Chemostratigraphy of the Upper Jurassic (Oxfordian) Smackover Formation for Little Cedar Creek and Brooklyn Fields, Alabama

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Abstract: The Upper Jurassic (Oxfordian Age) Smackover Formation is a significant source for hydrocarbon production in southwest Alabama. Brooklyn Field is in southeast Conecuh County, Alabama, and has been a major producer of oil and natural gas for the state. The Smackover is a carbonate formation that has been divided into seven distinct lithofacies in the Brooklyn and Little Cedar Creek fields. In southwest Alabama, the facies distribution in the Smackover Formation was influenced by paleotopography of the underlying Paleozoic rocks of the Appalachian system. The goal of this study is to determine elemental ratios in rock core within the Smackover Formation using an X-ray fluorescence (XRF) handheld scanner and to correlate these elemental characteristics to the lithofacies of the Smackover Formation in the Brooklyn and Little Cedar Creek fields. Eight wells were used for the study within Brooklyn Field and Little Cedar Creek fields. Cores from the eight wells were scanned at six-inch intervals. Chemical logs were produced to show elemental weights in relation to depth and lithofacies. The chemical signatures within producing zones were correlated to reservoir lithofacies and porosity. Aluminum, silicon, calcium, titanium, and iron were the most significant (>95% confidence level) predictors of porosity and may be related to the depositional environment and subsequent diageneses of the producing facies. The XRF data suggests relative enrichments in iron, titanium, and potassium. These elements may be related to deposition in relatively restricted marine waters.

Keywords: X-ray fluorescence; paleo-depositional environments; porosity

1. Introduction

The Upper Jurassic (Oxfordian Age) Smackover Formation is a significant source for hydrocarbon production in the Gulf of Mexico region. The Little Cedar Creek and Brooklyn fields in southeast Conecuh County, Alabama, have been a major producer of oil and natural gas, containing more than 79 producing wells. As of October 2018, total production from the fields was 59.400 million cubic feet (MMCF) of natural gas and 42.748 million barrels (MMbbl) of oil [1]. Exploration for Smackover Formation production in Alabama is primarily based on seismic profiles that target microbial buildups overlying paleo topographic highs of Paleozoic basement material [2–5].

The purpose of this study was to determine if abundances of selected elements could be correlated to the different depositional facies within the Smackover Formation in Little Cedar Creek and Brooklyn fields. Elemental concentration is commonly used in chemostratigraphy and can produce signatures

that may be unique to the basin or a formation. These signatures can be used to better understand the stratigraphy and the petroleum reservoir characteristics with a specific focus on predicting porosity. In this study, high-resolution elemental scans of core were collected using X-ray fluorescence (XRF) to capture elemental distribution. Elemental logs were generated and compared to petrophysical logs for advanced well logging, chemostratigraphy, and reservoir characterization within Little Cedar Creek and Brooklyn fields.

2. Geologic Setting

The Gulf of Mexico began to develop during the Late Triassic as a result of the initiation of rifting within the North American Plate and detachment from the African Plate and South American Plate [6]. This period of rifting continued until the Middle Jurassic and is recognized as the first of two distinct techno-stratigraphic periods in the Gulf of Mexico. During the first period of rifting, from the Late Triassic to the end of the Middle Jurassic, subsiding grabens and rift basins in the region controlled stratigraphic events. Thick sequences of non-marine clastic rocks and associated volcanic rocks characterized this period of rifting [6]. A second period of rifting followed during Late Jurassic. After a period of prolonged subsidence in the central portion of the Gulf of Mexico, the basin was rimmed by stable shelves and ramps composed of shale and limestone facies. These sedimentary units defined the Upper Jurassic sequence [3,6].

Southwest Alabama is located on the northern perimeter of the Gulf of Mexico basin (Figure 1). Sedimentary units in this region result from deposition from the Jurassic Period to the present-day. Paleozoic rocks of the Appalachian system uncomfortably underlie the Mesozoic and Cenozoic formations [7,8].
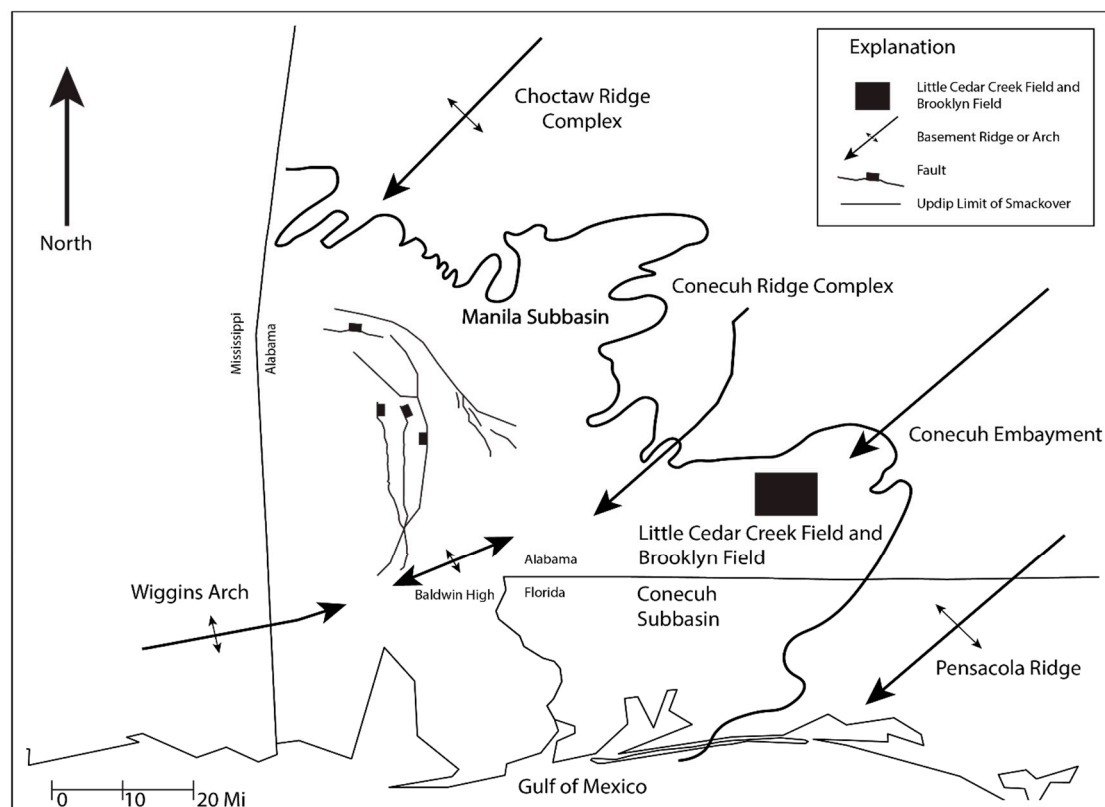

Figure 1. Paleography of southwest Alabama. (Original [9]. Modified from [10,11]).

The tectonic framework of the region controlled the depositional setting of the Smackover Formation on a carbonate ramp that gradually dips south to southwest [8,12–14]. Deposition of

the Smackover Formation in southwest Alabama was heavily influenced by local paleotopography, salt tectonics, and adjacent basins [12,13,15].

2.1. Regional Stratigraphy

The Haynesville Formation, Smackover Formation, and the Norphlet Formation define the regional Upper Jurassic units (Figure 2). The Upper Jurassic stratigraphic units within the region represent a conformable and transgressive sequence consisting of clastic, carbonate, and evaporate deposition [6,7,16]. Each unit oversteps the preceding one and pinches landward. This is interpreted as coastal onlap due to a eustatic sea-level rise [6]. Smaller regressive episodes have been identified within the overall transgressive cycle of the Upper Jurassic sequence [6,17].
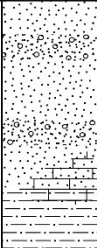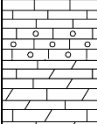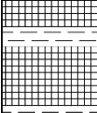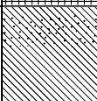
Erathem	System	Series	Group	Geologic Unit	Lithology and Descriptions
Mesozoic	Cretaceous	Lower Cretaceous	Cotton Valley	Schuler Formation	Sandstone, fine to coarse grains. Con-glomeratic in parts with traces of metamorphic rock fragments. Shale and sandy shale, thin limestone locally
	Jurassic	Upper Jurassic	Louark	Haynesville Formation	Shale, anhydrite, thin anhydritic and dolomitic limestone, sandstone
				Buckner Mbr	*Anhydrite, thin silty anhydritic and dolomitic shale beds*
				Smackover Formation	Limestone, microcrystal-line, oolitic in part, dolomitic in part, grades to dolomite
				Norphlet Formation	Sandstone, fine grained quartzose, calcareous in part
		Middle Jurassic		Louann Salt	Massive salt with thin anhydrite and shale beds
				Werner Formation	Anhydrite with sand and metamorphic rock fragments

Figure 2. Regional jurassic stratigraphy of Little Cedar Creek Field and Brooklyn fields (adapted from [10]).

2.1.1. Norphlet Formation

The Norphlet Formation is the lowest Jurassic formation in the study area and is composed mostly of sandstone and conglomeratic sandstone of varied lithologies that are influenced by the source of the detrital material, transporting agent, and depositional position within the basin [6].

In southwest Alabama, the Norphlet Formation is composed of fine- to medium-grained, well-sorted mature sandstone. Grains are commonly well-rounded and coated with hematite. Based on the high-angle cross-bedding and the lack of detrital clay matrix, these sandstones have been interpreted as eolian sands. These eolian strata grade laterally updip in a northeast trend into a section of siltstone, arkosic sandstone, and conglomeratic sandstone. Within Little Cedar Creek and Brooklyn fields, the top of the Norphlet Formation consists of conglomeratic-brecciated sandstone composed of igneous and metamorphic pebbles that are interpreted to represent deposition in coalescing alluvial fans and fluvial systems [18].

2.1.2. Smackover Formation

The Smackover Formation is an Upper Jurassic (Oxfordian Age) unit consisting of limestones and dolostones. The Smackover Formation uncomformably overlies the Norphlet Formation and is interpreted as the opening of the basin to widespread marine flooding [12,18,19]. In southwest Alabama, approximate depth to the Smackover ranges between 5000 feet and 20,000 feet. Three general lithofacies are recognized for the Smackover Formation in the surrounding Gulf of Mexico area: the lower, upper, and clastic members [20,21].

The lower member is described as a thin intertidal to subtidal series of laminated carbonate mudstone and peloidal oncolitic wackestone and packstone [12,22]. The middle unit is a thick interval of subtidal to supratidal laminated carbonate mudstone with interbedded peloidal and skeletal wackestone and packstone. Indications of subtidal deposition are found throughout the laminated carbonate mudstone. The upper unit is described as a series of subtidal to intertidal oolitic grainstone and packstone that are interbedded with laminated carbonate mudstone. Throughout the upper Smackover, an algal boundstone is associated with local paleohighs, such as the Choctaw and Conecuh ridge complexes [12,23].

2.1.3. Haynesville Formation

The Haynesville Formation is a Kimmeridgian-age unit composed of evaporitic deposits and anhydritic shale and sandstone [10]. The Haynesville Formation is divided into three separate units: lower, middle, and upper. The lower unit is defined as the Buckner Anhydrite Member, which conformably overlies the Smackover Formation [12,16]. The Buckner Anhydrite Member consists of massive anhydrite with intercalated dolomite beds. If the massive anhydrite is not present, the lower part of the Haynesville consists of anhydrite, shale, sandstone, thin anhydrite beds, and salt stringers. The middle unit is described as interbedded sandstones, shales, and anhydrites. The upper unit of the Haynesville Formation is composed of interbedded carbonate mudstone, dolomitic limestone, sandstone, shale, and anhydrite [12,16].

2.2. Local Stratigraphy

The upper Smackover within Little Cedar Creek and Brooklyn fields in southwest Alabama is characterized by seven distinct lithofacies. These lithofacies' descriptions were based on petrographic analysis conducted by [18,19,21] and are generalized in Table 1. These lithofacies formed the basis for correlating the XRF data to the productive units.

Table 1. The seven lithofacies of the Upper Smackover Formation in southwest Alabama (adapted from [21]).

Facies	Lithology	Color	Accessory Minerals	Texture	Cement	Depositional Environment
S-1	Limestone-Dolostone	Grey-Light Grey	Dolomite, Anhydrite, Gypsum, and Silt	Mudstone-Wackestone	Calcite-Anhydrite	Shallow-Water, Lagoon Environment, Low Energy
S-2	Limestone	Grey	Monocrystalline -Polycrystalline Quartz and Volcanic Pebbles less than 2cm	Rudstone-Floatstone-small interval of Grainstone	Sparry Calcite	Tidal Channel Environment
S-3	Partially Dolomitized Limestone	Tan-Grey	Calcite and Minor Dolomite Rhombs	Grainstone-Packstone-Mudstone	Sparry Calcite	High Energy, Subaqueous, Intertidal Shoal Environment
S-4	Limestone	Grey- Dark Grey	Dolomite	Wackestone-Mudstone-Packstone	Calcite	Deep-Water, Subtidal Marine Environment
S-5	Limestone	Grey-Dark Grey	Dolomite	Packstone, Wackestone	Calcite	Subtidal Marine Environment
S-6	Limestone	Grey-Tan and Grey-Light Grey	Dolomite	Boundstone	Sparry Calcite	Low-Energy Shallow-Water Environment
S-7	Limestone-Dolostone	Grey-Reddish Pink	Dolomite and Silt	Mudstone - Wackestone	Sparry Calcite	Rapid Marine Transgression

3. Petroleum System

The Smackover Formation is one of the most productive oil and gas units in Alabama, eastern Mississippi, and the Florida panhandle [19]. Smackover reservoirs are characterized by combination traps including salt anticlines and stratigraphic traps, faulted salt anticlines, and extensional fault traps that relate to the updip limit of the Louann Salt deposition [12,16]. Hydrocarbon accumulation within Little Cedar Creek and Brooklyn fields has been defined as a dual-reservoir, stratigraphic trap near the updip depositional limit of the Smackover [2]. The two productive reservoir facies within the Smackover Formation in Little Cedar Creek and Brooklyn fields are characterized as a leached subtidal microbial (thrombolite) boundstone (lower reservoir) and a peloidal-oolitic shoal grainstone-packstone (upper reservoir) [21,24]. The dual-reservoir system of Little Cedar Creek and Brooklyn are vertically separated by a lime mudstone and are not in communication [2,22]. Porosities of the Smackover Formation present in the two fields range from 3 to 36 percent. Porosity values in the nearby producing fields of northern Escambia County range from 6 to 30 percent [25]. By contrast, at locations further west, the porosity of grainstones at Black Creek field in Mississippi determined from core analysis is less than 1 percent. The porosity was filled by cementation [26].

4. Materials and Methods

The Alabama Geological Survey and the Alabama Oil and Gas Board provided the materials used in this study. Materials consisted of rock core samples, rock core analyses, and petrophysical logs of the Smackover Formation.

4.1. Well Selection and Sample Preparation

Using scout tickets and available well logs, eight wells were selected for scanning. Cores were scanned from these wells in six-inch intervals using a portable XRF device (Table 2). Figure 3 shows the location of the wells from which the core scans were conducted. Wells were selected based on their location and the availability of data from the Smackover Formation. The cores were one-third slabbed providing a flat surface for scanning. This allowed for a fast workflow and consistent instrument orientation. Cedar Creek Land and Timber 33-10 #1 and Johnson-Stewart 32-12 #1 were tested for core sample preparation. Using a clean, dry, 2-inch brush, the sample was cleaned for scanning. This method detected elements not normally associated with carbonate-dominated lithologies, such as barium. Barium, however, is a common component in drilling fluids. We modified our scan specimen

preparation by cleaning the surface of each core slab with deionized water. Further testing showed no detectable barium, indicating that the dust on the core was drilling fluid related. The standard preparation for each core box was to mist each length of slabbed core with deionized water and wipe clean with a cloth, being careful not to damage the surface or edge of the core. Note that great care was given to core preparation so that random surface contamination was all but eliminated.

Table 2. List of the wells used for this study.

Permit #	Well Name	Field Name [1]	Status [2]	Type	Longitude [3]	Latitude [3]
15934	Johnson-Stewart 32-12 #1	BK	DA	OIL	−86.78270	31.26628
16453	Mary Godwin 31-3	BK	PR	OIL	−86.79727	31.27349
16686	Cedar Creek Land and Timber 33-10 #1	BK	PR	OIL	−86.85973	31.26680
16882-B	Cedar Creek Land and Timber 27-15 #1	BK	DA	OIL	−86.74166	31.28043
17011-B	Benjamin 26-4	BK	PR	OIL	−86.83619	31.29008
14309	McCreary 13-16	LCC	PR	OIL	−86.80659	31.30684
16327-B	Craft-Ralls 28-16 #1 WI	LCC	CV	OIL	−86.75441	31.36430
17045-B	Craft-Barrow 12-8 #1	LCC	PR	OIL	−86.70495	31.41526

[1] BK = Brooklyn; LCC = Little Cedar Creek. [2] CV = Converted; DA = Dry and Abandoned; PR = Producing. [3] Geographic coordinates in WGS84.

4.2. X-ray Fluorescence

X-ray fluorescence (XRF) is based on the theory that atoms will emit X-ray photons when charged by an outside energy source. The contact between high-energy X-rays and electrons from the inner electron shell will eject an electron from that shell. With a lower energy slot now available, an electron from a higher energy shell shifts to fill the vacancy. The surplus of energy is emitted (fluoresced) as a secondary photon of X-ray energy, typically from 0.1 to 5 keV for K shell X-rays for lighter elements (e.g., Z = 4–24; Be to Cr) and approximately 0.6–15 keV for L and M shell X-rays for heavier elements (e.g., Z = 25–95; Mn to Am). The loss of energy emits radiation from the inner electron shell, which are X-ray photons that classifies the elements. The concentration of the element is defined by the count rate of emitted X-rays per unit time.

To employ the XRF method, we used the Bruker TRACER 5i (Figure 4). It is a handheld portable non-destructive energy dispersive X-ray fluorescence (ED-XRF) spectrometer capable of collecting elemental concentrations from most sample surfaces. Data collected by the TRACER 5i are reported in counts per second (cps) then processed to parts per million (mg/kg) or weight percent (wt%) using a selected calibration. The TRACER 5i has many available calibrations, and user-created calibrations are possible if there are adequate standards. The calibration applied for this study was the mudrock calibration provided by Bruker [27]. A reference sample was used to assure measurements were consistent with the calibration throughout the scanning effort. The rock core samples were scanned every six inches with no filter over the collimator. Resulting fluorescence spectra were processed and matched using the selected calibration. The major and minor elements are reported in units of the parts per million (Table 3).
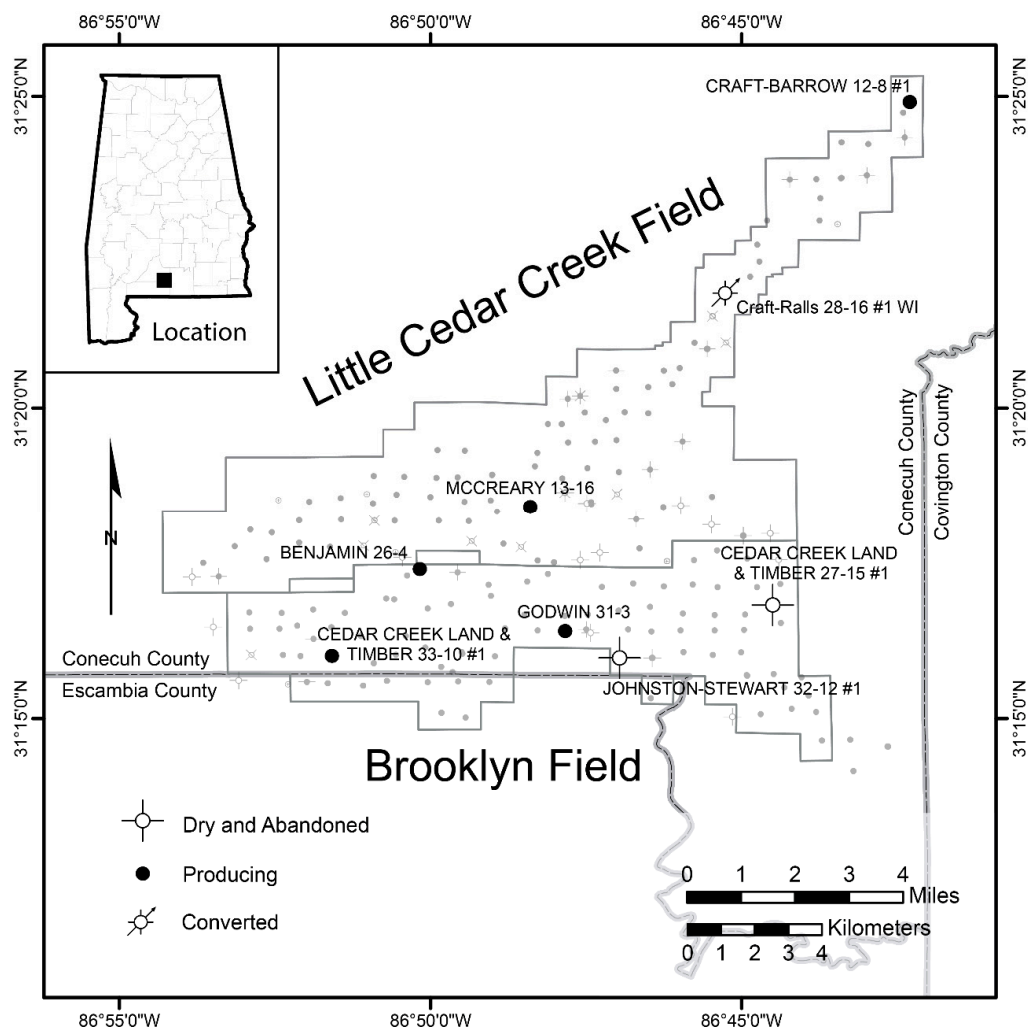
Figure 3. Wells used from the Little Cedar Creek (northern) and Brooklyn (southern) fields for this study in southern Alabama, United States. All wells in both fields are shown as of November 2018. Datum of geographic coordinate is NAD83.

Figure 4. Handheld Bruker Tracer 5i XRF.

Table 3. Major and minor elements detectable by XRF for this study.

Major Elements	Minor (Trace) Elements
Si, Ti, Al, Fe, Mn, Mg, Ca, K, P	Ba, Ce, Co, Cr, Cu, Ga, La, Nb, Ni, Rb, Sc, Sr, Rh, U, V, Y, Zr, Zn

4.3. Chemostratigraphy

Chemostratigraphy is the geochemical classification and correlation of sedimentary strata by using major and trace element geochemistry. It is an especially valuable method when applied to sequences with poor biostratigraphic control [28]. A fundamental aspect of chemostratigraphic data is its ability to improve lateral correlation of lithofacies. Chemostratigraphic zonation may be correlated to the facies identified in the Smackover Formation.

4.4. Porosity Data

In petroleum systems, porosity is one of the most important reservoir properties to characterize. In this study, we used core analyses performed by Weatherford Laboratories or Omni Laboratories. Plug samples were taken at approximate intervals between 0.3 and 1.1 feet along the core. These results include the basic rock properties of horizontal permeability, porosity (helium), pore volume saturation of oil and water, bulk saturation volume of oil and gas, and grain density. All data reports are provided by the Alabama Geological Survey State Oil and Gas Board Core Warehouse.

5. Results

Data from the XRF was tabulated by sample, depth, and elemental concentration. These tables are provided as Supplemental Materials and show major and select trace elements along the selected subset of the full data collection (see Tables S1–S8). Figure 5 shows the log generated for major elements with lithofacies defined for Cedar Creek Land and Timber 33-10 #1 well. An example X-ray spectrum is provided in Figure S1.

Multiple Regression Analysis

Using core porosity data and elemental data from the XRF analysis, multiple regression analyses were preformed to determine correlation between the variables. This was conducted on each of the eight wells in the investigation. Using the following relationship:

$$\hat{Y} = a_0 + a_1 x_1 + a_2 x_2 + \ldots + a_i x_i, \tag{1}$$

where $\hat{Y}$ is the expected value of the dependent variable, x_i is equal to a constant term plus the sum of a series of independent variables. The dependent variable, x_1 for the multiple regression was selected as core porosity and the x_{1-12} variables are the twelve elements selected for this study. The multiple regression analysis was conducted in three separate series for sensitivity analysis, in which individual samples of the elements were compared to porosity. For the first series of the F-test regression ANOVA, no restrictions were used and the entire sample population was used. The second series excluded outlier samples greater than four standard deviations from the sample mean ($<\pm 4\sigma$). The final series further restricted outliers by excluding samples greater than two standard deviations ($<\pm 2\sigma$). The summary of the ANOVA tables is provided in Table 4.
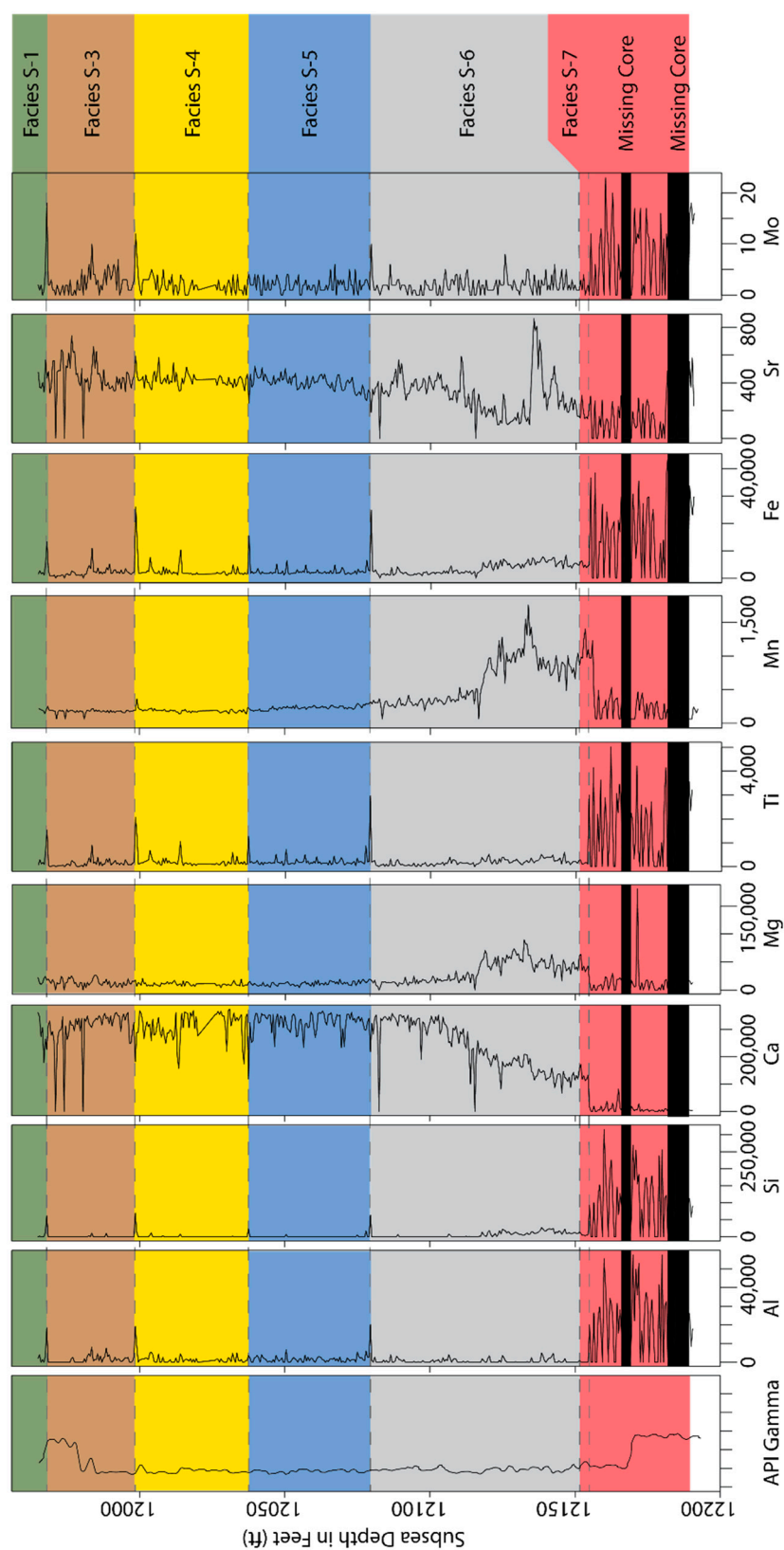
Figure 5. Cedar Creek Land and Timber 33-10 #1 elemental log generated from selected XRF data with defined lithofacies. All elemental values are reported in parts per million (mg/kg).

Table 4. All elemental data compared to porosity are compiled in increasing atomic number with various sample exclusions based on standard deviation of sample population. Values are listed in increasing atomic number. Elements with a significance greater than 95% (*p*-value < 0.05) are bolded.

Source of Variance	Degrees of Freedom	No Restrictions (All Data)		Samples < 4σ		Samples < 2σ	
		F-Value	*p*-Value	*F*-Value	*p*-Value	*F*-Value	*p*-Value
Regression	12	14.40	0.000	13.94	0.000	12.11	0.000
Mg	1	3.70	0.055	0.83	0.361	2.25	0.134
Al	1	7.03	**0.008**	5.94	**0.015**	0.94	0.333
Si	1	15.86	**0.000**	20.40	**0.000**	11.06	**0.001**
S	1	1.43	0.232	0.00	0.232	0.35	0.554
K	1	0.38	0.540	0.46	0.540	0.00	0.979
Ca	1	6.93	**0.009**	6.45	**0.009**	5.90	**0.015**
Ti	1	11.96	**0.000**	12.43	**0.000**	10.23	**0.001**
Mn	1	0.27	0.605	2.00	0.605	1.71	**0.001**
Fe	1	4.65	**0.031**	0.98	**0.031**	4.98	**0.026**
Sr	1	1.99	0.159	0.49	0.159	0.03	0.855
Zr	1	1.28	0.259	0.91	0.250	0.00	0.970
Mo	1	3.38	0.066	1.08	0.066	0.71	0.401

6. Discussion

The results from the multiple regression indicate that the elements Al, Si, Ca, Ti, and Fe show the strongest correlation to porosity (*p*-value < 0.05). The two elements most significant to accepting the alternative hypothesis of the F-test in regression of Equation (1) are Ca and Ti. Regardless of the sensitivity to sample exclusion in the ANOVA (Table 4), both elements had very low *p*-values and *F*-values significantly larger than the critical F-value of 4.747 ($\alpha = 0.05$). Al was the most affected by sample exclusion in the sensitivity analysis. As outliers of Al concentrations were removed from consideration, the significance to reject the null hypothesis was considerably reduced going from *p*-value = 0.008 with no restrictions on the data population to a *p*-value of 0.333 when excluding Al concentration greater than two standard deviations of the mean. The large variance of Al and its relationship to porosity may be related to the presence of clay minerals in the pore space, thereby reducing porosity.

Changes between lithofacies are visually well-correlated with elemental distribution logs produced from the XRF results (Figure 5). Delineation of the lithofacies zones is not possible using only the gamma log data. Only the occurrence of mudstones in the transgressive facies S-7 and the top of facies S-3 shows any significant response in the gamma log data. Peaks in occurrence of Mo, Fe, Ti, Si, and Al occur at the tops of a majority of the different facies. These data may help in the delineation of the facies within the upper Smackover. No discernable visual differences were reported at these locations in the core. The gradational change from one lithofacies to the next can be difficult to see in the core. The relationship between these various elements and the facies in the upper Smackover can be separated into two categories: paleoenvironment and diagenetic modification. [25–29].

6.1. Category 1: Paleoenvironment

The first category distinguishes the paleoenvironment of the upper Smackover lithofacies. The depositional setting of the Smackover Formation was a carbonate ramp similar to the modern western Persian Gulf. The microbial buildups, shoal grainstones, and sabkha environments resemble the vertical facies of the Smackover Formation in Little Cedar Creek and Brooklyn fields. The elements Al, Fe, Si, and Ti all show high values from the XRF data at the transition from one facies to another. The transition from facies S-6 to S-5 has been interpreted as a transgression, while the transition from S-4 to S-3 has been interpreted as a regression. Deposition of both S-6 and S-3 occurred during periods of shallow water and a higher energy environment. The weathering of onshore igneous rock may be the source of dust size particles that were transported from onshore areas into the shallow water depositional systems. The combination of Al, Fe, Si may be related to the kaolinite and illite clay minerals that are weathering products of feldspar-rich rocks. Al is relatively unstable and is commonly

found in authigenic clay minerals. It is worth noting that the mineralogy of the upper part of the Norphlet Formation commonly contains granite clasts and is commonly classified as arkosic sandstone. Titanium and silicon can relate to dust size particles [30]. Thin clay stringers between lithofacies can be seen in the well cores. The elements Mn, Mg and Fe can have multiple mineralogical affinities. To identify the clay mineral constituents responsible for the elemental contributions, additional mineralogical data will be needed in future investigations.

Generally, enriched concentrations of Al, Si, Fe, Ti, Mg and Mo in sediments are attributed to terrigenous origins [30,31]. Figure 6 provides an illustration of paleoenvironment of the Smackover Formation and possible origins for the associated elements. The increased concentrations of Ti and Mo suggest that, at the time of the facies S-7 deposition, the area of Little Cedar Creek and Brooklyn fields was at greater proximity to terrestrial source materials than younger facies of the Smackover Formation. Si can exist in biogenic Si, so one cannot assume that it occurs in wind-blown quartz or other detrital minerals. Given the depositional framework of the Smackover Formation and enrichment of associated elements, terrestrial-derived sediments are likely the source of mudstone and wackestone found in facies S-7. Gravitational separation of heavy minerals is common and results in fractionation during transport [30].
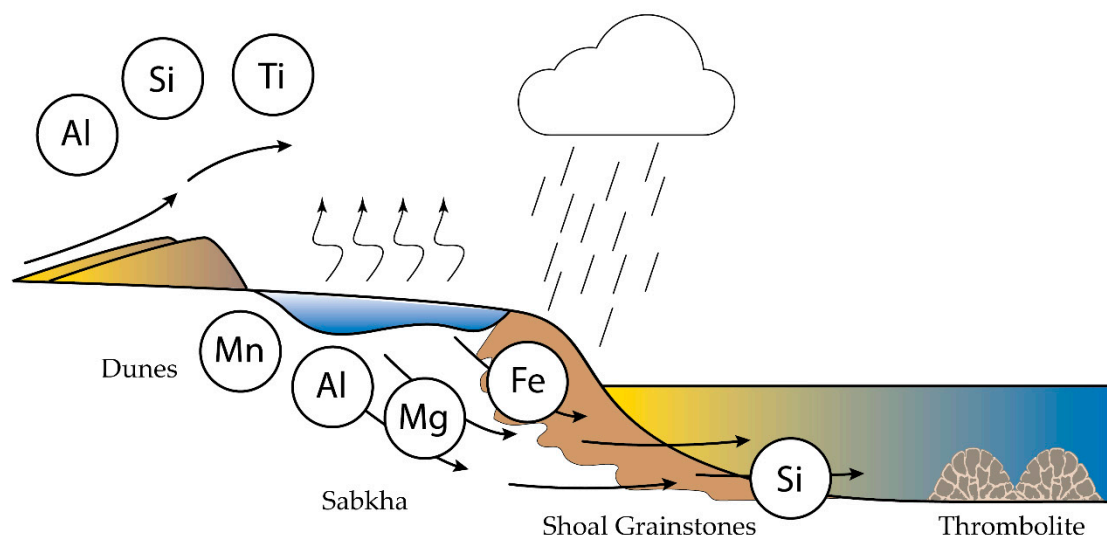

Figure 6. Effects of various elements within the depositional setting of the paleoenvironment of the Smackover Formation. Arrows indicate the possible generalized flow of elements by wind or water.

6.2. Category 2: Diagenetic Modifications

The second category is identifying the diagenetic effects of the upper and lower reservoirs that controlled porosity development. Figure 7 shows a diagenetic framework in the context of porosity. The left side of the figure shows terrigenous origins for the elemental enrichments while the right side provides the marine and subaerial origins. Diagenetic modification within the Smackover Formation is primarily eogenetic dolomitization of the limestone and porosity reduction through cementation. Secondary porosity from dissolution occurred later, improved reservoir quality and potentially introduced other elements, including iron, magnesium and manganese, into the rock fabric.
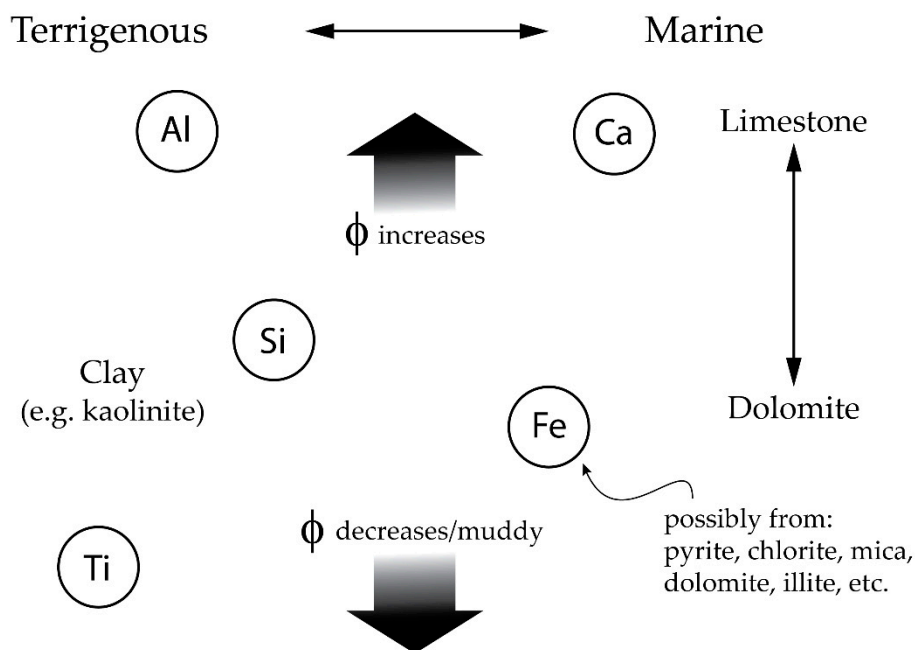
Figure 7. The five elements (aluminum, calcium, iron, silicon, and titanium) with most significance (*p*-value < 0.05) from the multiple regression and their relation to the depositional environment. Porosity increases from the bottom to top of the figure.

Marine Phreatic Zone

Within the upper Smackover Formation, eogenetic diagenesis occurs in three separate zones. The marine phreatic zone is described as the first zone. Diagenetic alteration of ooids and other allochems within the upper reservoir, facies S-3, began soon after deposition. Deposition in relatively calm waters is conducive to extensive micritization. In the upper section of facies S-3, biogenic micritization is most noticeable where many ooids have been moderately to entirely micritized. Micritization generated micro-porosity within the ooids, making later diagenetic replacement or dissolution more prone [29,32].

Cementation that occurs within the marine phreatic zone is described as fibrous to bladed thin crust and is usually thicker in oolitic grainstones and thinner in oncolitic and peloidal grainstones. This relates to a surge of water circulation in higher energy ooid shoal environments, resulting in marine phreatic cements that generally define overall lithology of less than 5 percent [29]. This suggests that sedimentation in the upper Smackover was abrupt and open to a marine phreatic environment for a short period of time.

7. Conclusions

The primary goal of this research was to determine if XRF data could provide information related to the different facies in the Brooklyn and Little Cedar Creek fields and potentially substitute for detailed log analysis. Porosity within the Upper Smackover in southwest Alabama originates from the depositional setting, and the degree of diagenetic alterations the lithology has experienced. Extensive dissolution and dolomitization are the contributing diagenetic factors that controlled porosity development. Using a multivariate regression, the various elements Al, Si, Ti, Fe, and Ca can be related to porosity, which is an important hydrocarbon production characteristic.

Generally, lithofacies boundaries are not visible on gamma ray logs. Various elements can describe the paleoenvironment of lithofacies in Little Cedar Creek and Brooklyn fields and the diagenetic controls that influenced them. Elemental contacts can distinguish between carbonate lithofacies based on increasing Al, Si, and Ti concentration peaks. Further research is needed to more completely explain the elemental peaks in XRF data that occur at or near the facies boundaries. Given the care in core

preparation, these peaks are reliable values from the core matrix and not the result of contamination. Some of the elemental distributions may be related to deposition, while others may be related to post deposition diagenesis and later karst alteration.

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