosphate			
D. Muscovite			
E. Biotite			
F. Pyrite	tr		
G. Hematite			
H. Zircon			
I. Rutile			
J. tourmaline	1	.05-.1mm	
K. Organics	7		

II. Detrital Matrix	%	Size	Remarks
1. Clayey			
2. Silty			
3. Limy			
4. Other			

III. Diagenetic Constituents — % — Size — Remarks

1. Cement
   - A. Quartz
     - 1. Overgrowth — 3
     - 2.
   - B. Opal
   - C. Chalcedony
   - D. Feldspar
   - E. Carbonate
     - 1. Calcite — 3
     - 2. Dolomite — 5
     - 3. Siderite
   - F. Hematite
   - G. Limonite
   - H. Phosphate
   - I. Gypsum
   - J. Anhydrite
   - K. Barite
   - L. Pyrite
   - M.

2. Authigenic Clays
   - A. Kaolinite-Dickite — 4 — booklets; pore filling
   - B. Illite
   - C. Smectite
   - D. Chlorite
   - E. Mixed-layered
   - F. illite-siderite — 33 — illite clasts partially replaced by siderite

3. Others
   - A. Zeolites
   - B.

IV. Porosity — % — Size — Remarks

4

1. Primary — 25
2. Secondary — 70
   - A. Moldic
   - B. Oversized
   - C. Micro (Intragrain)
3. Micro (Interclay) — 5

V. Classification

1. Name: sublitharenite
2. Plot on attached page

VI. Texture

1. Sphericity: sub rd - sub ang
2. Sorting: poorly sorted
3. Maturity
4.

VII. Description

Very fine to fine grained sublitharenite with poorly sorted sub rounded to sub angular grains

Hart 4-24 2901.3 (A)

Point Counting Table

periclire albite carlsbad Cement quartz grains coated w/ illite

Qtz	Poly Quartz	Plag	Micro	Ortho	Gran RF	Sed RF	Met RF	Matrix P-Mat	Chert	illitic-siderite clast	SiO_2	Calcite	Dol	Kaol	illite	Por ϕ	Pyrite	organics	tourmaline
27		partially 9 dissolved					8					2	7			secondary 5		2	
26							6					4	12					12	
26				3			4			5			6	13		2nd 3	1		
32		6														7		10	5
										60									
										55		3					2		

MATRIX: ______ %

		NORM.
Q:	111	76 %
F:	18	12
R:	18	12
	147	100 %

SANDSTONE PETROGRAPHY and DIAGENESIS

THIN SECTION NUMBER: Hart 4-24 2902.3 PETROGRAPHER: Justin
LOCATION: Osage Co, OK. 24-25N-2E DATE: 12/5/17

I. Detrital Constituents	%	Size mm	Remarks
1. QUARTZ			
A. Monocrystalline	53	.04-.24mm	sub rd - sub ang
B. Polycrystalline			
C.			
2. FELDSPAR			
A. Microcline			
B. Orthoclase			
C. Sanidine			
D. Plagioclase	1	.06-.12 mm	some partially dissolved
E.			
3. ROCK FRAGMENTS			
A. Shale			
B. Chert	3		
C. Sandstone			
D. Carbonate	tr	.06-.08 mm	very fine grained
E. Siltstone			
F. Metamorphic	6	varied (.08-.2)mm	SMRF
G. Plutonic			
H. Volcanic			
I.			
J.			
4. OTHER GRAINS			
A. Glauconite			
B. Shell Fragments			
1.			
2.			
3.			
C. Phosphate			
D. Muscovite	3		
E. Biotite	tr	.1-.16 mm	partially to fully chloritized
F. Pyrite	tr	>.03 mm	very small pyrite grains
G. Hematite			
H. Zircon	tr	.02-.08 mm	
I. Rutile			
J. tourmaline	tr		

II. Detrital Matrix	%	Size	Remarks
1. Clayey			
2. Silty			
3. Limy			
4. Other			

III. Diagenetic Constituents	%	Size	Remarks
1. Cement			
A. Quartz			
1. Overgrowth	4	.01-.02mm	
2.			
B. Opal			
C. Chalcedony			
D. Feldspar			
E. Carbonate			much more dolomite
1. Calcite	4	N/A	than calcite
2. Dolomite	9	N/A	
3. Siderite			
F. Hematite			
G. Limonite			
H. Phosphate			
I. Gypsum			
J. Anhydrite			
K. Barite			
L. Pyrite			
M.			
2. Authigenic Clays			
A. Kaolinite-Dickite	2	N/A	pore filling
B. Illite	tr	.04-.1mm	illitic claystone fragments
C. Smectite			
D. Chlorite			
E. Mixed-layered			
F.			
3. Others			
A. Zeolites			
B.			

IV. Porosity	%	Size	Remarks
	15		more Secondary than Primary
1. Primary	15		
2. Secondary	80		
A. Moldic			
B. Oversized	tr		
C. Micro (Intragrain)			within partially dissolved grains
3. Micro (Interclay)	5		Some micro between Kaolinite booklets.

V. Classification

1. Name Sublitharenite
2. Plot on attached page

VI. Texture

1. Sphericity sub rd - sub ang , more sub ang
2. Sorting poor sorted
3. Maturity
4.

VII. Description

fine grained sublitharenite w/ sub rd to sub ang grains, most of which be sub angular

Hart 4-24 2902.3

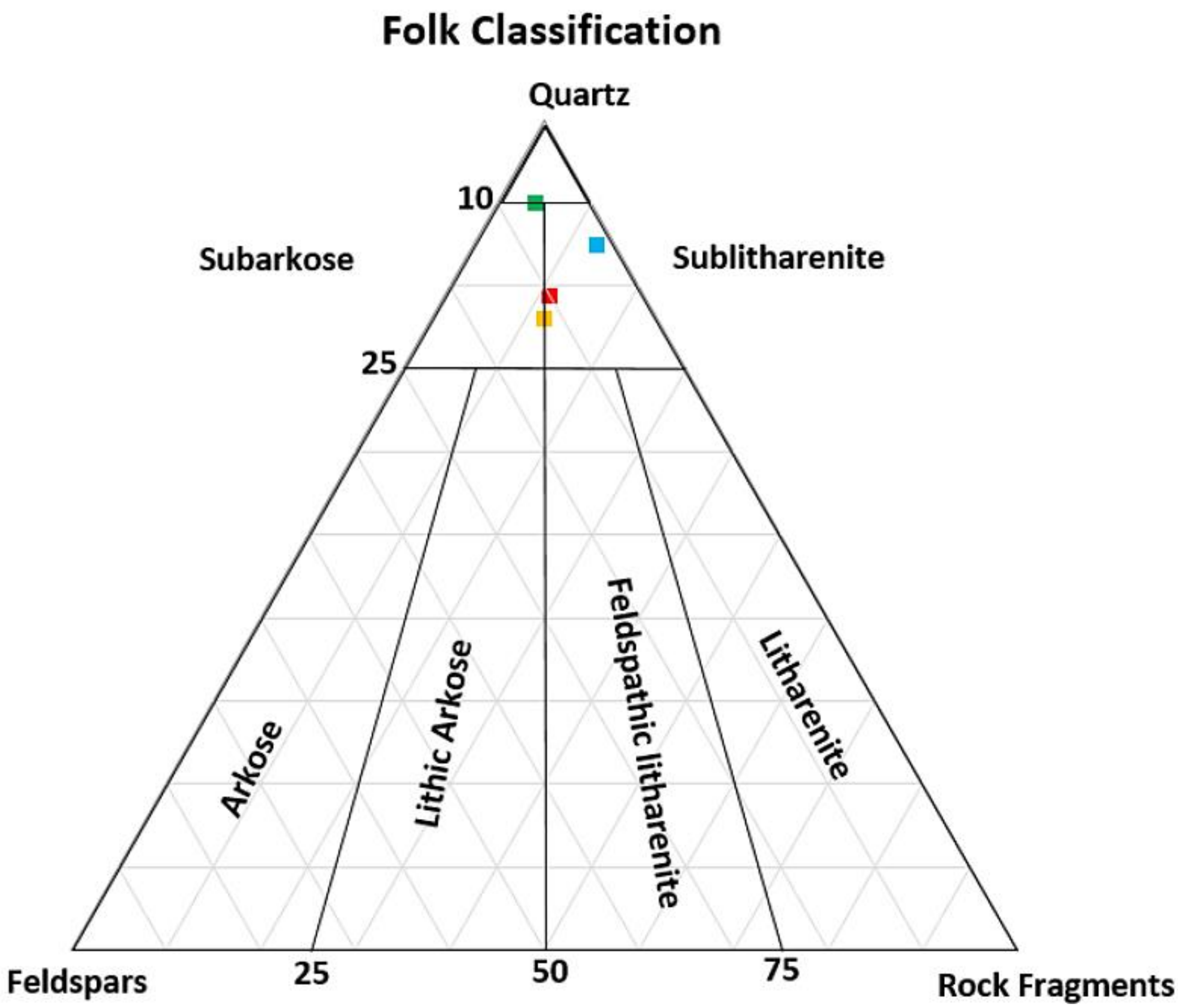
Point Counting Table

Qtz	Poly Quartz	Plag (Pericline)	Micro (albite)	Ortho (carlsbad)	Gran RF	Sed RF	Met RF	Matrix P-Mat	Chert	muscovite	SiO_2	Calcite	Dol	Kaol	Qtz ovg.	Por ϕ (Secondary)	Pyrite
38										5					7	7	
30							11						7			11	1
31												7	20			2	
38										4		3				13	
26		5					4					3		7		15	
28							6		9				6		3	6	2

MATRIX: ______ %

Q: 191
F: 5
R: 30
226

NORM.
85 %
2
13
100 %



Folk classification diagram with samples plotted and color-coded: 2840.4 (Red), 2898.6 (Green), 2901.3 (Yellow), 2902.3 (Blue).

Appendix F

Plates

Regional Cr

HS=100


Cross Section A-A' (NW-SE)
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COMP_DATE : 5/8/1983
35103008350000
MAGNOLIA PET CO
VERONNEAU ELLA 1
T22N R2E S10
ELEV_DF : 942
SPUD_DATE : 11/15/1942
COMP_DATE : 12/25/1942
35103217900000
GETTY OIL COMPANY
BYRON NEAL 14-1
T22N R2E S14
ELEV_KB : 987
SPUD_DATE : 8/16/1982
COMP_DATE : 8/27/1982
35103008550000
DIRICKSON BLAKE T
SCHULTZ 1
T22N R2E S25
ELEV_KB : 1,016
SPUD_DATE : 3/1/1951
COMP_DATE : 3/15/1951
Plate 1
A'
Kay County
Osage County
Noble County
Pawnee County
Osage-Layton
Base Osage-Layton
Shale marker
Hogshooter Limestone
Checkerboard Limestone
Big Lime
Datum = Checkboard Limestone

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BAINUM 4
JOHNSON-BATES DRLG
RICE 1
LIVINGSTON JULIUS
B H ROWAN 1
BECKER OIL CORP
BIG GOOSE 1
CEJA CORP ETAL
BEARS EAR 2
RAM OIL & GAS CO
DAISY #2 2
BUCCANEER PETRO INCO
WILSON 1
GLACIER PETR CO OKLA
KELLY 1-15
TEXAS COMPANY

Plate 2
B'
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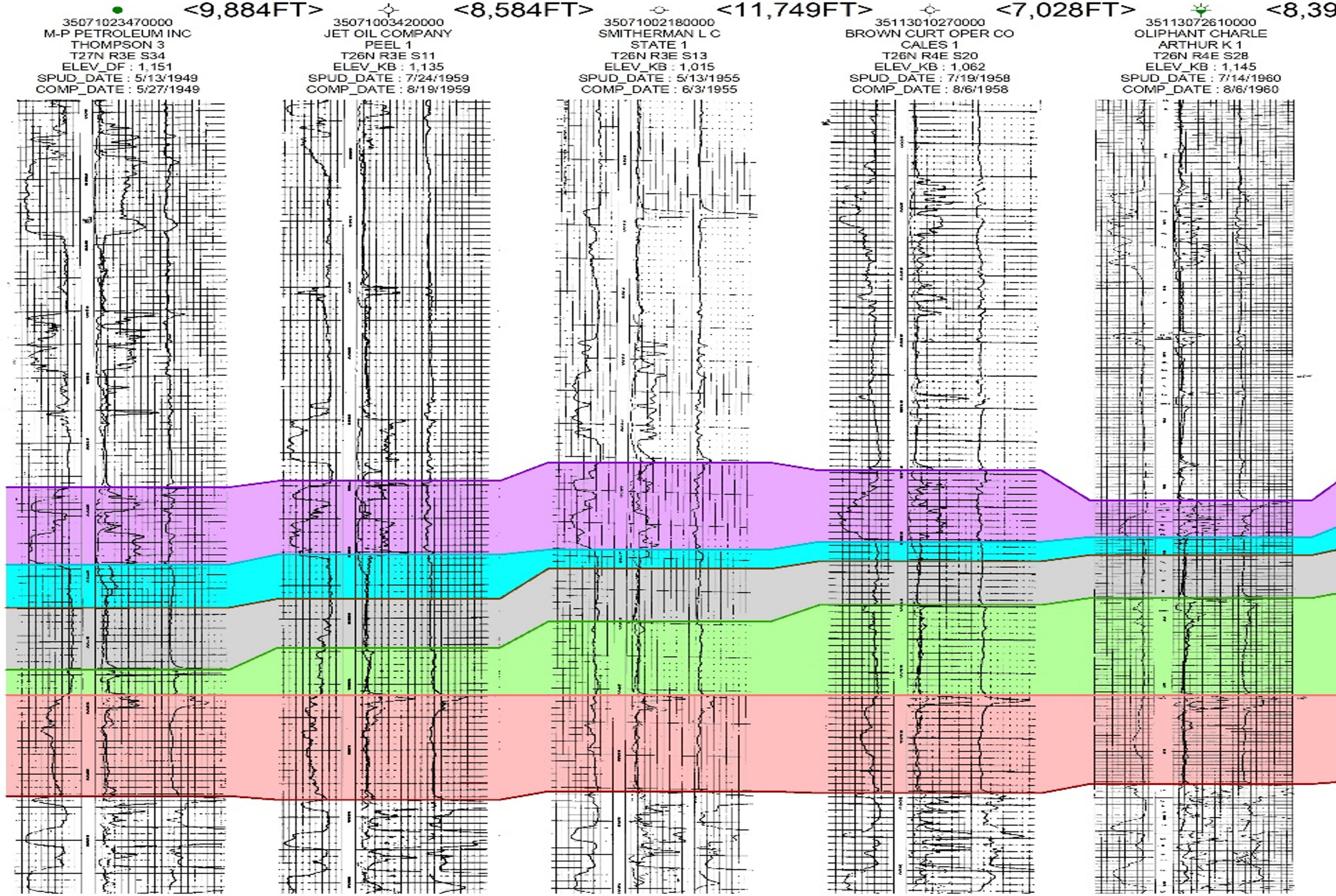
Kay County
Osage County
Noble County
Pawnee County
Osage-Layton
Base Osage-Layton
Shale marker
Hogshooter Limestone
Checkerboard Limestone
Big Lime
Datum = Checkboard Limestone

C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COMP_DATE : 5/27/1949
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JET OIL COMPANY
PEEL 1
T26N R3E S11
ELEV_KB : 1,135
SPUD_DATE : 7/24/1959
COMP_DATE : 8/19/1959
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SMITHERMAN L C
STATE 1
T26N R3E S13
ELEV_KB : 1,015
SPUD_DATE : 5/13/1955
COMP_DATE : 6/3/1955
35113010270000
BROWN CURT OPER CO
CALES 1
T26N R4E S20
ELEV_KB : 1,062
SPUD_DATE : 7/19/1958
COMP_DATE : 8/6/1958
35113072610000
OLIPHANT CHARLE
ARTHUR K 1
T26N R4E S28
ELEV_KB : 1,145
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COMP_DATE : 8/6/1960

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PETR RESOURCES CO
PICKERING 1
T22N R1E S10
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SPUD_DATE : 9/13/1968
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ANCHOR PRODUCTION CO
TRIBAL 1
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ELEV_KB : 921
SPUD_DATE : 4/4/1969
COMP_DATE : 4/15/1969
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WOODS PETROLEUM CORP
OTOE 1
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ELEV_KB : 876
SPUD_DATE : 7/17/1957
COMP_DATE : 8/7/1957
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SERVICE DRILLING CO
ARROW 1-31
T24N R3E S31
ELEV_KB : 897
SPUD_DATE : 5/16/1983
COMP_DATE : 5/27/1983
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SCHONWALD SUPPLY CO
MCDANIEL 21-1
T24N R3E S21
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COMP_DATE : 2/16/1983
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CAUGHLIN 2	BLUBAUGH 21-3	MARCI 1-15	HORSE JENNIE B H 2	DAN MCFARLIN 5
T25N R1E S30	T25N R1E S21	T25N R1E S15	T25N R1E S11	T25N R2E S6
ELEV_KB : 951	ELEV_KB : 972	ELEV_KB : 967	ELEV_KB : 959	ELEV_KB : 947
SPUD_DATE : 12/28/1987	SPUD_DATE : 5/27/2012	SPUD_DATE : 8/6/2012	SPUD_DATE : 11/4/1958	SPUD_DATE : 9/20/1975
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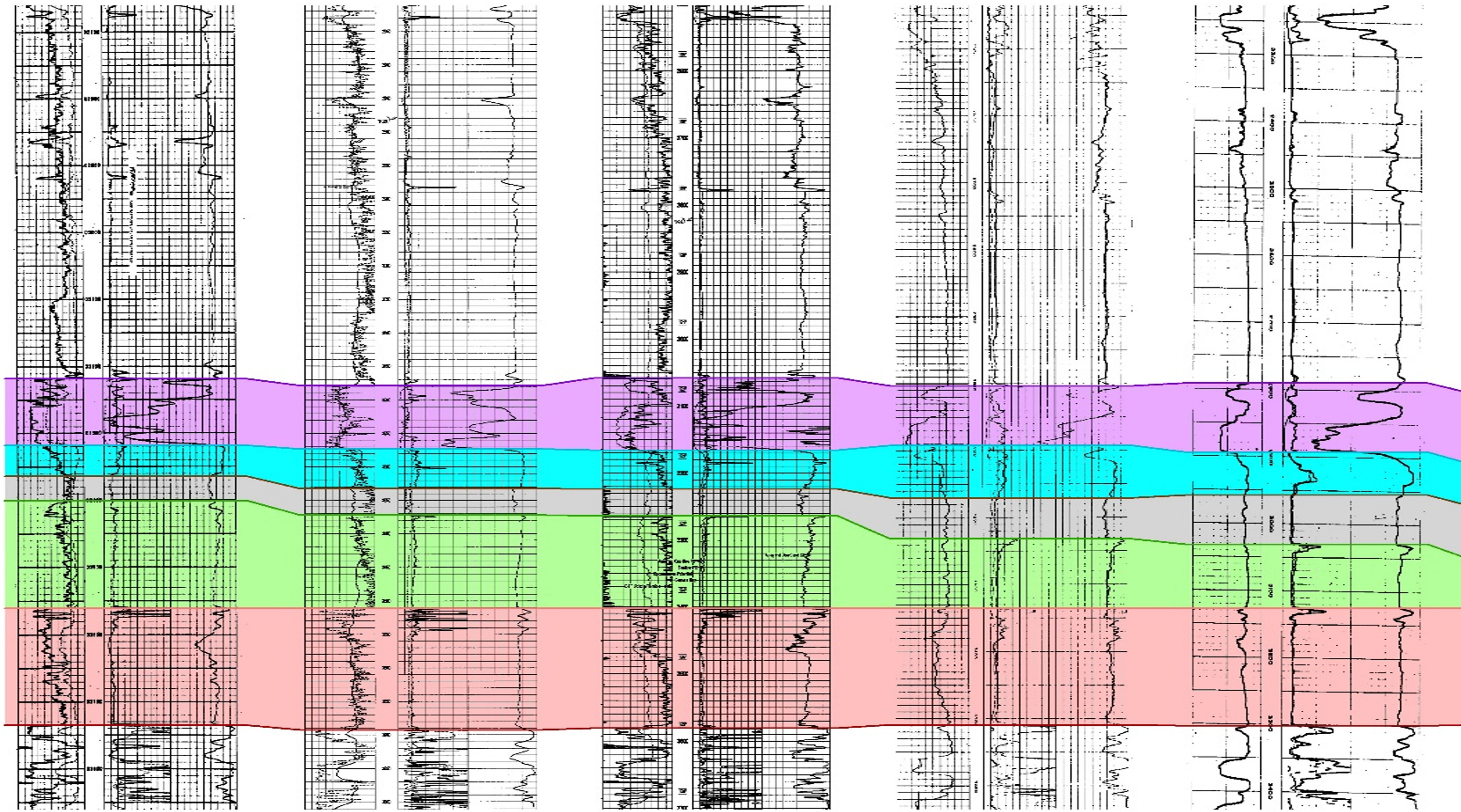
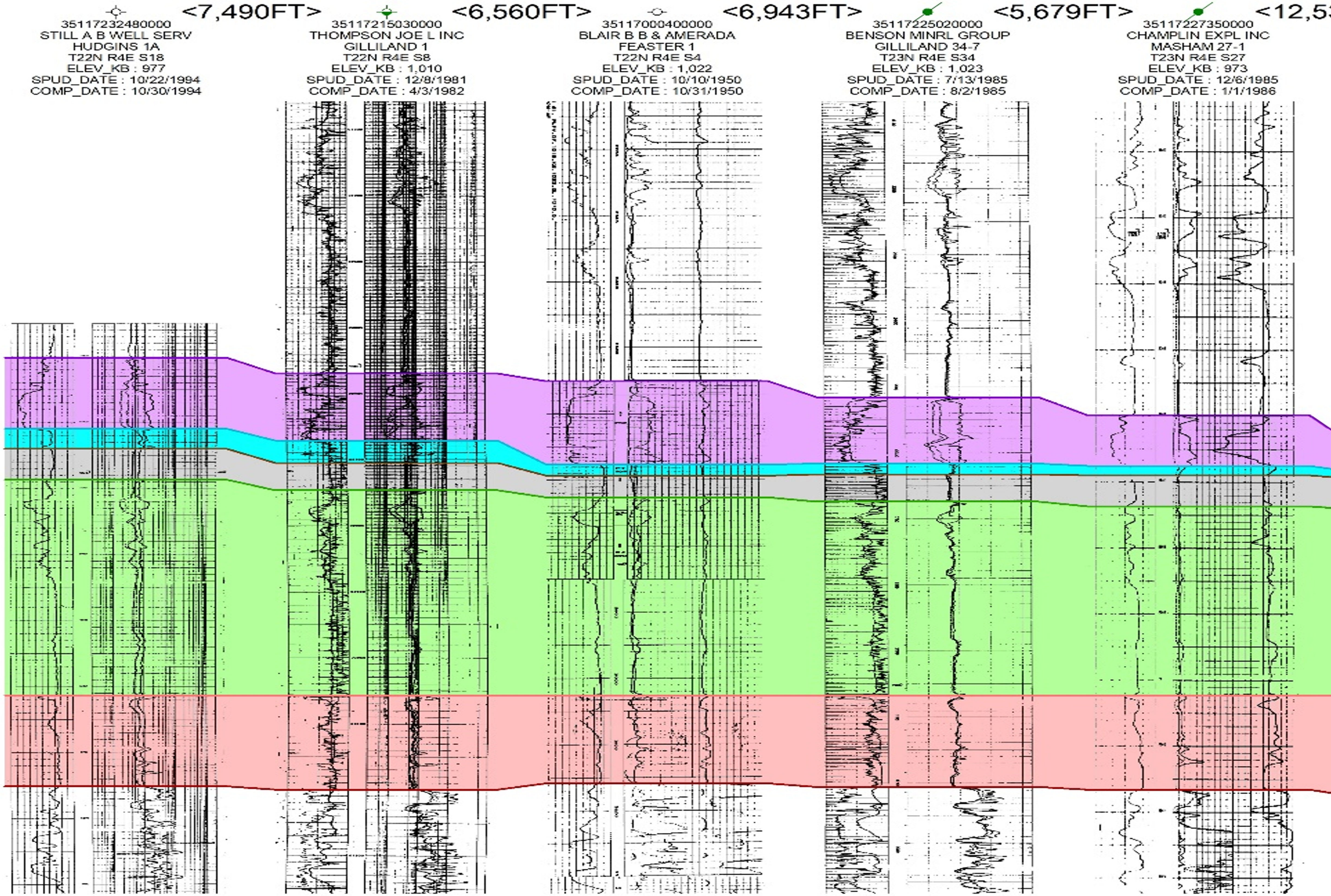


HS=100

Plate 5

Datum = Checkboard Limestone

F



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COMP_DATE : 10/30/1994
35117215030000
THOMPSON JOE L INC
GILLILAND 1
T22N R4E S8
ELEV_KB : 1,010
SPUD_DATE : 12/8/1981
COMP_DATE : 4/3/1982
35117000400000
BLAIR B B & AMERADA
FEASTER 1
T22N R4E S4
ELEV_KB : 1,022
SPUD_DATE : 10/10/1950
COMP_DATE : 10/31/1950
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BENSON MINRL GROUP
GILLILAND 34-7
T23N R4E S34
ELEV_KB : 1,023
SPUD_DATE : 7/13/1985
COMP_DATE : 8/2/1985
35117227350000
CHAMPLIN EXPL INC
MASHAM 27-1
T23N R4E S27
ELEV_KB : 973
SPUD_DATE : 12/6/1985
COMP_DATE : 1/1/1986

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Regional Cross Section F-F' (SW-NE)
Plate 6
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35117206060000
BALE CHARLES R
MITCHELL 1
T23N R4E S24
ELEV_KB : 983
SPUD_DATE : 12/8/1978
COMP_DATE : 12/22/1978
35117002050000
GILLESPIE & SONS
CURLEY 1
T23N R5E S17
ELEV_GR : 1,023
SPUD_DATE : 10/9/1955
COMP_DATE : 10/28/1955
35117219270000
GRAVES OIL PROP INC
BRYANT 1
T23N R5E S4
ELEV_KB : 960
SPUD_DATE : 6/23/1983
COMP_DATE : 8/4/1983
35117210180000
SUPERIOR OIL&GAS LLC
IRWIN 1
T24N R5E S34
ELEV_KB : 884
SPUD_DATE : 12/4/1980
COMP_DATE : 5/1/1981
35117003440000
TOTO GAS CO
EBERWEIN 1
T24N R5E S15
ELEV_KB : 857
SPUD_DATE : 2/7/1958
COMP_DATE : 3/1/1958
Kay County
Osage County
Noble County
Pawnee County
Osage-Layton
Base Osage-Layton
Shale marker
Hogshooter Limestone
Checkerboard Limestone
Big Lime
Datum = Checkboard Limestone

Hart #4-24

Core depth (log depth)
2814’ (2812’) to 2834’ (2832’)

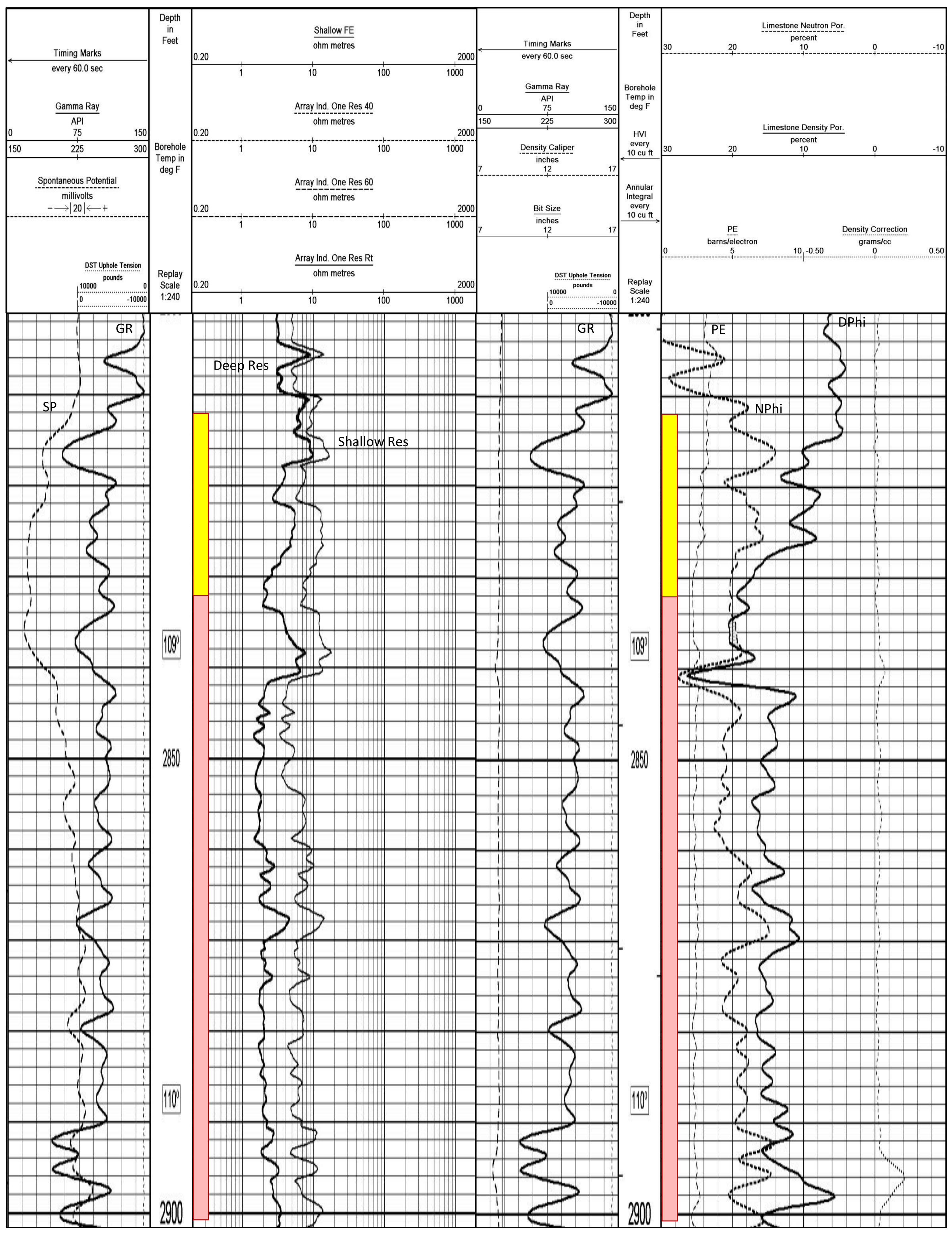
Log is 2’ higher than core

Cored interval

Picture core interval

Plain light | UV light

2814’ (2812’)
2815’ (2813’)
2816’ (2814’)
2817’ (2815’)
2818’ (2816’)
2819’ (2817’)
2820’ (2818’)
2821’ (2819’)
2822’ (2820’)
2823’ (2821’)



Plain light | UV light

2824’ (2822’)
2825’ (2823’)
2826’ (2824’)
2827’ (2825’)
2828’ (2826’)
2829’ (2827’)
2830’ (2828’)
2831’ (2829’)
2832’ (2830’)
2833’ (2831’)

Notable Features

- Erosional surface at 2816.5
- Interlaminated shale and sandstone
- Brown, oil stained sandstone mixed with grey, very fine grained to silty sandstone
  - These grey very fine grained to silty sandstones are probably also more clay rich then the surrounding coarser grained sandstone
- Oil shows in coarser grained, sandstone versus finer grained/siltier sandstones starting at 2828
- Vertical permeability barriers from shale/clay/tighter laminae
  - These types of barriers make EOR projects such as waterflooding very difficult.

Plate 7

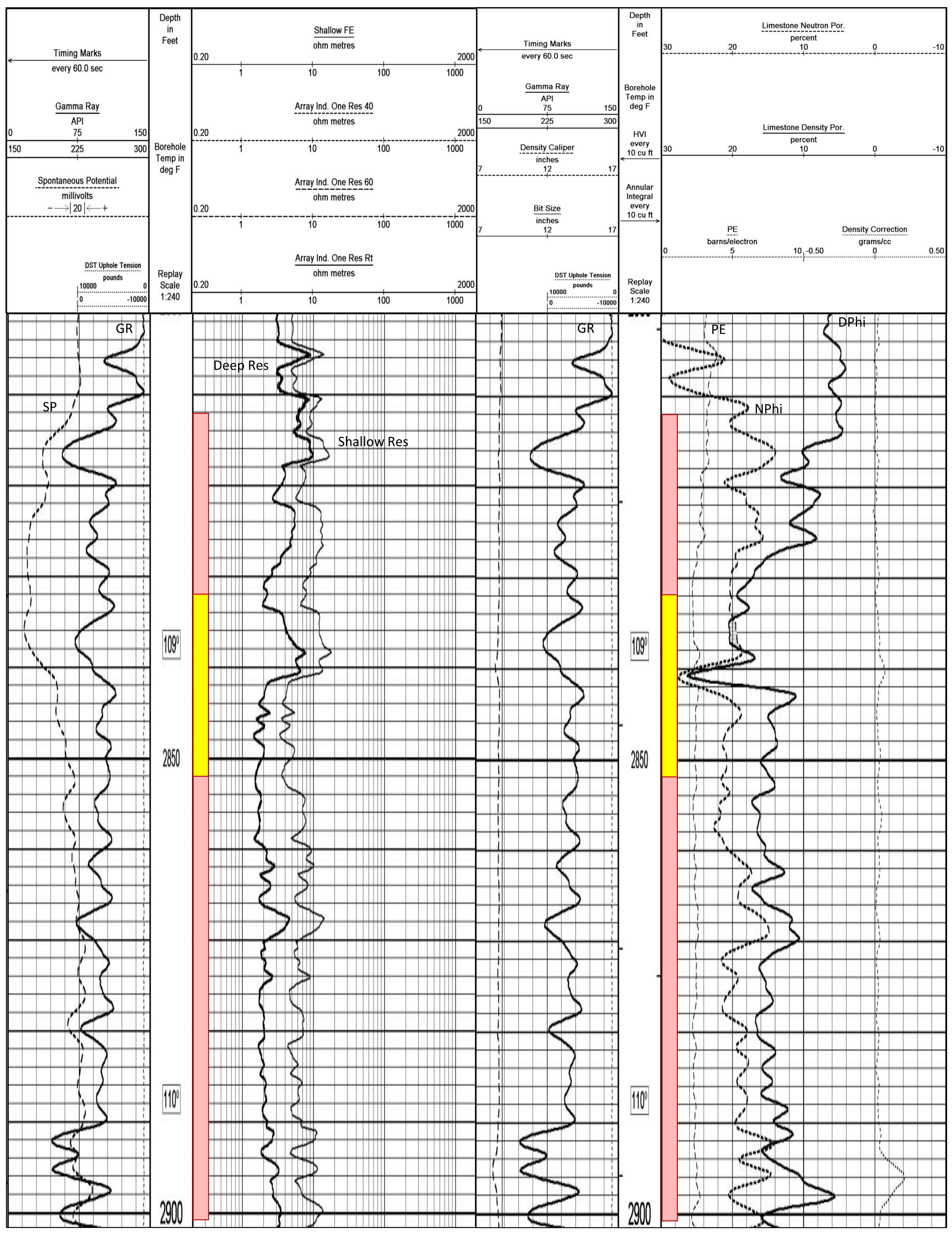
Hart #4-24

Core depth (log depth)
2834’ (2832’) to 2854’ (2852’)

Log is 2’ higher than core

Cored interval

Picture core interval



Notable Features

- Cleaner, more porous sandstone filled with oil
- Still some interlaminated sandstone and shale but less of it than up above
- Erosional surface at 2843’
  - Could be interpreted as a channel cutting into a thin coal bed
- Below the coal, grey to light grey sandstone and dark grey sandy shale
  - Low porosity and permeability
  - No migration of hydrocarbons
  - No flouresence
- Begin to see soft sediment deformation, and wavy/ripple bedded laminae

Plate 8

Hart #4-24

Core depth (log depth)
2854’ (2852’) to 2874’ (2872’)

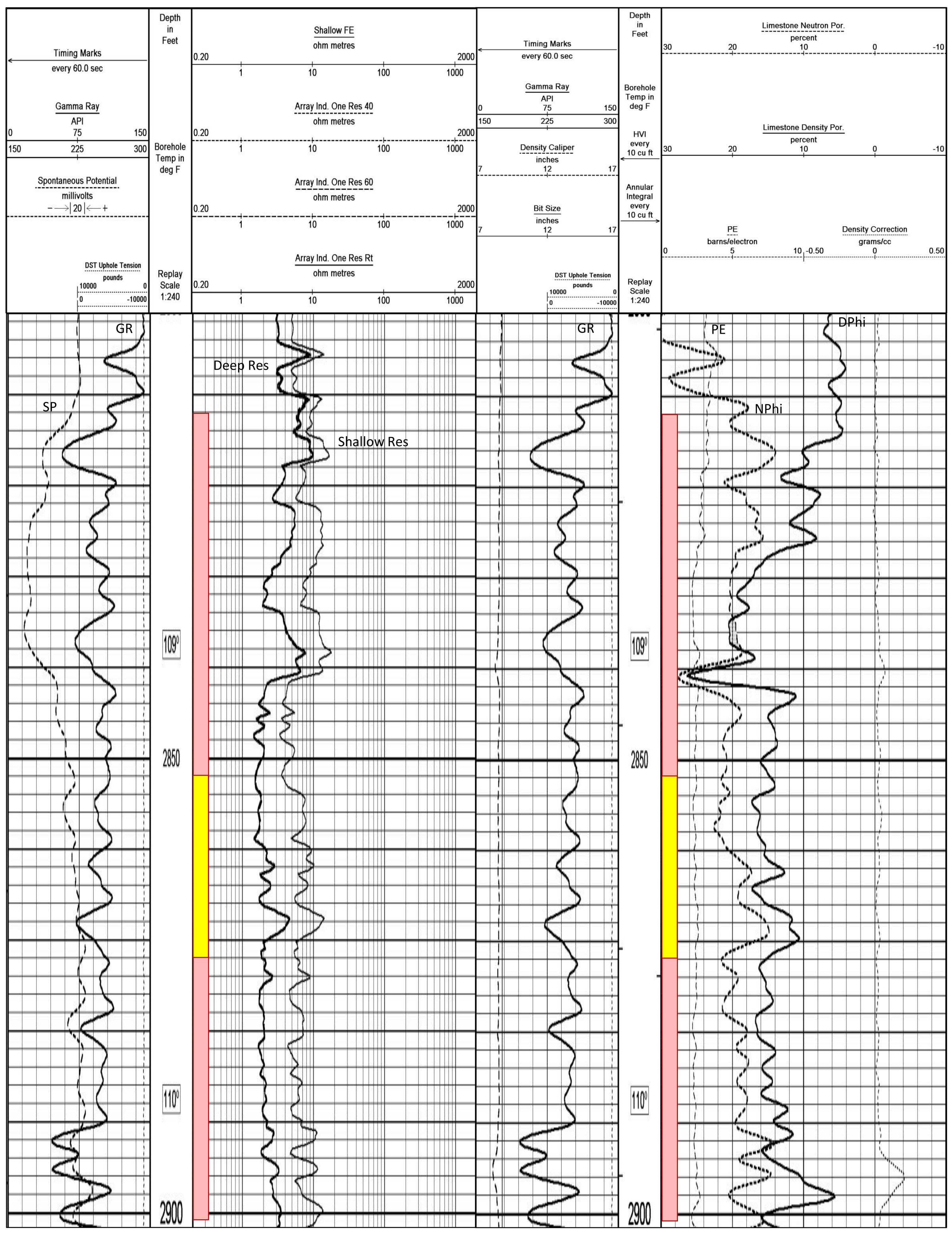
Log is 2’ higher than core

Cored interval

Picture core interval

Plain light | UV light

2854’ (2852’)
2855’ (2853’)
2856’ (2854’)
2857’ (2855’)
2858’ (2856’)
2859’ (2857’)
2860’ (2858’)
2861’ (2859’)
2862’ (2860’)
2863’ (2861’)



Plain light | UV light

2864’ (2862’)
2865’ (2863’)
2866’ (2864’)
2867’ (2865’)
2868’ (2866’)
2869’ (2867’)
2870’ (2868’)
2871’ (2869’)
2872’ (2870’)
2873’ (2871’)

Notable Features

- Increased amount of soft sediment deformation
- Silty to very fine-grained and with some very sandy shale laminae
- Soft sediment deformation decreases around 2859 and bedding becomes more planar with some hummocky cross-bedding scattered throughout

Plate 9

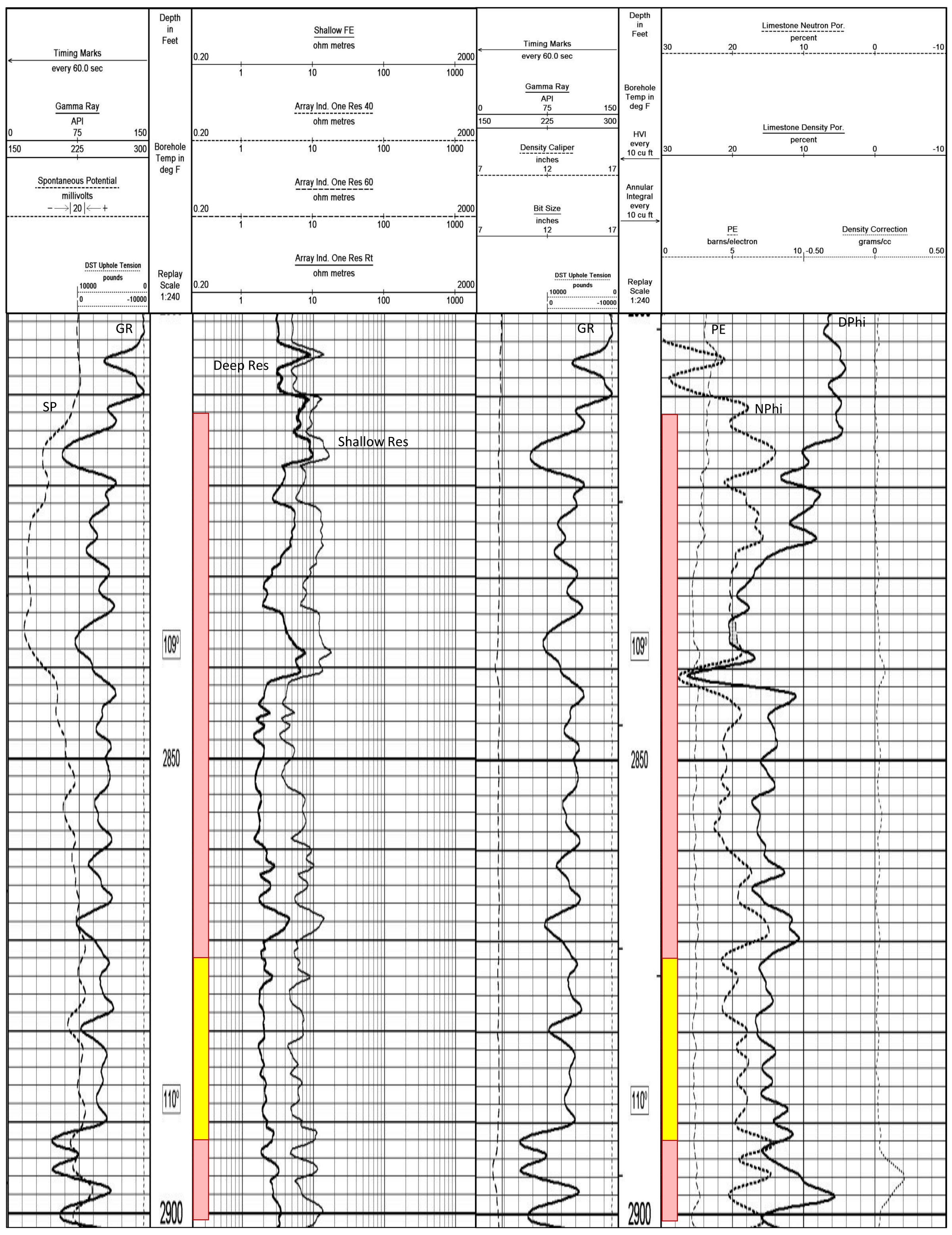
Hart #4-24

Core depth (log depth)
2874’ (2872’) to 2894’ (2892’)

Log is 2’ higher than core

Cored interval

Picture core interval



Plain light | UV light

2874’ (2872’)
2875’ (2873’)
2876’ (2874’)
2877’ (2875’)
2878’ (2876’)
2879’ (2877’)
2880’ (2878’)
2881’ (2879’)
2882’ (2880’)
2883’ (2881’)

Plain light | UV light

2884’ (2882’)
2885’ (2883’)
2886’ (2884’)
2887’ (2885’)
2888’ (2886’)
2889’ (2887’)
2890’ (2888’)
2891’ (2889’)
2892’ (2890’)
2893’ (2891’)

Notable Features

- Soft sediment deformation is still visible throughout this interval
- The shale laminae throughout is thicker than up hole and are less sandy than previous zones
- Very distinct alternating shale and sandstone laminae
- Hummocky cross-bedding, climbing ripples, and ripple/wavy bedding is evident
- This section could be interpreted as an interval of tidal couplets
- Near the base of this interval is what appears to be a marine shale overlaying a medium to coarse grained sandstone
  - This section can be interpreted as a distributary channel sand with a sudden rise in sea level, depositing the dark grey to black marine shale on top.
- Notice the high angle cross-bedding in the channel sand

Plate 10

Plain light UV light

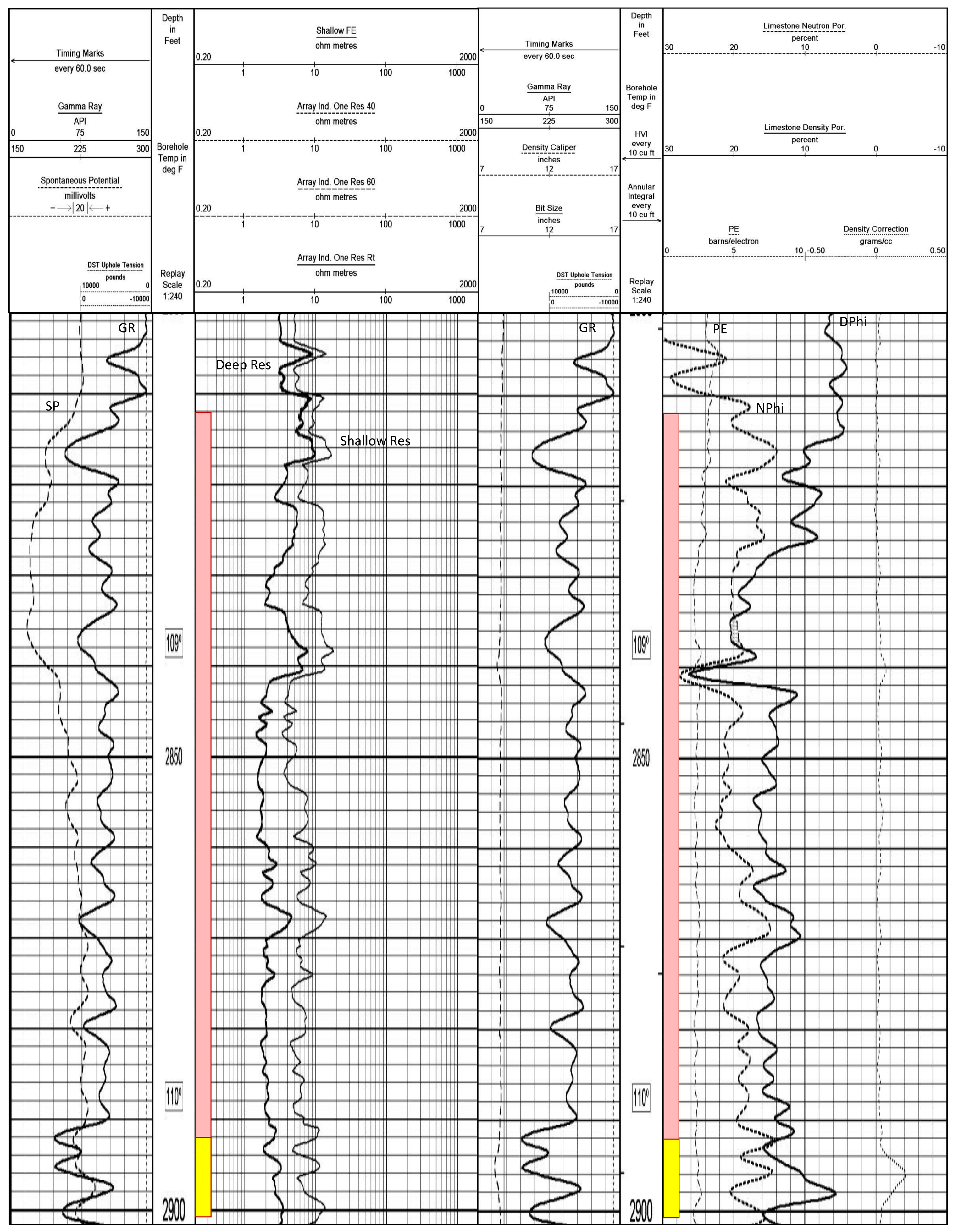
Hart #4-24

Core depth (log depth)
2894’ (2892’) to 2903’ (2901’)

Log is 2’ higher than core

Cored interval

Picture core interval



Notable Features

- Continuation of the channel sand environment
- Several sections of dark shale separating channel fills
- Could be interpreted as a series of stacked channels within an incised valley that had several flooding events and tidally reworked zones with thin alternating sandstone and shale laminae associated with it
- Rip up clasts are visible
- At 2901.5, coal streaks are observed
  - This could indicate woody fragments that were ripped up and mixed in with the conglomerate clasts

Plate 11

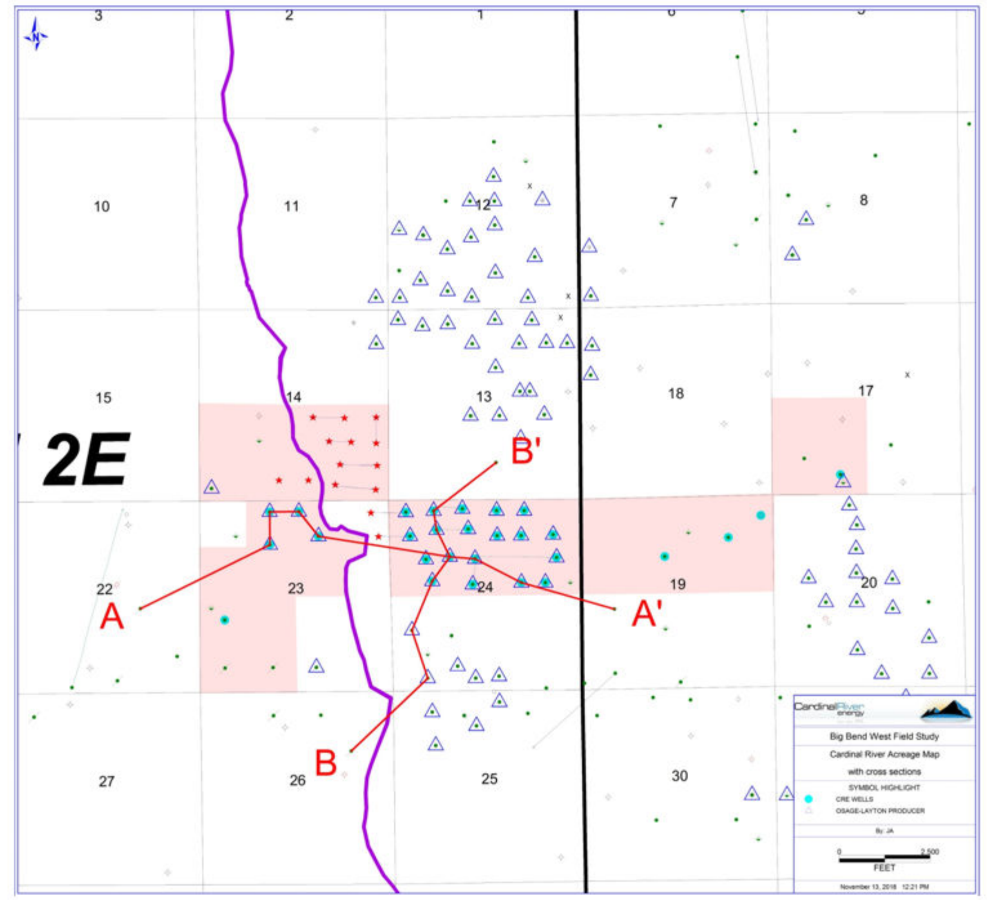
Big Bend West Field Stratigraphic Cross Section A-A'

Plate 12

PETRA 11/13/2018 12:17:37 PM (Big Bend A-A'.CSP)

Big Bend West Field Structural Cross Section A-A'

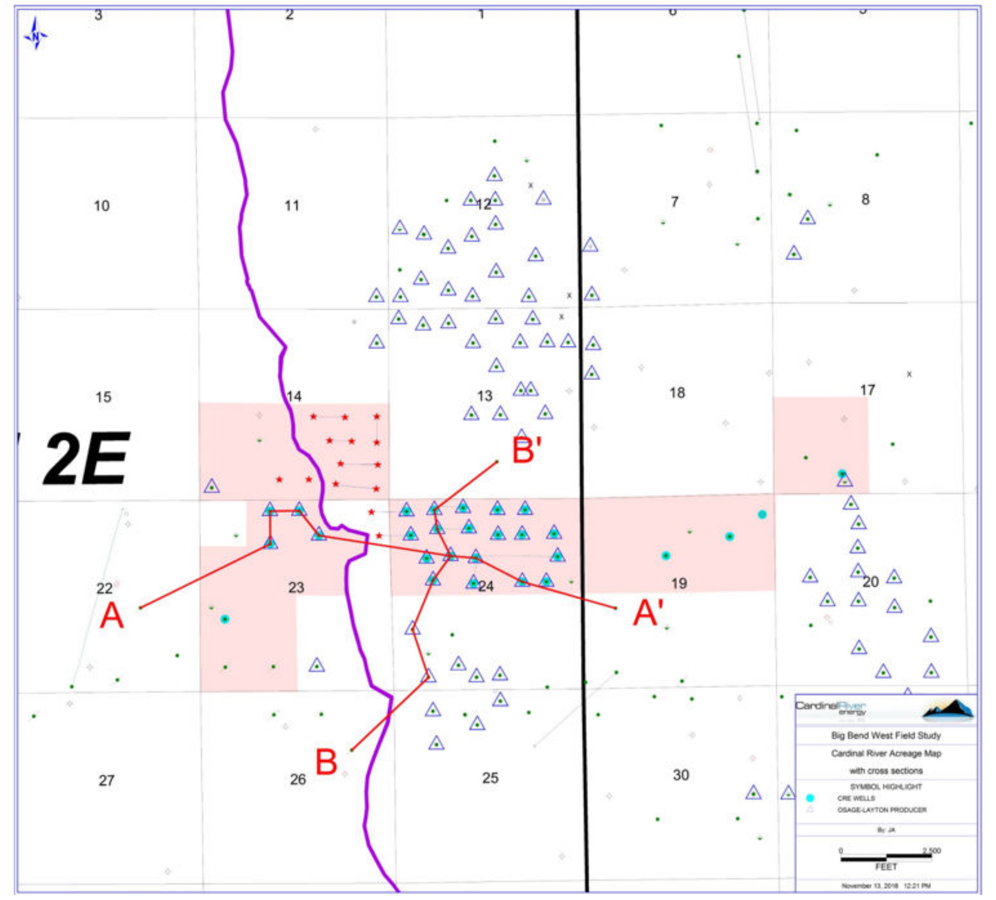
Plate 13



Big Bend West Field Stratigraphic Cross Section B-B'

Big Bend West Field Structural Cross Section B-B'

Plate 15



PETRA 11/13/2018 12:15:40 PM (Big Bend B-B' CSP)

VITA

Justin P. Allen

Candidate for the Degree of

Master of Science

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Society of Petrophysicists and Well Log Analysts (SPWLA)
Society for Sedimentary Geology (SPEM)
Tulsa Geological Society (TGS)