Identification of Producible and Bypassed Pay Oil Zones in the Smackover Formation by Using API Gravity Determined on Core Samples Together with Determination of Recoverable Oil Reserves through Pyrolysis Analysis

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Search and Discovery Article #42585 (2023)**
Posted June 22, 2023

*Adapted from extended abstract based on oral presentation given at 2023 GeoGulf, Houston, TX, 23-25 April
 DOI:10.1306/42585Maende2023

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Abstract

The HAWK's pyrolysis instrument's Petroleum Assessment Method (HAWK–PAM) was used to analyze cores of the Upper Jurassic Smackover Formation in the Little Cedar Creek Field, Conecuh sub-basin, Alabama, USA. The objective was determination of parameters for locating producible and bypassed oil zones. The Geological Survey of Alabama provided cores from eight wells. Two hundred thirteen core samples obtained from these cores at intervals of 5 to 10 ft, were analyzed using HAWK–PAM which, is a pyrolysis method whereby, through heating for 45 min over a 50 to 650°C range, five carbon number groupings are generated; C4–C5, C6–C10, C11–C19, C20–C36, and C37+. API gravity and maturity are determined too. After the pyrolysis run, measurement of CO and CO_2 to a maximum temperature of 750°C is done. Thus total organic carbon (TOC) is also determined. Core samples whose C4–C36 was ≥2 mgHC/g rock were computed for their API gravity and then grouped into perforated and not perforated (bypassed oil).

Results were: Permit 10,560, perforated zone not detected; Permit 14,181, API gravity, 23 and 18 (perforated); Permit 15,496–B, API gravity, 22, 18, 19, 21, and 17 (perforated); and Permit 13,472, API gravity, 16 (perforated), and 11 and 15 (bypassed).

Perforated and bypassed oil recoverable reserves were computed from the sum of C19 and C20–C23. TOC and ratios of C4–C36/TOC to non-generating organic carbon, C4–C36/C4–C37+, C4–C19/C20–C36 and maturity were similar for producible and bypassed oil zones. Five out of the eight wells are oil producers. API gravity values identified all the perforated zones in four out of these five wells and located bypassed oil zones in one of them. HAWK–PAM identifies and quantifies producible and bypassed oil zones in Smackover Formation in Little Cedar Creek Field and is also applicable to similar microbial carbonate ramp buildups.

Introduction

The HAWK's pyrolysis instrument's Petroleum Assessment Method (HAWK–PAM) (Maende et al., 2017) was used to analyze cores of the Upper Jurassic Smackover Formation in the Little Cedar Creek Field, Conecuh sub-basin, Alabama, USA. The objective was determination of parameters for locating producible and bypassed oil zones. The Geological Survey of Alabama provided Smackover Formation cores from eight wells that were drilled in Little Cedar Creek Field. The location of Little Cedar Creek Field together with the regional structural setting is shown in Figure 1. The Smackover Formation is Late Jurassic in age, constrained to the Oxfordian (Heydari et al., 1997). The Smackover producing trend discussed in this paper extends along the U.S. Gulf Coast spanning from Florida, Alabama, Mississippi, to Arkansas, bordering southeast Texas and centered around the ancestral Mississippi River, with depocenters in Conecuh and Manila sub-basins or embayments, as well as in the Mississippi Interior Salt Basin (Figure 1). These two embayments together with the salt basin formed by extensional tectonics during Early Triassic breakup of Pangea and are separated from each other and from the Gulf of Mexico proper by a series of structural highs.

The stratigraphy of the Smackover Formation is nicely illustrated as a continuum within the northern Gulf of Mexico's Late Triassic–Jurassic stratigraphic column (Figure 2) that is portrayed by Heydari et al. (1997). Triassic and Lower Jurassic strata are predominantly red shales and siltstones of the Eagle Mills Formation. Marine flooding of the Triassic–Lower Jurassic rift basins first occurred during the Middle Jurassic, perhaps through a passage in south-central Mexico that connected the ancestral Gulf of Mexico to the Pacific Ocean (Heydari et al., 1997). Upper Middle Jurassic (Bathonian-Callovian) depositional units include locally developed basal conglomerates, red clastics, and evaporites of the Werner anhydrite. Continued basinwide restriction resulted in deposition of a thick succession of the Louann Salt during the Callovian. Alluvial fan sandstones and conglomerates, wadi and interdune red beds, and eolian sandstones of the Norphlet Formation were deposited during relative sea level low stand. Marine deposition followed in the late Oxfordian, as Late Jurassic seas transgressed and reworked the upper most sandstones of the Norphlet Formation and promoted deposition of the Smackover carbonates. Smackover carbonates in turn were overlain by mixed evaporites, siliciclastics, and dolomites of the Buckner Formation, and then by a thick Kimmeridgian-Tithonian succession of marine, deltaic and fluvial silciclastics of the Haynesville Formation and Cotton Valley Group.

The Little Cedar Creek Field's location of the eight wells (Table 1) whose cores were sampled for this study is shown in Figure 3.

According to Haddad and Mancini (2013), the geologic history of the Little Cedar Creek Field is directly related to the evolution of the Conecuh Embayment and the Conecuh Ridge complex to the northwest and west and the Pensacola ridge to the southeast and east of this embayment (Figure 1). These Paleozoic ridges are associated with the Appalachian structural trend and were paleohighs at the time of Smackover deposition. These ridges served as barriers to ocean currents and wave energy, producing a protected and at times restricted embayment area near the Smackover shoreline in the northern part of the Conecuh Embayment area.

In this Conecuh Embayment, Smackover carbonates were deposited in an inner carbonate ramp setting, for the most part, under tranquil conditions in bays and lagoons subjected to periodic influxes of fresh-water, terrestrial plant material and terrigenous clay and silt (Haddad and Mancini, 2013).

In the Little Cedar Creek Field, Mancini et al. (2008) depicted that late Oxfordian Smackover deposition (Figure 4) began with a marine transgression resulting in the accumulation of subtidal lime mudstone and wackestone that disconformably overlie Norphlet alluvial and fluvial breccias, conglomerates, and sandstones. The development of microbial carbonate buildups occurred in the early part of this marine transgression with microbe nucleation on localized firm to hard surfaces associated with wackestone to packestones deposition. The microbial (thrombolite, having a peloidal clotted fabric) boundstone buildups exhibit a southwest to northeast trend in the Little Cedar Creek Field (Haddad and Mancini, 2013).

Kopaska-Merkel et al. (1994) reckoned that reservoirs of the Upper Jurassic Smackover Formation in Alabama are predominantly oolitic and pelletal dolostone and that they have been strongly affected by early cementation, dissolution of calcium carbonate allochems, and dolomitization. They avered that porosity evolution is controlled regionally by level of thermal exposure, mode of dolomitization, and proximity to the Wiggins arch (Figure 1). They postulated that movement of the Middle Jurassic Louann Salt (Figure 2), has strongly affected the structural development of southwest Alabama. Anhydrite layers that block vertical fluid movement formed on some early topographic highs that were created by halokinesis.

Kopaska-Merkel et al. (1994), stated that Louann Salt is the oldest Mesozoic unit that significantly affected Smackover Formation sedimentation in Alabama. The updip limit of the salt approximately coincides with the regional peripheral fault trend; the Louann is thin or absent over paleohighs. The Smackover Formation conformably overlies the Upper Jurassic Norphlet Formation (Figure 3), a predominantly continental siliciclastic deposit formed in an arid climate. The contact is commonly sharp but is locally gradational over an interval of a few feet or less. The Smackover Formation was deposited on a carbonate ramp in much of the Gulf Coast region but in southwest Alabama, a system of preexisting ridges and basins (Figure 1) influenced Smackover deposition.

Sassen and Moore (1988) portrayed the geologic setting of the Late Jurassic across Gulf of Mexico to be as shown in Figure 5. They avered that a major tensional graben system occurs along the updip limits of Upper Jurassic marine deposits from Texas to Florida and is known from west to east as the Mexia-Talco, South Arkansas, and Pickens-Gilbertown fault zones. This system is thought to be related to tensional forces caused by Upper Jurassic sediments gliding toward the adjacent salt basin as the sequences were tilted toward the basin during subsidence. Activity on these faults commenced during the Late Jurassic and extended into the Cretaceous. During the Late Jurassic, marine incursion formed a series of shallow marine embayments, the Manila to the north and the Conecuh to the south, which received an attenuated sequence of Louann/Werner evaporites and Smackover limestones.

Sassen and Moore (1988) analyzed rock samples from the Conecuh Embayment and assigned them a maturity range of 0.6–0.90% vitrinite reflectance (Ro) equivalent (Jarvie et al., 2001). Based on pyrolysis and TOC analysis of 81 Smackover Formation core samples ranging from depths of 5120 to 20,113 ft that Sassen and Moore (1988) retrieved, a summary of their analytical results shows that Tmax ranged from 422–595°C, whereas Ro equivalent ranged from 0.44–3.55% and averaged 1.00. S1 ranged from 0.06–3.19 mg HC/g rock and averaged 0.53 whereas S2 ranged from 0.06–10.11 mg HC/g rock with an average of 1.57. Total organic carbon (TOC) ranged from 0.28–4.05 wt. % and averaged 1.37, whereas hydrogen index (HI) ranged from 1–656 and averaged 112. The core samples were retrieved from the locations shown in Figure 6, spanning Florida, Alabama, and Mississippi. Sassen and Moore (1988) believed that the laminated lime mudstone facies of the lower Smackover Formation is the main source of hydrocarbons in the Smackover Formation.

Our portrayal of their maturity data of the Smackover Formation appears to show the regional maturity occurrence that is shown in Figure 6. Sassen and Moore (1988) suggested that source potential of the lower Smackover source facies is enhanced by effects of pressure solution that redistributed kerogen initially preserved during deposition. Pressure solution of carbonate rock concentrates insoluble rock components including minerals and organic matter along features, such as stylolites and pressure seams. Cores show that stylolites are abundant in the Smackover Formation. They determined that the mean TOC of 48 stylolites isolated from core samples was 10.3%, with individual values as high as 63.3%. The redistribution of source kerogen to form continuous organic phases along potential conduits for fluid movement may well increase the efficiency of hydrocarbon expulsion from source facies. Sassen and Moore (1988) were of the opinion that the lower Smackover is a regionally significant source rock and that the main factor controlling distribution and nature of hydrocarbons is, therefore, thermal maturity as demonstrated by the API gravity of hydrocarbons together with the equivalent maturity values of the various Gulf Coast fields that are shown in Table 2, whereby API gravity ranges from 30.3 to 62.7 for equivalent Ro's that range from 0.5 to 1.3, respectively. They avered that the typical signature for the hydrocarbons from upper Smackover Formation reservoirs (Table 2) are non-waxy chromatographic signatures indicative of an algal source.

In the Little Cedar Creek Field, the Smackover Formation ranges from 58 to 117 ft (18 to 36 m) thick according to Mancini et al. (2008), while reservoir thickness ranges from 4 to 43 ft (1 to 13 m), which causes seismic resolution issues, so operators in the Little Cedar Creek Field have developed the field based on a rigorous well coring program and without the use of extensive seismic data (Haddad and Mancini, 2013). The reservoir facies in Little Cedar Creek Field are interpreted to have accumulated in shallow subtidal water depths of approximately 10 ft (3 m) and in 3 mi (5 km) of the Late Jurassic (Oxfordian) Smackover paleo-shoreline in the eastern Gulf Coastal Plain, within an inner carbonate ramp setting (Mancini et al., 2008). In contrast to most other thrombolites identified in the Gulf Coastal Plain, these buildups did not grow directly on paleohighs associated with Paleozoic basement rocks. The petroleum trap at Little Cedar Creek Field is stratigraphic.

Methods

The Geological Survey of Alabama provided cores from eight wells drilled in the Little Cedar Creek Field (Figure 3) which, were subsampled at 5 to 10 ft (1.5 to 3 m) giving a total of 213 samples. The cores were then ground to a powder; about 70 mg of each, was analyzed on the HAWK Pyrolysis, TOC, and Carbonate Carbon instrument using the instrument's petroleum assessment method known as HAWK–PAM. HAWK–PAM is a pyrolysis method whereby, using helium as the carrier gas, a ramp rate of 25°C is utilized in heating for 45 min over a 50 to 650°C range, to generate five petroleum peaks corresponding to the occurrence of five carbon number groupings: C4–C5, C6–C10, C11–C19, C20–C36, and C37+. API gravity and maturity are determined too. Peak hydrocarbons generation from C37+ fraction gives Tmax maturity. After pyrolysis, air is used as a carrier gas for measurement of both CO and CO_2 to a maximum temperature of 750°C. Thus, TOC is also determined. Core samples whose sum of C4–C36 was ≥2 mg HC/g rock were computed for their API gravity and then grouped into perforated and not perforated (bypassed oil).

A derivation of the five HAWK–PAM pyrolysis peaks is used to predict API gravity. The correlation of API gravity derived from HAWK–PAM parameters with the API gravity measured in the Laboratory using the hydrometer method has a correlation coefficient of 0.95, as can be seen in Figure 7, from the results obtained when running HAWK–PAM on the oils that are listed in Table 3. In addition to prediction of API gravity on oils and extracts using HAWK–PAM derived parameters as outlined above, HAWK–PAM can also be used to predict API gravity on rock samples (drill cuttings, cores, and outcrops) directly based on the relationship between oils and extracts samples API gravity with those of rock samples as shown Figure 8.

Determination of recoverable oil reserves was done on the basis of restoring 80% of the C19 oil fraction (this was used to quantify the evaporative loss that occurs during drilling) to the C23 fraction. Odiachi et al. (2021) demonstrated that Eagle Ford Shale recoverable oil in 6 cycles of HuffnPuff CO_2 is only up to C23.

Results

Table 1 references the State of Alabama Oil and Gas Board permit numbers to well names. The HAWK–PAM results that were obtained for the 213 core samples that were sampled from the eight wells of the Little Cedar Creek Field are shown in Table 4. For each of these 213 samples, these results comprise of the pyrolysis determination of oil occurrence on the basis of five carbon number groupings in mg HC/g rock; C4–C5, C6–C10, C11–C19, C20–C36, and C37+. Maturity (Tmax C37+) which is measured as the temperature at which peak generation of the C37+ (kerogen plus any asphalt) component occurs, is shown in Table 4, only for the samples whose C37+ content either equals or exceeds 0.5 mg HC/g of rock and is therefore a valid source rock potential content for determining Tmax values. For each of the 213 core samples, the results in Table 4 also show the measured wt. % of generative organic carbon (GOC); this is derived from the measurement of the five carbon number groupings that are obtained during pyrolysis including both CO and CO_2 that is derived from organic matter break-down during pyrolysis.

Also shown in Table 4 is the measured wt. % of non-generative organic carbon (NGOC); this is derived from the measurement of both CO and CO_2 derived from the oxidation of the residual organic carbon present after the pyrolysis cycle is complete. The sum of GOC and NGOC provide the TOC wt. % value. The results of API gravity are shown for core samples whose sum of C4–C36 was ≥2 mg HC/g rock. HI values (C37+/TOC x 100) of the 213 core samples analyzed are also shown for those samples whose source potential values as shown by C37+ content either exceeds or equals 0.5 mg HC/g rock.

For the eight wells for which core samples were provided by the Geological Survey of Alabama, Table 5 shows API gravity from HAWK–PAM analysis on rock sample for the core samples whose sum of C11–C19 is ≥2 mg HC/g rock. Cores sampled from the eight wells were retrieved ~10 to 20 yr ago, evidently considerable loss of their oil content has occurred due to evaporation during storage; computation of this evaporative loss is unlikely to restore the whole sum of light oils that have been lost. In view of the foregoing, a present day HAWK–PAM predicted API gravity value of greater than 10 was deemed to be sufficient to be indicative of a producible zone that in real-time produced oil of API gravity of 30 to 45. Using this reasoning for API gravity prediction, all depth intervals (whose cores were analyzed in the eight wells) were used to determine the intervals at which HAWK–PAM predicted API gravity of at least 10 when their sum of C11–C19 is ≥2 mg HC/g rock.

After identifying depth intervals that were successfully perforated by the operator and actually produced oil, those depth intervals that attained a HAWK–PAM API gravity prediction value of greater than 10 but were not perforated by the operator were interpreted to be bypassed oil pay zones. One well fulfilled this criteria for identification of a bypassed oil pay zone—Permit 13,472, in which for the depths of 11,546.7, 11,554, and 11,559 ft, the HAWK–PAM API gravity was predicted to be 15.99, 11.01, and 14.62, respectively (Table 5). In this well, the perforated depth intervals from which oil was produced are 11,490–11,520 ft and 11,544–11,550 ft. Therefore, the depth interval of 11,554–11,559 ft in Permit 13,472 is interpreted to be a bypassed oil pay zone.

HAWK–PAM API gravity prediction for identifying a producible oil zone matched perforated zones from which oil has been produced in permits 15,496–B, 14,181, and 13,472.

The predicted API gravity was:

- 17.47–21.51 for the 11,102–11,112 ft perforated and produced interval in Permit 15,496–B,
- 18.01–23.21 in the 11,226–11,242 ft perforated and produced interval of Permit 14,181 and
- 15.99 for the 11,544–11,520 ft perforated and produced interval of Permit 13,472.

Table 5 shows the perforated zones from which oil and gas was produced from 7 out of the 8 wells that were sampled for this study and Table 5 also shows the bypassed oil pay zone in Permit 13,472. In addition, Table 5 shows recoverable oil reserves determined on the basis of restoring 80% of the C19 oil fraction (this was used to quantify the evaporative loss that occurs during drilling) to the C23 fraction.

Recoverable reserves ranges and (totals) in mg HC/g rock are:

- Permit 12,872: 0.28–0.59 (1.28),
- Permit 10,560: 0.26–1.18 (1.70),
- Permit 17,045-B: 0.20–0.37 (2.21),
- Permit 15,496-B: 0.37–3.07 (17.23),
- Permit 14,181: 0.01–4.80 (9.01),
- Permit 13,176: 0.24–0.26 (0.50), and
- Permit 13,472: 0.33–1.50 (7.59).

Table 5 also shows perforation dates, time frame of production, as well as both cumulative oil and gas production as per the year this was recorded by the State Oil and Gas Board of Alabama (SOGBA), on the Geological Survey of Alabama website (https://www.gsa.state.al.us/ogb/).

The southwestern tip of Little Cedar Creek Field is evidently the most mature part of this field as demonstrated by the Ro equivalent of 0.92–3.71% in Permit 10,560 (Figure 3 and Table 6), which is the only well that bestrides the oil window, condensate/wet gas, and dry gas zones. This agrees with the structure map of the Little Cedar Creek Field that Haddad and Mancini (2013) presented as having a depth of 11,600 ft to the southwest in the Permit 10,560 region while the northeastern tip of this field is the shallowest at 10,000 ft. The rest of the Little Cedar Creek Field is within the incipient to oil window range, as exemplified by the maturities of Ro equivalent of 0.78, 0.42–0.83, 0.49–0.76 and

0.53–0.69% at permits 12,872, 14,181, 15,496–B, and 17,045–B, respectively (Figure 3 and Table 6). For the analyzed core samples from Little Cedar Creek Field, TOC values range from 0.34 wt. % to 0.94 wt.% and average 0.63, while their Hydrogen Index values range from 57 to 201 and average 120, for the samples whose C37+ fraction is at least 0.5 mg HC/g rock (Table 6). The C37+ fraction that is at least 0.5 mg HC/g rock in the wells whose cores were analyzed has a range of 0.48 to 1.43, with Permit 15496–B having the highest (Figure 3). The HAWK–PAM TOC pyrograms for these samples that have a C37+ fraction of at least 0.5 mg HC/g rock are shown in Figure 9 and it is interesting to note that the C37+ pyrogram of the 11,780–11,790 ft in Permit 10,560 (Cedar Creek Land & Timber Co. 30–1) shows incomplete decomposition by the time a pyrolysis oven temperature of 650°C is reached, which is indicative of a difficult to break-down kerogen fraction that is most probably a type III terrestrial sourced component that infiltrated the type II marine source rock of the lower Smackover laminated mudstones that Sassen and Moore (1988) discussed.

HAWK–PAM pyrograms from the 12 depth intervals of Permit 13,472 cores indicate the presence of both primary and secondary cracking of the C37+ organic matter fraction (Figure 10). Note that this C37+ fraction can be either kerogen or asphalt.

Summary and Conclusions

The HAWK's pyrolysis instrument's Petroleum Assessment Method (HAWK–PAM) was used to analyze cores of the Upper Jurassic Smackover Formation in the Little Cedar Creek Field, Conecuh sub-basin, Alabama. The objective was determination of parameters for locating producible and bypassed oil zones. The Geological Survey of Alabama provided Smackover Formation cores from 8 wells that were drilled in Little Cedar Creek Field.

The Smackover Formation is Late Jurassic in age, constrained to the Oxfordian (Heydari et. al., 1997).The Smackover producing trend discussed in this paper extends along the U.S. Gulf Coast spanning from Florida, Alabama, Mississippi, to Arkansas, bordering southeast Texas and centered around the ancestral Mississippi River, with depocenters in Conecuh and Manila subbasins which are embayments, as well as in the Mississippi Interior Salt Basin (Figure 1).

In the Conecuh Embayment, Smackover carbonates were deposited in an inner carbonate ramp setting, for the most part (Haddad and Mancini, 2013).

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For the eight wells for which core samples were provided by the Geological Survey of Alabama, Table 5 shows API gravity from HAWK–PAM pyrolysis analysis on rock sample for the core samples whose sum of C11–C19 is ≥2 mg HC/g rock. All depth intervals (whose cores were analyzed in the eight wells) were used to determine the intervals at which HAWK–PAM predicted API gravity was at least 10 when their sum of C11–C19 is ≥2 mg HC/g rock. After identifying depth intervals that were successfully perforated by the operator and produced oil, those depth intervals that attained a HAWK–PAM API gravity prediction value of greater than 10 but were not perforated by the operator were interpreted to be bypassed oil pay zones. One well fulfilled these criteria for identification of a bypassed oil pay zone—Permit 13472, in which for the depths of 11,546.7, 11,554, and 11,559 ft, the HAWK–PAM, API gravity was predicted to be 15.99, 11.01, and 14.62, respectively (Table 5). In this well, the perforated depth intervals from which oil was produced are 11490–11520 ft and 11544–11550 ft. Therefore the depth interval of 11554–11559 ft in Permit 13,472 is interpreted to be a bypassed oil pay zone. HAWK–PAM API gravity prediction identifying a producible oil zone matched perforated zones from which oil has been produced in Permit 15,496-B, 14,181 and 13,472.

Recoverable reserves ranges and (totals) in mg HC/g rock are:

- Permit 12,872: 0.28–0.59 (1.28),
- Permit 10,560: 0.26–1.18 (1.70),
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HAWK–PAM pyrograms from the 12 depth intervals of Permit 13,472, whose cores were sampled, indicate presence of both primary and secondary cracking of the C37+ organic matter fraction in this well (Figure 10). Note that this C37+ fraction can be either kerogen or asphalt.

Acknowledgments

We are very grateful to the Geological Survey of Alabama for providing the cores that we used for this study. We wish to particularly thank Ms. Marcella McIntyre-Redden of the Energy Investigations Division of the Geological Survey of Alabama for availing to us the cores that we needed and also for going out of her way to help us with the core sampling. We are also thankful to Dorene West and Norman Rosen whose review of this paper greatly improved it.

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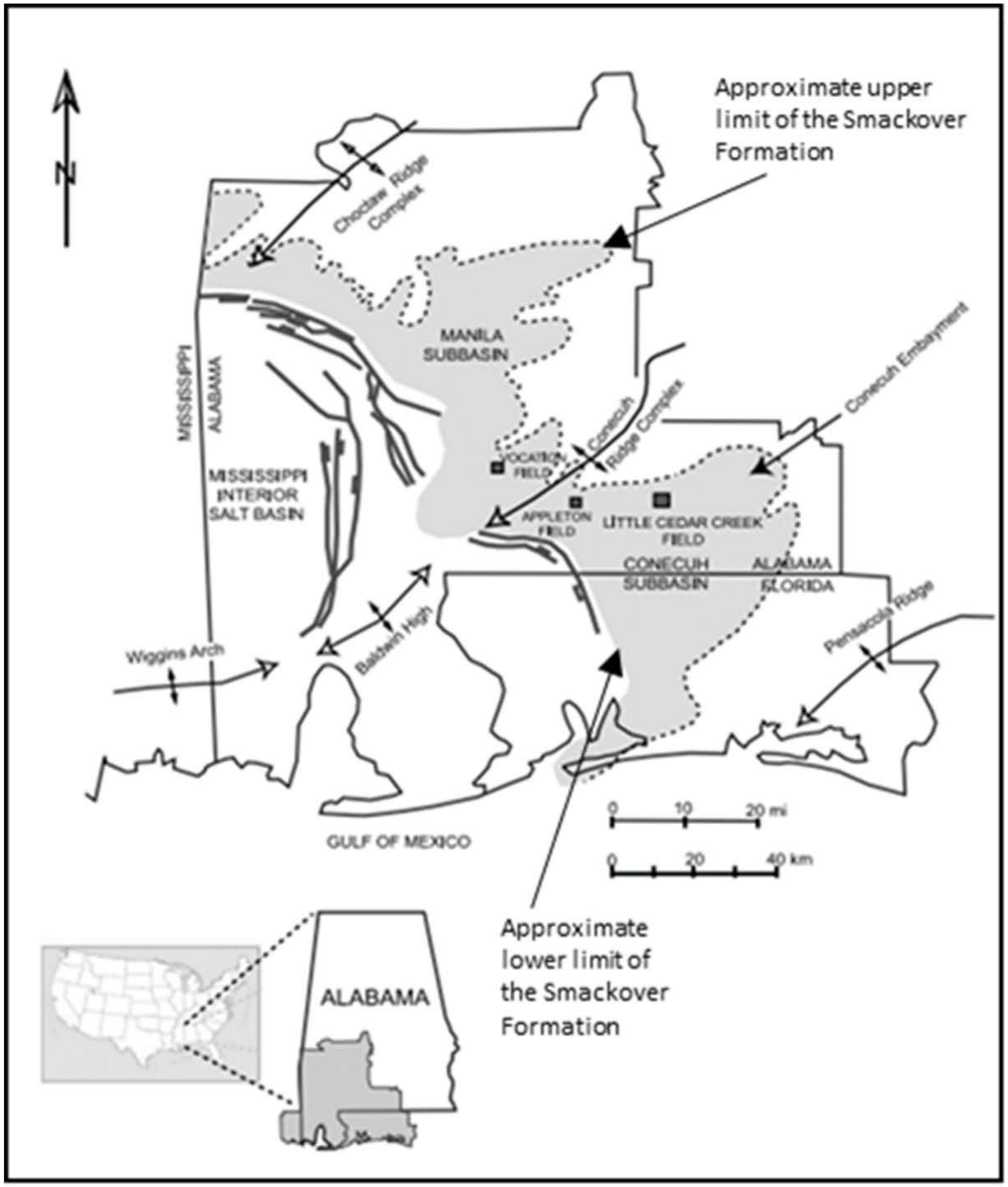


Figure 1. Location of Little Cedar Creek Field and regional structural setting (modified after Haddad and Mancini, 2013).

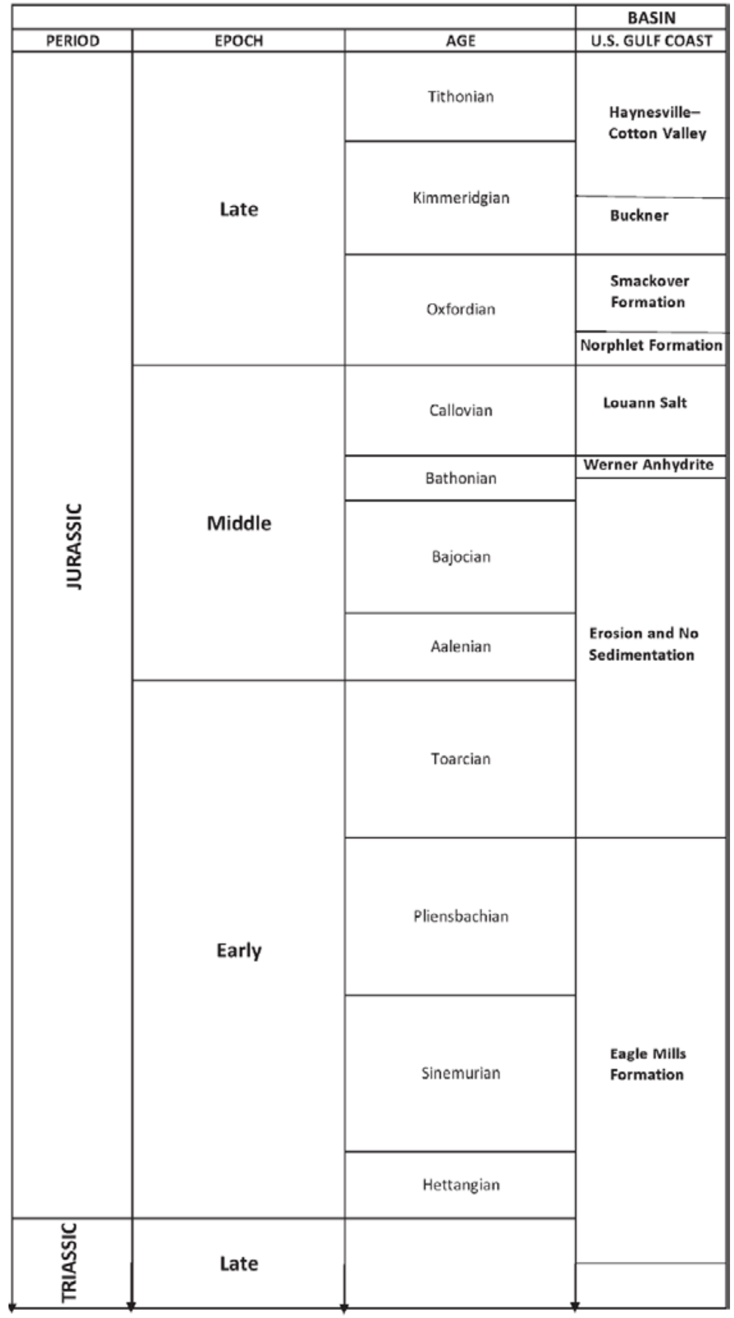


Figure 2. Smackover Formation illustrated as a continuum within the Late Triassic–Jurassic stratigraphic column of the Northern Gulf of Mexico (modified after Heydari et al. [1997]).

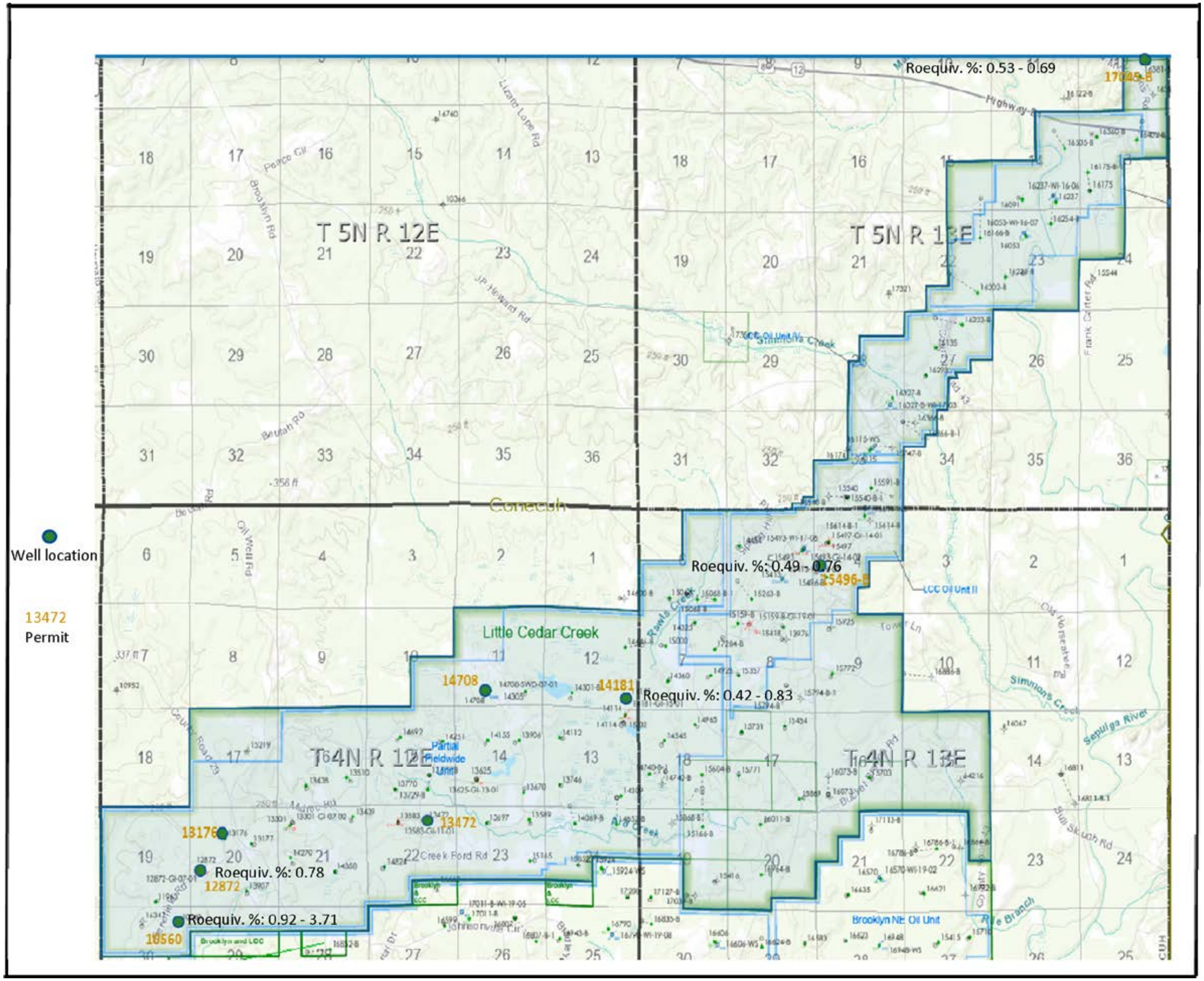


Figure 3. Little Cedar Creek Field showing locations of the eight wells that were sampled for this study (permits 10,560, 12,872, 13,176, 13,472, 14,708, 14,181, 15496–B and 17045–B). Table 1 lists permit numbers and well names. Data were obtained from the Geological Survey of Alabama website at https://www.gsa.state.al.us/ogb/.

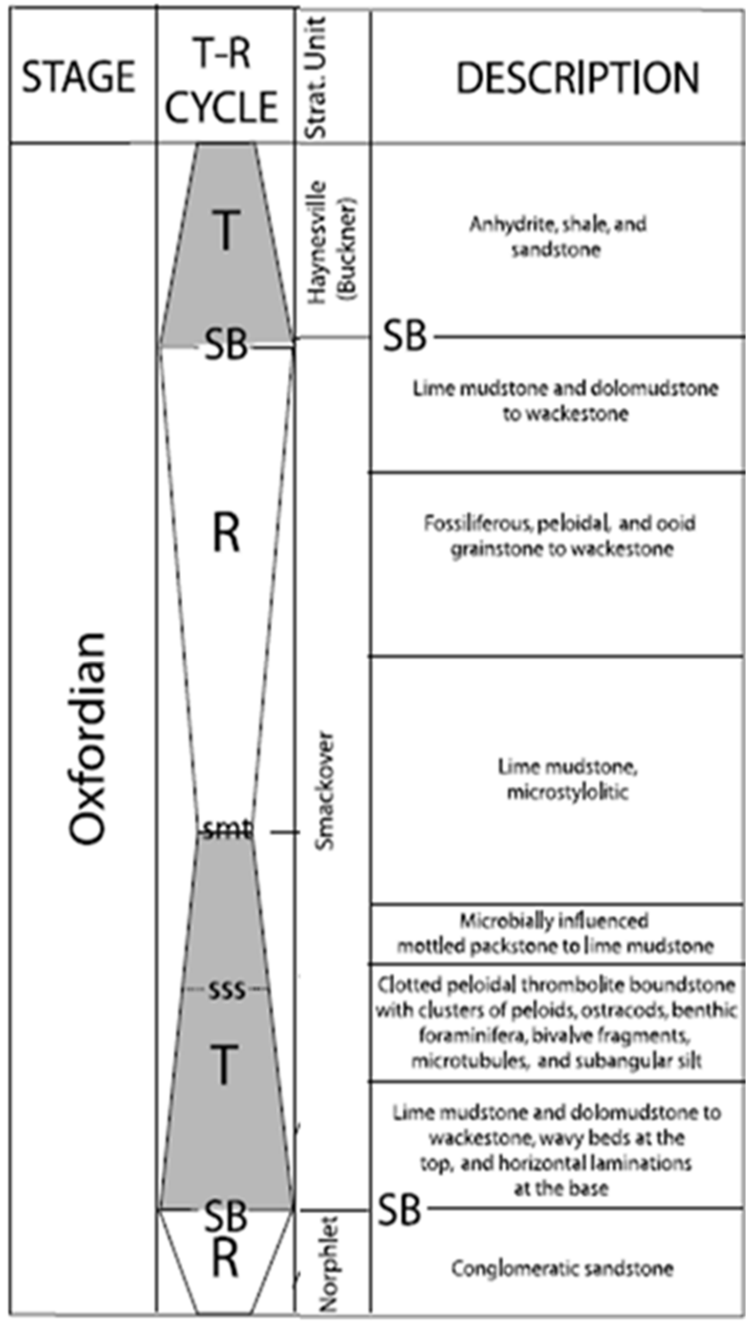


Figure 4. Stratigraphy of the Smackover Formation in Little Cedar Creek Field (from Mancini et al. [2008], reproduced with permission).

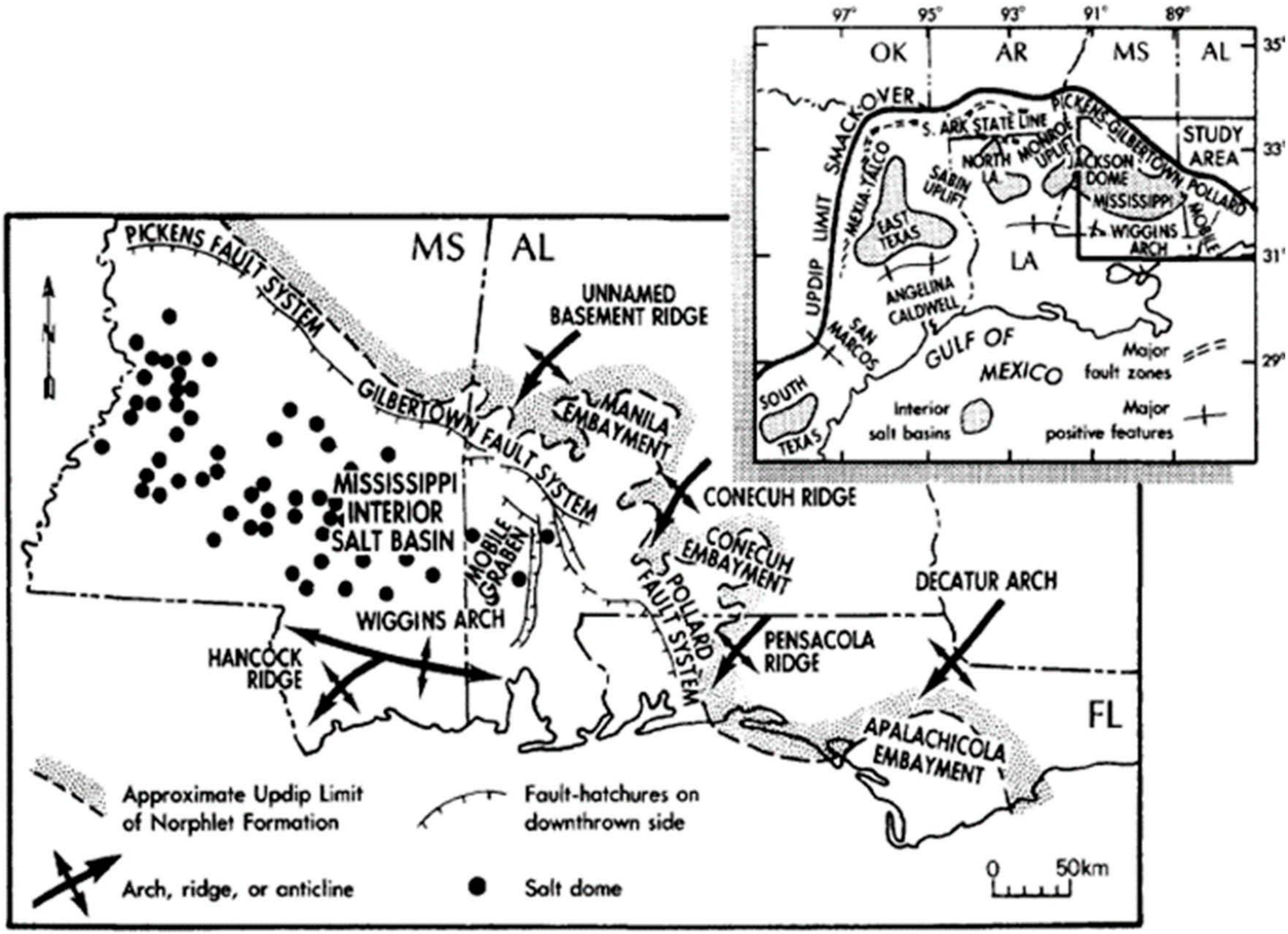


Figure 5. Geologic setting of Late Jurassic across Gulf of Mexico (from Sassen and Moore [1988], reproduced with permission).

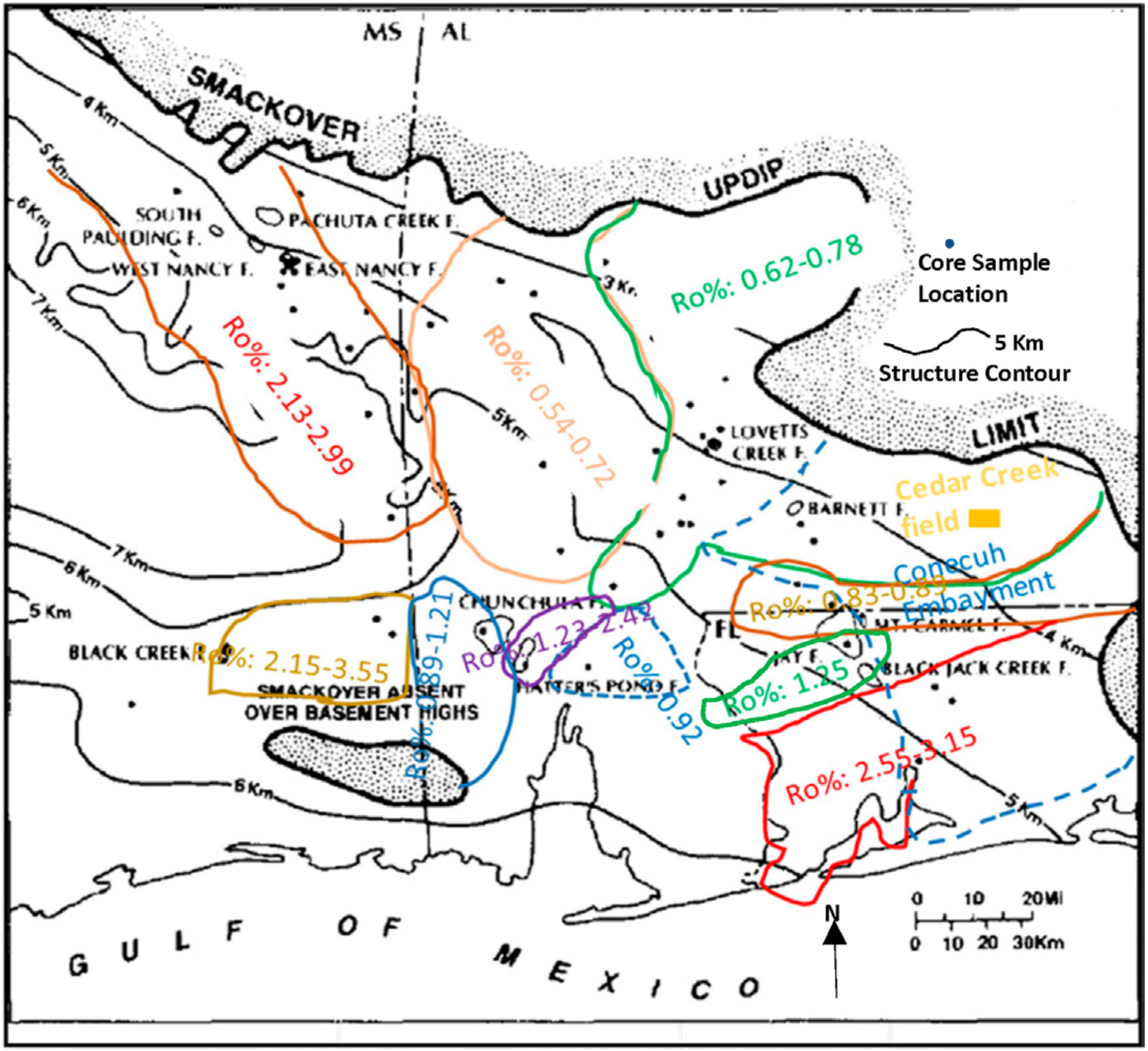


Figure 6. Location of cores sampled for pyrolysis and TOC analyses and Ro equivalent plus mapping of Ro equivalent (modified after Sassen and Moore [1988]).

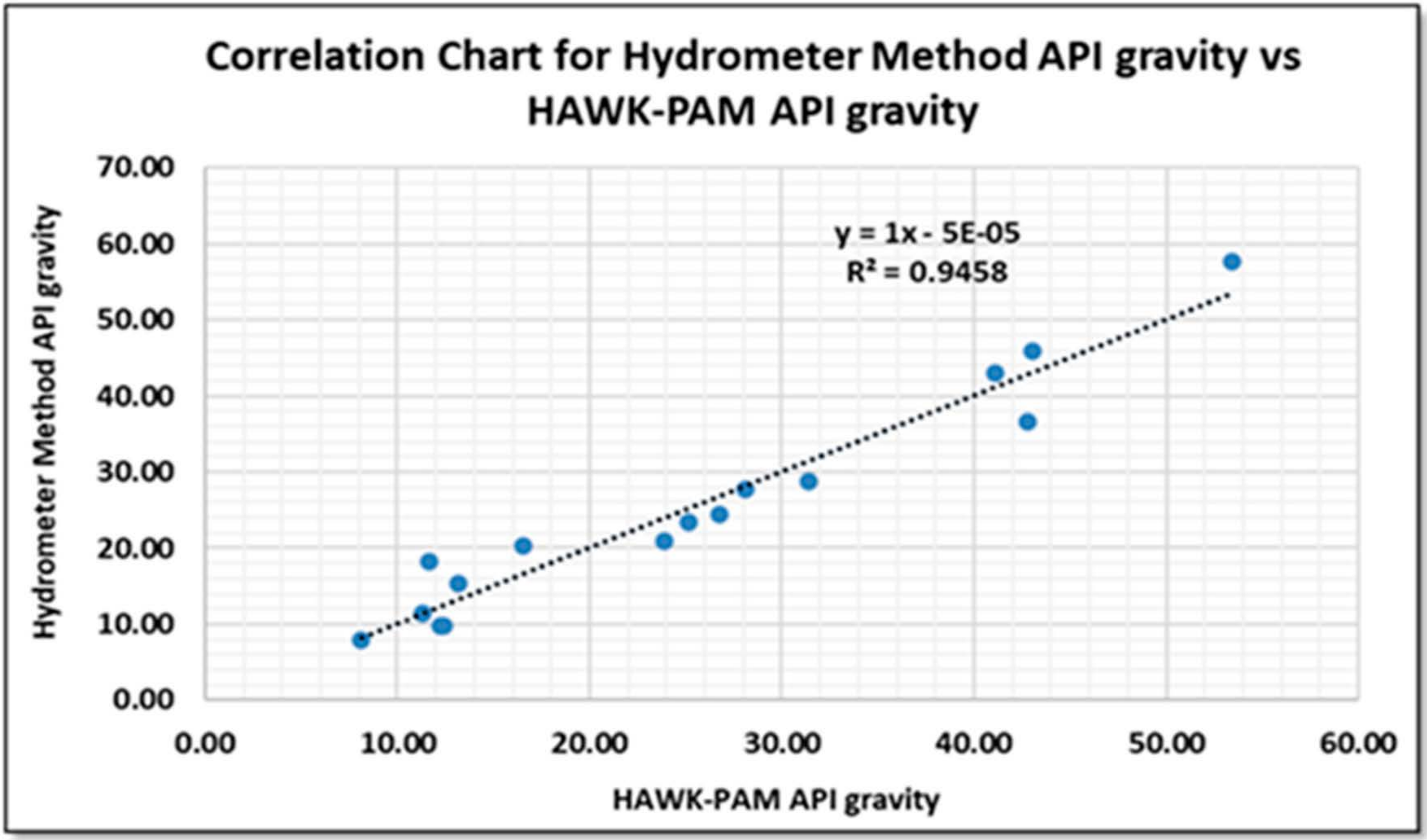


Figure 7. Correlation chart for hydrometer method API gravity vs. HAWK–PAM API gravity.

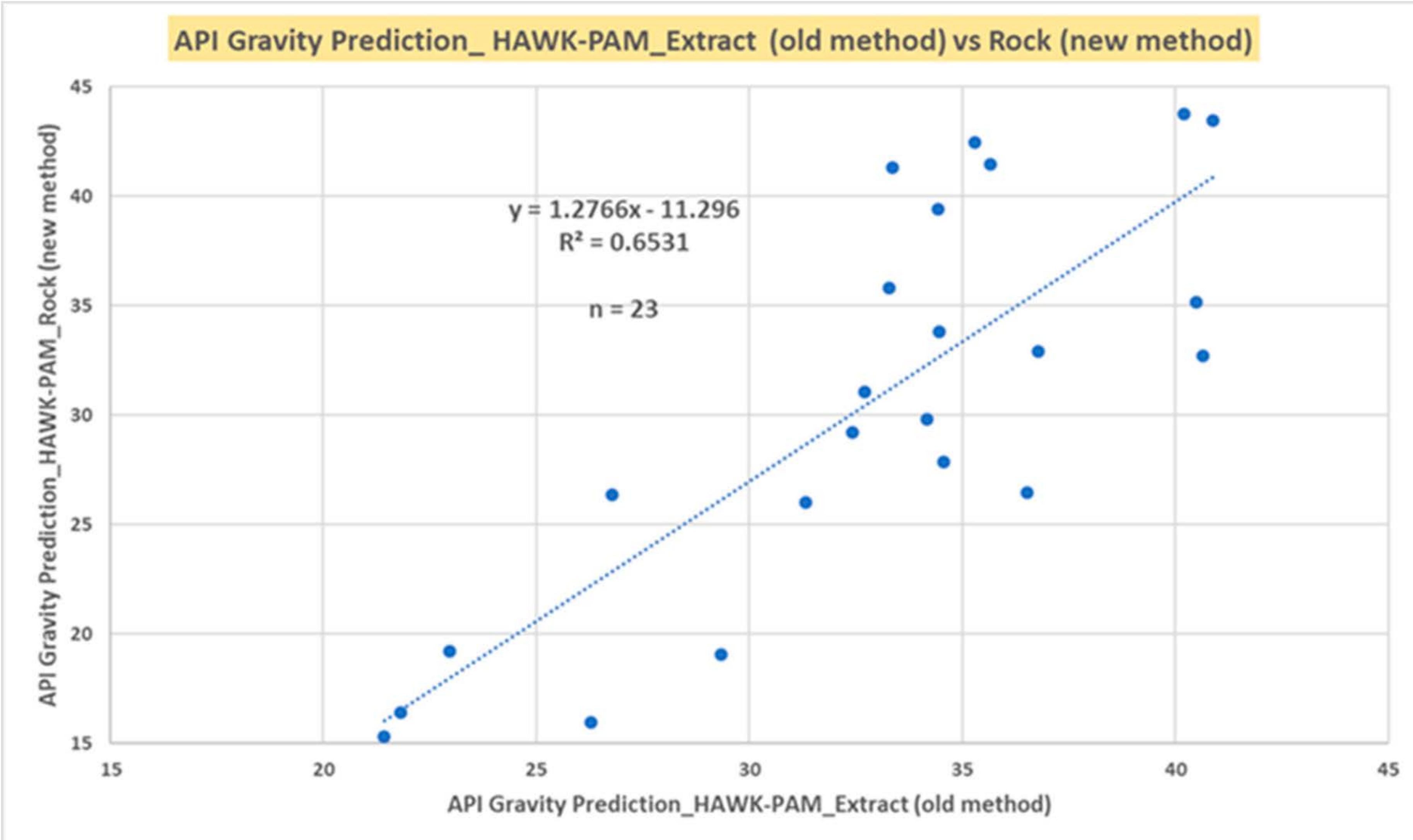


Figure 8. Basis for HAWK–PAM prediction of API gravity directly on rock samples (drill cuttings, cores, and outcrops).

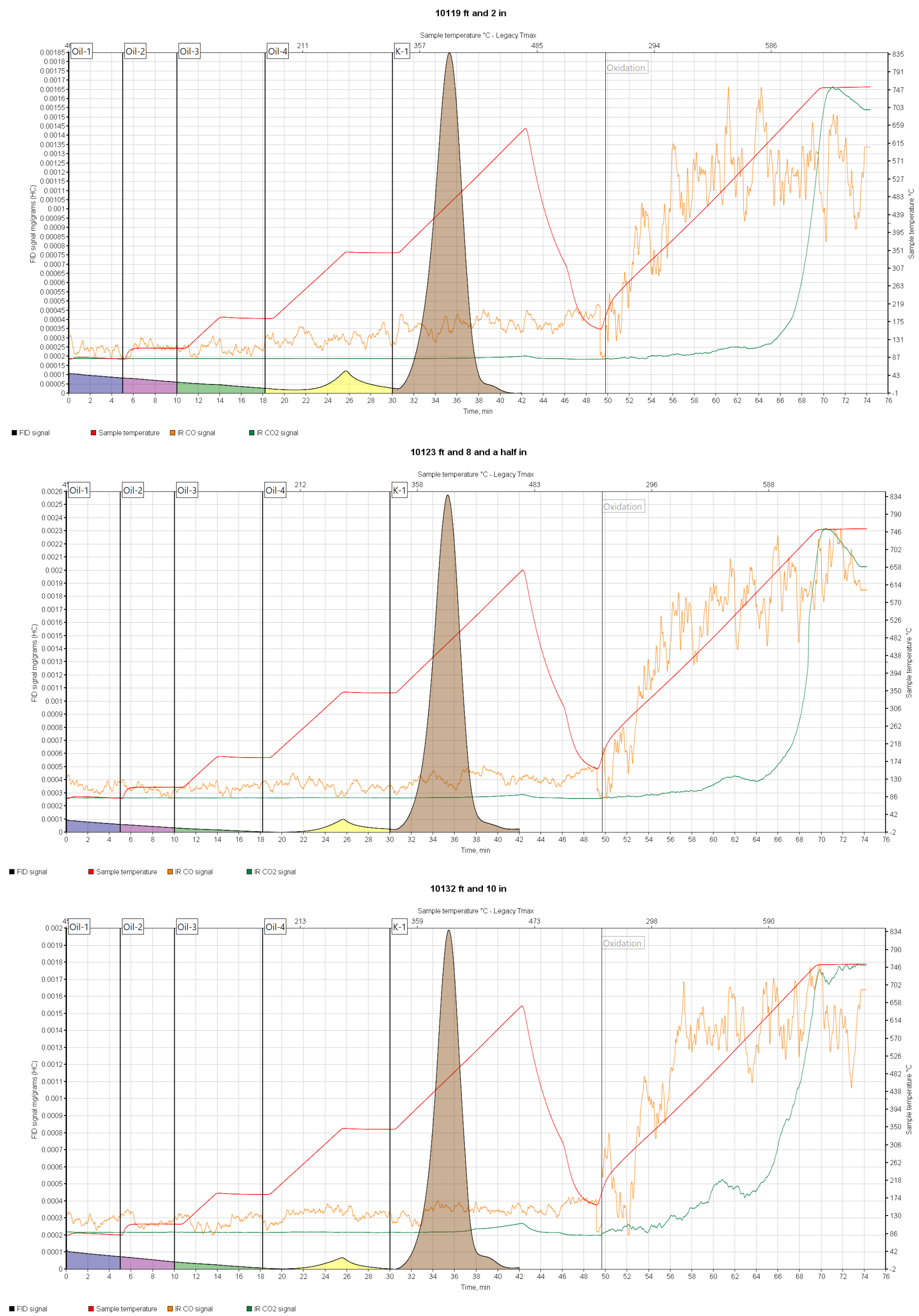
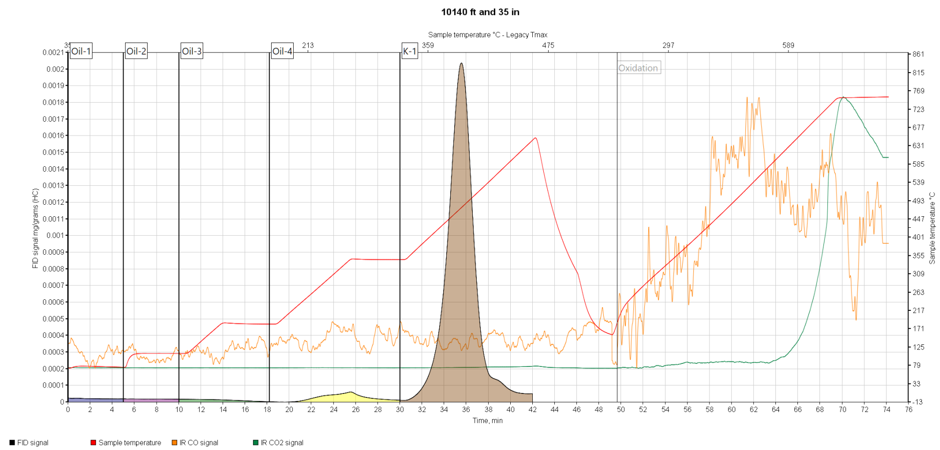
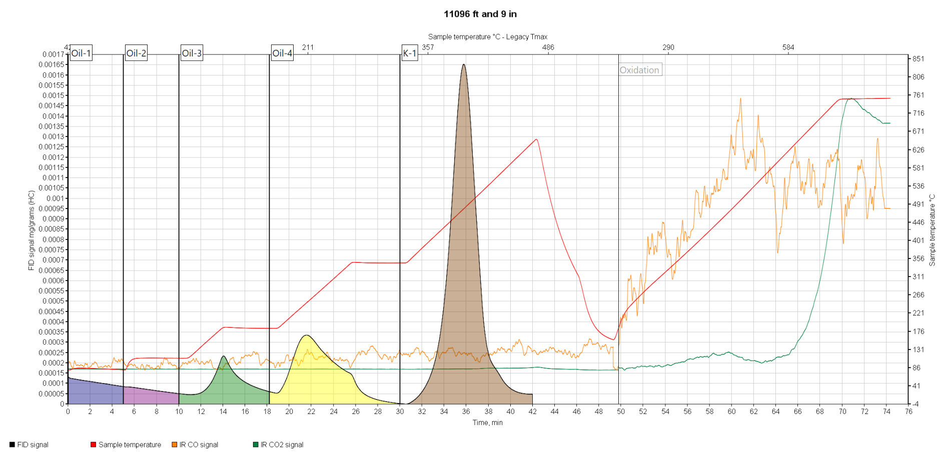


Figure 9. HAWK–PAM pyrograms for samples whose C37+ mg HC/g value equals or exceeds 0.5. Note: Each pyrogram shows HAWK–PAM plus TOC analysis for a single sample and displays the pyrolysis analysis flame ionization detection (FID) signal (black line) for the petroleum fractions, oil–1 (C4–C5), oil–2 (C6–C10), oil–3 (C11–C19), oil–4 (C20–C36), and K–1 (C37+, which maybe kerogen or asphalt). Also shown are the infrared spectroscopy CO_2 (green line) and CO (orange line) signals from both the pyrolysis and oxidation cycles together with the pertinent temperature (red line) at which the various petroleum fractions are retrieved.





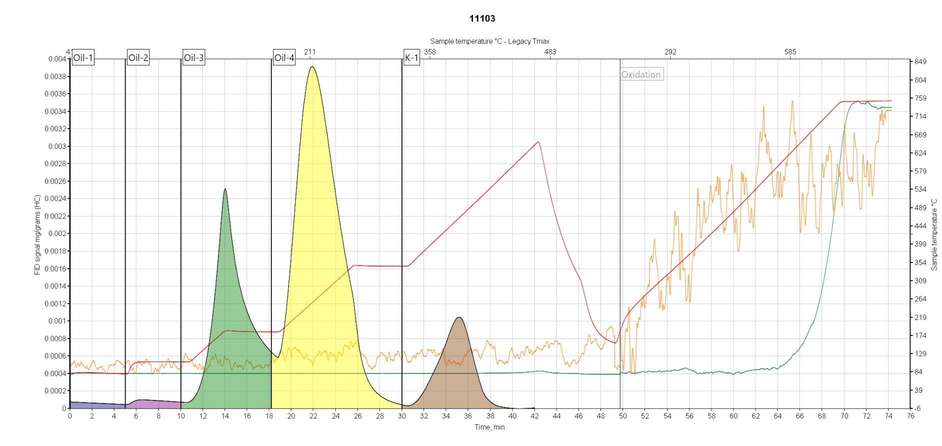


Figure 9, continued.

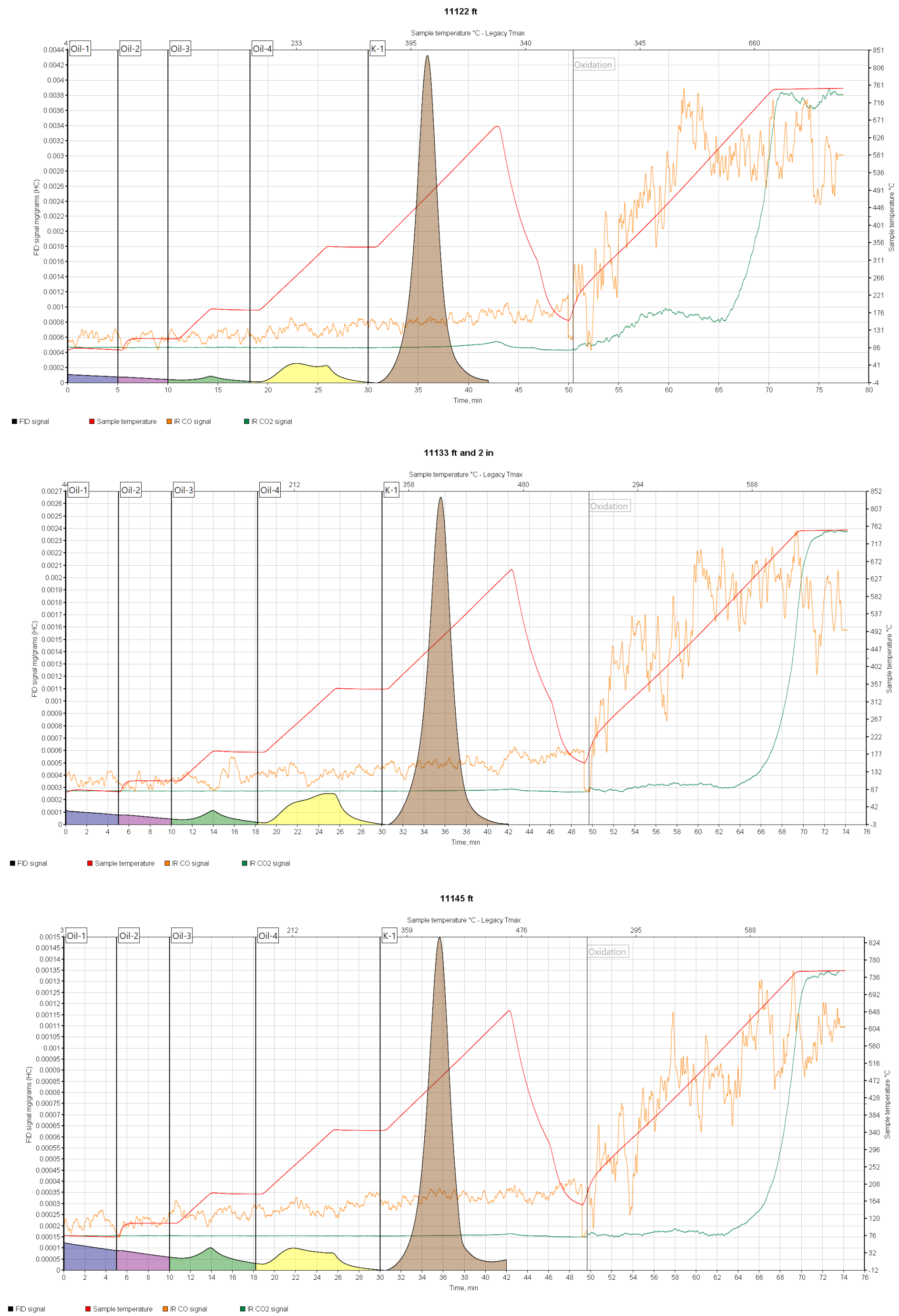


Figure 9, continued.

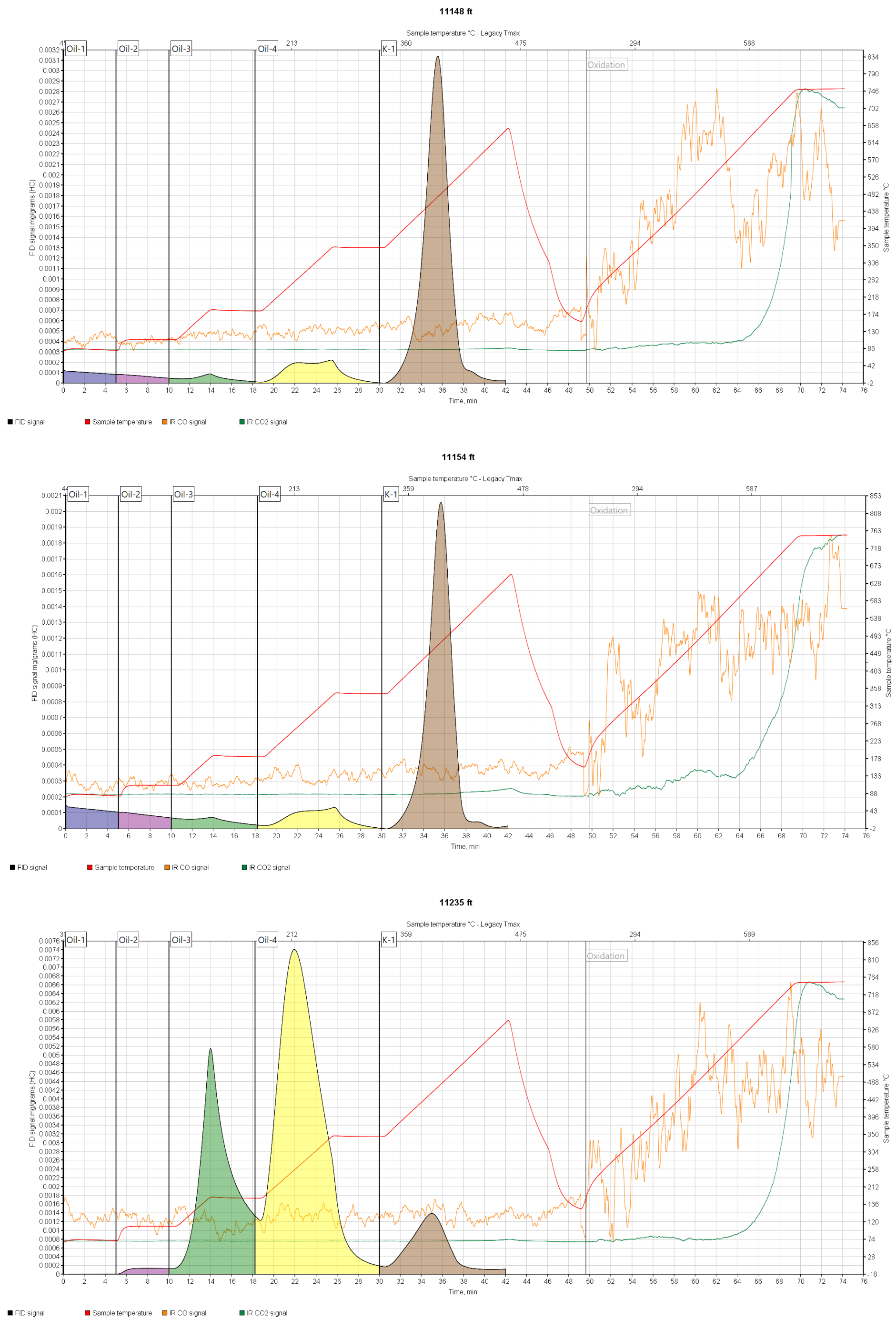


Figure 9, continued

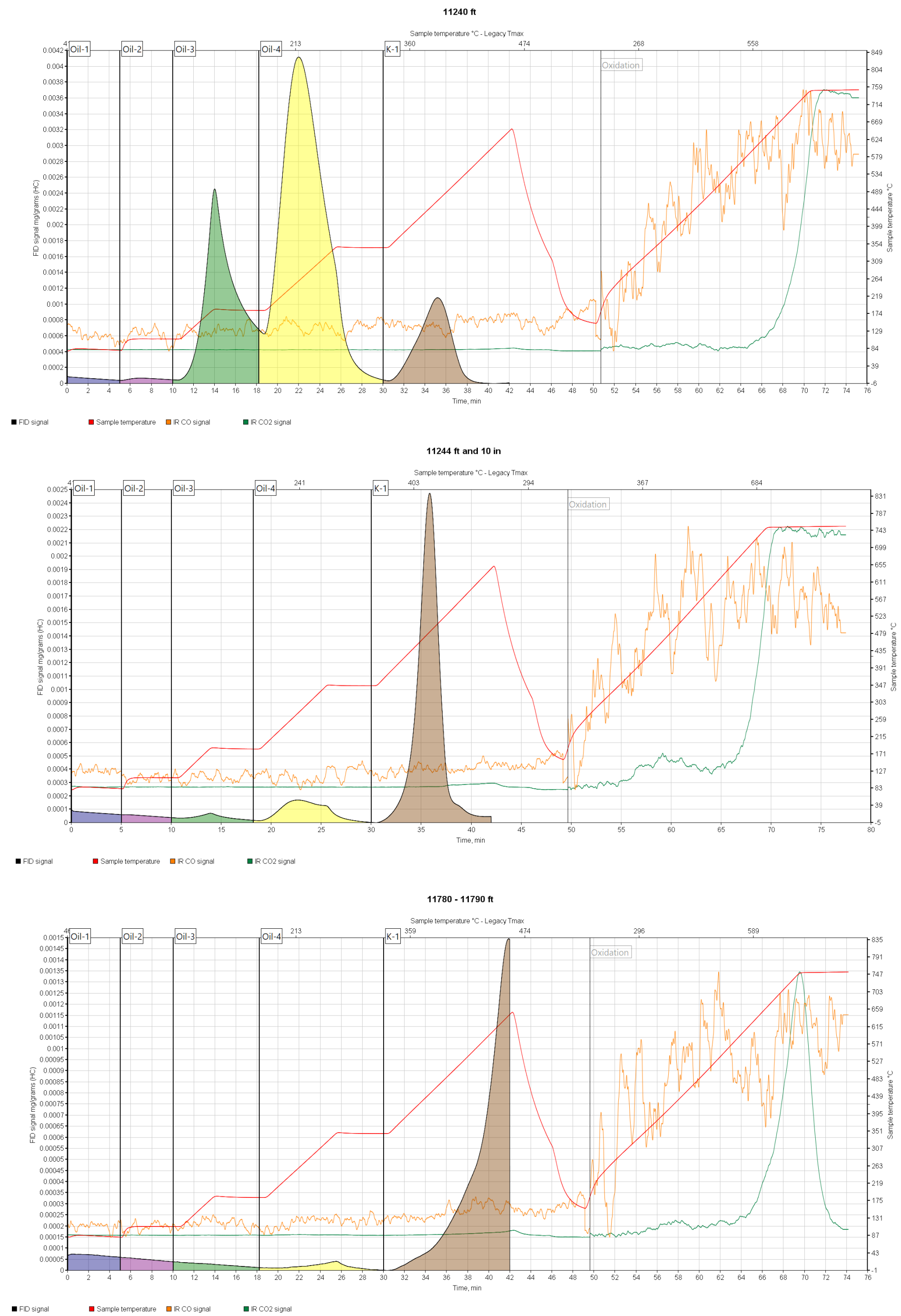


Figure 9, continued

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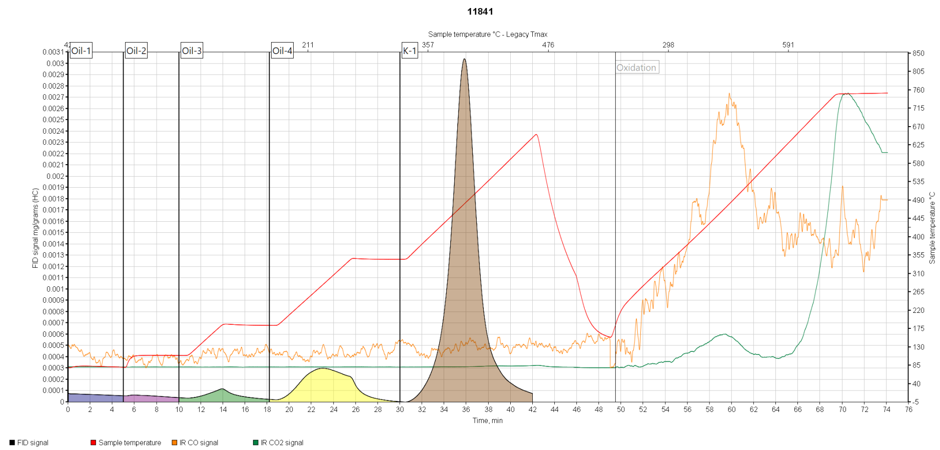


11880 - 11890 ft

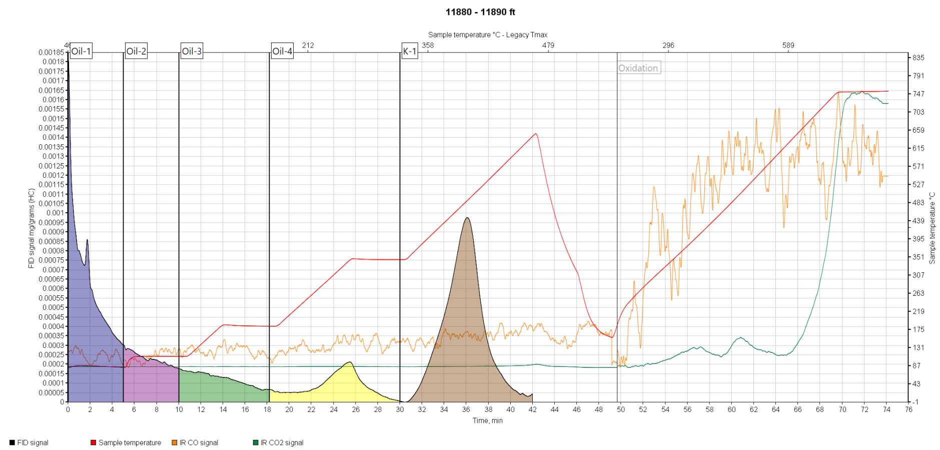


Figure 9, continued

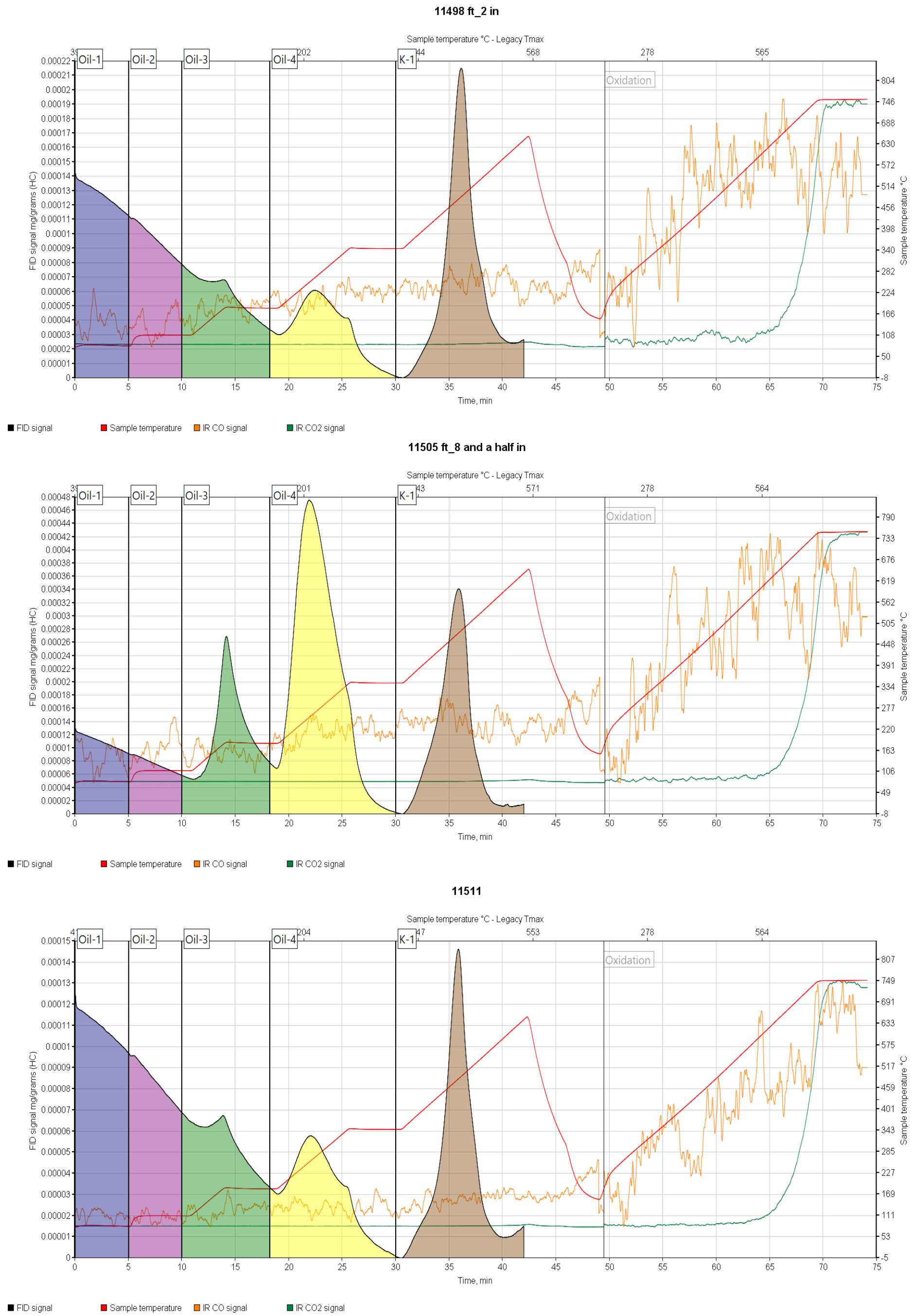
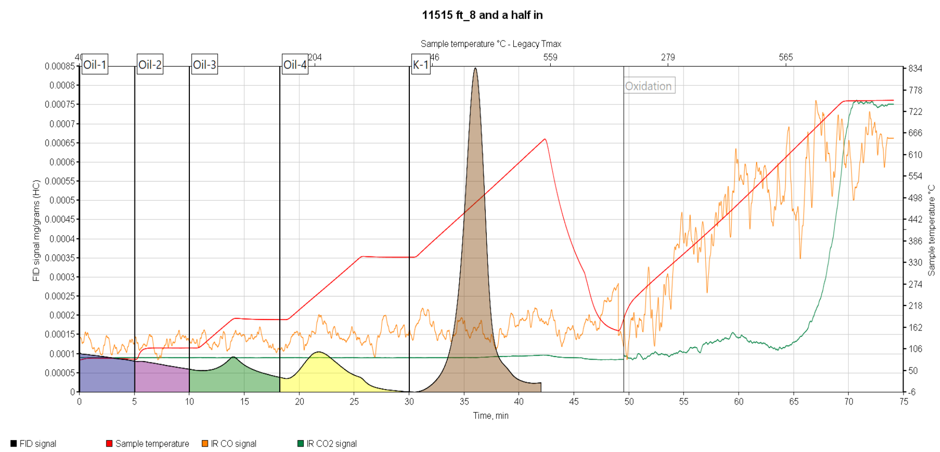
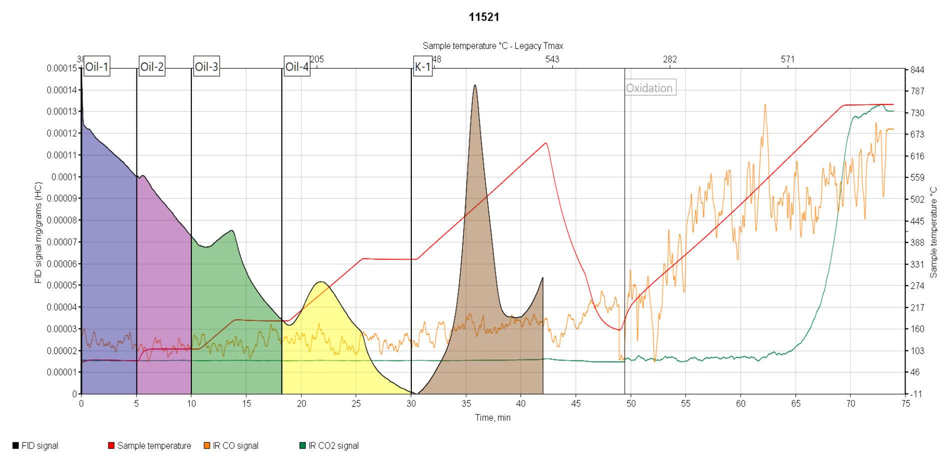


Figure 10. HAWK–PAM pyrograms from 12 depth intervals of Permit 13,472, Pugh 22–2 well. Note: Each pyrogram shows HAWK–PAM plus TOC analysis for a single sample and displays the pyrolysis analysis flame ionization detection (FID) signal (black line) for the petroleum fractions, oil–1 (C4–C5), oil–2 (C6–C10), oil–3 (C11–C19), oil–4 (C20–C36), and K–1 (C37+, which maybe kerogen or asphalt). Also shown are the infrared spectroscopy CO_2 (green line) and CO (orange line) signals from both the pyrolysis and oxidation cycles together with the pertinent temperature (red line) at which the various petroleum fractions are retrieved.





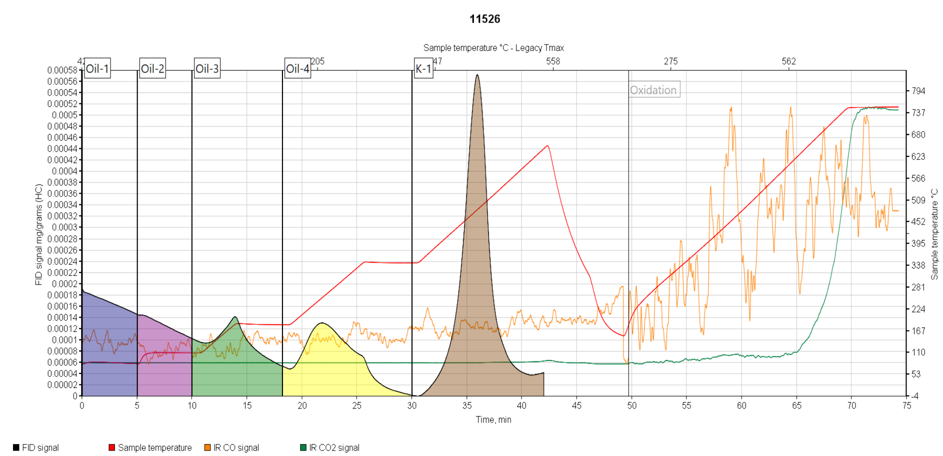


Figure 10, continued.

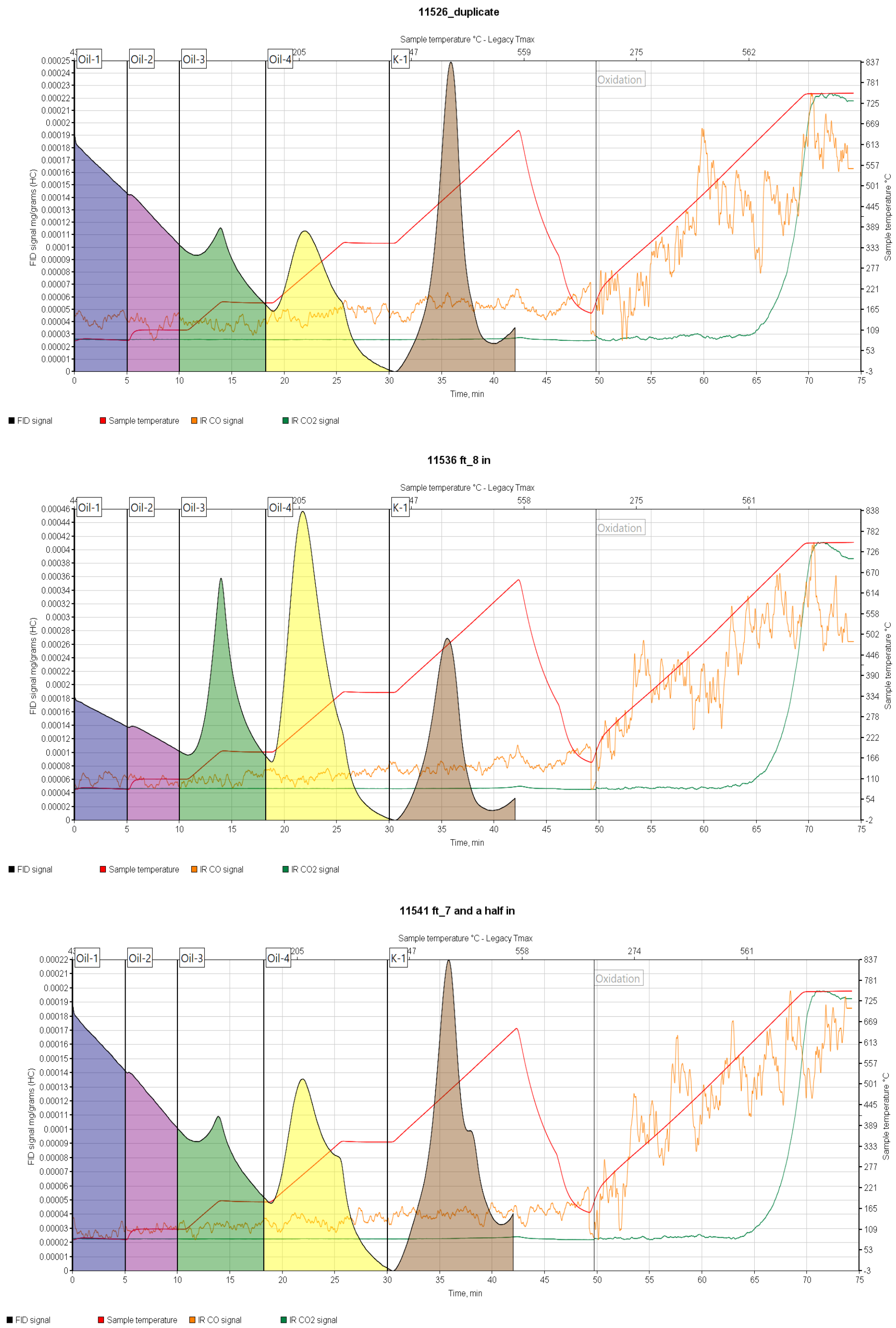


Figure 10, continued.

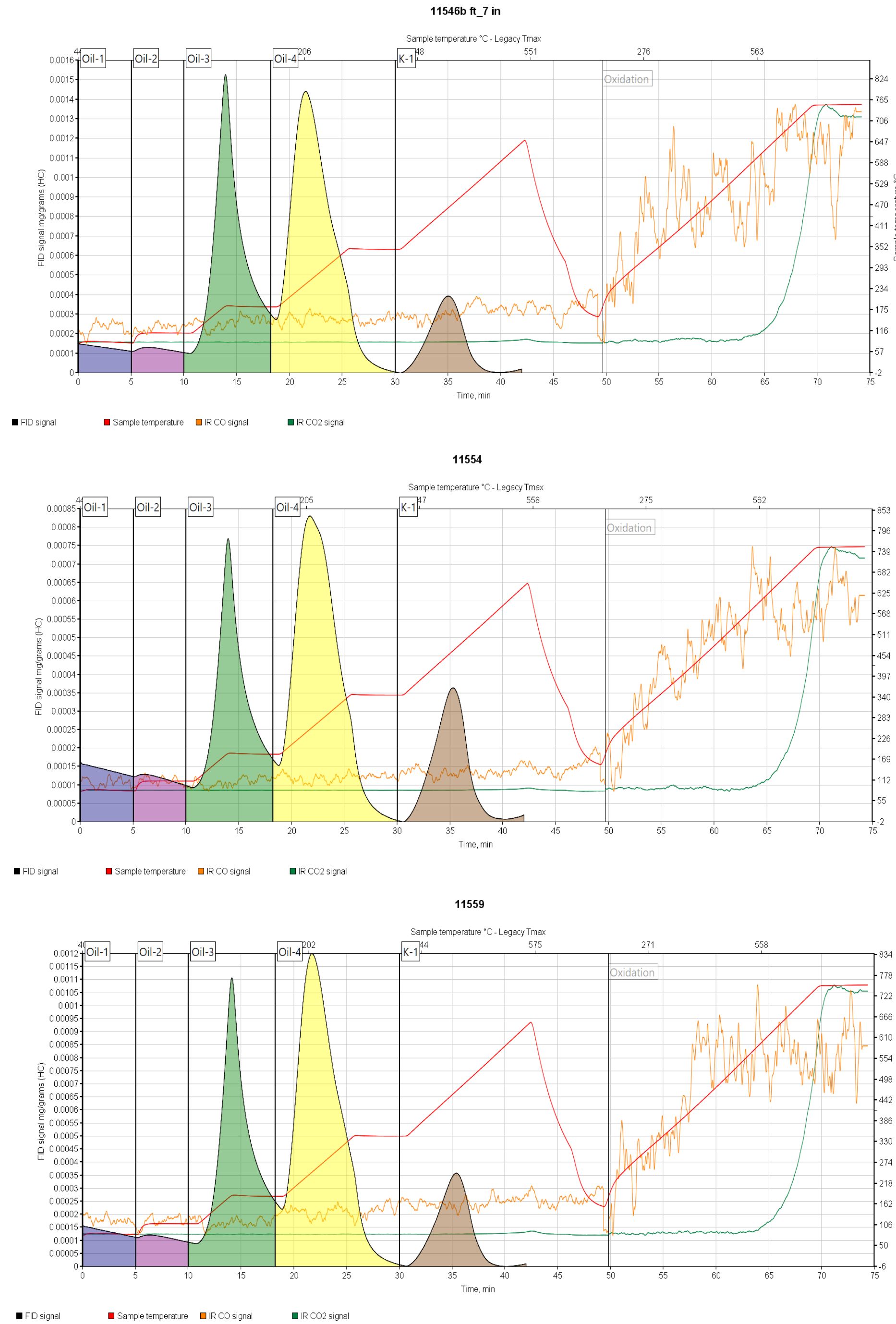


Figure 10, continued.

Permit	**Well Name**
10560	Cedar Creek Land & Timber Co. 30–1 #1
12872	Cedar Creek Land & Timber Co. 20–12
13176	McCreary 20–6L
13472	Pugh 22–2
14181	McCreary 12–16L
14708	Horton 11–14
15496-B	Craft Ralls 4–12 #1
17045-B	Craft-Barrow 12–8 #1

Table 1. Permit numbers and well names for the eight wells from the Little Cedar Creek Field sampled for this study.

Field	Location	Reservoir	°API	Depth (ft)	Equivalent R_o (%)
Pachuta Creek	Clarke County, Mississippi	upper Smackover	37.6	12,995	0.5
South Paulding	Jasper County, Mississippi	upper Smackover	37.9	14,563	0.6
West Nancy	Clarke County, Mississippi	upper Smackover	39.9	13,897	0.6
East Nancy	Clarke County, Mississippi	upper Smackover	39.5	13,596	0.6
Lovetts Creek	Monroe County, Alabama	upper Smackover	30.3	12,999	0.55
Barnett	Conecuh County, Alabama	upper Smackover	47.8	13,497	0.8
Mt. Carmel	Santa Rosa County, Florida	Norphlet Formation	44	15,295	0.8
Jay	Santa Rosa County, Florida	upper Smackover	53.6	15,495	1.1
Black Jack Creek	Santa Rosa County, Florida	upper Smackover	53.2	15,796	1.1
Chunchula	Mobile County, Alabama	upper Smackover	62.7	18,496	1.3
Hatters Pond	Mobile County, Alabama	upper Smackover		18,368	1.3

Table 2. API gravity and Ro equivalent in upper Smackover Formation fields and a Norphlet field (modified after Sassen and Moore, 1988).

Sample Description	API Gravity measured in Laboratory (Hydrometer method)	API Gravity Prediction from HAWK-PAM
Condensate	57.70	53.39
Black oil	9.72	12.26
Black oil	20.30	16.51
Black oil	28.70	31.42
Black oil	43.05	41.09
Black oil	45.96	43.05
Light-brown oil	36.57	42.77
Black oil	23.30	25.12
Black oil	24.50	26.79
Black oil	21.00	23.89
Black oil	27.70	28.12
Black oil	11.41	11.28
Black oil	9.72	12.41
Black oil	7.91	8.12

Table 3. List of oils on which API gravity was measured using both the hydrometer lab method and HAWK–PAM.

Formation	Permit	Sample ID	Depth	C4–C19	C20–C36	C37+	Tmax C37+	Roe	Sum	GOC	NGOC	TOC	API Grav.	HI
Smackover	13176	11748 ft and 9 in	11749	0.14	0.05	0.10			0.19	0.09	0.19	0.28		
Smackover	13176	11758 ft	11758	0.12	0.09	0.19			0.21	0.11	0.23	0.33		
Smackover	13176	11769 ft	11769	0.12	0.02	0.06			0.14	0.1	0.26	0.35		
Smackover	13176	11779 ft	11779	0.17	0.02	0.14			0.19	0.12	0.35	0.47		
Smackover	13176	11790 ft	11790	0.14	0.02	0.09			0.16	0.11	0.32	0.43		
Smackover	13176	11806 ft	11806	0.13	0.02	0.06			0.14	0.09	0.22	0.31		
Average						0.11			0.17	0.10	0.26	0.36		
Range						0.06–0.19			0.14–0.21	0.09–0.12	0.19–0.35	0.28–0.47		
Smackover	17045–B	10119 ft and 2 in	10119	0.14	0.06	0.70	427	0.53	0.21	0.16	0.38	0.54		128
Smackover	17045–B	10123 ft and 8 and a half in	10124	0.1	0.04	0.94	430	0.58	0.13	0.16	0.54	0.71		132
Smackover	17045–B	10126 ft and 8 and a half in	10127	0.13	0.03	0.25			0.16	0.12	0.35	0.46		
Smackover	17045–B	10132 ft and 10 in	10133	0.11	0.03	0.68	434	0.65	0.14	0.15	0.43	0.58		116
Smackover	17045–B	10136 ft	10136	0.12	0.03	0.23			0.15	0.11	0.25	0.35		
Smackover	17045–B	10140 ft and 35 in	10141	0.03	0.03	0.68	436	0.69	0.07	0.15	0.35	0.5		137
Smackover	17045–B	10144 ft and 7 in	10144	0.13	0.23	0.21			0.37	0.12	0.34	0.46		
Smackover	17045–B	10145 ft and 4 and a half in	10145	0.19	0.08	0.13			0.27	0.12	0.22	0.33		
Smackover	17045–B	10147 ft and 7 in	10148	0.2	0.06	0.09			0.26	0.13	0.27	0.39		
Smackover	17045–B	10149 ft and 1 in	10149	0.11	0.1	0.23			0.22	0.12	0.3	0.41		
Smackover	17045–B	10154 ft	10154	0.11	0.05	0.11			0.16	0.09	0.29	0.39		
Smackover	17045–B	10154 ft and 2 in	10154	0.14	0.1	0.17			0.25	0.11	0.26	0.37		
Smackover	17045–B	10163 ft	10163	0.1	0.09	0.32			0.2	0.12	0.29	0.41		
Smackover	17045–B	10163 ft and 5 in	10163	0.17	0.02	0.08			0.19	0.12	0.29	0.41		
Smackover	17045–B	10166 ft and 8 in	10167	0.14	0.02	0.08			0.16	0.11	0.41	0.51		
Smackover	17045–B	10171 ft and 10 in	10171	0.21	0.04	0.12			0.25	0.13	0.29	0.42		
Smackover	17045–B	10177 ft and 11 in	10177	0.14	0.02	0.07			0.16	0.09	0.33	0.42		
Average						0.30	432	0.61	0.20	0.12	0.33	0.45		128
Range						0.07–0.94	427–436	0.53–0.69	0.07–0.37	0.09–0.16	0.22–0.54	0.33–0.71		116–137

Table 4. HAWK–PAM results for 213 core samples retrieved from eight wells in the Little Cedar Creek Field. Depth in ft; C4–C19, C20–C36, and C37+ in mg HC/g rock; Tmax C37+ in °C, shown only for samples with C37+ ≥0.5 mg HC/g rock; Ro equivalent in % (Jarvie et al., 2001), shown only for samples with C37+ ≥0.5 mg HC/g rock; Sum of C4–C36 in mg HC/g rock; GOC (generative organic carbon) in wt. %; NGOC (non-generative organic carbon) in wt. %; TOC (total organic carbon) in wt. %; API gravity in degrees from HAWK–PAM analysis on rock sample; and HI (hydrogen index) (C37+/TOC x 100).

Table 4, continued.

Formation	Permit	Sample ID	Depth	C4–C19	C20–C36	C37+	Tmax C37+	Roe	Sum	GOC	NGOC	TOC	API Grav.	HI
Smackover	10560	11000–11010 ft	11010	0.1	0.09	0.06			0.2	0.11	0.22	0.33		
Smackover	10560	11010–11020 ft	11020	0.15	0.05	0.04			0.19	0.1	0.24	0.34		
Smackover	10560	11030–11040 ft	11040	0.55	0.08	0.03			0.62	0.16	0.27	0.43		
Smackover	10560	11040–11050 ft	11050	0.18	0.04	0.04			0.22	0.11	0.3	0.4		
Smackover	10560	11050–11060 ft	11060	0.14	0.03	0.04			0.18	0.09	0.28	0.37		
Smackover	10560	11060–11070 ft	11070	0.13	0.03	0.04			0.15	0.09	0.31	0.41		
Smackover	10560	11070–11080 ft	11080	0.15	0.04	0.03			0.19	0.11	0.28	0.39		
Smackover	10560	11080–11090 ft	11090	0.17	0.04	0.03			0.21	0.1	0.28	0.38		
Smackover	10560	11090–11100 ft	11100	0.14	0.08	0.04			0.22	0.1	0.26	0.36		
Smackover	10560	11100–11100 ft	11100	0.14	0.18	0.05			0.31	0.11	0.26	0.37		
Smackover	10560	11101 ft and 8 and a half in	11102	0.26	0.13	0.09			0.4	0.15	0.23	0.38		
Smackover	10560	11119–11120 ft	11120	0.16	0.04	0.03			0.2	0.1	0.23	0.33		
Smackover	10560	11120–11130 ft	11130	0.17	0.03	0.03			0.2	0.1	0.26	0.35		
Smackover	10560	11130–11140 ft	11140	0.17	0.04	0.03			0.2	0.11	0.3	0.41		
Smackover	10560	11140–11150 ft	11150	0.17	0.04	0.03			0.21	0.1	0.3	0.4		
Smackover	10560	11150–11160 ft	11160	0	0.02	0.05			0.03	0.08	0.25	0.33		
Smackover	10560	11160–11170 ft	11170	0.17	0.03	0.02			0.2	0.09	0.22	0.32		
Smackover	10560	11180–11190 ft	11190	0.17	0.03	0.02			0.19	0.11	0.25	0.36		
Smackover	10560	11190–11200 ft	11200	0.17	0.05	0.03			0.22	0.11	0.26	0.37		
Smackover	10560	11200–11210 ft	11210	0.17	0.05	0.03			0.22	0.11	0.27	0.38		
Smackover	10560	11210–11220 ft	11220	0.14	0.03	0.02			0.18	0.08	0.23	0.31		
Smackover	10560	11220–11230 ft	11230	0.16	0.03	0.08			0.19	0.1	0.35	0.45		
Smackover	10560	11230–11240 ft	11240	3.31	1.45	1.00			4.75	0.58	0.26	0.85	19.68	
Smackover	10560	11240–11250 ft	11250	1.14	0.42	0.18			1.55	0.23	0.29	0.52	17.89	
Smackover	10560	11250–11260 ft	11260	1.11	0.33	0.10			1.45	0.22	0.26	0.48	21.10	
Smackover	10560	11260–11270 ft	11270	0.56	0.22	0.10			0.78	0.14	0.18	0.31		
Smackover	10560	11270–11280 ft	11280	0.62	0.26	0.18			0.86	0.17	0.21	0.38		
Smackover	10560	11280–11290 ft	11290	0.49	0.17	0.11			0.66	0.14	0.3	0.44		
Smackover	10560	11290–11300 ft	11300	0.43	0.27	0.21			0.7	0.16	0.27	0.43		
Smackover	10560	11300–11310 ft	11310	0.45	0.35	0.28			0.8	0.18	0.3	0.49		
Smackover	10560	11310–11320 ft	11320	0.3	0.14	0.11			0.44	0.12	0.21	0.33		
Smackover	10560	11320–11330 ft	11330	0.37	0.17	0.18			0.54	0.14	0.25	0.39		
Smackover	10560	11330–11340 ft	11340	0.24	0.09	0.07			0.34	0.11	0.28	0.39		
Smackover	10560	11340–11350 ft	11350	0.3	0.15	0.25			0.45	0.13	0.4	0.54		
Smackover	10560	11350–11360 ft	11360	1.19	0.08	0.10			1.27	0.21	0.3	0.51	20.51	

Table 4, continued.

Formation	Permit	Sample ID	Depth	C4–C19	C20–C36	C37+	Tmax C37+	Roe	Sum	GOC	NGOC	TOC	API Grav.	HI
Smackover	10560	11360–11370 ft	11370	0.3	0.08	0.04			0.39	0.13	0.27	0.41		
Smackover	10560	11370–11380 ft	11380	0.34	0.19	0.16			0.52	0.14	0.23	0.36		
Smackover	10560	11380–11390 ft	11390	0.22	0.07	0.07			0.29	0.12	0.34	0.45		
Smackover	10560	11390–11400 ft	11400	0.26	0.12	0.08			0.39	0.12	0.21	0.33		
Smackover	10560	11400–11410 ft	11410	0.25	0.13	0.11			0.38	0.11	0.24	0.35		
Smackover	10560	11410–11420 ft	11420	0.4	0.06	0.06			0.47	0.13	0.33	0.46		
Smackover	10560	11420–11430 ft	11430	0.37	0.12	0.06			0.49	0.12	0.28	0.39		
Smackover	10560	11430–11440 ft	11440	0.28	0.1	0.08			0.39	0.13	0.24	0.37		
Smackover	10560	11440–11450 ft	11450	0.38	0.08	0.05			0.46	0.12	0.28	0.4		
Smackover	10560	11460–11470 ft	11470	0.22	0.09	0.09			0.31	0.1	0.31	0.41		
Smackover	10560	11560–11480 ft	11480	0.27	0.1	0.08			0.37	0.1	0.28	0.38		
Smackover	10560	11480–11490 ft	11490	0.31	0.06	0.04			0.36	0.11	0.19	0.3		
Smackover	10560	11490–11500 ft	11500	0.26	0.14	0.09			0.4	0.13	0.27	0.39		
Smackover	10560	11500–11510 ft	11510	0.31	0.2	0.11			0.5	0.14	0.25	0.38		
Smackover	10560	11510–11520 ft	11520	0.28	0.07	0.02			0.35	0.12	0.21	0.33		
Smackover	10560	11520–11530 ft	11530	0.41	0.18	0.14			0.59	0.13	0.3	0.43		
Smackover	10560	11530–11540 ft	11540	0.4	0.16	0.12			0.56	0.13	0.21	0.34		
Smackover	10560	11540–11550 ft	11550	0.43	0.17	0.19			0.6	0.14	0.28	0.42		
Smackover	10560	11550–11560 ft	11560	0.35	0.16	0.11			0.51	0.14	0.25	0.39		
Smackover	10560	11570–11580 ft	11580	0.39	0.16	0.10			0.54	0.14	0.33	0.47		
Smackover	10560	11580–11590 ft	11590	0.4	0.16	0.12			0.55	0.14	0.26	0.4		
Smackover	10560	11590–11600 ft	11600	0.33	0.11	0.10			0.44	0.14	0.31	0.45		
Smackover	10560	11600–11610 ft	11610	0.31	0.3	0.35			0.61	0.15	0.23	0.38		
Smackover	10560	11610–11620 ft	11620	0.25	0.07	0.03			0.32	0.1	0.26	0.36		
Smackover	10560	11620–11630 ft	11630	0.17	0.05	0.03			0.22	0.1	0.25	0.35		
Smackover	10560	11630–11640 ft	11640	0.17	0.04	0.02			0.21	0.09	0.26	0.35		
Smackover	10560	11640–11650 ft	11650	0.18	0.05	0.02			0.23	0.11	0.23	0.34		
Smackover	10560	11650–11660 ft	11660	0.17	0.03	0.16			0.2	0.11	0.23	0.34		
Smackover	10560	11660–11670 ft	11670	0.13	0.04	0.03			0.18	0.08	0.2	0.28		
Smackover	10560	11670–11680 ft	11680	0.16	0.04	0.05			0.2	0.09	0.24	0.33		
Smackover	10560	11680–11690 ft	11690	0.17	0.04	0.05			0.21	0.11	0.29	0.4		
Smackover	10560	11690–11700 ft	11700	0.15	0.06	0.06			0.21	0.1	0.21	0.31		
Smackover	10560	11710–11720 ft	11720	0.45	0.06	0.03			0.51	0.15	0.2	0.35		
Smackover	10560	11720–11730 ft	11730	0.15	0.03	0.05			0.18	0.1	0.27	0.37		

Table 4, continued.

Formation	Permit	Sample ID	Depth	C4–C19	C20–C36	C37+	Tmax C37+	Roe	Sum	GOC	NGOC	TOC	API Grav.	HI
Smackover	10560	11730–11740 ft	11740	0.13	0.03	0.04			0.16	0.08	0.22	0.3		
Smackover	10560	11740–11750 ft	11750	0.14	0.03	0.08			0.16	0.1	0.22	0.32		
Smackover	10560	11750–11760 ft	11760	0.15	0.03	0.06			0.18	0.1	0.22	0.33		
Smackover	10560	11760–11770 ft	11770	0.14	0.03	0.13			0.17	0.1	0.29	0.4		
Smackover	10560	11770–11780 ft	11780	0.15	0.03	0.06			0.18	0.1	0.25	0.35		
Smackover	10560	11780–11790 ft	11790	0.1	0.02	0.52			0.12	0.11	0.23	0.34		
Smackover	10560	11790–11800 ft	11800	0.13	0.05	0.09			0.17	0.11	0.29	0.4		
Smackover	10560	11800–11810 ft	11810	0.14	0.04	0.09			0.17	0.1	0.29	0.39		
Smackover	10560	11810–11820 ft	11820	0.12	0.04	0.24			0.16	0.12	0.49	0.61		
Smackover	10560	11820–11830 ft	11830	0.12	0.02	0.09			0.15	0.1	0.26	0.36		
Smackover	10560	11830–11840 ft	11840	0.14	0.03	0.09			0.16	0.1	0.25	0.35		
Smackover	10560	11840–11850 ft	11850	0.12	0.03	0.06			0.15	0.09	0.22	0.31		
Smackover	10560	11850–11860 ft	11860	0.14	0.03	0.05			0.17	0.1	0.26	0.36		
Smackover	10560	11860–11870 ft	11870	0.14	0.03	0.08			0.16	0.09	0.24	0.33		
Smackover	10560	11870–11880 ft	11880	0.14	0.04	0.11			0.19	0.12	0.27	0.39		
Smackover	10560	11880–11890 ft	11890	0.64	0.12	0.46	449	0.92	0.76	0.19	0.61	0.8		57
Smackover	10560	11890–11900 ft	11900	0.1	0.12	0.20			0.21	0.12	0.35	0.47		
Smackover	10560	11900–11910 ft	11910	0.08	0.18	0.25			0.27	0.11	0.27	0.38		
Smackover	10560	11910–11920 ft	11920	0.1	0.05	0.26			0.16	0.12	0.45	0.57		
Smackover	10560	11920–11930 ft	11930	0.12	0.04	0.08			0.15	0.09	0.33	0.42		
Smackover	10560	11930–11940 ft	11940	0.14	0.03	0.13			0.17	0.11	0.28	0.39		
Smackover	10560	11940–11950 ft	11950	0.12	0.03	0.09			0.16	0.1	0.22	0.32		
Smackover	10560	11950–11960 ft	11960	0.14	0.03	0.06			0.16	0.09	0.28	0.38		
Smackover	10560	11960–11970 ft	11970	0.11	0.02	0.06			0.13	0.08	0.25	0.33		
Smackover	10560	11970–11980 ft	11980	0.14	0.03	0.07			0.16	0.11	0.19	0.3		
Smackover	10560	11980–11990 ft	11990	0.14	0.03	0.07			0.17	0.1	0.25	0.35		
Smackover	10560	11990–12000 ft	12000	0.11	0.05	0.05			0.16	0.09	0.3	0.39		
Smackover	10560	12010–12020 ft	12020	0.13	0.04	0.09			0.17	0.11	0.24	0.35		
Smackover	10560	12030–12040 ft	12040	0.15	0.03	0.05			0.18	0.11	0.25	0.35		
Smackover	10560	12040–12050 ft	12050	0.1	0.02	0.05			0.12	0.07	0.22	0.29		
Smackover	10560	12050–12060 ft	12060	0.14	0.03	0.03			0.17	0.09	0.28	0.37		
Smackover	10560	12060–12070 ft	12070	0.06	0.01	0.05			0.07	0.08	0.21	0.29		
Smackover	10560	12070–12080 ft	12080	0.14	0.03	0.06			0.17	0.1	0.25	0.35		
Smackover	10560	12080–12090 ft	12090	0.14	0.03	0.08			0.16	0.09	0.26	0.35		

Table 4, continued.

Formation	Permit	Sample ID	Depth	C4–C19	C20–C36	C37+	Tmax C37+	Roe	Sum	GOC	NGOC	TOC	API Grav.	HI
Smackover	10560	12000–12100 ft	12100	0.11	0.08	0.08			0.19	0.1	0.22	0.32		
Average						0.10	449	0.92	0.38	0.12	0.27	0.39		57
Range						0.02–0.52			0.07–4.75	0.08–0.58	0.18–0.49	0.28–0.85		
Smackover	14181	11235 ft	11235	2.09	4.41	0.74	421	0.42	6.51	0.7	0.24	0.94	23.21	79
Smackover	14181	11240 ft	11240	1.04	2.41	0.48	427	0.53	3.45	0.42	0.32	0.74	18.01	64
Smackover	14181	11244 ft and 10 in	11244	0.11	0.11	0.74	444	0.83	0.23	0.16	0.4	0.56		132
Smackover	14181	11251 ft	11251	0	0.03	0.08			0.04	0.12	0.03	0.15		
Smackover	14181	11256 ft	11256	0	0.03	0.13			0.04	0.1	0.17	0.27		
Smackover	14181	11260 ft and 6 in	11261	0.19	0.05	0.10			0.24	0.1	0.23	0.33		
Smackover	14181	11266 ft and 10 in	11266	0.2	0.04	0.04			0.25	0.11	0.27	0.38		
Smackover	14181	11267 ft and 11 in	11267	0.16	0.04	0.08			0.2	0.11	0.26	0.36		
Smackover	14181	11268 ft	11268	0.18	0.07	0.06			0.26	0.11	0.23	0.34		
Smackover	14181	11271 ft and 11 in	11271	0.17	0.04	0.05			0.21	0.1	0.23	0.32		
Smackover	14181	11277 ft	11277	0.02	0.11	0.12			0.14	0.09	0.22	0.31		
Smackover	14181	11281 ft	11281	0.01	0.03	0.15			0.06	0.09	0.31	0.4		
Smackover	14181	11283 ft and 3 in	11283	0	0.04	0.12			0.06	0.09	0.2	0.29		
Average						0.22	431	0.59	0.90	0.18	0.24	0.41		92
Range						0.04–0.74	421–444	0.42–0.83	0.04–6.51	0.09–0.7	0.03–0.4	0.15–0.94		64–132
Smackover	14708	11231 ft	11231	0.17	0.03	0.04			0.2	0.1	0.32	0.42		
Smackover	14708	11232 ft and 3 in	11232	0.12	0.07	0.16			0.19	0.11	0.31	0.42		
Smackover	14708	11236 ft and 8 in	11237	0.19	0.05	0.12			0.24	0.11	0.32	0.42		
Smackover	14708	11242 ft and 2 in	11242	0.19	0.04	0.06			0.22	0.1	0.25	0.35		
Smackover	14708	11257 ft	11257	0.18	0.05	0.14			0.23	0.11	0.22	0.33		
Smackover	14708	11268 ft	11268	0.18	0.05	0.17			0.22	0.11	0.28	0.39		
Smackover	14708	11279 ft	11279	0.2	0.05	0.18			0.26	0.12	0.26	0.37		
Smackover	14708	11284 ft and 4 point 5 in	11284	0.21	0.03	0.04			0.23	0.12	0.23	0.35		
Smackover	14708	11286 ft_cgl	11286	0.2	0.04	0.03			0.24	0.11	0.23	0.34		
Smackover	14708	11286 ft_cgl cmt	11286	0.2	0.04	0.04			0.25	0.12	0.22	0.33		
Smackover	14708	11286 ft_cgl clasts_rerun	11286	0.25	0.03	0.02			0.28	0.14	0.28	0.42		
Smackover	14708	11291 ft_shale bed under cgl_source of cgl clasts	11291	0.2	0.04	0.03			0.24	0.11	0.31	0.42		

Table 4, continued.

Formation	Permit	Sample ID	Depth	C4–C19	C20–C36	C37+	Tmax C37+	Roe	Sum	GOC	NGOC	TOC	API Grav.	HI
Average						0.08			0.23	0.11	0.27	0.38		
Range						0.02–0.18			0.22–0.28	0.1–0.14	0.22–0.32	0.33–0.42		

Smackover	15496–B	11087 ft amd 9 in	11088	0.15	0.03	0.04			0.18	0.09	0.21	0.3		
Smackover	15496–B	11088 ft and 6 in	11089	0.14	0.04	0.04			0.17	0.1	0.25	0.35		
Smackover	15496–B	11090 ft and 11 and a half in	11090	0.17	0.05	0.02			0.23	0.1	0.25	0.35		
Smackover	15496–B	11093 ft	11093	0.16	0.05	0.08			0.21	0.1	0.24	0.34		
Smackover	15496–B	11096 ft and 9 in	11097	0.2	0.2	0.59	440	0.76	0.41	0.16	0.5	0.66		90
Smackover	15496–B	11098 ft and 2 in	11098	0.21	0.15	0.41			0.36	0.15	0.34	0.49		
Smackover	15496–B	11100 ft and 4 in	11100	1.47	2.44	0.40			3.91	0.45	0.27	0.73	21.51	
Smackover	15496–B	11103	11103	1.07	2.25	0.45	425	0.49	3.31	0.39	0.26	0.65	18.15	68
Smackover	15496–B	11103 ft and 6 and a half in	11104	1.18	2.12	0.43			3.3	0.4	0.31	0.71	18.68	
Smackover	15496–B	11105 ft_1 in	11105	1.43	2.12	0.39			3.55	0.41	0.23	0.64	20.66	
Smackover	15496–B	11110 ft_4 in	11110	0.26	0.12	0.17			0.38	0.13	0.27	0.4		
Smackover	15496–B	11111 ft	11111	1.03	1.8	0.39			2.83	0.36	0.27	0.63	17.47	
Smackover	15496–B	11113 ft_1 in	11113	0.22	0.12	0.22			0.35	0.15	0.31	0.45		
Smackover	15496–B	11119 ft_2 in	11119	0.21	0.07	0.20			0.28	0.11	0.25	0.37		
Smackover	15496–B	11122 ft	11122	0.15	0.18	1.43	437	0.71	0.32	0.23	0.48	0.71		201
Smackover	15496–B	11127 ft	11127	0.24	0.06	0.11			0.3	0.12	0.18	0.3		
Smackover	15496–B	11130 ft_6 and a half in	11131	0.18	0.07	0.26			0.25	0.14	0.32	0.46		
Smackover	15496–B	11133 ft and 2 in	11133	0.16	0.17	0.88	436	0.69	0.32	0.18	0.34	0.52		169
Smackover	15496–B	11136 ft_1 in	11136	0.21	0.05	0.15			0.26	0.12	0.23	0.35		
Smackover	15496–B	11145 ft	11145	0.17	0.08	0.49	438	0.72	0.24	0.16	0.27	0.43		111
Smackover	15496–B	11148 ft	11148	0.15	0.15	1.02	436	0.69	0.3	0.2	0.4	0.6		170
Smackover	15496–B	11148 ft_7 and a half in	11149	0.2	0.08	0.36			0.28	0.14	0.32	0.46		
Smackover	15496–B	11154 ft	11154	0.17	0.09	0.64	438	0.72	0.27	0.16	0.37	0.53		120
Smackover	15496–B	11157 ft_7 in	11158	0.2	0.07	0.24			0.27	0.13	0.31	0.44		
Smackover	15496–B	11165 ft and 10 in	11165	0.2	0.16	0.29			0.36	0.14	0.34	0.48		
Smackover	15496–B	11166 ft	11166	0.52	0.69	0.25			1.21	0.21	0.29	0.51		
Smackover	15496–B	11166 ft and 9 in	11167	0.37	0.43	0.16			0.8	0.16	0.27	0.43		
Smackover	15496–B	11170 ft and 2 and a half in	11170	0.2	0.05	0.07			0.25	0.11	0.3	0.41		
Smackover	15496–B	11174 ft and 10 and a half in	11174	0.25	0.05	0.09			0.3	0.12	0.22	0.35		
Smackover	15496–B	11752 ft and 2 in	11752	0.26	0.06	0.11			0.31	0.14	0.2	0.34		

Table 4, continued.

Formation	Permit	Sample ID	Depth	C4–C19	C20–C36	C37+	Tmax C37+	Roe	Sum	GOC	NGOC	TOC	API Grav.	HI
Average						0.35	436	0.68	0.85	0.19	0.29	0.48		133
Range						0.02–1.43	425–440	0.49–0.76	0.17–3.91	0.09–0.45	0.18–0.48	0.3–0.73		68–201
Smackover	13472	11498 ft_2 in	11498	0.2	0.05	0.09			0.24	0.15	0.23	0.38		
Smackover	13472	11505 ft_8 and a half in	11506	0.24	0.27	0.14			0.51	0.16	0.2	0.36		
Smackover	13472	11511	11511	0.17	0.04	0.05			0.21	0.11	0.25	0.36		
Smackover	13472	11515 ft_8 and a half in	11516	0.15	0.07	0.26			0.22	0.13	0.33	0.46		
Smackover	13472	11521	11521	0.18	0.04	0.07			0.22	0.11	0.25	0.36		
Smackover	13472	11526	11526	0.27	0.09	0.21			0.36	0.13	0.23	0.36		
Smackover	13472	11526_duplicate	11526	0.26	0.08	0.10			0.34	0.13	0.22	0.36		
Smackover	13472	11536 ft_8 in	11537	0.34	0.25	0.11			0.59	0.14	0.24	0.38		
Smackover	13472	11541 ft_7 and a half in	11542	0.25	0.09	0.11			0.35	0.12	0.27	0.39		
Smackover	13472	11546b ft_7 in	11547	0.73	0.81	0.18			1.54	0.24	0.27	0.5	15.99	
Smackover	13472	11554	11554	0.46	0.5	0.16			0.97	0.17	0.3	0.47	11.01	
Smackover	13472	11559	11559	0.58	0.68	0.15			1.26	0.21	0.26	0.47	14.62	
Smackover	13472	11564 ft and 2 in	11564	0.25	0.05	0.04			0.3	0.11	0.21	0.32		
Smackover	13472	11569	11569	0.24	0.06	0.04			0.3	0.13	0.28	0.41		
Smackover	13472	11575 ft and 11 in	11575	0.25	0.05	0.05			0.3	0.13	0.28	0.41		
Smackover	13472	11576_photo taken	11576	0.37	0.06	0.02			0.42	0.14	0.25	0.39		
Smackover	13472	11581_photo taken	11581	0.26	0.05	0.03			0.32	0.12	0.25	0.37		
Smackover	13472	11585_photo taken	11585	0.33	0.06	0.02			0.39	0.13	0.32	0.45		
Average						0.10			0.49	0.14	0.26	0.40		
Range						0.02–			0.22–	0.11–	0.2–	0.32–		
Smackover	12872	11826 ft_2 in	11826	0.22	0.04	0.04			0.26	0.13	0.26	0.39		
Smackover	12872	11836 ft_5 in	11837	0.28	0.38	0.17			0.65	0.17	0.29	0.46		
Smackover	12872	11841	11841	0.13	0.19	1.07			0.32	0.2	0.68	0.88		
Smackover	12872	11847	11847	0.23	0.04	0.07			0.27	0.15	0.25	0.4		

Table 4, continued.

Formation	Permit	Sample ID	Depth	C4–C19	C20–C36	C37+	Tmax C37+	Roe	Sum	GOC	NGOC	TOC	API Grav.	HI
Smackover	12872	11851 ft_11 in	11851	0.19	0.06	0.07			0.24	0.13	0.27	0.4		
Smackover	12872	11857	11857	0.15	0.04	0.08			0.19	0.12	0.32	0.44		
Smackover	12872	11857_duplicate	11857	0.15	0.03	0.04			0.18	0.1	0.29	0.39		
Smackover	12872	11863	11863	0.22	0.08	0.12			0.29	0.14	0.32	0.46		
Smackover	12872	11868	11868	0.11	0.04	0.06			0.15	0.12	0.22	0.34		
Smackover	12872	11873	11873	0.17	0.03	0.03			0.2	0.11	0.25	0.36		
Smackover	12872	11877 ft_8 in	11878	0.17	0.03	0.04			0.22	0.12	0.27	0.38		
Smackover	12872	11884	11884	0.18	0.04	0.07			0.21	0.13	0.26	0.38		
Average						0.16			0.27	0.14	0.31	0.44		
Range						0.03–			0.18–	0.11–	0.22–	0.34–		

Permit	Sample ID	Depth	API Grav.	Recov. Res.	Perf. Zone	Perf. Date	Start/End Prod.	Cum. Oil Prod.	Cum. Gas Prod.	Bypassed Oil Payzone
12872 12872 12872	11826 ft_2 in 11836 ft_5 in 11841	11826.2 11836.5 11841	n/a	0.41 0.59 0.28	11826–11846	6/19/2003	2003–2007	127,679 bbls	120,340 Mcf	
Total Recoverable Reserves				1.28						
10560 10560 10560	11860–11870 ft 11870–11880 ft 11880–11890 ft	11870 11880 11890	n/a	0.26 0.26 1.18	11870–11883	11/22/1994	1994–2005	110,176 bbls	84,682 Mcf	
Total Recoverable Reserves				1.70						
17045–B 17045–B 17045–B 17045–B 17045–B 17045–B 17045–B 17045–B	10145 ft and 4 and a half in 10147 ft and 7 in 10149 ft and 1 in 10154 ft 10154 ft and 2 in 10163 ft 10163 ft and 5 in 10166 ft and 8 in	10145 10148 10149 10154 10154 10163 10163 10167	n/a	0.36 0.37 0.22 0.21 0.28 0.20 0.31 0.26	10145–10167	10/9/2014	Production Test done on 01/28/2015 on 10145 ft to 10167 ft interval; API Gravity: 43.7	Started in 2015 and still ongoing in 2022; 45,381 bbls	0 Mcf	
Total Recoverable Reserves				2.21						

Table 5. API gravity from HAWK–PAM, recoverable reserves, perforated zones, cumulative oil and gas production, and bypassed oil pay zones in seven wells drilled in Little Cedar Creek Field. Depth in ft; API gravity in degrees from HAWK–PAM analysis on rock sample (only applicable if sum of C4–C36 is $\geq$2 mg HC/g rock; Recoverable Reserve Sum [(C4–C19) + (4/17 x (C20–C36)) + C19 – evaporative loss] in mg HC/g rock); Perforated Zone in ft; Cumulative Oil Production in barrels; Cumulative Gas Production in Mcf; and Bypassed Oil Payzone in ft.

Table 5, continued.

Permit	Sample ID	Depth	API Grav.	Recov. Res.	Perf. Zone	Perf. Date	Start/End Prod.	Cum. Oil Prod.	Cum. Gas Prod.	Bypassed Oil Payzone
15496–B	11100 ft and 4 in	11100.4	21.51	3.22						
15496–B	11103	11103	18.15	2.46						
15496–B	11103 ft and 6 and a half in	11103.65	18.68	2.62						
15496–B	11105 ft_1 in	11105.1	20.66	3.07	11102–11112	3/3/2010	Started in 2008 and was still ongoing in 2022	164, 862 bbls	147,520 Mcf	
15496–B	11111 ft	11111	17.47	2.28						
15496–B	11165 ft and 10 in	11165.1		0.40						
15496–B	11166 ft	11166		1.10						
15496–B	11166 ft and 9 in	11166.9		0.77						
15496–B	11170 ft and 2 and a half in	11170.25	n/a	0.37	11164–11172	9/3/2008	Production Test done on 09/15/2008 on the 11164–11172 ft interval; API Gravity: 43.3	Started in 2008 and was still on-going in 2022; 164, 862 bbls	147,520 Mcf	
15496–B	11174 ft and 10 and a half in	11174.11		0.46						
15496–B	11752 ft and 2 in	11752.2		0.48						
Total Recoverable Reserves				17.23						

Permit	
14708	Converted to salt water disposal well

Permit	Sample ID	Depth	API Grav.	Recov. Res.	Perf. Zone	Perf. Date	Start/End Prod.	Cum. Oil Prod.	Cum. Gas Prod.	Bypassed Oil Payzone
14181	10119 ft and 2 in	11235	23.21	4.80	11226–11242					
14181	10123 ft and 8 and a half in	11240	18.01	2.44		1/5/2007	2005–2015	311,243 bbls	221,081 Mcf	
14181	10140 ft and 35 in	11260.6		0.35						
14181	10144 ft and 7 in	11266.1		0.37						
14181	10145 ft and 4 and a half in	11267.11		0.30						
14181	10147 ft and 7 in	11268	n/a	0.34	11262–11292	9/29/2005	2005–2015	311,244 bbls	221,081 Mcf	
14181	10149 ft and 1 in	11271.11		0.32						
14181	10154 ft	11277		0.06						
14181	10154 ft and 2 in	11281		0.03						
14181	10163 ft	11283.3		0.01						
Total Recoverable Reserves				9.01						

Table 5, continued.

Permit	Sample ID	Depth	API Grav.	Recov. Res.	Perf. Zone	Perf. Date	Start/End Prod.	Cum. Oil Prod.	Cum. Gas Prod.	Bypassed Oil Payzone
13176	11748 ft and 9 in	11749	n/a	0.26	11740–11760	4/9/2004	Started in 2004 and still ongoing in 2022	320,247 bbls	2,777,430 Mcf	
13176	11758 ft	11758		0.24						
Total Recoverable Reserves				0.50						
13472	11498 ft_2 in	11498.2	n/a	0.37	11490–11520	6/22/2007	Started in 2004 and was still ongoing in 2022	565,249 bbls	439,975 Mcf	
13472	11505 ft_8 and a half in	11505.85		0.50						
13472	11511	11511		0.32						
13472	11515 ft_8 and a half in	11515.85		0.29						
13472	11521	11521		0.33						
13472	11526	11526		0.51						
13472	11526_duplicate	11526		0.49						
13472	11536 ft_8 in	11536.8		0.67						
13472	11541 ft_7 and a half in	11541.75		0.47	11544–11550	5/21/2004				
13472	11546b ft_7 in	11546.7	15.99	1.50						11554–11559
13472	11554	11554	11.01	0.95						
13472	11559	11559	14.62	1.20						
Total Recoverable Reserves				7.59						

Formation	Permit	Sample ID	Depth	C4–C19	C20–C36	C37+	Tmax C37+	Roe	Sum	GOC	NGOC	TOC	API Grav.	HI
Smackover	17045–B	10119 ft and 2 in	10119	0.14	0.06	0.70	427	0.53	0.21	0.16	0.38	0.54		128
Smackover	17045–B	10123 ft and 8 and a half in	10124	0.1	0.04	0.94	430	0.58	0.13	0.16	0.54	0.71		132
Smackover	17045–B	10132 ft and 10 in	10133	0.11	0.03	0.68	434	0.65	0.14	0.15	0.43	0.58		116
Smackover	17045–B	10140 ft and 35 in	10141	0.03	0.03	0.68	436	0.69	0.07	0.15	0.35	0.5		137
Smackover	10560	11780–11790 ft	11790	0.1	0.02	0.52	604	3.71	0.12	0.11	0.23	0.34		150
Smackover	10560	11880–11890 ft	11890	0.64	0.12	0.46	449	0.92	0.76	0.19	0.61	0.8		57
Smackover	14181	11235 ft	11235	2.09	4.41	0.74	421	0.42	6.51	0.7	0.24	0.94	23.21	79
Smackover	14181	11240 ft	11240	1.04	2.41	0.48	427	0.53	3.45	0.42	0.32	0.74	18.01	64
Smackover	14181	11244 ft and 10 in	11244.1	0.11	0.11	0.74	444	0.83	0.23	0.16	0.4	0.56		132
Smackover	15496–B	11096 ft and 9 in	11096.9	0.2	0.2	0.59	440	0.76	0.41	0.16	0.5	0.66		90
Smackover	15496–B	11103	11103	1.07	2.25	0.45	425	0.49	3.31	0.39	0.26	0.65	18.15	68
Smackover	15496–B	11122 ft	11122	0.15	0.18	1.43	437	0.71	0.32	0.23	0.48	0.71		201
Smackover	15496–B	11133 ft and 2 in	11133.2	0.16	0.17	0.88	436	0.69	0.32	0.18	0.34	0.52		169
Smackover	15496–B	11145 ft	11145	0.17	0.08	0.49	438	0.72	0.24	0.16	0.27	0.43		111
Smackover	15496–B	11148 ft	11148	0.15	0.15	1.02	436	0.69	0.3	0.2	0.4	0.6		170
Smackover	15496–B	11154 ft	11154	0.17	0.09	0.64	438	0.72	0.27	0.16	0.37	0.53		120
Smackover	12872	11841	11841	0.13	0.19	1.07	441	0.78	0.32	0.2	0.68	0.88		120
Average						0.74						0.63		120

Table 6. HAWK–PAM petroleum fractions, TOC, API gravity, and HI values for samples whose C37+ mg HC/g value equals or exceeds 0.5. Depth in ft; C4–C19, C20–C36, and C37+ in mg HC/g rock; Tmax C37+ in °C, shown only for samples with C37+ ≥0.5 mg HC/g rock; Ro equivalent in % (Jarvie et al., 2001), shown only for samples with C37+ ≥0.5 mg HC/g rock; Sum of C4–C36 in mg HC/g rock; GOC (generative organic carbon) in wt. %; NGOC (non-generative organic carbon) in wt. %; TOC (total organic carbon) in wt. %; API gravity in degrees from HAWK-PAM analysis on rock sample; and HI (hydrogen index) (C37+/TOC x 100).