

**Analysis of the Potential for Carbon Sequestration in the Subsurface
Tuscaloosa Group, southwestern Alabama**

by

Nora V. Lopez Rivera

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Approved by

Ashraf Uddin, Chair, Professor of Geosciences
David King, Co-Chair, Professor of Geosciences
Ann Ojeda, Professor of Geosciences

Abstract

In this project, the sedimentology and stratigraphy of the Upper Cretaceous Tuscaloosa Group of the subsurface of an area in southwestern Alabama has been analyzed for carbon sequestration purposes. While collecting the samples for this study, it was noted that the sandstones that make up part of the Tuscaloosa Group were found to contain large amount of glauconites. Glauconitic sands, sometimes referred to as greensand formations, are associated with continental shelf sediments typically deposited during Cambrian, Cretaceous, and Cenozoic . Previous studies suggest that the Tuscaloosa's sands, which include some glauconite intervals, may be adequate reservoirs for geologic CO₂ storage. The Tuscaloosa Group has an overall subsurface thickness of 183 m -369 m (600 ft – 1213 ft) in southwestern Alabama, and an approximate porosity of 25%. An essential part of this study was to observe and explore how the injected CO₂ fluid interacts with porous rocks. Samples from the drill core Julian F. McGowin No #1 were collected in order to observe lithological changes, sedimentary structures and vertical changes in grain size and mineralogy, as well as measuring thickness of porous units. Petrographic thin sections, as well as core observations, show evidence of glauconite throughout most of the core. XRD results show the mineralogical bulk composition of mostly quartz, berlinite, micas, K-feldspar, glauconite, chlorite, and illite. A design for a geochemical experiment was formulated using brine data collected by the Geological Survey of Alabama. Tuscaloosa brine is mostly composed of Na-Ca-Cl, with high concentrations of Mg. This part of the experiment took place inside a rocking autoclave apparatus at the University of Wyoming, and the software Geochemist's Workbench was used to create a geochemical model. An activity diagram was created to observe stability fields of Fe minerals in the Tuscaloosa Group. The model shows evidence of siderite precipitation under reducing conditions. Given its wide geographic distribution, substantial thickness, substantial

porosity, permeability, the Tuscaloosa Group could potentially serve as a near-limitless reservoir for storing CO₂. In support of this notion, geochemical results are positive in that they showed release of Fe²⁺, which suggest the onset of carbonate mineral precipitation.

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1. Introduction

The burning of fossil fuels accompanying acceleration in the pace of human activities is one of the major factors contributing to the increase of greenhouse effects and climate change. Thus, it is important to look for alternatives to mitigate the effects of CO₂ from the atmosphere.

In this study, the Tuscaloosa Group in southwest Alabama was examined from a geological perspective to understand its carbon sequestration potential. The Tuscaloosa Group is a substantially thick sedimentary formation in the Gulf Coastal Plain's southwestern Alabama subsurface. According to previous studies, the formation qualifies as a substantial reservoir for CO₂ because it has the proper composition, porosity, permeability, and depth required for a CO₂ reservoir (Pashin et al., 2008; Lu et al., 2014). In this study, drill-core samples from the Tuscaloosa Group, southwestern Alabama, were collected and analyzed in order to study their porosity, permeability, mineralogical composition, and CO₂-brine-rock interactions. One of this study's main objectives was to observe how the Tuscaloosa's sandstone composition reacted with injected supercritical CO₂ and gain insight into the Tuscaloosa's qualities for being a CO₂ reservoir. When the samples were collected for this study, it was noted that some sandy zones in the Tuscaloosa were glauconite-rich. The objective then changed to observe if the glauconites that make up the sandstones affect the Tuscaloosa Group's qualities for a CO₂ reservoir.

Understanding the sedimentary petrology and stratigraphy of this stratigraphic unit is crucial when analyzing a formation for carbon sequestration purposes (Kaszuba et al., 2003). Thus, petrographic analyses, geochemical experiments, and well-log correlations were completed in order to understand the composition, porosity, and sandstone continuity, as well as observe the interaction between the glauconite and supercritical CO₂, to better determine if the sandstones that make up most of the Tuscaloosa Group in southwest Alabama are ideal for carbon storage.

Carbon Capture and Sequestration: Globally and in the Gulf Coast

The significant factors contributing to greenhouse effects and climate change are the burning of fossil fuels and the related accelerated pace of human activities (Lu et al., 2013; Rinehart et al., 2016; Feng et al., 2017; Fuchs et al., 2019). Therefore, it is extremely important to search for alternatives to mitigate these effects produced by the continuous accumulation of CO₂ in our atmosphere. Although the carbon cycle is the natural way CO₂ is removed from the atmosphere, this natural process is insufficient due to the rapid acceleration in emissions of CO₂ (Sundquist et al., 2008; Jones and Maginn, 2010; Herzog, 2018). For example, in 2017, it was reported that the United States alone emitted approximately 5.1 billion metric tons of energy-related CO₂, while global emissions totaled about 32.5 billion metric tons during the same year (Sundquist et al., 2008). Each year, these emissions increase; therefore, it is crucial to study alternatives to remove CO₂ from the atmosphere (Fuchs et al., 2019). A promising and effective way of mitigating greenhouse gases is by carbon capture and geological carbon sequestration process.

Carbon capture and sequestration (CCS) prevents these greenhouse gases from entering the atmosphere and thus reduces the chances of CO₂ emissions from affecting our atmosphere and contributing to climate change (Herzog, 2018). In this process (CCS), the CO₂ is captured either naturally or deliberately and stored (Herzog, 2018). The two main types of carbon sequestration are biological and geological. This project focuses on the later geological carbon sequestration. In this process, the CO₂ is stored in a porous geological formation. These reservoirs exist naturally in Earth's crust. (Chopping and Kaszuba, 2012; Chopping and Kaszuba, 2017). Some of the most common and available storage include deep saline aquifers, active as well as depleted oil and gas reservoirs, salt domes, and coal seams (Raza et al., 2016). However, previous studies suggest that

hydrocarbon reservoirs are the most viable and cost-effective (Esposito et al., 2011; Raza et al., 2016). According to Herzog (2018), for a geological unit to be considered adequate geological storage, it must meet four main criteria: (1) the unit must be porous and have good permeability; (2) the geological unit needs to be at a depth below 800 m (2624 ft); (3) the unit needs to have an effective cap rock, and (4) the unit needs to be continuous and thick enough to store a large volume of supercritical CO₂.

In 2013, the USGS completed an assessment of carbon sequestration, which mentioned the US Gulf Coastal Plain region as the area with most CO₂ storage potential (Sundquist et al., 2008). This area includes coastal basins from Texas to Georgia. This USGS study mentioned that the US Gulf Coast Plain could store approximately 2,000 metric gigatons of CO₂ (Sundquist et al., 2008). The Tuscaloosa Group in southwest Alabama falls in this area. The formation in the studied area has an overall subsurface thickness of 183-369 m (600-1210 ft), an approximate porosity of 25%, and permeability of 0.213 d (Pashin et al., 2008). This unit's lithology consists mainly of glauconitic sandstone in its lower and upper parts and shale in the middle, suggesting fluvial and fluvial deltaic deposition of sediments (Mancini et al., 1987; Mancini and Puckett, 2002). The Tuscaloosa Group is overlain by the Eutaw Formation, and in turn, the relatively thick Selma Group (chalks) could serve as an excellent local and regional seal (Mancini et al., 1987; Pashin et al., 2008).

Although previous studies suggest that this area is already an ideal prospect for CO₂ storage, it is important to understand the consequences that this injecting process could have within a reservoir (Wigand et al., 2009; Soong et al., 2018). The Tuscaloosa Group, southwest Alabama is part of the saline formation, and its brine is mainly made up of sodium (Na), calcium (Ca) and chloride (Cl), with high amounts of magnesium (Mg). Previous studies on structures located in the

of southwest Alabama for carbon sequestration purposes contain part of the Tuscaloosa Group (Lu et al., 2013, 2014; Yang et al., 2018). For example, in a study done by Esposito et al. 2008, at the Citronelle Dome, located in the eastern Mississippi Interior Salt Basin of southwest Alabama, could serve as a safe storage reservoir for CO₂. Contour maps from the Citronelle were studied by Esposito et al. (2008) to investigate any structural closures in which CO₂ could be stored safely and enhance oil recovery at once. Stratigraphic analyses were also done by studying the rock units that make up the Citronelle Dome. The dome contains sandstone units from the Lower Cretaceous strata and lower Tuscaloosa, as well as some units from the upper Tuscaloosa and Eutaw Formation (Esposito et al., 2008; Conaway et al., 2016). These sandstones are well characterized by their high porosity, high permeability, and low heterogeneity (Esposito et al., 2008).

To further understand the consequences of carbon sequestration, it is essential and beneficial to study in-depth brine-rock interactions with injected supercritical CO₂ to improve understanding of CO₂-brine-rock systems and analyze and observe mineralogical changes in rocks (Cortis et al., 2008; Price and Oldenburg, 2009; Carter and Spikes, 2013). One of this research's main objectives was to understand the interaction between the supercritical CO₂ in brine-rock interaction with the Tuscaloosa Group's glauconitic sandstones. Previous studies focusing on greensand formations, made up of iron (Fe) rich sedimentary rocks containing the clay mineral glauconite, and how under carbonation processes, it likely converts to the mineral siderite (FeCO₃) (Tutolo et al., 2020b). These greensand formations are globally abundant and associated with continental shelf sediments deposited during transgressive events and are found most commonly within Cambrian, Cretaceous, and Cenozoic strata (Erraioui et al., 2005; Tutolo et al., 2020b). Greensand formations are said to contain hydrocarbon accumulations and, therefore, may be great candidates for CO₂ storage (Tutolo et al., 2020b).

During geologic carbon sequestration, CO₂ is injected in a supercritical form. Supercritical CO₂, as shown in **Figure 1**, is a phase in which CO₂ is at a temperature of around 31° C (88° F), and the pressure is around 7.4 MPa (1073 psi) (Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration, 2019). This temperature and pressure define the critical point for CO₂. The CO₂ has similar properties to both a gas and a liquid at such high temperatures and pressure. In summary, it is dense like a liquid but has a similar viscosity to gas. The main advantage of storing CO₂ in the supercritical condition is that the required storage volume is less than if the CO₂ were at standard conditions (Committee on Developing a Research Agenda for CO₂ Removal and Reliable Sequestration et al., 2019).

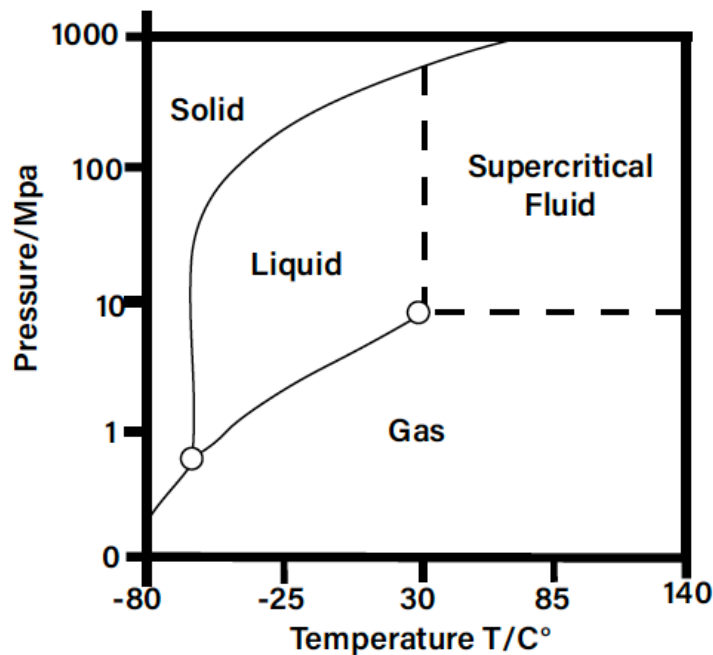


Figure 1: Transition diagram showing the conditions in which CO₂ exists in both a liquid and gas phase. Modified from Yang et al. (2018).

Research Questions

By analyzing drill-core samples from the Tuscaloosa Group, southwest Alabama, specifically by using petrographic thin sections, scanning electron microscopy, x-ray diffraction, and autoclave analysis, I answered the following questions:

- 1) It has been suggested that the Tuscaloosa Group may be a viable candidate for carbon-dioxide storage. Do the studied Tuscaloosa samples from southwest Alabama have the proper mineralogical composition, porosity, and depth to store CO₂?
- 2) What is the general stratigraphy of the Tuscaloosa Group in the study area? What is the composition and distribution of the sand bodies that make up part of the Tuscaloosa Group? Is the formation thick enough and does it have sufficient sand bodies within to store large amounts of CO₂?
- 3) How will the injected supercritical CO₂ interact with the porous sandstones, specifically with the mineral glauconite?

Structural Features of the Tuscaloosa

General structural features that dominate southwestern Alabama are (1) salt domes and anticlines and (2) the regional peripheral trend (Mancini et al., 1987; Folaranmi, 2015). These structural features can be seen in **Figure 2**. Other general structural features found are the Mobile graben and the Wiggins arch. The area also has structural domes that were included in previous studies for petroleum and CCS purposes. The salt domes in the area are the McIntosh, Klepac, Gilbertown, Chamtom, and the Citronelle dome (Mancini et al, 1987). The structural domes were formed by salt movements. (Mancini et al., 1987). The peripheral fault trend consists of other fault systems, which are: (1) Pickens-Gilbertown; (2) Gilbertown; (3) West Bend; and (4) the Pollard-Foshee fault system. All these faults vary in length and have displacements of 61 m - 305 m (200 ft – 1000 ft) in the Tuscaloosa Group, at depths of 122 m -1829 m (400 ft – 6000 ft) (Mancini et al., 1987). Understanding the Tuscaloosa Group's structural features will help understand the continuity and depositional history of the sediments that make up most of the Tuscaloosa Group in southwest Alabama and how they can affect reservoir quality.

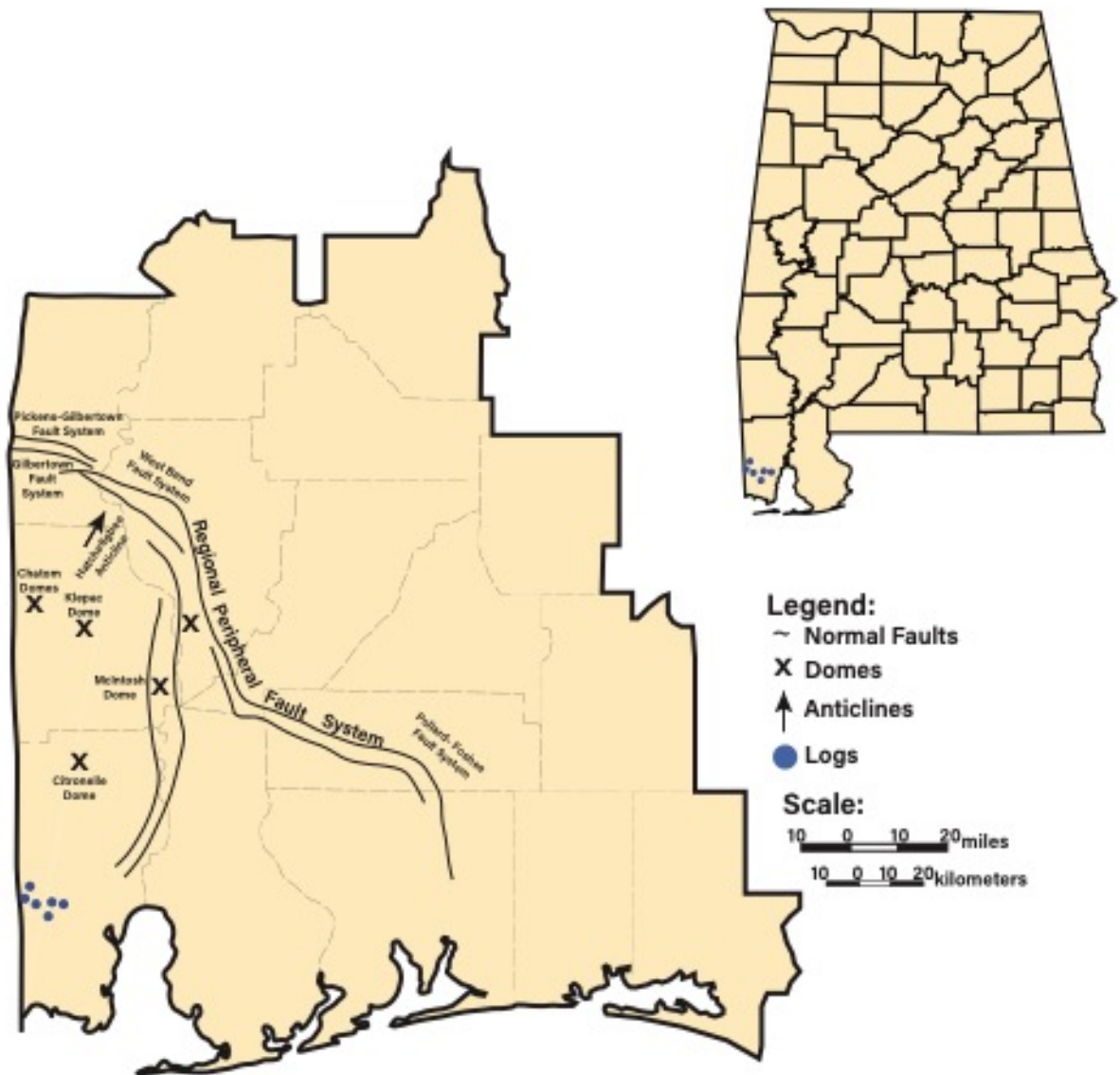


Figure 2: Map showing the structural features in southwest Alabama. (Modified from Mancini et; al 1987). The **X** symbols represent the structural domes formed by salt movements, while the bolded lines represent normal fault of the peripheral fault trend. The blue dots represent the location of the six well-logs used later in this study.

Depositional Environments of the Tuscaloosa Group, southwest Alabama

The Upper Cretaceous Tuscaloosa Group overlies various Lower Cretaceous fluvial-deltaic clastic deposits and is in turn overlain by the Upper Cretaceous Eutaw Formation and overlying Selma Group chalks (Mancini et al., 1987). Thus, the Tuscaloosa Group of southwestern Alabama, as shown in **Figure 3**, is divided into four informal formations: (1) lower Tuscaloosa, (2) Marine Shales, and the (3) upper Tuscaloosa, which is divided into the Pilot sand and the Massive sand (Pashin et al., 2008). The upper Tuscaloosa corresponds approximately to the Coker and Gordo formations of the outcrop area in Alabama's inner Coastal Plain.

Lower Tuscaloosa

The lower Tuscaloosa consists of two informal units, the Massive sand, and the overlying Pilot sand. Both sand units have similar compositions, both thought to be Cenomanian, and have a total thickness of approximately 234 m (770 ft) in southwest Alabama (Mancini et al., 1987). The lower Tuscaloosa sandstones are interpreted as transgressive with an upward gradation from fluvial and deltaic sedimentation to shelf deposits during Cenomanian (Mancini et al., 1987; Pashin et al., 2008).

The Massive sand unit consists primarily of well-sorted, micaceous, fossiliferous, calcareous, glauconitic, fine-grained, and quartz-rich sand, containing subangular quartz grains (Mancini et al., 1987). According to Mancini et al. (1987), this unit's sediments accumulated as sand in a marine-high destructive deltaic system in an adjacent subsurface area of southern Alabama, as seen in **Figure 4**. The Massive sand is interpreted to represent deposition in a wave-dominated and high destructive delta system (Mancini et al., 1987). These medium-grained, well-sorted sands that contain angular quartz grains suggest fluvial, deltaic deposition (Mancini et al., 1987; Pashin et al., 2008). The sandstones are made up of interbedded sandstone and claystone

(Mancini et al., 1987; Mancini and Puckett, 2002; Pashin et al., 2008). This marks the change from fluvial, deltaic depositions (Lower Cretaceous) to marine-dominated depositions (Mancini and Puckett, 2002). The glauconite present in this unit suggests a marine depositional environment (Pashin et al., 2008). The Massive sand has an overall thickness of 137 m, and it is named after the blocky signature it shows in geophysical well logs as observed in **Figure 4** (Pashin et al., 2008). The well logs' signature is interpreted as aggradational sedimentation in the lower part of the Massive sand and the upper part of the unit, fining upward (Pashin et al., 2008). This indicates backstepping that could be associated with marine transgression (Mancini et al., 1987; Pashin et al., 2008). Bivalves and inoceramids have been discovered in these sandstones in this Massive sand unit, confirming marine influence (Mancini et al., 1987).

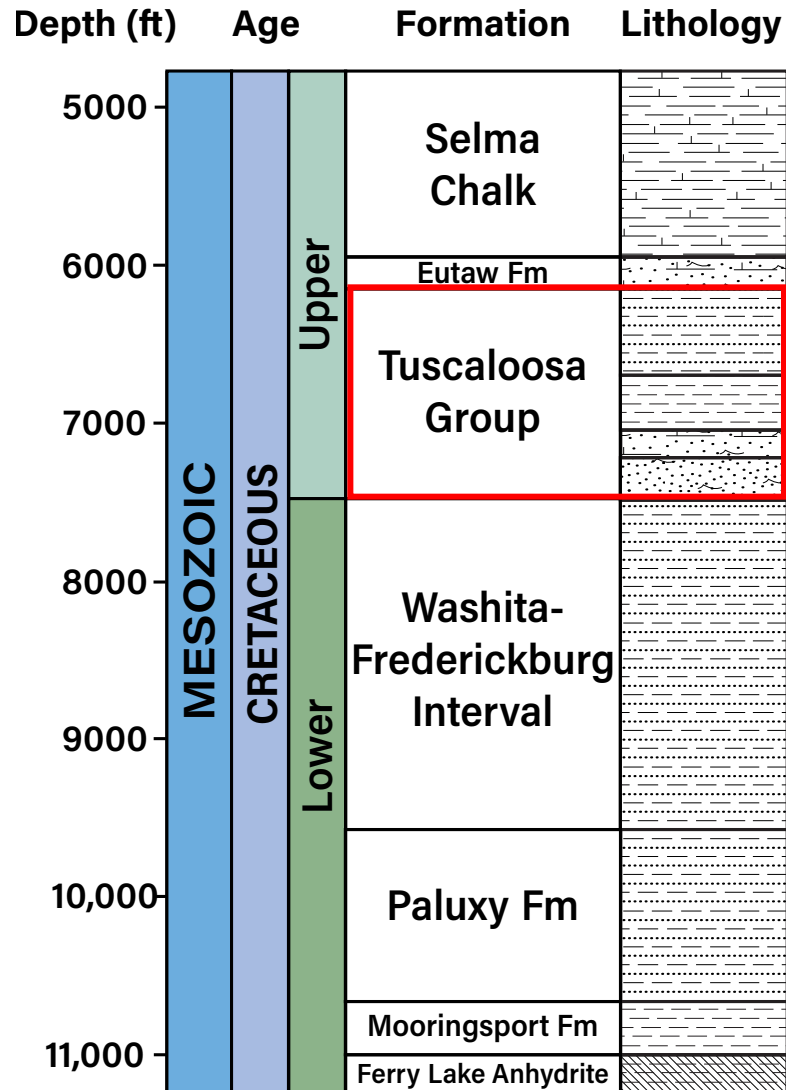
In an adjacent subsurface area of southern Alabama, the Pilot sand unit of the lower Tuscaloosa consists of well-sorted, micaceous, fossiliferous, calcareous, glauconitic, very fine grained, quartz-rich subangular to subrounded quartz grains and has an approximate thickness of 45 m (Pashin et al., 2008). The Pilot sand unit have accumulated as shelf sands during a transgression, marking a return to a strand plain and shelf depositions in coastal and offshore Alabama (Mancini and Puckett, 2002). This unit, as well as the Massive sand unit, contains organic material such as macroinvertebrates, planktonic foraminifera, and calcareous nannofossils (Mancini et al., 1987).

Marine Shales

The Marine shale unit overlies the Pilots and composes the middle part of the Tuscaloosa Group, and has an approximate thickness of 113 m (371 ft). Furthermore, it is Cenomanian-Turonian (Pashin et al., 2008). There is substantial organic content in the Tuscaloosa Group's lower part (Mancini et al., 1987). The deposition of the Marine Shales, as seen in **Figure 4**, may represent a significant rise in sea level in Mexico's northern Gulf (Mancini and Puckett, 2002; Borrok et al., 2019). The Marine Shale unit consist of dark gray, glauconitic, fossiliferous, calcareous laminated claystone interbedded with siltstones of the same composition (Mancini and Puckett, 2002; Pashin et al., 2008).

Upper Tuscaloosa

The upper Tuscaloosa interval is approximately 168 m (550 ft) thick, and it varies in grain size and is Turonian. It is challenging to distinguish the upper Tuscaloosa from the overlying Eutaw Formation (Pashin et al., 2008). In some studies, they are put together for this specific reason. The upper Tuscaloosa consists of mostly green-gray, glauconitic, fossiliferous, medium grained sandstones (Pashin et al., 2008). The deposition of these sandstones may have been initiated by a major fall in sea level. It is thought that these sediments were accumulated in a marine shelf environment, shown in **Figure 4** (Mancini et al., 1987; Mancini and Puckett, 2002).



Legend:

-  Interbedded anhydrite and shale
-  Shale
-  Interbedded sandstone and shale
-  Massive calcareous glauconitic sandstone
-  Calcareous glauconitic sandstone
-  Chalk

Figure 3: Generalized stratigraphic column showing the lower and Upper Cretaceous with their corresponding lithologies and main formations. The Tuscaloosa Group is divided into four informal units or formations, which are the Pilot and Massive sand units from the lower Tuscaloosa, the Marine Shales, and upper Tuscaloosa. (Modified from Pashin et al. 2008).

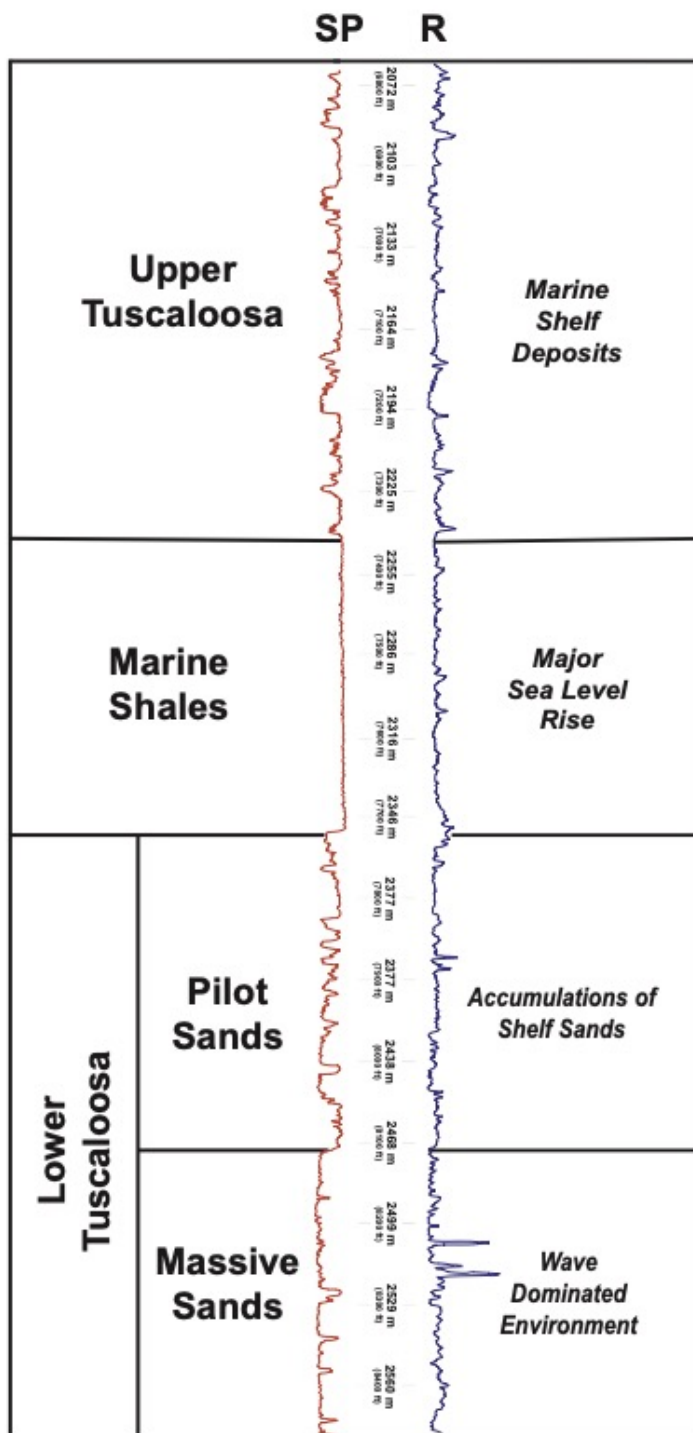


Figure 4: Well log for Julian F. McGowin #1 (permit 1419), southwest Alabama, showing the four informal stratigraphic units within the Tuscaloosa Group, and their perspective depositional environments based on their log reading and previous studies.

Mineralogy of Glauconite

Glauconite $[(K, Na) (Fe^{3+}, Al, Mg)_2(Si, Al_4O_{10}(OH)_2)]$ is commonly known as an authigenic mineral in the clay and mica family (Holland, 2014; Baldermann et al., 2015). It is most commonly found in peloidal forms found in sandstones and carbonate rocks. This mineral forms under various physical conditions. The common peloidal form likely forms from material that originated from fecal pellets, and the mineral also has nine different morphologies (Holland, 2014). These individual pellets are usually associated with environments with low sedimentation rates and shallow marine continental shelf deposits, around 30 m to 500 m (98 ft - 1640 ft) (Chafetz and Reid, 2000; Holland, 2014). As for the chemical conditions, glauconite is believed to be constrained. Because the mineral can form in sandstones (acid) and carbonates (basic), it could be assumed that pH is not essential for its formation (Holland, 2014). The key factor for the chemical condition in which this mineral form is the reduction of iron in its environment (Thompson and Hower, 1975). The mineral overall is iron-rich and contains different amounts of potassium (Oddin, 1988). Typically, there are more Fe_2O_3 than FeO , making the mineral ferric (Holland, 2014; López-Quirós, 2019).

Because of the high iron content, there could be a clear distinction between glauconite and illite/smectite. Overall, the mineral can be easily identified by its green, yellow-green color and its distinctive peloidal form. Glauconite may also replace other grains such as quartz, cherts, micas, feldspars, calcareous grains, and volcanic fragments (Zhang et al., 2017). The colors do vary with maturation, as it is seen in **Table 1.1**. The darker the glauconite, the more mature it is, and the higher the micaceous content (Amorosi, 1997; López-Quirós et al., 2019). The maturity of glauconite can also be read recognized in an XRD analysis as a progressive shift from a more clay glauconite, which can peak at 14 Å, to more micaceous glauconite, which peaks at 10 Å (Amouric,

1985; Amorosi, 1997; Huggett and Gale, 1997). Precipitation of glauconite within fractures of other existing grains, also indicative of a more highly evolved glauconite. In order for mature glauconite to form, the depositional environment needs to have this low sedimentation rate (Holland, 2014).

Color	K ₂ O content	Mineralogical Structure	XRD Peak	Maturity
Pale Green	< 4%	Glauconite Smectite	14 Å	LOW
Light Green	4 – 6%	↓	↓	MODERATE
Green	6 – 8%			HIGH
Dark Green	> 8%	Glauconite Mica	10 Å	VERY HIGH

Table 1.1: Maturity labels of glauconite based on color, K₂O content and XRD peaks. (Modified from (Amouric, 1985; Huggett and Gale, 1997; Adriaens et al., 2014).

2. Methods

Drill-Core Sampling

A set of 43 drill core samples were obtained from the Geological Survey of Alabama. The samples were collected from the Julian F. McGowin #1 (permit no. 1419) drilled core, shown in *Figure 5*. The samples were taken at a rate of one to 3-6 meters (10-20 ft) intervals. The interval depended on the length and completion of the drill core. This drill core was used to (1) document lithological changes, (2) describe textural characteristics and mineralogy, (3) study and photograph sedimentary structures, and (4) observe and record vertical changes in texture and mineralogy about the well's e-logs. Approximately 500 grams (1 lb.) of each sample were collected at selected depth points for rock preparation in the sedimentary geology laboratory at the Department of Geosciences at Auburn University. Refer to *Appendix: Part 1* for all core photographs.



Figure 5: Sections from the Julian F. McGowin #1 (permit no. 1419) drill core. Drill core samples were obtained from the Geological Survey of Alabama. This drill core's overall depth ranges from 7137-8435 ft (2175 - 2571 m).

Well Log Correlation

Well-log data were obtained from the Geological Survey of Alabama to corroborate the textural and mineralogical information of the sampled drill cores and correlate between wells in the area to assess continuity of sand bodies, specifically of the glauconitic sandstones, within the informal units of the Tuscaloosa Group. A total of six electronic well logs were used for this study, including the Julian F. McGowin #1, which was used to locate the glauconites in the study area. These electronic logs (e-logs) included conductivity, resistivity, gamma-ray, and spontaneous potential logs. As the first step, the tops and bottoms of each location were picked by analyzing each individual e-logs. A datum was also chosen to serve as a reference for the entire correlation. Because spontaneous potential (SP) and Resistivity (R) logs were present in all the e-logs, they were the two main types of logs used to correlate. Gamma-ray log was used to confirm the presence of sandstones with high amounts of glauconite.

This part of the methods is useful in assessing the lateral continuity of the informal units within the Tuscaloosa Group and the sand bodies within those units. The correlation is also useful because it shows the extent and internal properties of the Tuscaloosa Marine Shales, which could serve as a potential seal regarding CO₂ injection. All six well logs are shown in *Figure 6*.

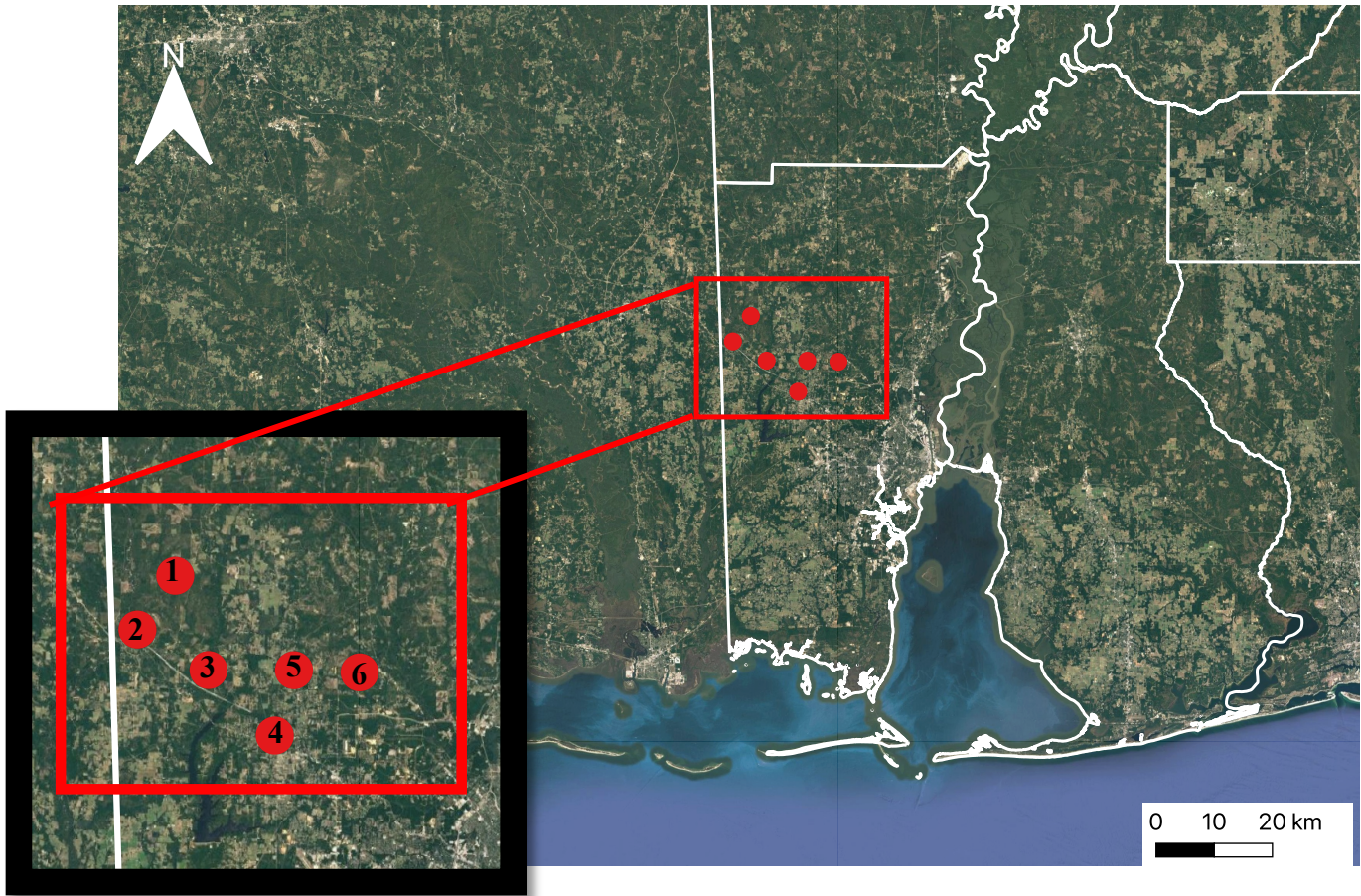


Figure 6: Map showing the location of the six e-logs that were used for log correlation. This method aimed to observe the stratigraphy and thickness of the sandstones that make up most of the Tuscaloosa Group in the study area.

Petrographic Thin Sections

A total of 25 samples were sent by mail to the National Petrographic Services, Inc., for thin section preparation. The samples were chosen based on visible glauconite content, sample size, and specific depth points in which lithological changes were abruptly marked, as shown in **Figure 7**. The thin sections were impregnated with blue epoxy to identify the porosity of the sandstones easier. Thin sections were also stained to identify any available feldspathic minerals. If there were any visible thin sections by identifying feldspars, the sandstones' depositional environment and provenance could be better understood. Refer to **Appendix: Part 2** to see thin section photographs of all 25 samples.

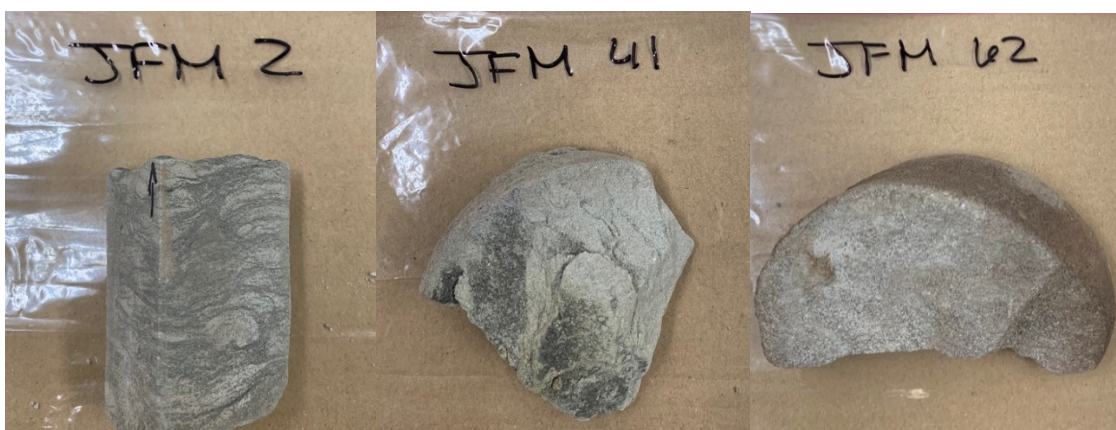


Figure 7: Three samples from the forty-three collected from the Juliann F. McGowin #1 drill core were chosen for thin section preparation. Each sample is from a different depth.

X-Ray Diffraction Analyses

The XRD analysis was used alongside petrographic observations to understand the mineralogical composition of porous and sand intervals more in-depth. For this method, a total of 20 samples were chosen based on visible glauconitic content and depth. The instrument used was the Bruker D2 Phaser X-ray Diffractometer. This instrument contains a scintillation counter and Lynxeye detector and uses Cu-K α radiation. Before being run in the XRD, the samples were hand

crushed and powdered using a spinning ball mill machine. The results and peaks were analyzed using the PC-based DIFRAC EVA software. A table was created to show each sample's most prominent minerals' bulk composition based on the peaks. Refer to *Appendix: Part 3* to see bulk composition of the sandstones, as well as their peak graphs.

Scanning Electron Microscopy (SEM)

The SEM was used to observe microstructures, glauconite grains, and sand-grain topography. A total of six samples were chosen from various depths based on glauconitic content. The six samples were divided into two different sets: (1) three containing the most glauconite throughout the entire drill core and (2) three that contained small amounts of glauconite. By doing drill core observation and thin sections, it was noted that the bottom of the core contained sandstones that did not contain a large amount of glauconite. The samples were first gold coated using an EMS150R Plus Rotary Pumped Coater. Samples were 1.27 cm to 2.50 cm (0.5 in to 1 in) in size. After coating, they were mounted on studs for scanning on a Zeiss EVO 50 microscope, *Figure 8*. More porous samples, such as JFM47, JFM48, and JFM55-2, needed to be double coated. The reason for double coating the samples was because the samples were too brittle and porous and were not fully covered in gold. With only one gold coat, it was hard to look at any grains through the SEM. For better imaging purposes, the samples were observed through backscatter electron microscopy (BSE), as seen in *Appendix: Part 4*.

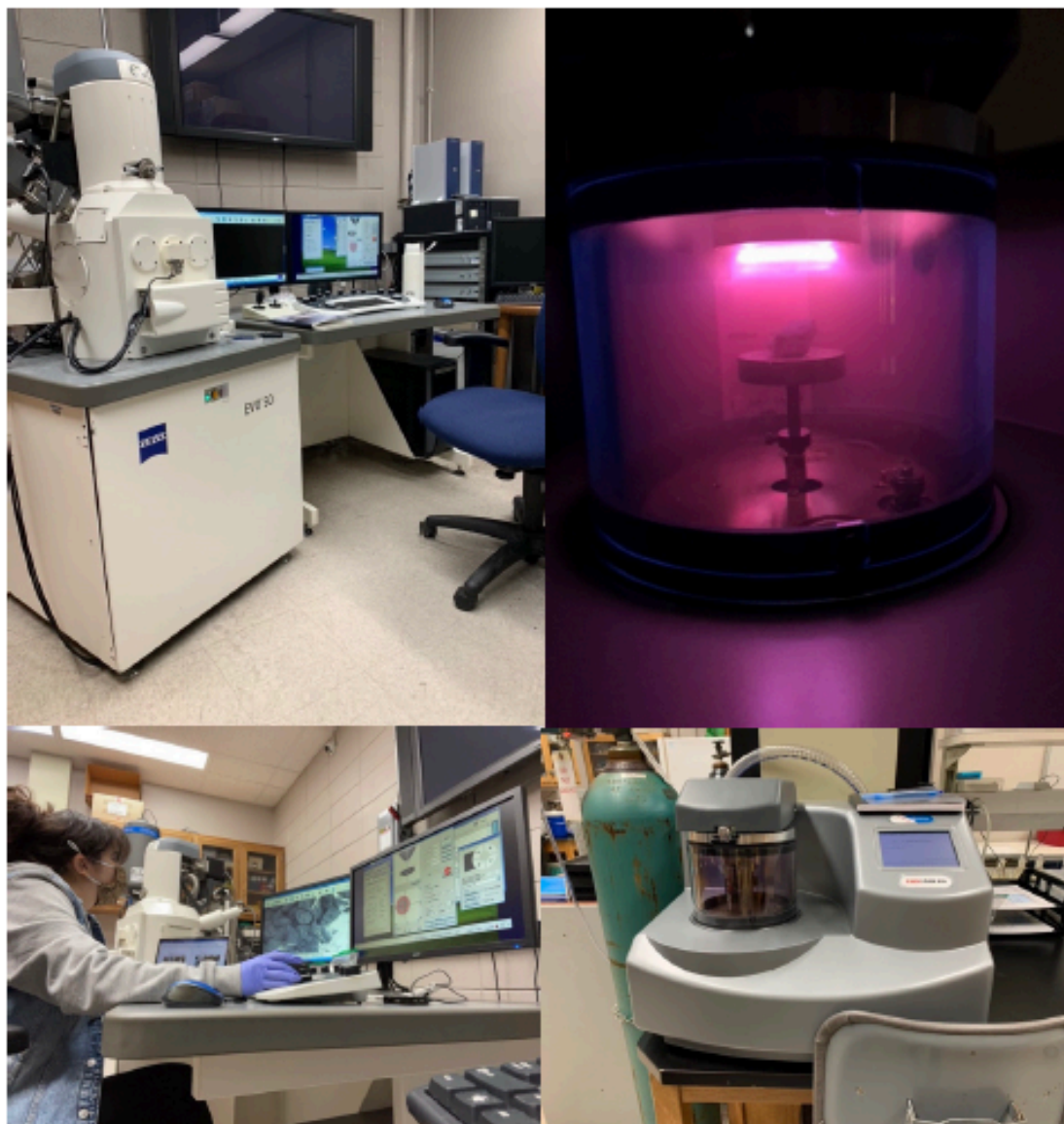


Figure 8: The SEM analysis instrument was a Zeiss Evo 50 in the James Harrison School of Pharmacy lab, run by Dr. Michael Miller.

Geochemical Experiments

For this method, mineralogical data and aquifer brine conditions from previous studies and the Geological Survey of Alabama were obtained. A total of six samples were hand-crushed and interacted with synthetic brine and CO₂ inside a rocking autoclave. This rocking autoclave apparatus allowed external control, and it also monitored temperature and pressure. The temperature and pressure conditions were similar to the natural conditions of the Tuscaloosa Group from southwest Alabama. The temperature used in the experiment was 88°C (190°F), the bottom hole temperature and maximum temperature recorded from the Julian F. McGowin #1 log. Pressure data were obtained from previous studies, and the general formation pressure for the Tuscaloosa Group in southwest Alabama is 24 MPa (3480 psi) (Tucker and Kidd, 1993). The synthetic brine was created using aqueous geochemical data from the Geological Survey of Alabama and previous work, and it can be seen in **Table 2.1**. The setup for this experiment was similar to the one done in Kaszuba et. al (2003).

The six samples sent were divided into two sets of experiment, and this ran concurrently next to each other. One set contained sandstones which contained little to no glauconite (Set A) and the second set contained sandstones approximately made out of 20%-25% glauconite (Set B). The glauconites for this second set were removed by the hand-picking method. As seen in **Figure 9**, the unconsolidated sandstones interacted with the synthetic brine inside an apparatus like the one shown in **Figure 10**, for approximately 30-40 days. After this initial month, the supercritical CO₂ was injected into samples and fluid. Measurements were taken once every week, and experiments ran for a total of two months. The measurements taken through this method were: pH, Eh, dissolved inorganic carbon (DIC), and amount dissolved Fe²⁺ concentration.

In-situ pH was also measured to give a better understating of the conditions of the Tuscaloosa Group, southwest Alabama. This part of the method was done using the program Geochemist Workbench (Bethke, 2008). An activity diagram was also created using Geochemist Workbench (GW) to observe mineral stability of the sandstones of the Tuscaloosa Group, southwest Alabama, as a function of oxygen and pH values. The thermodynamic properties used for glauconite were obtained from Blanc et al. (2015). Refer *Appendix: Part 5* to see see geochemical data and the thermodynamic parameters used to create the activity diagram.

Original basis	moles	mass (g)	Molecular wt.	comment
Al+++	0.00E+00	0.00	26.98	from analysis for well A-25-11
Ca++	9.56E-01	38.30	40.07	
Cl-	3.383	119.93	35.45	
Fe++	0.00E+00	0.00	55.84	
H+	6.31E-06	0.00	1.00	
H2O	55.50	999.84	18.01	
HCO3-	1.60E-03	0.09	61.02	
K+	4.90E-03	0.19	39.10	
Mg++	1.57E-01	3.81	24.30	
Na+	1.18E+00	27.02	22.98	
O2(aq)			31.99	
SO4--	1.10E-02	1.05	96.06	from the calculation, the solubility of quartz at 50°C (122° F)
SiO2(aq)	2.35E-04	0.01	60.08	
Si	2.35E-04	0.00	28.08	

Table 2.1: Basis species with their respective amounts used for measuring in-situ pH in Geochemist Workbench. Data obtained from the Geological Survey of Alabama.

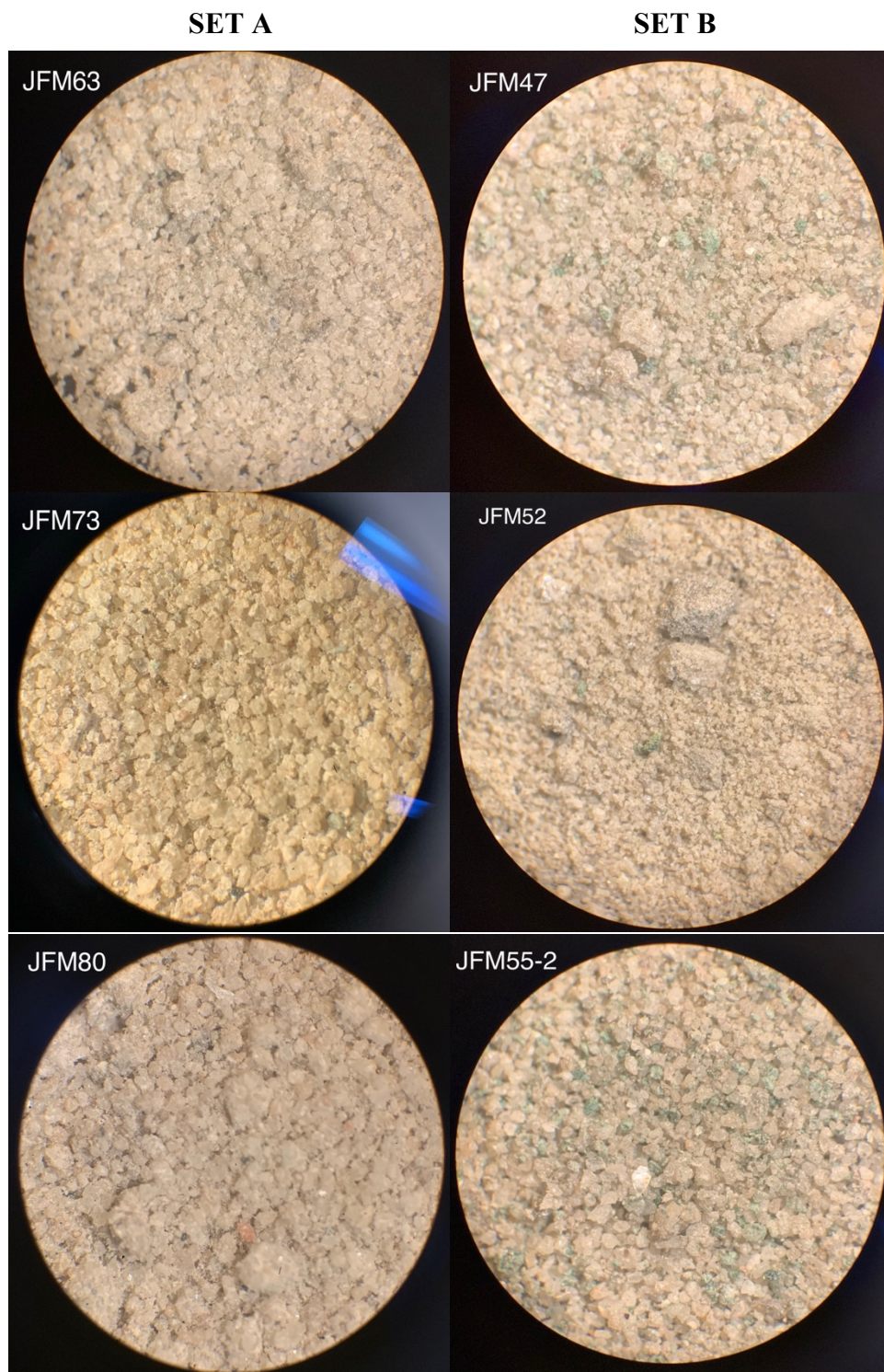


Figure 9: Set of six samples used for the hydrothermal experiments. Samples JFM 47, 52, and 55-2 (right) contained the most visible glauconite of all 43 collected samples. Samples JFM 63, 73, and 80 (left) contained little to no glauconite grains.

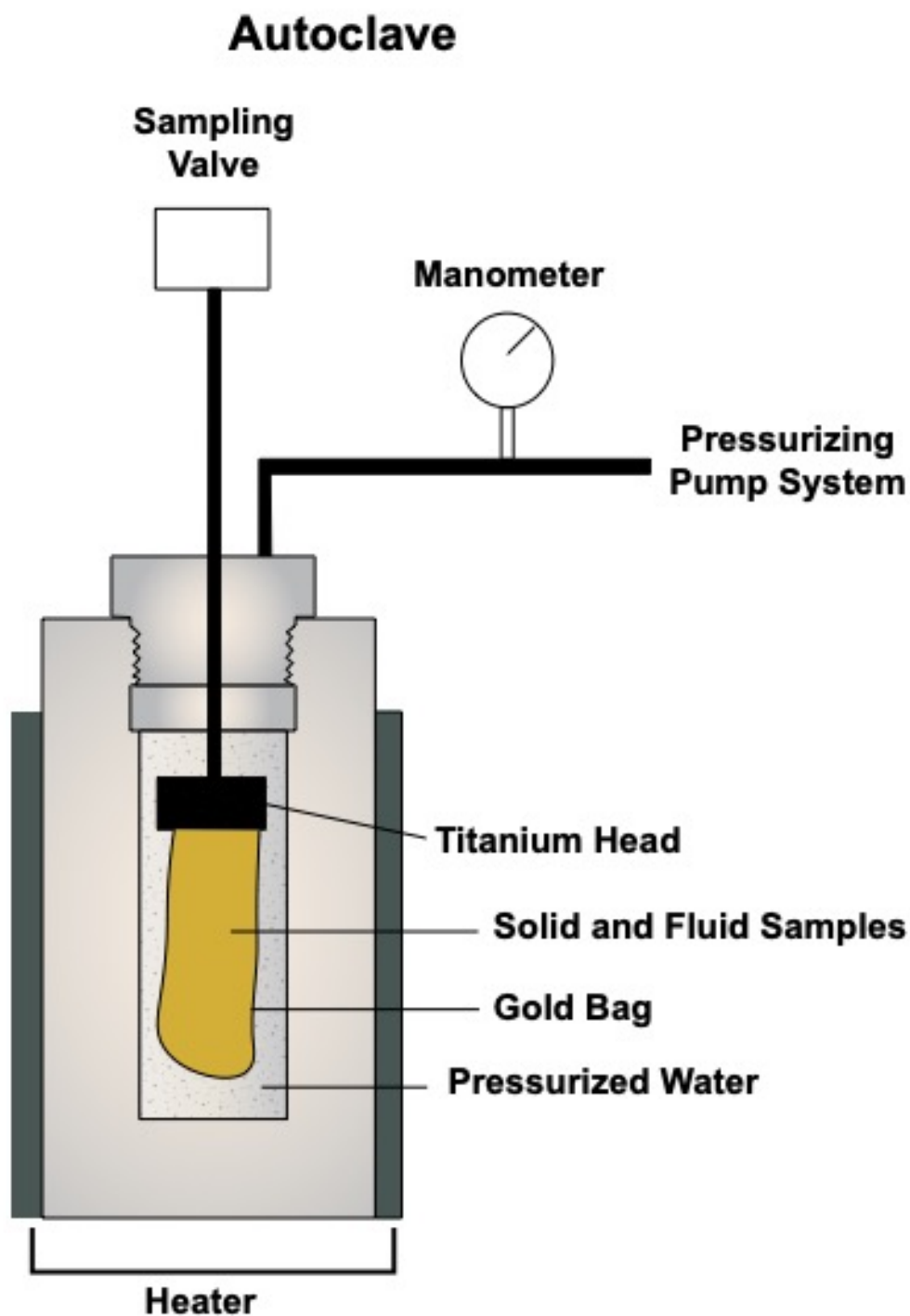


Figure 10: Schematic diagram of an experimental hydrothermal system. Brine-rock interactions and supercritical CO₂ injection took place inside an apparatus similar to this one. Previous hydrothermal studies have used this type of autoclave to analyze fluid and solid interactions. (Modified from Seyfried et al. 1987).

3. Results

Well-Log Correlations

A total of six e-logs were used for log correlation to delineate the internal stratigraphy of the Tuscaloosa Group in the study area. The six wells for which there were e-logs used in this study are all located 6437 m – 9656 m (4-6 miles) from each other. **Table 3.1** shows the exact location of these six e-logs as well as their tops and bottoms. Before correlating, the tops for each Tuscaloosa subgroup were chosen by their log characteristics, as shown in **Table 3.2**. The average thickness in this region is approximately 513 m (1686 ft), with the thickest informal unit being the lower Tuscaloosa, and the overall study area where the well logs were located was approximately 302.4 km² (116.8 miles²). **Figure 11** shows a panel diagram that shows the lithological correlation of the informal units within the Tuscaloosa Group.

The overall Tuscaloosa Group can be divided into sandstones and shales, based on the log curves and core observations. The porous sandstones had low spontaneous potential (SP) readings, with resistivity (R) curves varying. This was the case for most of the upper Tuscaloosa, in which R readings varied greatly, indicating that the informal unit mainly comprises interbedded sandstones and shales and changes in porosity. This pattern was also observed in the Pilot sands from the lower Tuscaloosa. For the Marine Shales, the SP reading was the highest, and resistivity was the lowest of all the informal units. The Massive sands in the lower Tuscaloosa gave a low SP reading with R also varying. As for the sections that contained sandstones with a large amount of glauconite grains, **Figure 12**, the logs read as high SP and R again varying. Previous studies suggest that sandstones that glauconite grains, or greensands, can sometimes read as shales or tight rocks and have low resistivity readings (Kennedy, 2015).

Well ID	Permit #	Lat	Long	Top	Bottom
Illinois Central Gulf Railroad #1	2888	30.90804	-88.36506	6650	8500
Julian F. McGowin #1	1419	30.86816	-88.39678	6790	8500
Arco Millertown 25-14 #1	6306	30.83896	-88.33569	6800	8500
Board of Supervisors #1	971	30.79124	-88.27849	6895	8500
North Woods Unit 27-16 #1	2408	30.83956	-88.26275	6890	8500
Harriet Kelly Gill #1	251	30.8385	-88.20671	6900	8500

***Table 3.1:** Name and location of the six electronic logs that were used for correlation. These logs were close by each other in southwestern Alabama.*

Well ID	UT Top	UT Bottom	MS Top	MS Bottom	LT Top	LT Bottom
Illinois Central Gulf Railroad #1	6650	7220	7220	7600	7600	8500
Julian F. McGowin #1	6790	7350	7350	7710	7710	8500
Arco Millertown 25-14 #1	6800	7345	7345	7725	7725	8500
Board of Supervisors #1	6895	7480	7480	7845	7845	8500
North Woods Unit 27-16 #1	6820	7360	7360	7750	7750	8500
Harriet Kelly Gill #1	6900	7400	7400	7750	7750	8500

***Table 3.2:** Tops and bottoms (in feet) for each of the Tuscaloosa Group, southwestern Alabama. All six e-logs ended at 2590 m (8500 ft).*

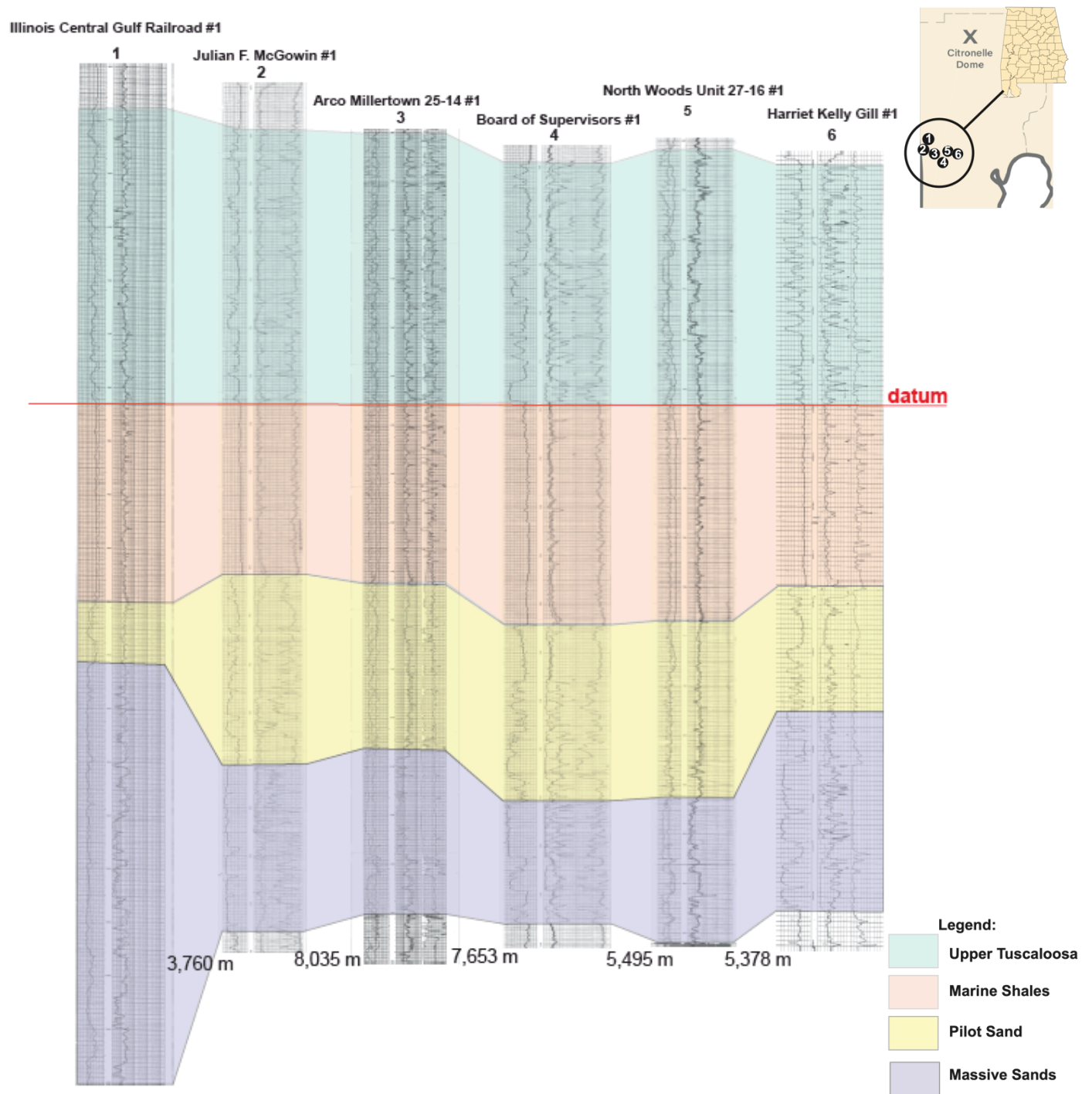


Figure 11: Panel diagram of the correlation of the Tuscaloosa Group in the study area.

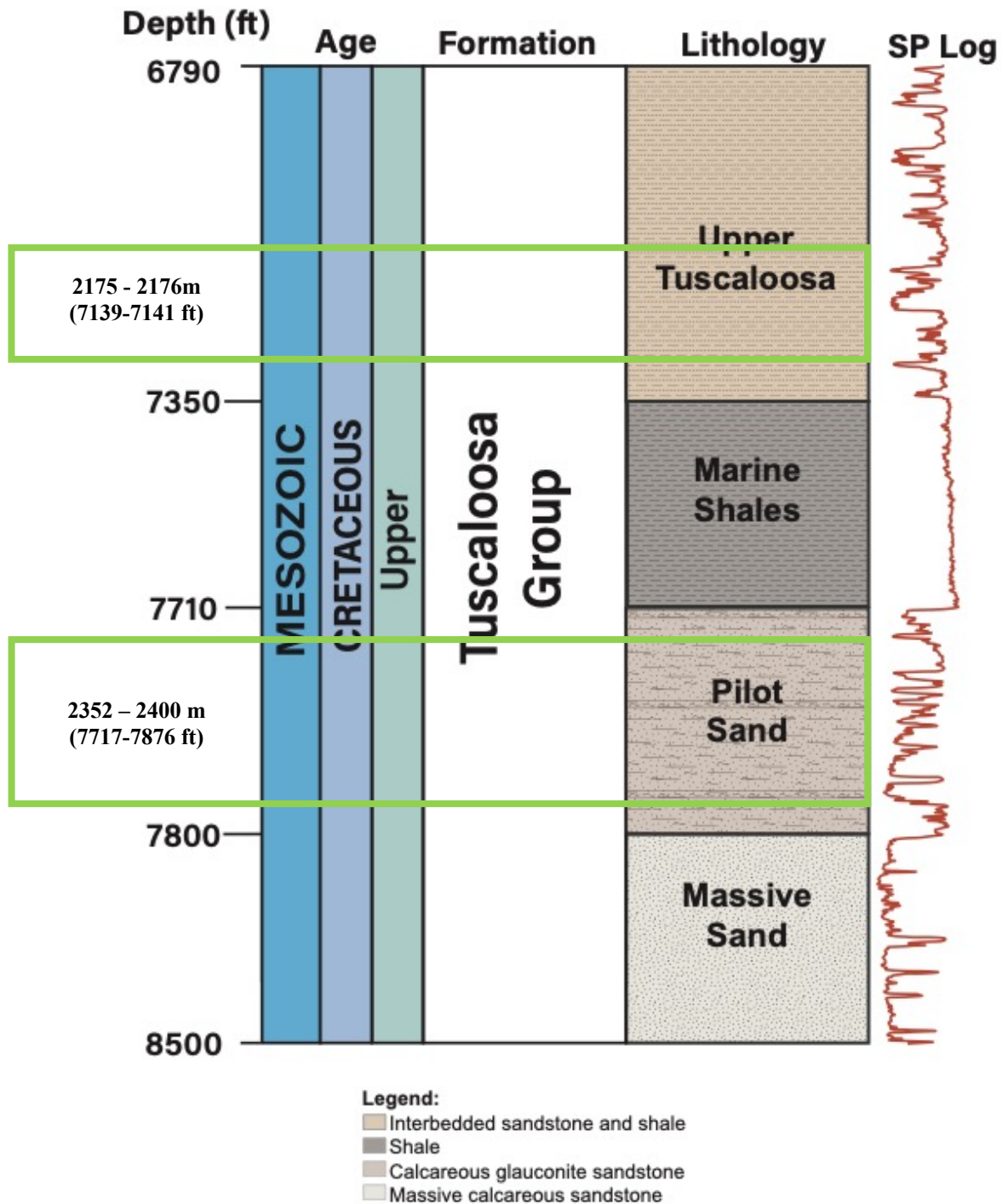


Figure 12: Julian F. McGowin #1 well log showing the four informal units of the Tuscaloosa Group, southwest Alabama, and the location of the glauconitic sandstones throughout the log. The location of the glauconite-rich zones were identified based on lithological, petrographic and log observations.

Correlation of the Lower Tuscaloosa

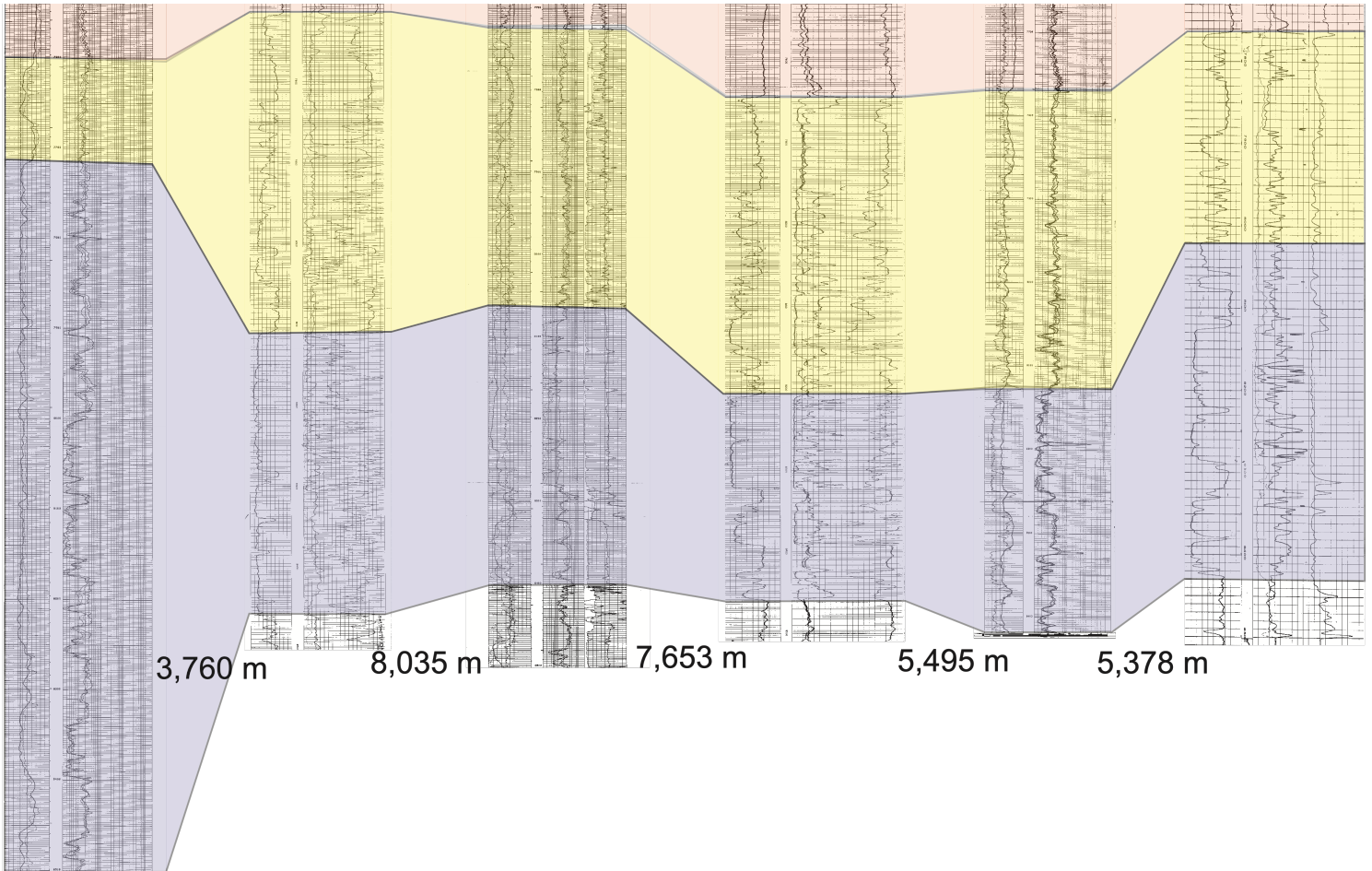


Figure 13: Log section showing the lower Tuscaloosa and its two informal units: Pilots and (yellow) and Massive sands (purple).

The lower Tuscaloosa, **Figure 13**, was divided into the two informal units, Pilot (yellow) and Massive sands (purple), for the log correlation. The Pilots read as interbedded sandstones and shales, and the Massive sand read as very porous sand and, as it was mentioned in Pashin et al. (2008), they gave very distinctively "blocky signature" addition. The Massive sands were the thickest in northwest direction, while the Pilot sands were southeast. The overall top of the lower Tuscaloosa ranged from 2316 m – 2391 m (7600 ft – 7845 ft).

The Pilot sands gave overall high resistivity values. The SP, GR, and R readings were similar to those of the Upper Tuscaloosa, with SP and GR deflecting to the left. This reading could have been attributed to the fact that glauconite was present at 2352 m – 2553 m (7717 ft – 7876 ft) in the Julian F. McGowin #1 drill core, **Figure 14**. The mineral glauconite is primarily present at these depths, and although petrographic and core observations indicate that the rocks are porous sandstones, well logs suggested only a high clay content and porosity, therefore, a good indicator to identify glauconite presence in the cores was to look for low SP and GR values, as well relatively high R values. However, this was not the case for the majority of the glauconite bearing sandstones in this study. As shown in **Figure 14**, some of the sandstones that make up part of the Pilot sands did not contain much glauconite, but they did have large amounts of micas and their grains were cemented together. These gave a higher SP and GR reading in comparison to the sandstones with large amount of glauconites.

The contact between the Pilot and the Massive sands was not evident in all logs. However, this contact point was chosen based on sharp changes observed in the SP and GR lines, as shown in **Figure 15**. Petrographic observations suggested that the Massive sands are mostly made up of quartz grain, and XRD data showed intensity percentages of clay minerals and glauconite. These observations correlate with the reading of the well logs. Since these Massive sand samples contain low to no glauconite content, the SP and GR lines read as porous sands. These sand bodies were continuous were also continuous through the correlated area of southwest Alabama.

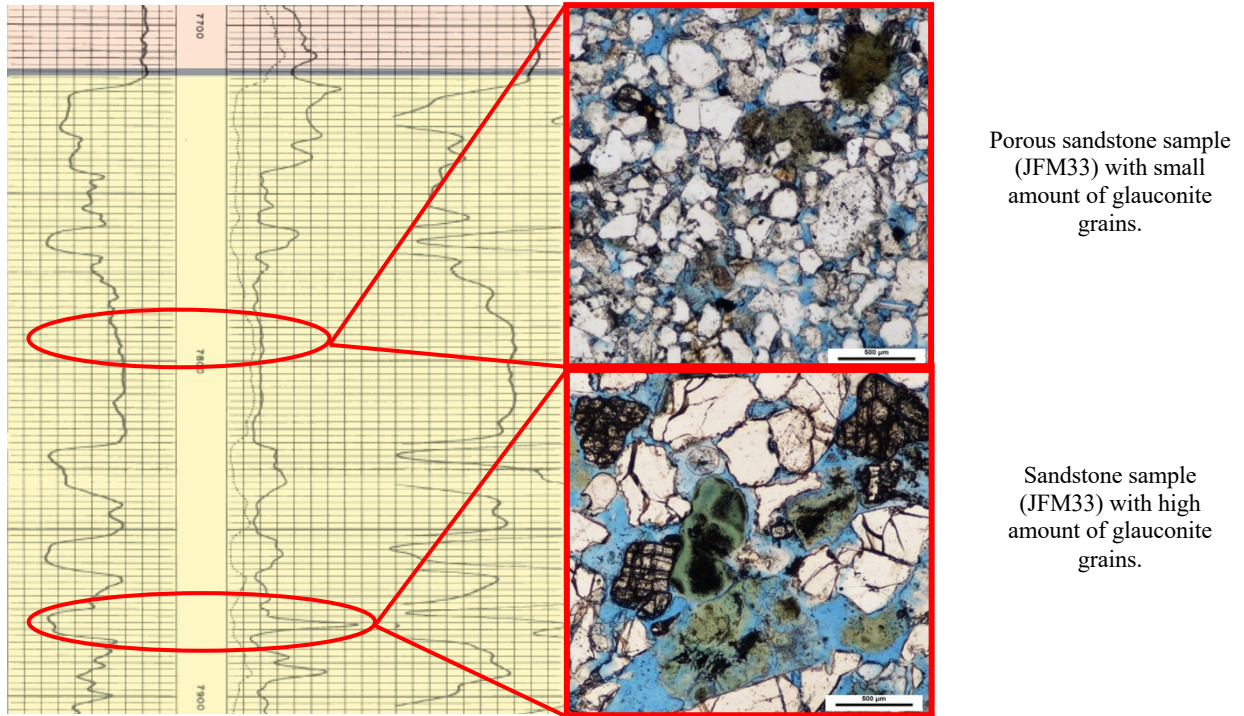


Figure 14: Section of the Julian F. McGowin #1 SP and R readings and the sharp contact between the bottom of the Marine Shales, and the top of the Pilot sands.

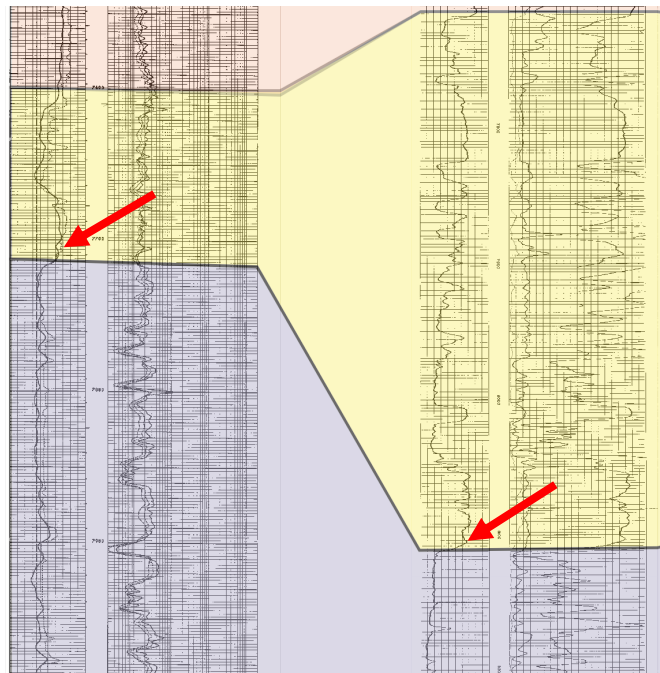


Figure 15: Sections Illinois Central Gulf Railroad #1 and Julian F, McGowin #1 showing the sharp change in SP and R readings between the contact of the top Pilots and the top of Massive sands.

Correlation of the Marine Shales

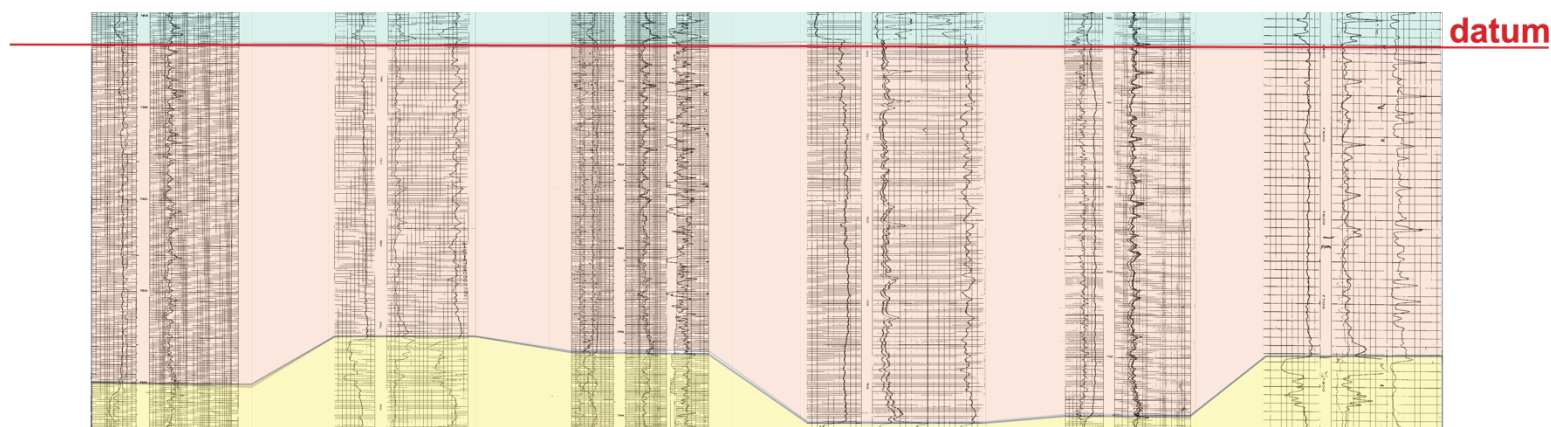


Figure 16: Log section showing the Marine Shales (red) of the Tuscaloosa Group.

The Marine Shales were easier to identify in the logs. Gamma-rays' curves and SP were used to locate the shales, and the tops were at depths ranging from 2200 m – 2280 m (7220 ft – 7480 ft). Resistivity and conductivity (C) curves varied, but overall maintained low-negative values, as it is shown in **Figure 16**. The top of this subgroup (Marine Shales) was used as the datum for the log correlation because it marks a sharp sea level change. The top of the Marine Shales and the bottom of the upper Tuscaloosa mark sea level fall, while the bottom of the Marine Shales and the top Pilot sands mark a drastic sea level rise. These shales were continuous across the correlation section, and because of this, they could potentially serve as a cap rock if CO₂ is sequestered in the unit below, the lower Tuscaloosa.

Correlation of the Upper Tuscaloosa

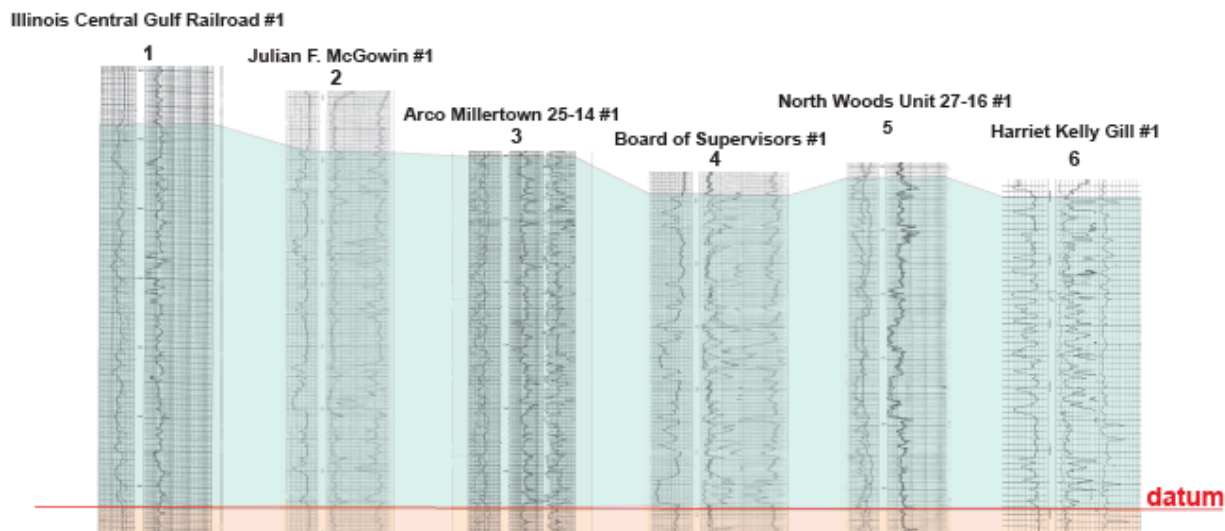


Figure 17: Log section showing the upper Tuscaloosa (green of the Tuscaloosa Group).

The upper Tuscaloosa read as interbedded sandstones and shales, **Figure 17**. Therefore, based on previous studies and log characteristics, it can be assumed that the top ranges from 2026 m – 2103 m (6650 ft - 6900 ft) in all six e-logs. The interbedded sandstones with shales were best observed in SP and R logs. This sand body was the most continuous of all the informal units, and it kept the same thickness throughout the entire correlated area.

Resistivity (R) reading varied in the upper Tuscaloosa, similar to the Pilot sands of the lower Tuscaloosa. This distinctive read possibly be because of the presence of glauconite in the sands and the difference in porosity. The mineral glauconite is mainly present at depths intervals of 2175 m – 2182 m (7139 ft – 7160 ft) in the Julian F. McGowin #1 drill core, which are part of the upper Tuscaloosa and the Pilot sands of the lower Tuscaloosa.

Drill Core and Petrographic Analyses

Petrographic observations show that the sandstones that makeup part of the Tuscaloosa Group are mostly made up of subangular to subrounded quartz grains, glauconite, chlorite, orthoclase, kaolinite, muscovite, and small amounts of calcite grains, as shown **Figure 18**. In some samples, kaolinite, and iron-rich minerals such as hematite act as pore cement for the grains. The sorting of the sandstones varies, from moderately sorted to very well sorted. The sandstones plot mainly as quartz arenite in Folk's ternary diagram (1980), as shown in **Figure 19**.

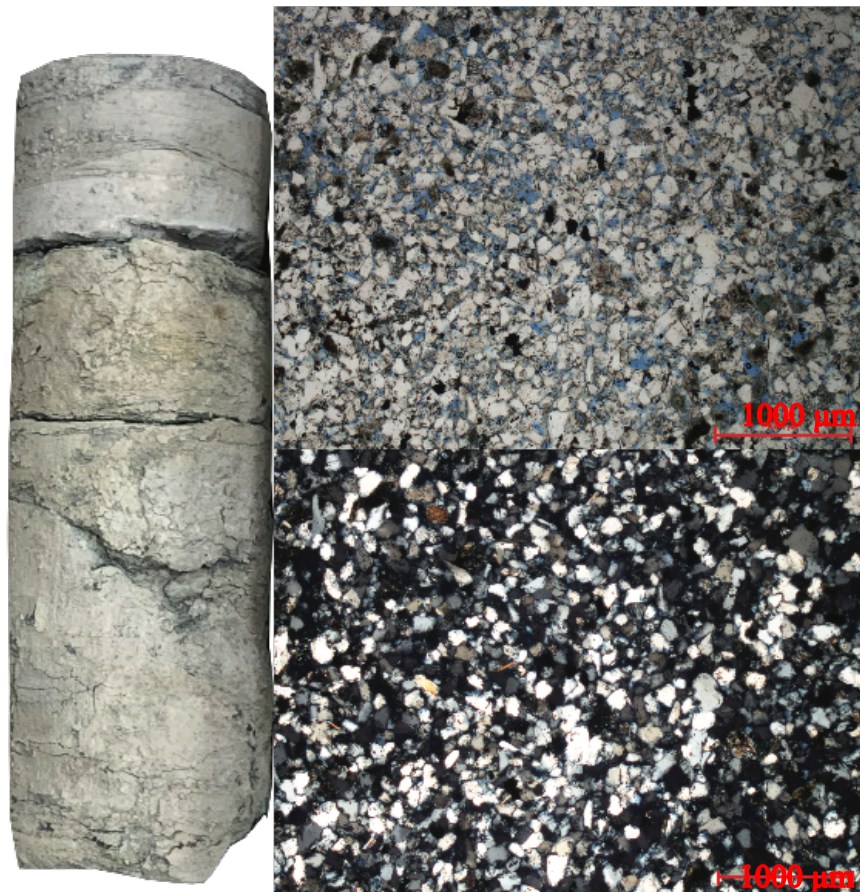


Figure 18: Thin sections in PPL and XPL from a section of the Julian F. McGowin #1 drill core at 2384 m (7821 ft) on the left of the figure. Thin sections show the subangular detrital quartz grains that make up most of the Tuscaloosa Group's sandstones in the southwest of Alabama.

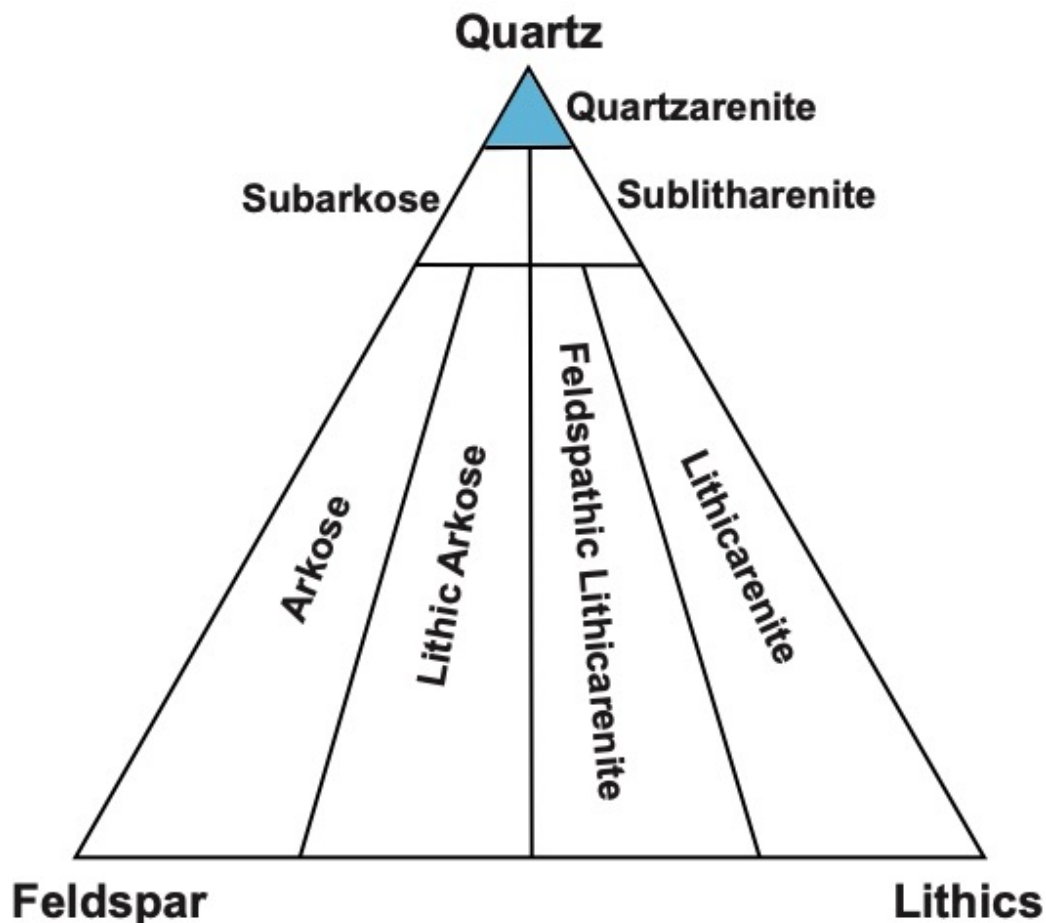


Figure 19: Most samples plot in the quartz arenite, shaded in blue, section of the Folk diagram (1980) due to the high content of quartz grains in all samples. (Modified from Folk 1980.)

The dominant framework detrital grain is quartz, and its content ranges from approximately 65% - 95%. These quartz grains vary in size, from fine to coarse-grained. Quartz grains showed undulate extinction in most samples. These detrital quartz grains were most commonly white and light grey. Quartz grain size varied throughout the core, finning upward, as shown in **Figure 20**. Potassium feldspar (K-feldspar) was another abundant framework mineral. The framework grain content varies from 5%-10%. Although the thin sections were stained to better observed feldspars, it was hard to distinguish between plagioclase and orthoclase. However, XRD data later

determined that the feldspars mineral present in these samples was orthoclase. At lower depths, orthoclase was most abundant. Another dominant framework grain found throughout most collected samples was muscovite, with content ranging from 5%-20%. This mineral appeared as elongated platy fragments through most thin sections, as shown in *Figure 21*. The minerals chlorite and calcite were present but at very low amounts, ranging from 2%- 5% throughout the whole drill core, based on thin section observations. These major framework grains were cemented together, in some samples, by hematite and clay cement. The formation of these cements could have resulted from feldspars being dissolved, especially with clays around the quartz grains and glauconite pellets, *Figure 22*.

The dissolution of these minerals could have led to secondary porosity, enhancing the sandstones' permeability to serve as a CO₂ reservoir. Based on previous studies and petrographic observations made in this research, the chronological sequence of the Tuscaloosa Group could be interpreted as follows: (1) deposition of detrital minerals such as quartz, feldspars, and micas, (2) feldspar and mica dissolution; (3) formation of glauconite pellets; (4) pore-filling clays such as kaolinite; and (5) opaque minerals filling pore and fractures within pre-existing grains.

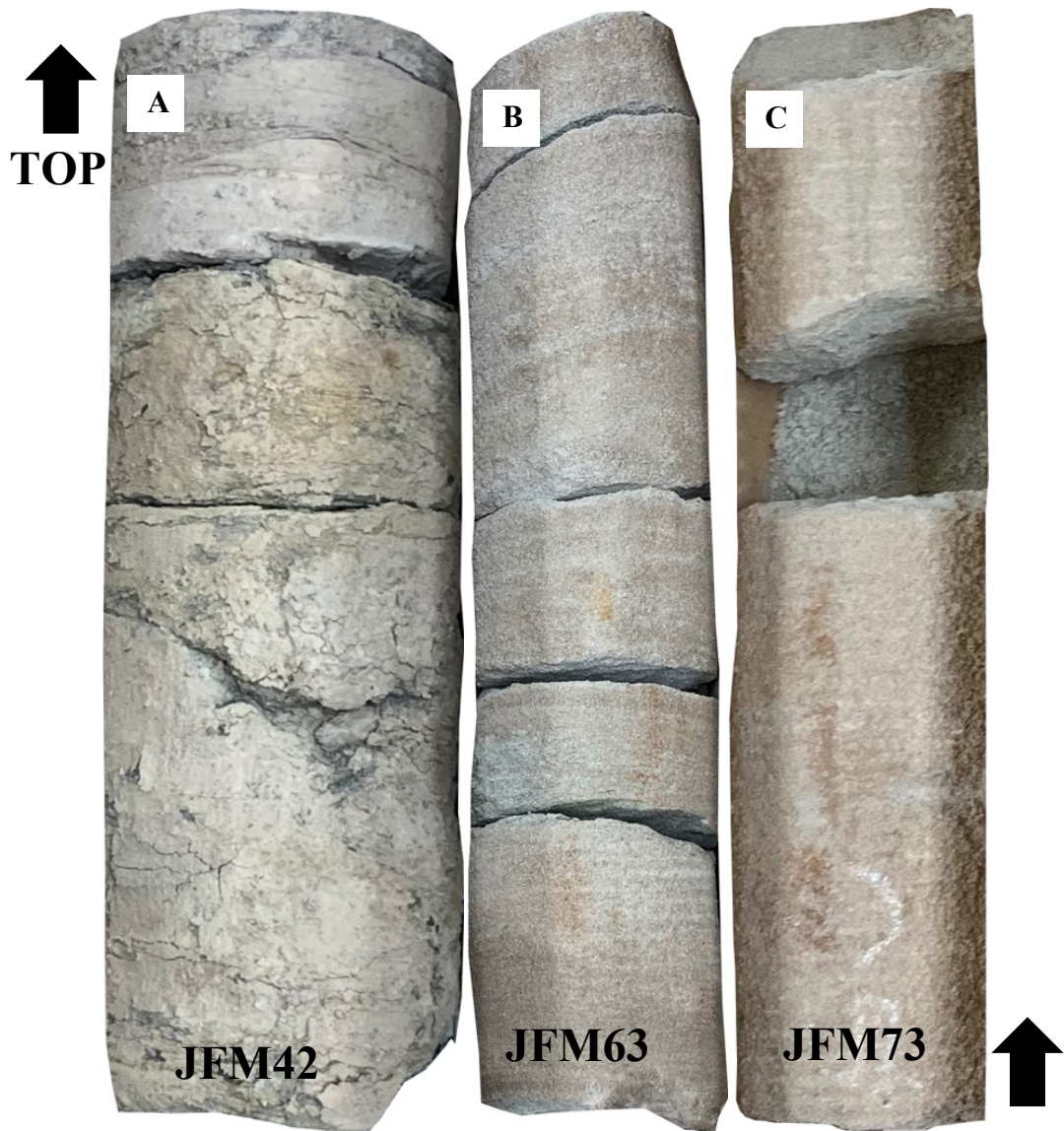


Figure 20: Three different core sections from different depths from the Julian F. McGowin drill core. The sandstones that make part of the drill core have detrital quartz grains as the dominant framework grain, and these grains' sizes vary in size. At more shallow depths at 2384 m (7821 ft), the quartz grains are finer (A) and coarser as the depths increase, around 2560 m (8398 ft) (B).

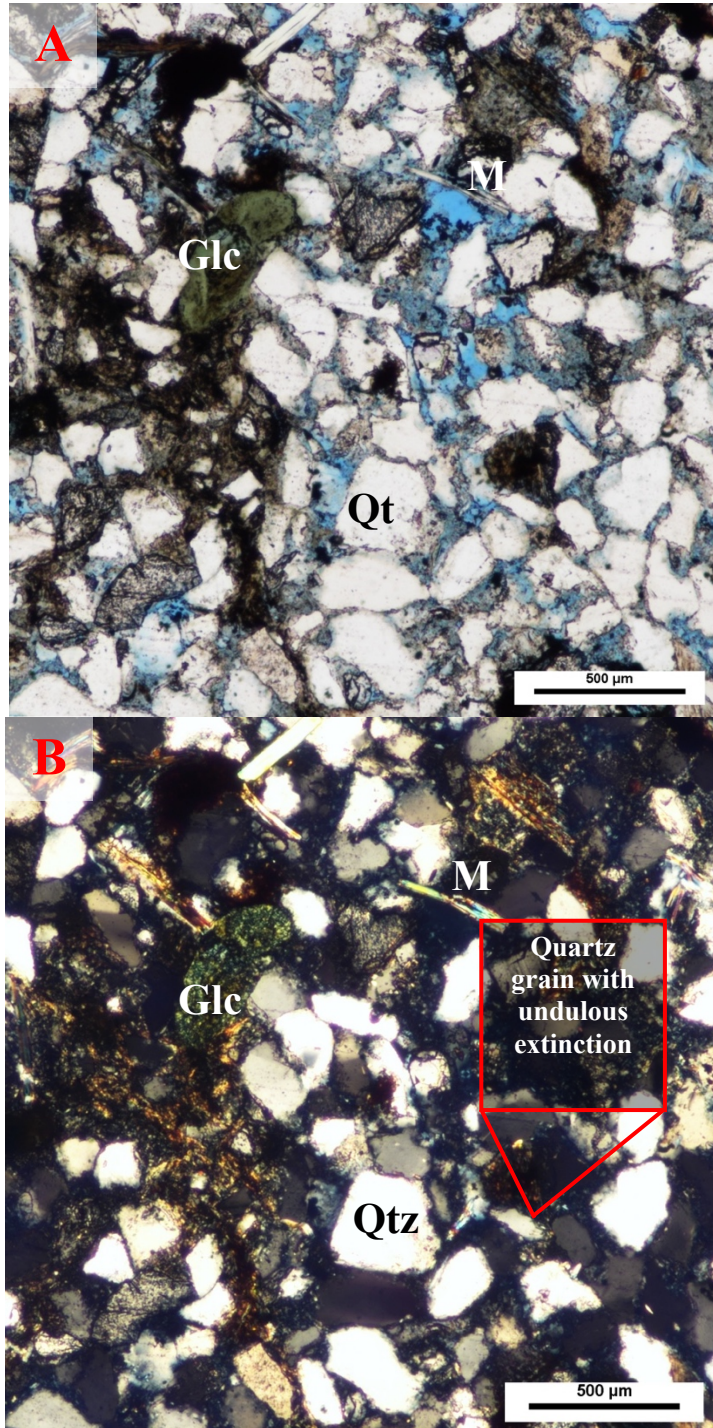


Figure 21: Two thin sections from sample JFM2 in plane-polarized (A) and cross-polarized (B). The green grain in both figures is the mineral glauconite (Glc) figure shows the angularity of the quartz (Qt) grains and elongated platy micaceous minerals (M). Both figures also show an opaque mineral acting as cement for some grains.

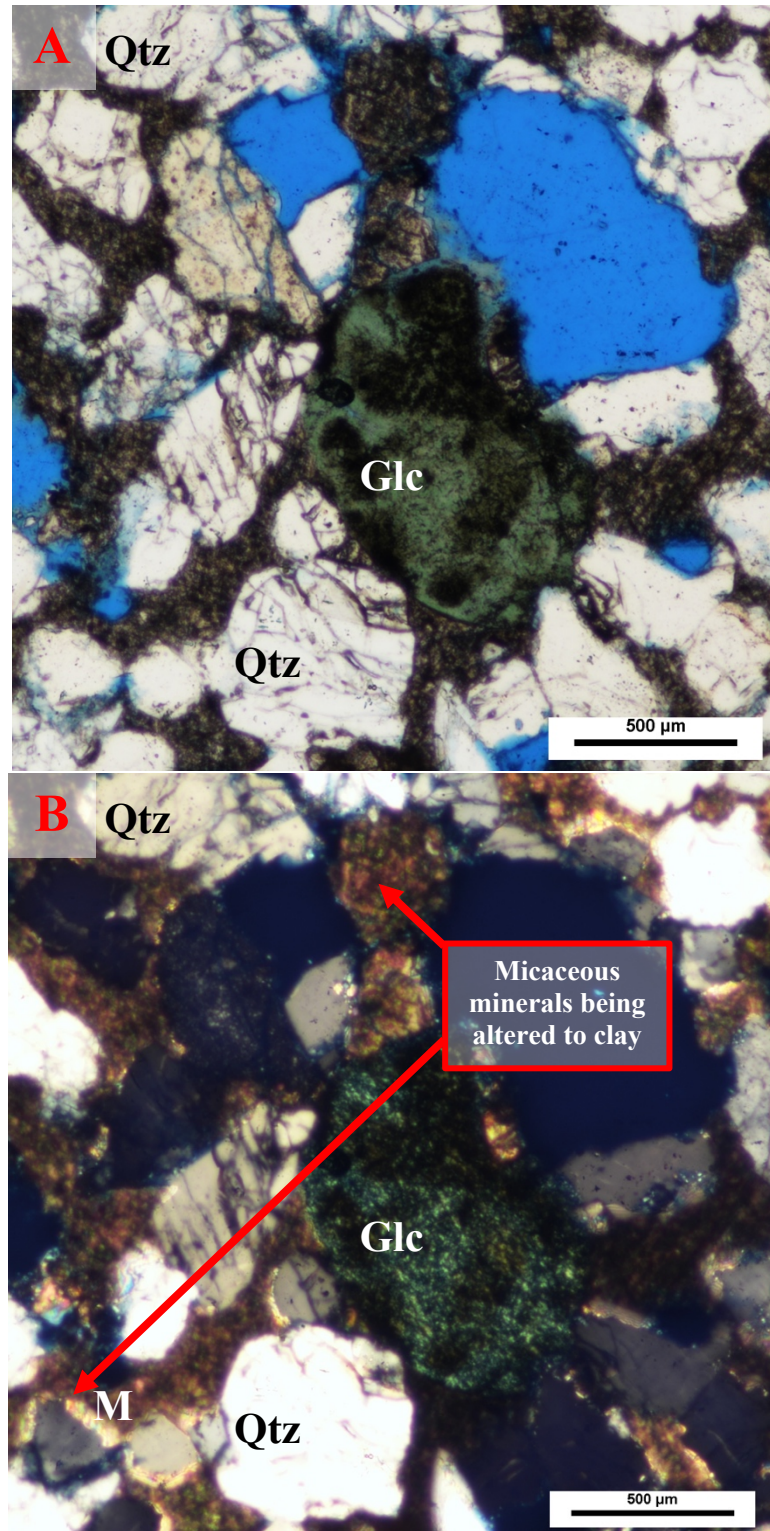


Figure 22: Two thin-section photographs in plane polarized (A) and cross-polarized (B) from sample JFM47. Quartz (Qtz) grains glauconite (Glc) is cemented by calcite and clay replacement of feldspars (brownish in plane-polarized).

XRD and SEM Analyses

XRD data revealed that quartz is the most abundant mineral. The intensity percentage varied from 62% - 96%. The other abundant minerals recognized by XRD analysis were berlinite, (30%-50%), illite (4%-7%), biotite (1%-11%), muscovite (1%-11%) and glauconite (3%- 4%). The samples that contained large amount of glauconites had relatively low intensity, peaking at approximately 12 Å. This suggest that the glauconite grains are highly mature. SEM imaging, *Figure 23*, also showed the oval shape of these grains. This observation gave a better understanding on the maturity of the glauconite grains. For the sandstones that contained little to no glauconite, the peaks did not match in the XRD graph readings. Chlorite appeared to be more abundant in those sandstones. There was an increase in chlorite percentage in the XRD data. These sandstones, which are part of the Massive sands of the lower Tuscaloosa, had a higher orthoclase content in comparison to the sandstones that make part of the Pilot sands and the upper Tuscaloosa.

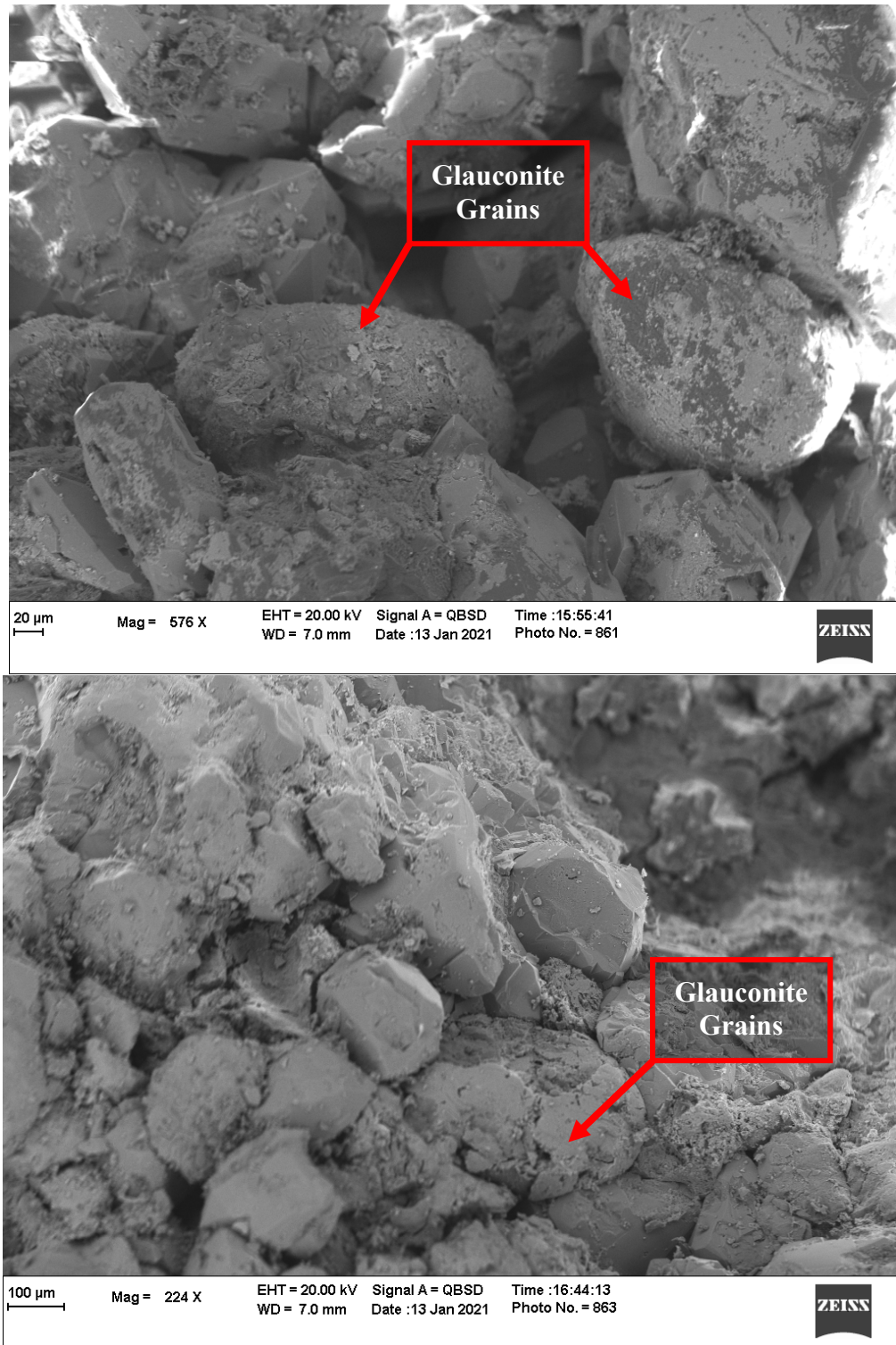


Figure 23: Scanning electron microscope (SEM) image showing the pellet glauconites before geochemical experiments.

Geochemical Experiments

Pre-CO₂ Injection:

Two set experiments ran simultaneously to compare how supercritical CO₂ affects glauconites present in the Pilot sands of the lower Tuscaloosa. First, a series of measurements were performed and were interpreted together for a more accurate description and analysis. Samples JFM63, JFM73, and JFM80 (Set A) contained no glauconite, and samples JFM42, JFM52, and JFM 55-2 contained glauconite (Set B), shown in **Tables 3.4** and **Table 3.5**. Before CO₂ injection, both experimental sets maintained a constant pH value, between 5-6. The behavior in pH suggests that there were no major interactions between rock samples and brine fluid. Other measurements such as Fe²⁺ and Eh differ between sets, with Set B having lower values for Eh, and higher Fe²⁺ concentration, before injection of CO₂. Additionally, it was observed in petrographic analyses that: (1) hematite acts as a cement between the grains of the sandstones of the Tuscaloosa Group in the study area, and (2) hematite was slowly replacing glauconite, **Figure 24**. These two observations were more evident in the sandstones that contained glauconite, suggesting that natural reservoir conditions are favorable for the precipitation of hematite under oxidizing conditions.

The in-situ pH values were calculated using React in Geochemist Workbench (GW) using benchtop pH and DIC measurements. In-situ pH measurements gave a better understanding about reservoir conditions, which is used to give a more accurate understanding of the consequences of injecting CO₂ into the sandstones study in these experiments later on. Measurements suggested that the reservoir does have a high buffering capacity based on pH values. This part of the experiment was useful to better compare the effects of supercritical fluid post injection later on.

Set A: No <i>Glauconite</i>	Sample ID	Hours Condition	pH	DIC (ppm)	Fe (II) ppm	Eh (V)
	01-000	-	5.3	-	-	-
	01-001	0.3	6.0	0.91		0.07
	01-002	334.3	5.2	0	<0.2	0.12
	01-003	1080	5.7	1.09	0.21	0.28
<i>Sample ID</i>	<i>Depth</i>	<i>Amount each</i>	<i>Total Amount</i>			
JFM63	8383-8385	4.42g				
JFM73	8403-8405	4.95g	12.63g			
JFM80	8417-8419	3.48g				

Table 3.4: Data obtained from the geochemical experiments before CO₂ injection. Set of samples with no glauconites.

Set B: <i>Glauconite</i>	Sample ID	Hours Condition	pH	DIC (ppm)	Fe (II) ppm	Eh (V)
	02-000	-	5.3			
	02-001	523.4	5.5	6.59	<0.1	0.15
	02-002	744.1	5.6	4.05	0.42	0.09
	02-003	1339	5.5	2.52	0.45	0.10
<i>Sample ID</i>	<i>Depth</i>	<i>Amount each</i>	<i>Total Amount</i>			
JFM47	7832-7836	4.81g				
JFM52	7852-7856	3.81g	14.63g			
JFM55-2	7864-7868	6.46g				

Table 3.5: Data obtained from the geochemical experiments before CO₂ injection. Set of samples with no glauconites.

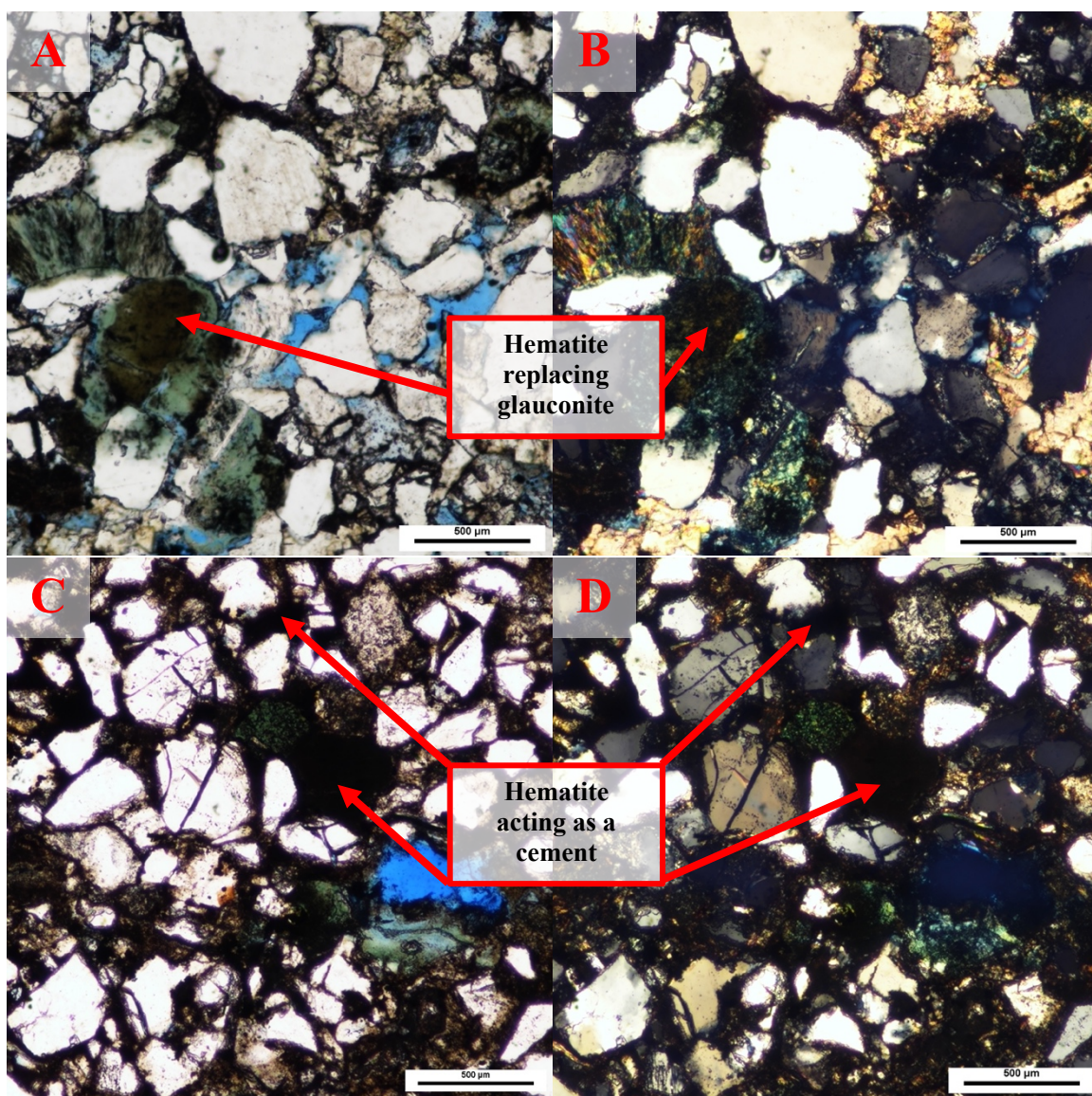


Figure 24: Thin section photographs from the lower Tuscaloosa showing hematite replacing glauconite (A) and (B) in sample JFM20, and hematite acting as a cement between quartz grains in sample JFM57 (C, D).

Post-CO₂ Injection:

The data obtained from this part of the experiment shows a greater decrease in pH values, as shown in *Tables 3.6 and 3.7*. For both experimental sets the in-situ pH ranged from 3-4, becoming more acidic due to the injection of CO₂. This was expected since CO₂ increases acidity (Lu et al., 2012). For both sets of experiments, pH started to decrease in small increments as the experiment ran. For Set B, pH continued to decrease, suggesting the solution has not reached equilibrium, (*Figure 25*). The only difference between Set A and Set B is that Fe²⁺ and Eh measurements slightly differ. For Set A, Fe²⁺ measurements ranged between 0.6-5 ppm, and Eh values ranging between 0.07-0.28 V. As for Set B, Fe²⁺ measurements ranged from 3-12 ppm, and Eh values decreased from 0.12 V to 0.07 V. This decrease in Eh in Set B could be an indication of conditions starting to reduce in the solution. These conditions are favorable for the formation of minerals such as siderite, according to previous studies (FeCO₃) (Tutolo et al., 2020b). Based on previous research (Tutolo et al., 2020b), it was expected that Fe²⁺ measurements increased once CO₂ was injected. This increase suggests that Fe²⁺ is being added to the solution, as a result mineral dissolution. This, however, is not an indication of mineral precipitation.

Set A: No Glauconite	Sample ID	Hours Condition	In-situ pH	DIC (ppm)	Fe (II) ppm	Eh (V)
	01-004	1540	3.5	672	0.6	-
	01-005	1583	3.6	565	3.7	0.07
	01-006	1680	3.5	618	4.1	0.12
	01-007	1846	3.6	552	5.7	0.28
Sample ID	Depth	Amount each	Total Amount			
JFM63	8383-8385	4.42g				
JFM73	8403-8405	4.95g	12.63g			
JFM80	8417-8419	3.48g				

Table 3.6: Data obtained from the geochemical experiments after CO₂ injection. Set of samples with glauconites.

Set B: Glauconite	Sample ID	Hours Condition	In-situ pH	DIC (ppm)	Fe (II) ppm	Eh (V)
	02-004	1408	3.6	423	3.2	0.12
	02-005	1480	3.5	576	6.4	0.08
	02-006	1575	3.5	842	8.5	0.08
	02-007	1742	3.6	564	12	0.07
Sample ID	Depth	Amount	Total Amount			
JFM47	7832-7836	4.81g				
JFM52	7852-7856	3.81g	14.63g			
JFM55-2	7864-7868	6.46g				

Table 3.7: Data obtained from the geochemical experiments after CO₂ injection. Set of samples with glauconites.

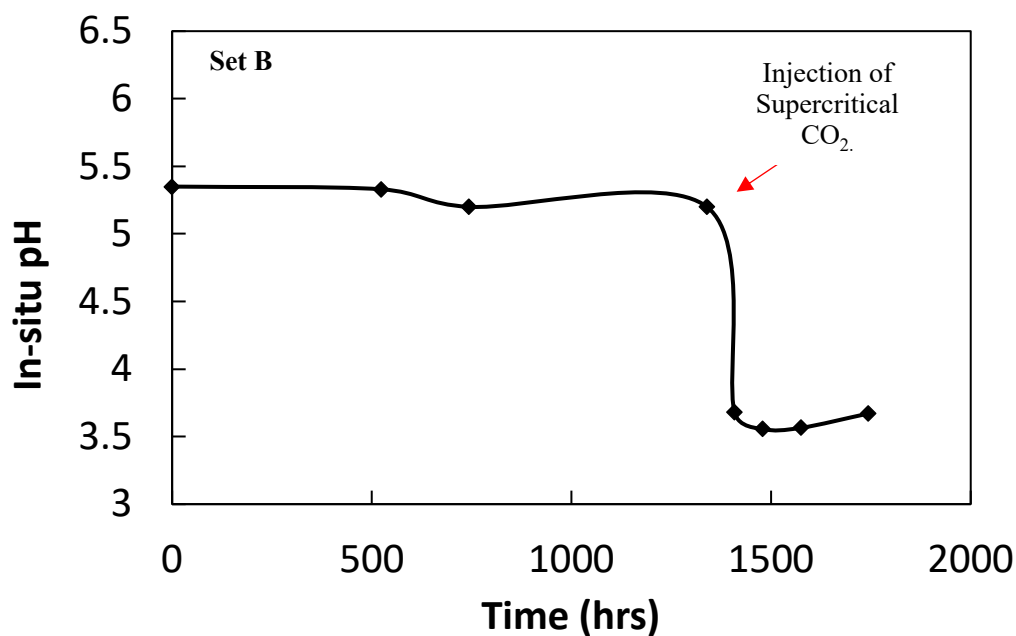


Figure 25: Graph showing the relationship between time (hrs.) and calculated in-situ pH for Set B. Dotted red line shows the trend of pH in relation to time..

Geochemical Model

To better understand stability fields of Fe minerals in the samples of the Tuscaloosa Group, an activity diagram was constructed using the synthetic brine measurements showed in **Table 2.1**, and thermodynamic properties of “ideal” glauconites as suggested by Blanc et al. (2015). This diagram, **Figure 26**, shows the mineral pyrite and siderite dominating at reducing and acidic conditions. The diagram in **Figure 26** also shows evidence iron bicarbonate forming at even more acidic conditions ($\text{pH} < 3$). The presence of FeHCO_3^+ in the solution could be the reason why we see an increase of Fe^{2+} values in both sets of experiments (**Table 3.6** and **Table 3.7**). The diagram in **Figure 26** shows evidence of glauconite being thermodynamically unstable under reducing and acidic conditions. Based on the geochemical model in **Figure 26**, it can be assumed that glauconite dissolution forms siderite, pyrite, and FeHCO_3^+ . The mineral siderite, however, does not seem to

be stable, only forming at conditions where pH=3.3 and Eh ranges from 0.07-1.0 V in the diagram. The diagram also suggests that dissolution of siderite forms FeHCO_3^+ , since siderite seems to only form at very specific conditions.

In summary, the activity diagram suggests that glauconite dissolves as a result of pH decreasing and reducing conditions. The samples of this present study did not seem to show evidence of mineral precipitation, based on the diagram in **Figure 26**, because after the experimental run, the samples still plot within the glauconite phase. If CO_2 were to be injected in these glauconitic sandstones of the Tuscaloosa Group, southwest Alabama, at similar temperature and pressure conditions, the mineral glauconite could dissolve and form siderite, FeHCO_3^+ and pyrite. Although no physical observations were made on the rock samples that interacted with fluid and CO_2 , based on the obtained data it can be assumed that glauconite does not affect reservoir quality in this area, since CO_2 injection will result in the formation of FeHCO_3^+ and siderite.

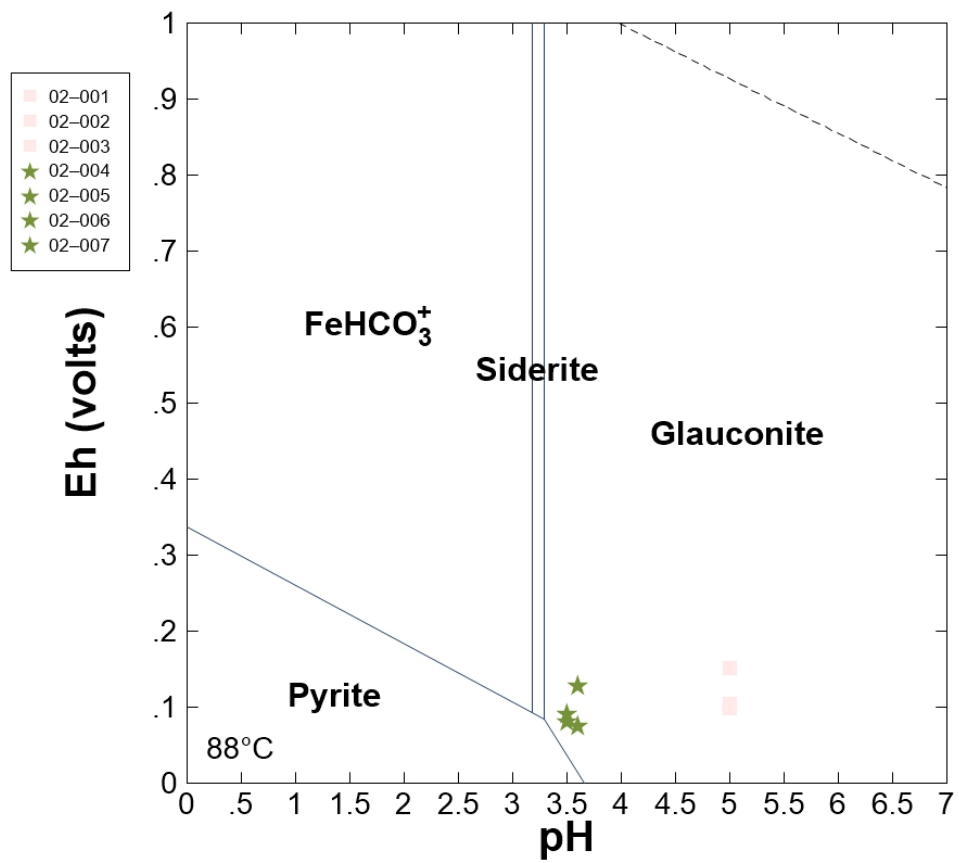


Figure 26: Activity diagram showing stability fields of Fe minerals in the Tuscaloosa Group, southwest Alabama. The green stars represent the glauconite rich sandstones of the Tuscaloosa Group.

4. Discussion

Well-Log Correlation

Well log correlation gave a better understanding of the stratigraphy of the study area, as well as a clearer overview of the distribution of porosity and permeability of the sand bodies, glauconites in sand, and adjacent confining units (i.e., shales). The glauconitic sandstones of the Pilot sands and the upper Tuscaloosa Group were the main focus for this study. This research as well as previous studies show that these sandstones meet the criteria of composition, porosity (25%), permeability (0.213d), depth >800m (>2627 ft) (Mancini et al., 1987; Pashin et al., 2008; Herzog, 2018). Overall, it was observed in most e-logs that the presence of glauconite in the sandstones did not significantly affect the log curves. The only e-log that included a gamma-ray (GR) curve did read the part of glauconitic sandstones as clays. **Figure 27** shows the GR curve (bold line) deflecting to the left as if it were a clay or shale, whereas the spontaneous potential (SP) curve (dotted line) indicates coarser siliciclastic grain size; this is a combined e-log indicator of glauconite-rich sand. Although previous studies suggest that in some cases, glauconite may give a clay effect on well logs, this was not the case for these glauconitic sandstones. However, well log correlation help interpret the porosity and extension of the sandstones in the study area.

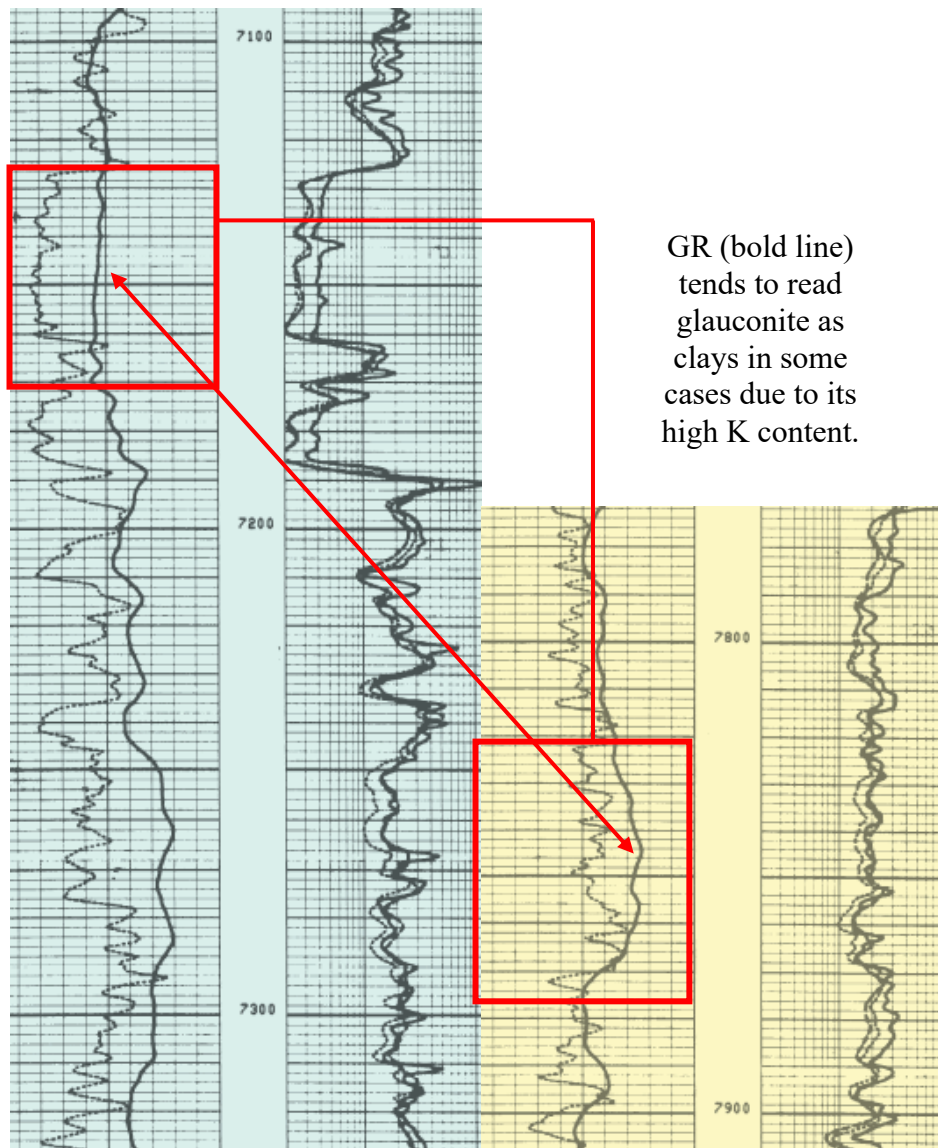


Figure 27: Section of the North Woods Unit 27-26 #1 e-log showing evidence of glauconite-rich sands

Diagenetic Processes

Petrographic analysis of the sandstones of the Tuscaloosa Group, southwest Alabama, helped interpret possible diagenetic processes. The presence of clay minerals, such as kaolinite and illite, shows the mineral dissolution of feldspathic and micaceous minerals such as orthoclase, muscovite, and possibly biotite. Although there is not much evidence of plagioclase in hand samples, it was present in thin sections from the Pilot sands and the Massive sands of the lower

Tuscaloosa. This evidence of feldspar mineral indicates that it could have been abundantly present at some point. The presence of this mineral may have paved the way for the precipitation of certain minerals such as kaolinite and other clays. However, one of the most important observations in this present study was the evidence of hematite replacing the glauconite. Although the precipitation of hematite is common in quartz arenites with high iron content, this specific observation was of great important when analyzing geochemical data later in the research, because it served as supporting evidence of the redox conditions within the formation (Boggs, 2019).

CO₂ Mineralization in Glauconitic Sandstones:

The mineral glauconite does not seem to negatively affect reservoir conditions because mineral dissolution results in mineral precipitation. The only difference between the sets of experiments was the increase in Fe²⁺ and decrease in Eh values between the samples in Set B, before and after CO₂ injection. The increase in Fe²⁺ concentrations in the post CO₂ injection data, may have been the result of FeHCO₃⁺ being added into the solution, after the dissolution of siderite and glauconite. Glauconite most likely dissolved after the solution became more acidic, which previous studies have shown that glauconitic grains indeed dissolve under acidic conditions (**Figure 28**). This dissolution of glauconite may eventually lead to the precipitation siderite or pyrite as it was shown in **Figure 26**. However, the diagram also shows that siderite has a small stability field and seems to only form at specific pH conditions. The mineral most likely will dissolve to form pyrite at reducing conditions, and aqueous FeHCO₃⁺ at conditions where pH<3, as it was mentioned. Geochemical experiments and the activity diagram of **Figure 26** show pH and Eh as the key variables for the dissolution of glauconite and precipitation of other minerals such as pyrite and siderite. Overall, the samples of this study do not show evidence of mineral

precipitation. After the glauconitic sandstones of Set B interacted with CO₂, the samples did not dissolve enough to precipitate either siderite or pyrite.

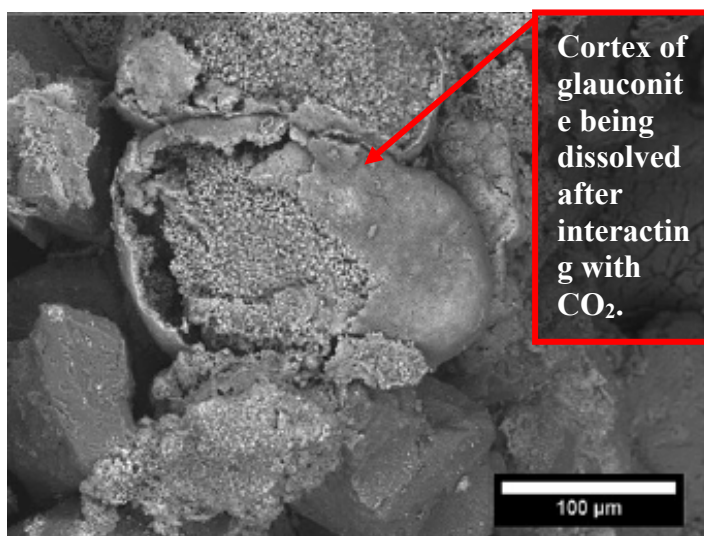


Figure 28: SEM image showing a glauconite grain being dissolved after interacting with CO₂. Image from Tutolo et al. (2020b).

Although the geochemical model constructed in this project shows evidence of siderite at reducing conditions, no physical observations were made on the samples, to confirm the presence of this mineral. It is suggested, for future work to run XRD analyses, as well as SEM and petrographic thin sections to see any visible mineral formation and physical alterations on the glauconitic grains. In addition, to build a more accurate geochemical model, it is also suggested to create one using thermodynamic properties of the glauconitic sandstones of the Tuscaloosa Group, southwest Alabama, instead of the “ideal” glauconite properties used for this study. The mineral glauconite varies chemically and as it is suggested in Zhang and Tutolo (2021), the thermodynamic properties of the mineral may also vary significantly (Tutolo et al., 2020a). Therefore, the “ideal” glauconite properties might not accurately reflect the glauconites of the Tuscaloosa Group, southwest Alabama. However, the diagram created for this study share similarities with the

diagram made by Zhang and Tutolo (2021), which shows pyrite and siderite dominating at reducing conditions (**Figure 29**). In this study, they obtained their own thermodynamic properties from glauconitic sandstones of the upper Manville Formation in southern Alberta, Canada. The reason they calculated their own thermodynamic properties was to create a more accurate diagram based on the composition of their glauconite grains of the Manville Formation and the synthetic brine data. The Manville sandstones are different also different in age. The Manville Formation is mostly composed of sandstones from the Lower Cretaceous while the Tuscaloosa Group contains sandstones from the Upper Cretaceous. The parameters in which both experiments were conducted, such as pressure and temperature, and the composition of the brine also differed. Although no direct comparison can be made with the diagram from the Manville glauconites, we can still have a better understanding of the dissolution of glauconite at different conditions and different compositions. The amount of research done in the carbonization process of glauconites is very limited. Therefore, more research needs to be done to better understand the complexity of CO₂ mineralization in glauconites.

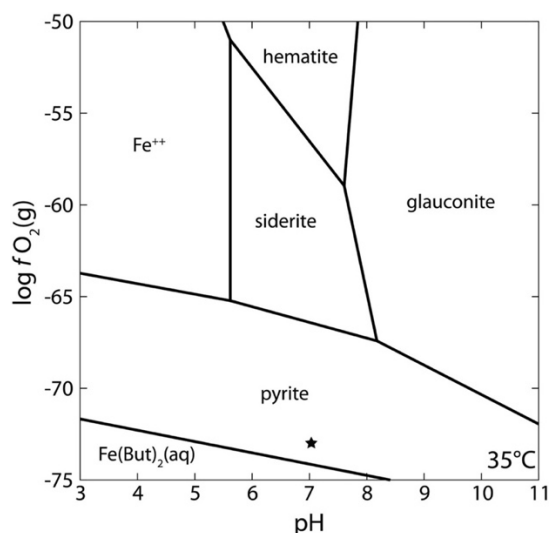


Figure 29: Activity diagram showing Fe stability fields from the Lower Cretaceous Upper Mannville Group in western Alberta, Canada. The star represents approximate conditions of the Mannville pore fluid.

5. Conclusions

The Tuscaloosa Group might hold great potential for carbon sequestration; however, more research is needed on nanoscale mineral precipitation. The present project partially addresses this need. We observed that it was difficult to make observations in experiments that focus on converting silicates to carbonates for carbon sequestration purposes, and to also recreate these processes in a laboratory. Nevertheless, this study showed that the Tuscaloosa Group, in southwest Alabama, may qualify as an adequate reservoir for CO₂ because it meets most of the criteria needed, according to past studies. The pressure and temperature conditions aligned with the criteria needed in a reservoir (Herzog, 2018). The formation has an overall pressure of 24 MPa and a temperature of 88° C. Additionally the glauconitic sandstones are at an adequate depth. Other studies such as Lu et al. (2012) showed that the Tuscaloosa Group has proven to be an ideal CO₂ reservoir in other areas such as southeast Mississippi. Greensands or glauconitic sandstones have also been said to be great candidates for CO₂ storage, as shown in the work done in Tutolo et al. (2020b). For future work it would be recommended to take into consideration the presence of hydrocarbons, as it could potentially alter the interaction of supercritical CO₂ with the sands (Helgeson et al., 1993). Another recommendation would be to analyze the bulk mineralogy of the samples post CO₂ injection, as to observe any physical changes of the grains through an SEM. Potential carbon storage units need to be evaluated in depth in order to ensure security.

By using petrographic, XRD, SEM, and geochemical analyses, as well as log correlations, the following concluding remarks can be made:

- The Tuscaloosa Group in southwest Alabama is mainly composed of quartz-rich sandstones and interbedded sandstones and shales.
- Well log correlation showed that the sand bodies that make part of the Tuscaloosa Group are continuous in the southwest. The Marine Shales are also extensive in this area, and they could serve as a seal cap if CO₂ is injected in the lower Tuscaloosa.
- The sandstones and shales that make up most of the Tuscaloosa are extensive and consistent in-depth, which CO₂ could be stored in various locations.
- The glauconites that make part of the formation are primarily found in the upper and shallow lower Tuscaloosa and do not alter the process of supercritical CO₂ injection.
- Although this research did not cover the full spectrum of the CO₂-brine-interactions in the Tuscaloosa Group southwest Alabama, it did give a better understanding on possible chemical interactions between glauconites and CO₂ in the study area.
- Formation of siderite is possible under reducing conditions, and likely forms as a result of glauconite dissolving after interacting with glauconite.
- Glauconite-rich sandstones of the upper Tuscaloosa and the Pilot sands of the lower Tuscaloosa could potentially serve as a CO₂ reservoir because they have the adequate porosity, permeability, and depth.
- The Tuscaloosa meets most of the criteria needed for carbon sequestration purposes because it showed it has a suitable composition, porosity, temperature, and depth.

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Appendix
Part 1: Drill-Core Photographs



Figure 1.1: Section of the Julian F. McGowin #1 drill core. This section is part of the Massive sands of the lower Tuscaloosa. Depth ranges from 2568 m – 2570 m (8427 ft – 8435 ft).



Figure 1.2: Section of the Julian F. McGowin #1 drill core. This section is part of the Massive sands of the lower Tuscaloosa. Depth ranges from 2566 m – 2568 m (8419 ft- 8427 ft).



Figure 1.3: Section of the Julian F. McGowin #1 drill core. This section is part of the Massive sands of the lower Tuscaloosa. Depth ranges from 2563 m – 2568 m (8411 ft – 8427 ft).



Figure 1.4: Section of the Julian F. McGowin #1 drill core. This section is part of the Massive sands of the lower Tuscaloosa. Depth ranges from 2562 m – 2563 m (8408 ft – 8411 ft).



Figure 1.5: Section of the Julian F. McGowin #1 drill core. This section is part of the Massive sands of the lower Tuscaloosa. Depth ranges from 2560 m- 2562 m (8399 ft – 8408 ft).



Figure 1.6: Section of the Julian F. McGowin #1 drill core. This section is part of the Massive sands of the lower Tuscaloosa. Depth ranges from 2556 m -2559 m (8387 ft – 8397 ft).



Figure 1.7: Section of the Julian F. McGowin #1 drill core. This section is part of the Pilot sands of the lower Tuscaloosa Potassium feldspar was abundant in these sections of the core. Depth ranges from 2399 m – 2551 m (7872 ft – 8370 ft).



Figure 1.8: Section of the Julian F. McGowin #1 drill core. This section is part of the Pilot sands of the lower Tuscaloosa. There is clear distinction in lithology. These sandstones contained large amounts of glauconites. Depth ranges from 2394 m – 2399 m (7856 ft – 7872 ft).



Figure 1.9: Section of the Julian F. McGowin #1 drill core. This section is part of the Pilot sands of the lower Tuscaloosa. The samples taken from this section were interbedded sandstones and shales. Glauconite was also very abundant in this section of the core. Depth ranges from 2389 m -2394 m (7840 ft – 7856 ft).



Figure 1.10: Section of the Julian F. McGowin #1 drill core. This section is part of the Pilot sands of the lower Tuscaloosa. The samples taken from this section were interbedded sandstones and shales. Glauconite was also very abundant in this section of the core. Depth ranges from 2385 m – 2389 m (7826 ft – 7840 ft).



Figure 1.11: Section of the Julian F. McGowin #1 drill core. This section is part of the Pilots sands of the lower Tuscaloosa. The samples taken from this section were interbedded sandstones and shales. Glauconite was also very abundant in this section of the core 2382 m – 2385 m (7818 ft – 7826 ft).



Figure 1.12: Section of the Julian F. McGowin #1 drill core. This section is part of the Pilot sands of the lower Tuscaloosa. Glauconite was also very abundant in this section of the core. Depth ranges from 2366 m – 2368 m (7765 ft – 7772 ft).



Figure 1.13: Section of the Julian F. McGowin #1 drill core. This section is part of the Pilot sands of the lower Tuscaloosa. Depth ranges from 2363 m – 2366 m (7753 ft – 7764 ft).



Figure 1.14: Section of the Julian F. McGowin #1 drill core. This section is part of the Pilot sands of the lower Tuscaloosa. Depth ranges from 2360 m – 2362 m (7743 ft – 7752 ft).



Figure 1.15: Section of the Julian F. McGowin #1 drill core. This section is part of the Pilot sands of the lower Tuscaloosa. Depth ranges from 2357 m – 2359 m (7734 ft – 7742 ft).



Figure 1.16: Section of the Julian F. McGowin #1 drill core. This section is part of the Pilot sands of the lower Tuscaloosa. Depth ranges from 2355 m – 2357 m (7727 ft – 7734 ft).



Figure 1.17: Section of the the Julian F. McGowin #1 drill core. This section is part of the Pilot sands of the lower Tuscaloosa. Depth ranges from 2352 m – 2354 m (7718 ft – 7726 ft).



Figure 1.18: Section of the Julian F. McGowin #1 drill core. This section is part of the Pilot sands of the lower Tuscaloosa. This section of the core contained large amount of muscovite. Depth ranges from 2242 m, and 2350 m – 2351 m (7358 ft and 7711-7716 ft).



Figure 1.19: Section of the Julian F. McGowin #1 drill core. This section is part of the of the sandstones that make part of the upper Tuscaloosa. Glauconite was not as abundant as the last section of the core. Depth ranges from 2180 m – 2183 m (7154 ft – 7163 ft).



Figure 1.20: Section of the Julian F. McGowin #1 drill core. Glauconite was not as abundant as the last section of the core. Depth ranges from 2178 m – 2180 m (7148 ft – 7153 ft).



Figure 1.21: Section of the Julian F. McGowin #1 drill core. Glauconite was not as abundant as the last section of the core. This section is also the top of the drill core. Depth ranges from 2175 m – 2177 m (7137 ft – 7145 ft).

Appendix

Part 2: Petrographic Thin Section Photographs

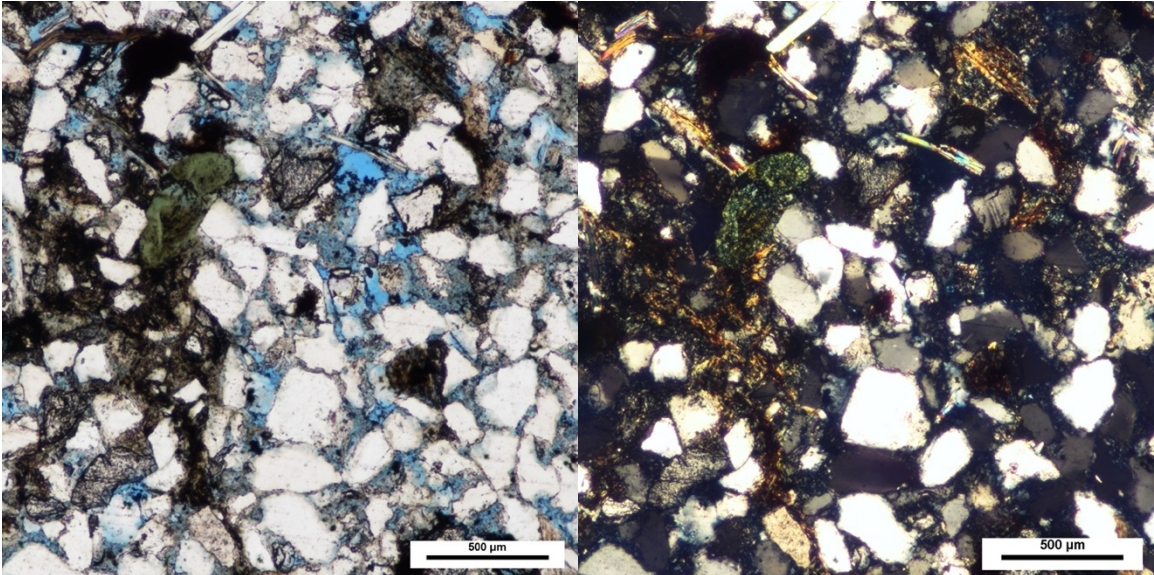


Figure 2.1: Sample JFM2 in PPL (left) and XPL (right). Sample is from the upper Tuscaloosa. Depth ranging from 2175 m - 2177 m (7139 ft – 7141 ft).

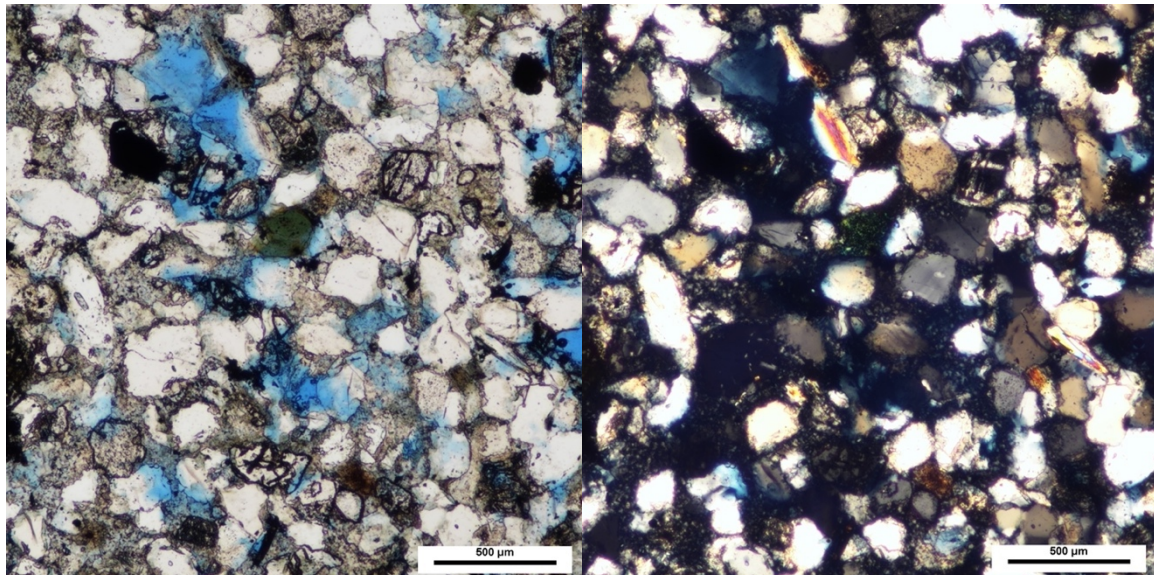


Figure 2.2: Sample JFM3 in PPL (left) and XPL (right). Sample is from the upper Tuscaloosa. Depth ranging from 2176 m – 2178 m (7142 ft – 7148 ft).

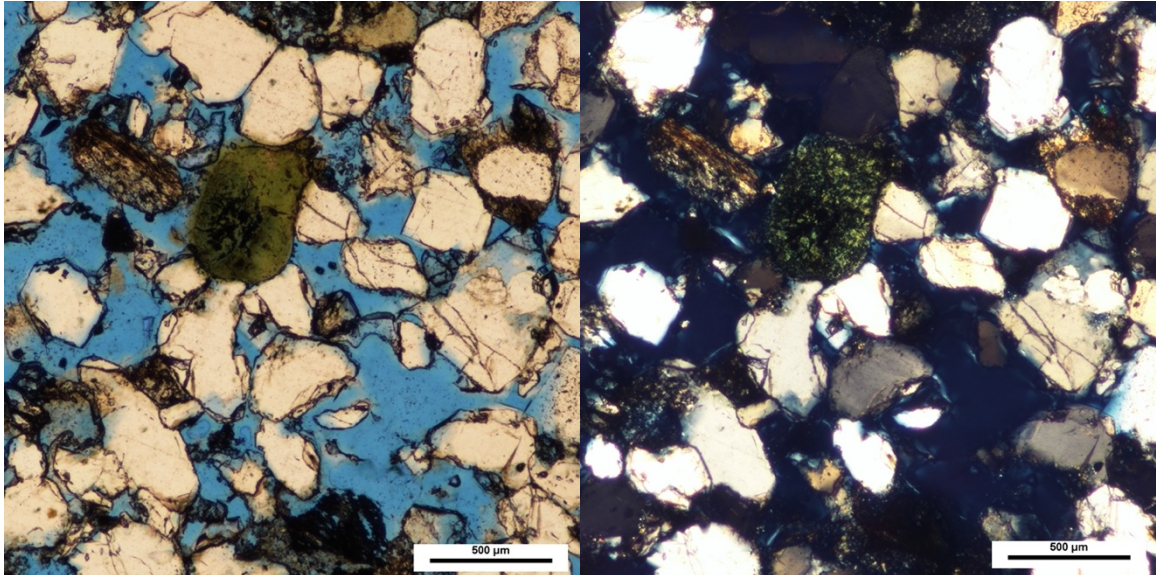


Figure 2.3: Sample JFM6 in PPL (left) and XPL (right). Sample from the upper Tuscaloosa. Depth ranging from 2178 m – 2179 m (7148 ft – 7149 ft).

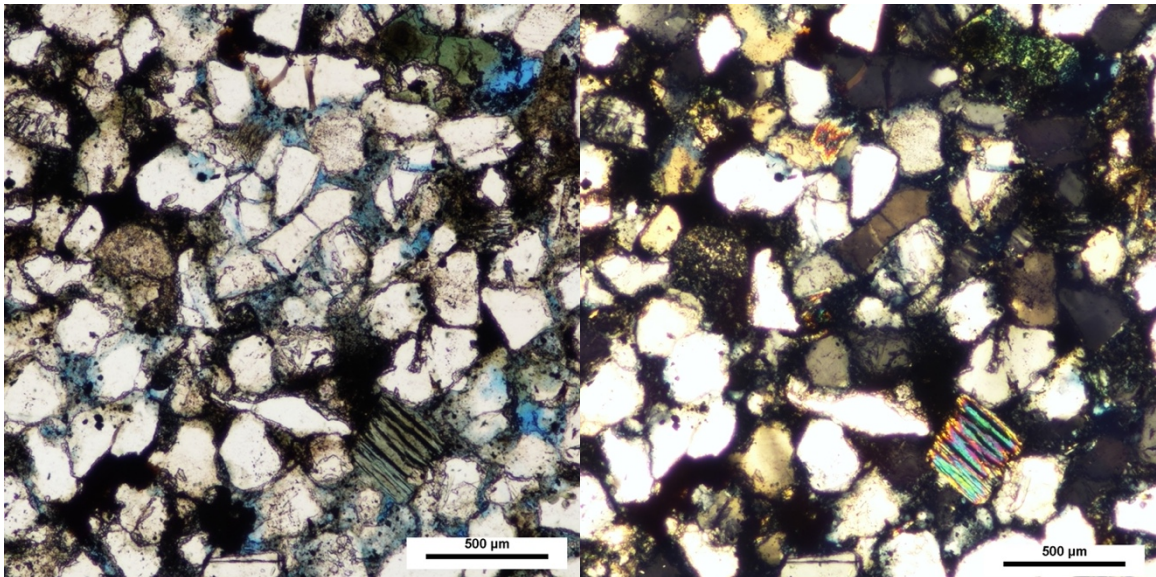


Figure 2.4: JFM13 in PPL (left) and XPL (right). Sample from the Pilot sands of the lower Tuscaloosa. Depth ranging from 2351 m – 2352 m (7717 ft – 7718 ft).

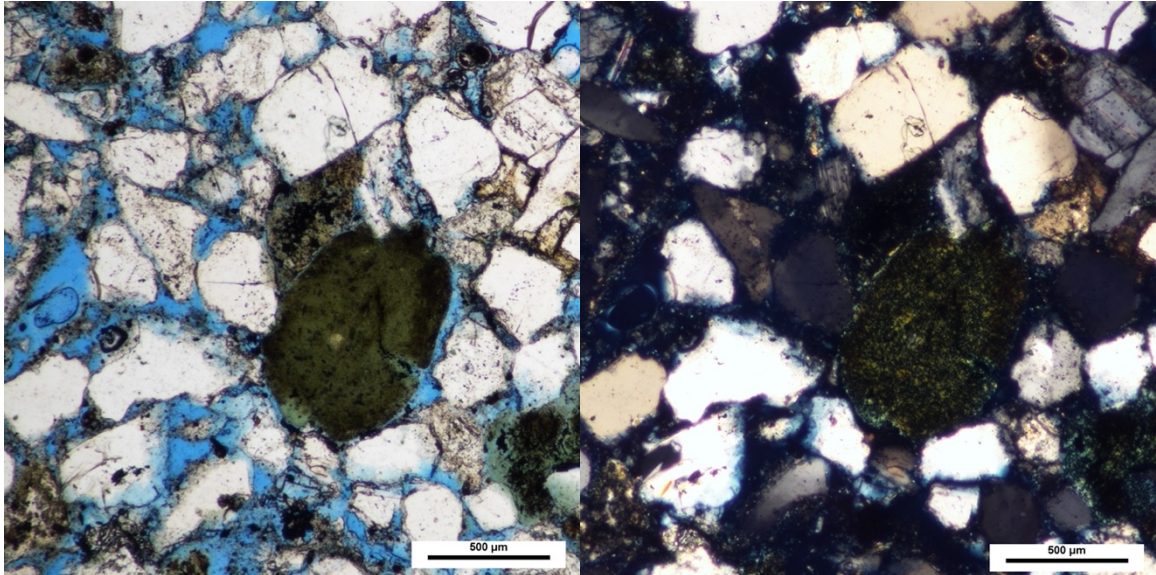


Figure 2.5: JFM19 in PPL (left) and XPL (right). Sample from the Pilot sands of the lower Tuscaloosa. Depth ranging from 2353 m – 2354 m (7722 ft – 7724 ft).

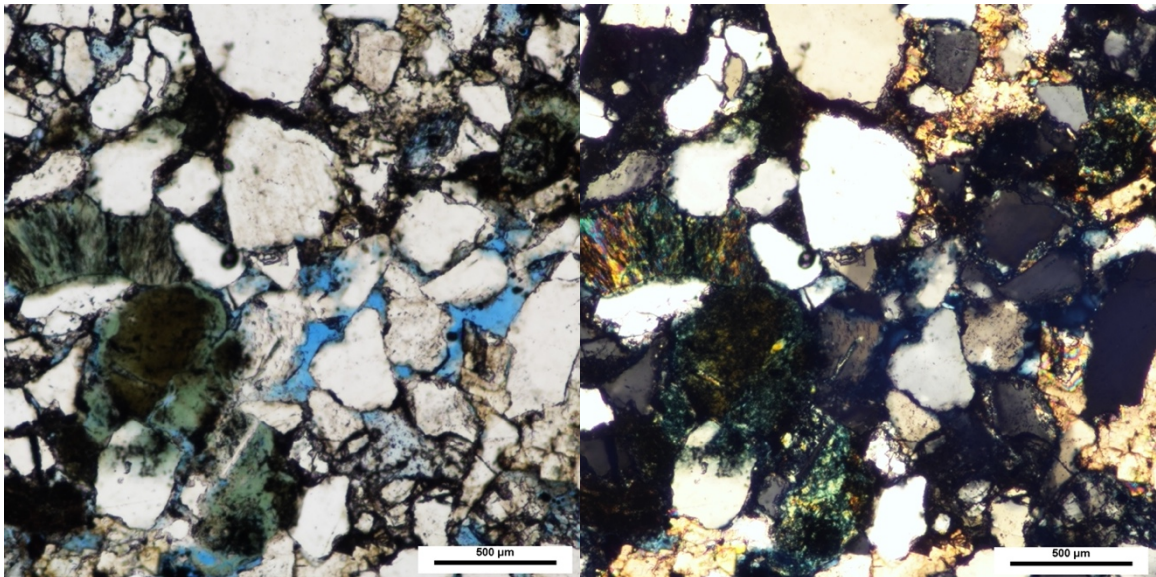


Figure 2.6: JFM20 in PPL (left) and XPL (right). Sample from the Pilot sands of the lower Tuscaloosa. Depth ranging from 2353 m – 2355 m (7725 ft – 7726 ft). In this thin section, the mineral hematite is precipitating inside the glauconite grains, suggesting oxidizing conditions.

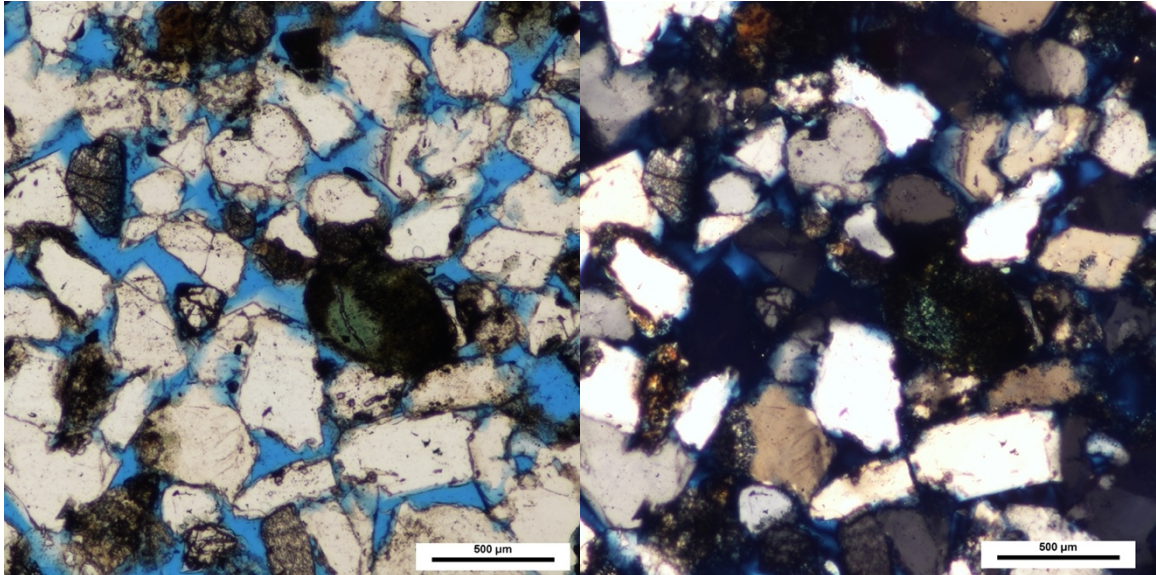


Figure 2.7: JFM32 in PPL (left) and XPL (right). Sample from the Pilot sands of the lower Tuscaloosa. Depth ranging from 2362 m - 2363 m (7751 ft – 7752 ft).

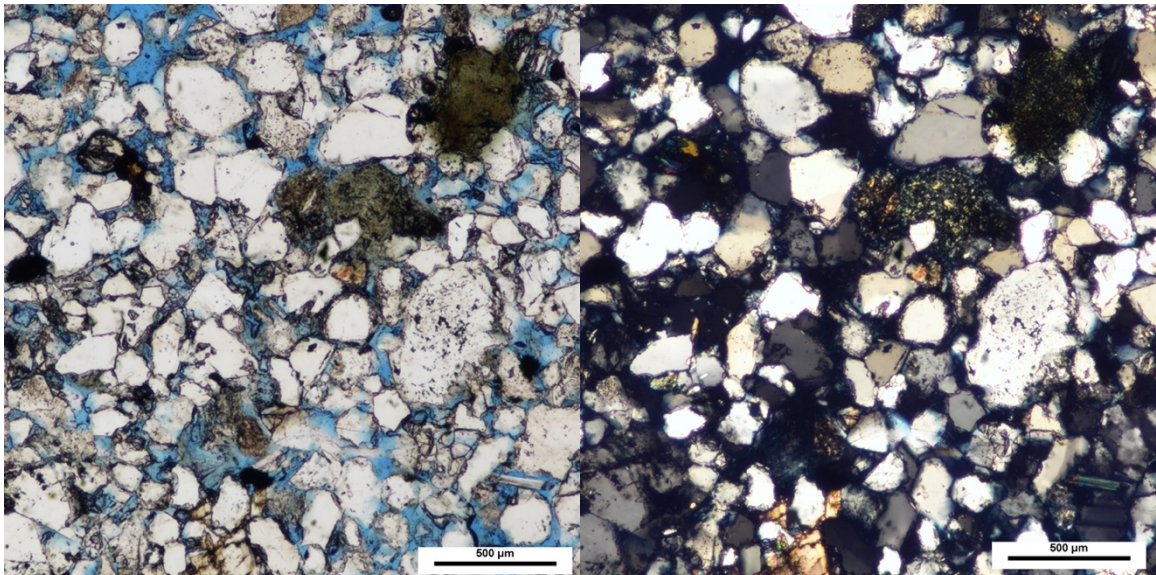


Figure 2.8: JFM33 in PPL (left) and XPL (right). Sample from the Pilot sands of the lower Tuscaloosa. Depth ranging from 2363 m – 2364 m (7753 ft – 7755 ft).

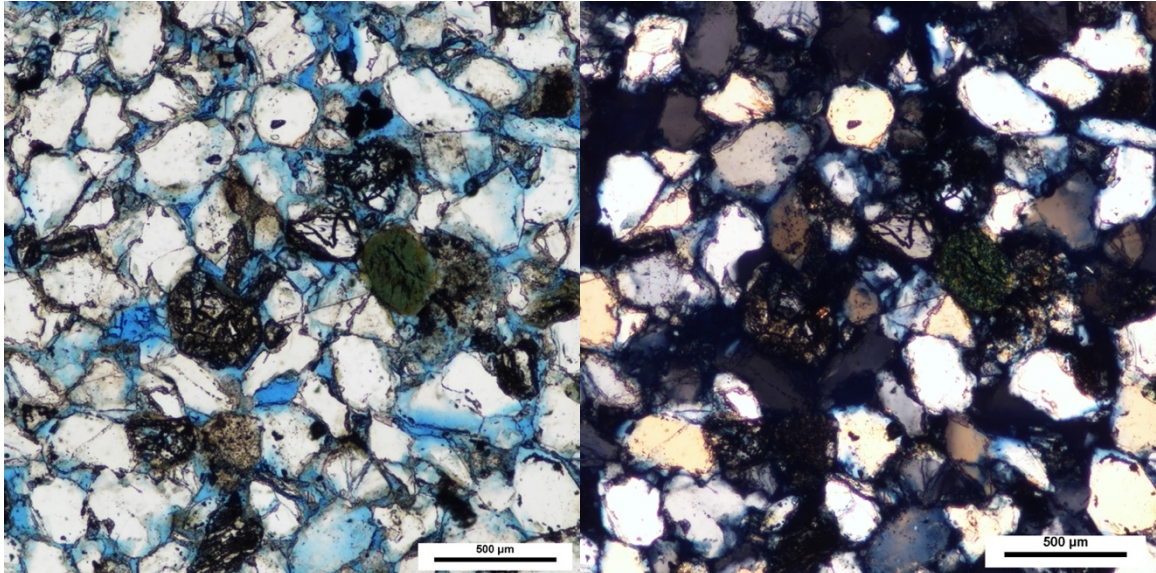


Figure 2.9: Sample JFM41 in PPL (left) and XPL (right). Sample from the Pilot sands of the lower Tuscaloosa. Depth ranging from 2382 m – 2386 m (7818 ft – 7820 ft).

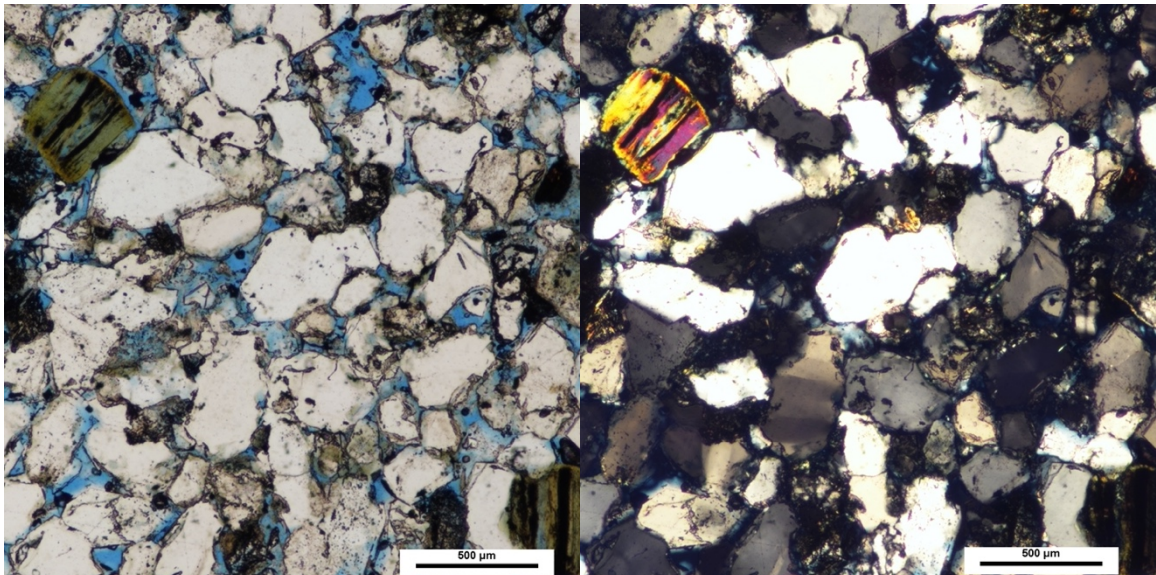


Figure 2.10: Sample JFM42 in PPL (left) and XPL (right). Sample from the Pilot sands of the lower Tuscaloosa. Depth at 2384 m (7822 ft).

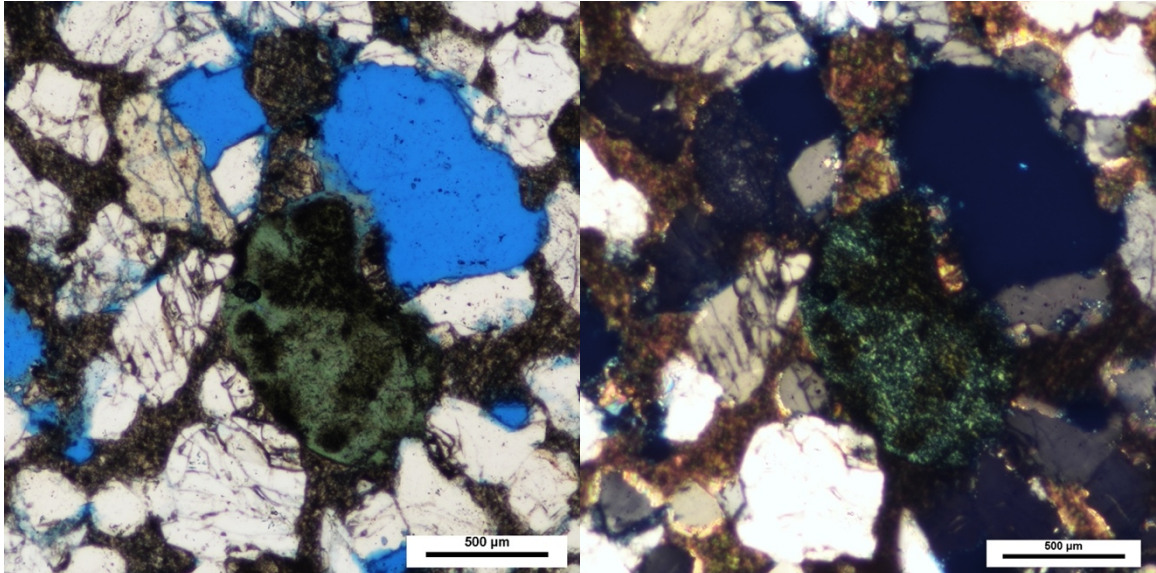


Figure 2.11: Sample JFM47 in PPL (left) and XPL (right). Sample from the Pilot sands of the lower Tuscaloosa. Depth ranging from 2387 m – 2388 m (7832 ft – 7836 ft).

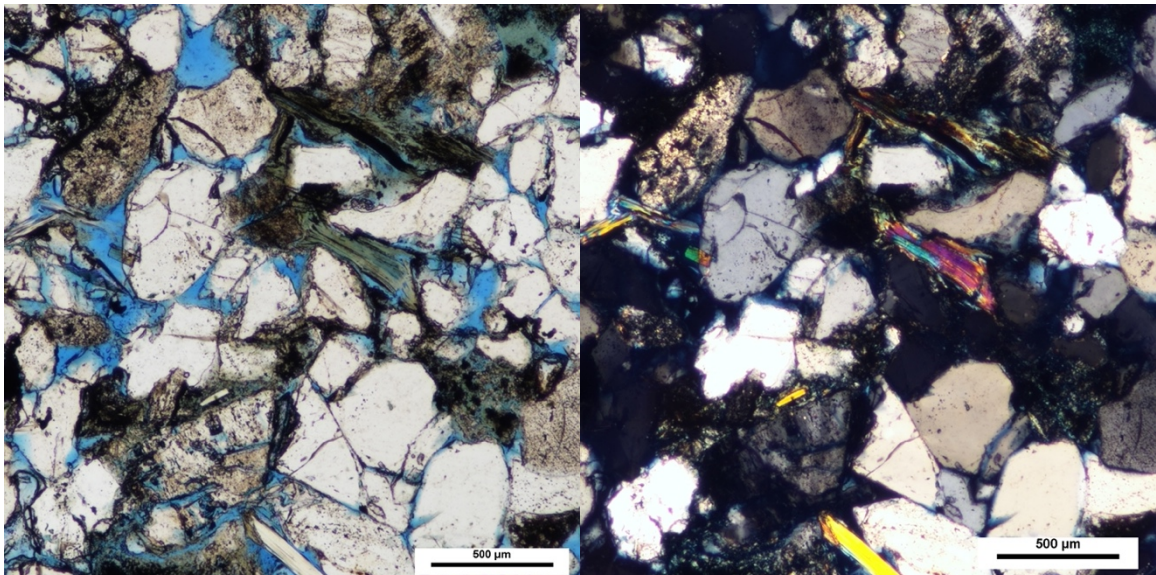


Figure 2.12: Sample JFM48 in PPL (left) and XPL (right). Sample from the Pilot sands of the lower Tuscaloosa. Depth ranging from 2388 m – 2390 (7836 ft – 7840 ft).

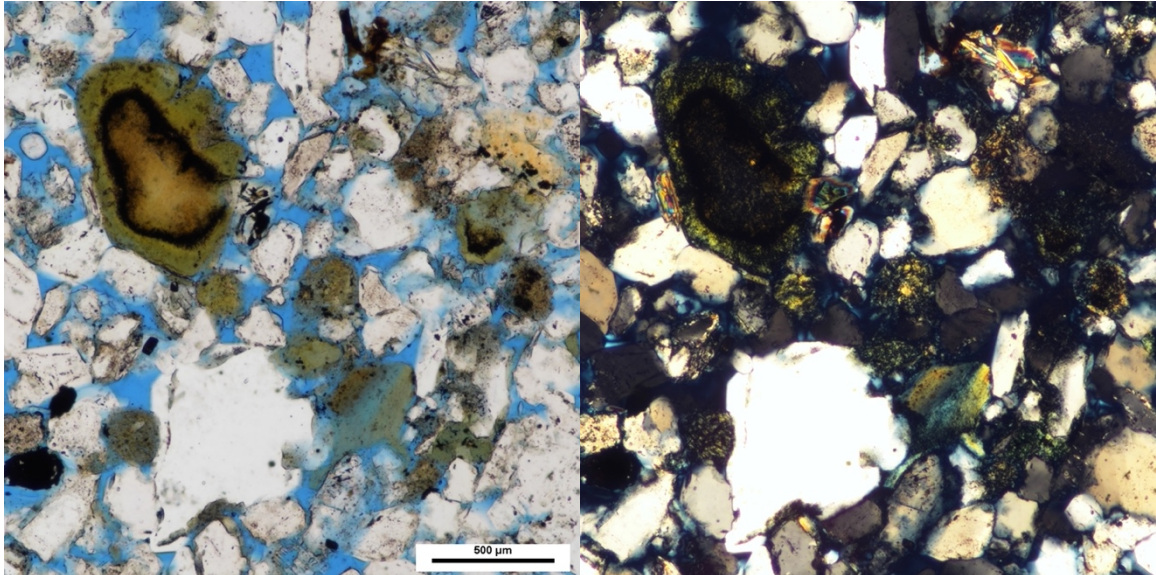


Figure 2.13: Sample JFM52 (left) and XPL (right). Sample from the Pilot sands of the lower Tuscaloosa. Depth ranging from 2393 m – 2395 m (7852 ft – 7856 ft).

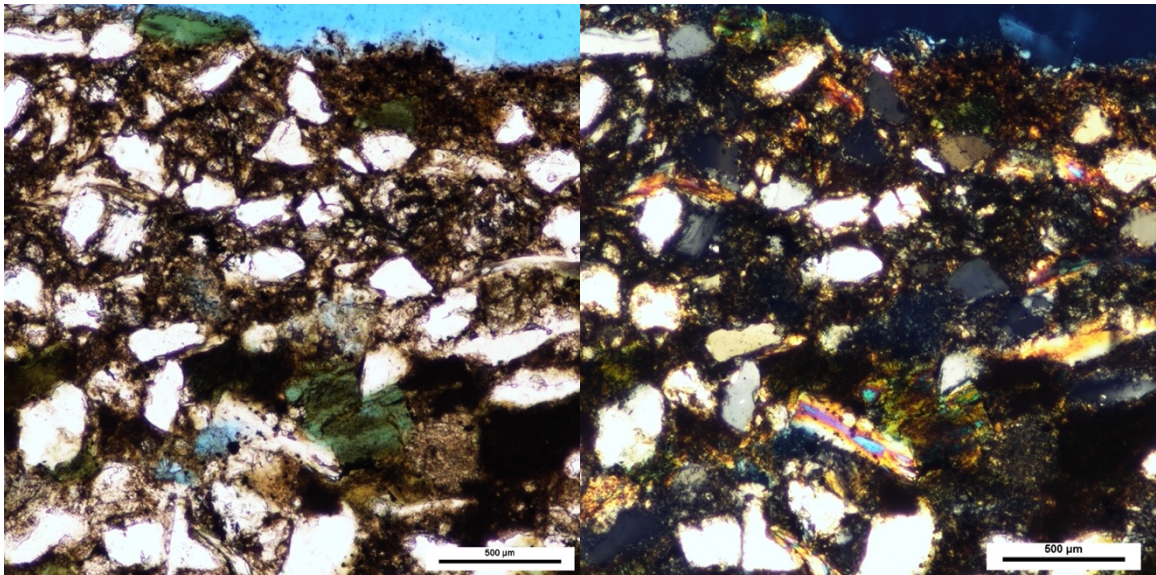


Figure 2.14: Sample JFM 55-1 in PPL (left) and XPL (right). Sample from the Pilot sands of the lower Tuscaloosa. Depth ranging from 2396 m – 2398 m (7864 ft – 7868 ft). The sample used for this thin section was interbedded sandstone and shale.

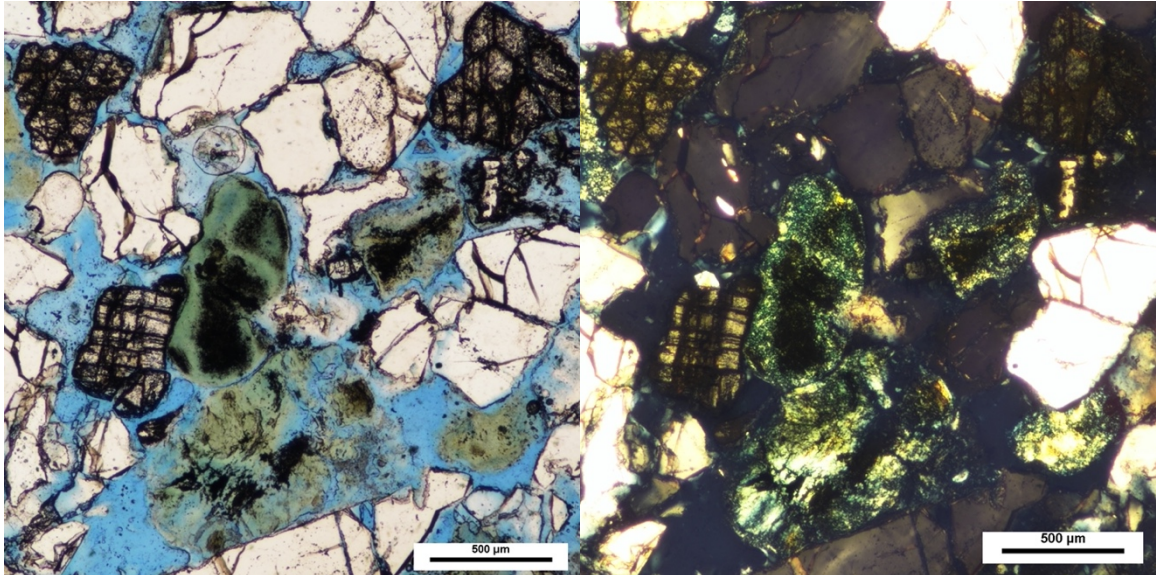


Figure 2.15: Sample JFM55-2 in PPL (left) and XPL (right). Sample from the Pilot sands of the lower Tuscaloosa. Depth ranging from 2396 m – 2398 m (7864 ft – 7868 ft). This section was from the same depth as sample JFM55-1. There was a difference in lithology in these two samples. JFM55-1 contained more clay minerals than JFM55-2, which contained a high amount of glauconites.

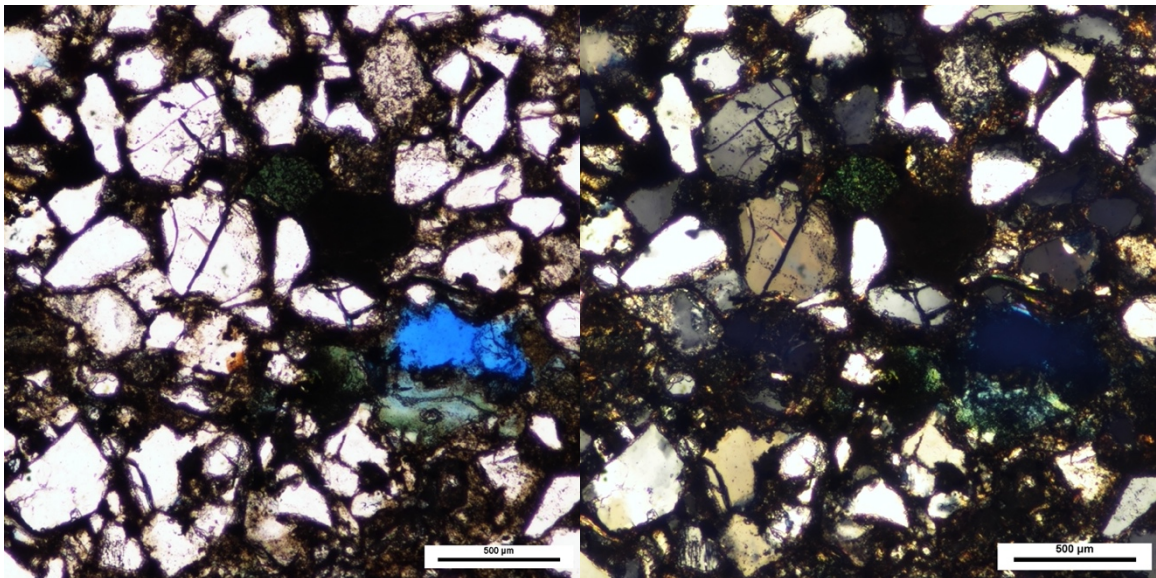


Figure 2.16: Sample JFM57 in PPL (left) and XPL (right). Sample from the Pilot sands of the lower Tuscaloosa. Depth ranging from 2399 m – 2340 m (7872 ft – 7874 ft).

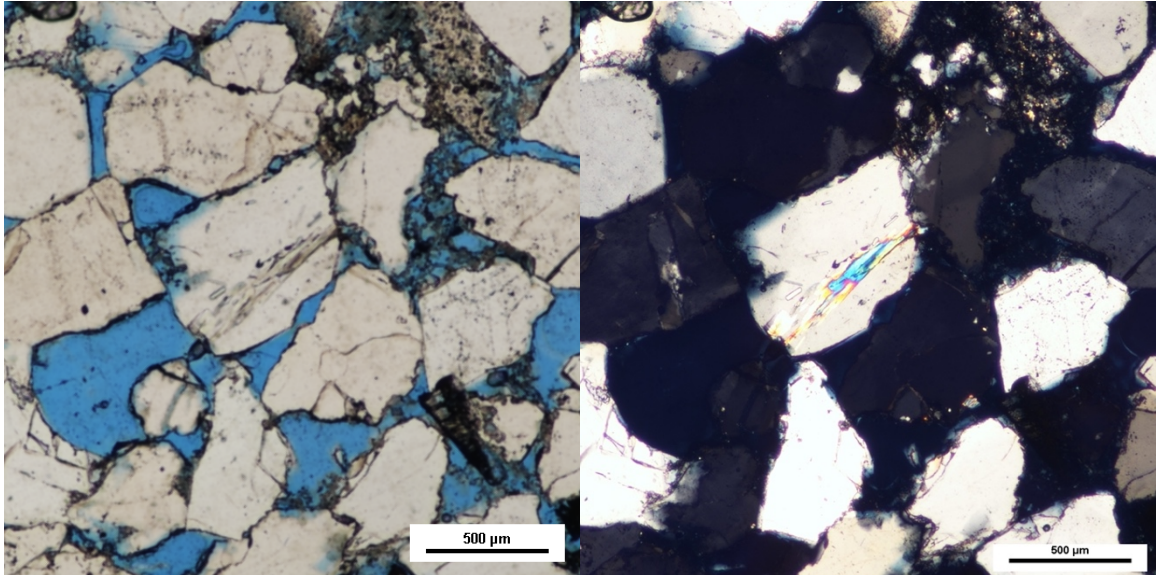


Figure 2.17: Sample JFM60 in PPL (left) and XPL (right). Sample from the Massive sands of the lower Tuscaloosa. Depth ranging from 2555 m - 2554 m (8377 ft – 8379 ft). Sample mostly made up of angular to subangular quartz grains.

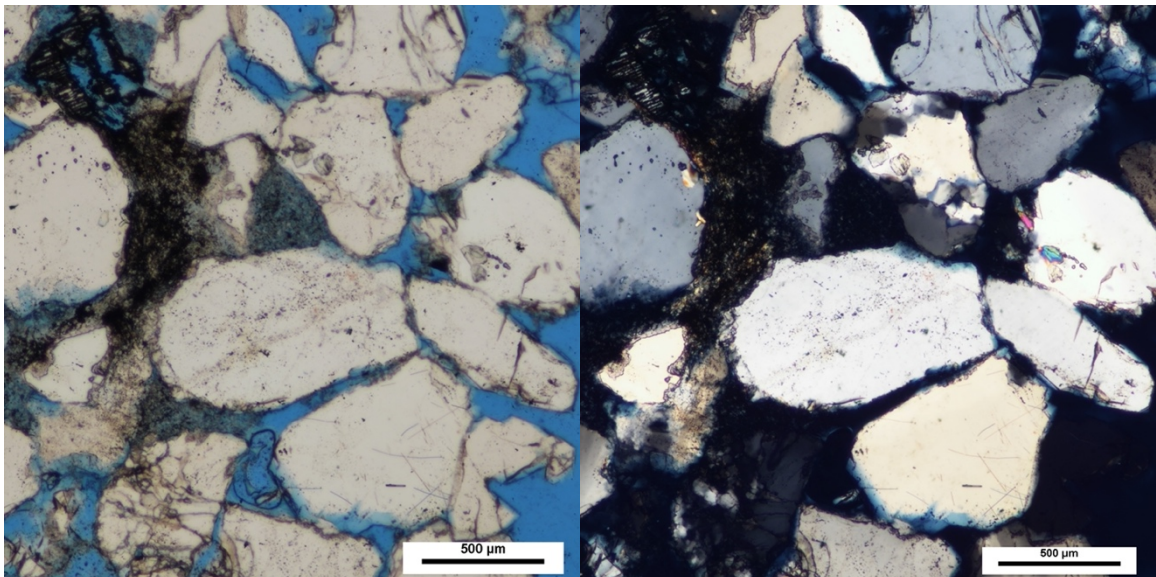


Figure 2.18: Sample JFM62 in PPL (left) and XPL (right). Sample from the Massive sands of the lower Tuscaloosa. Depth ranging from 2554 m – 2555 m (8379 ft – 8382 ft).

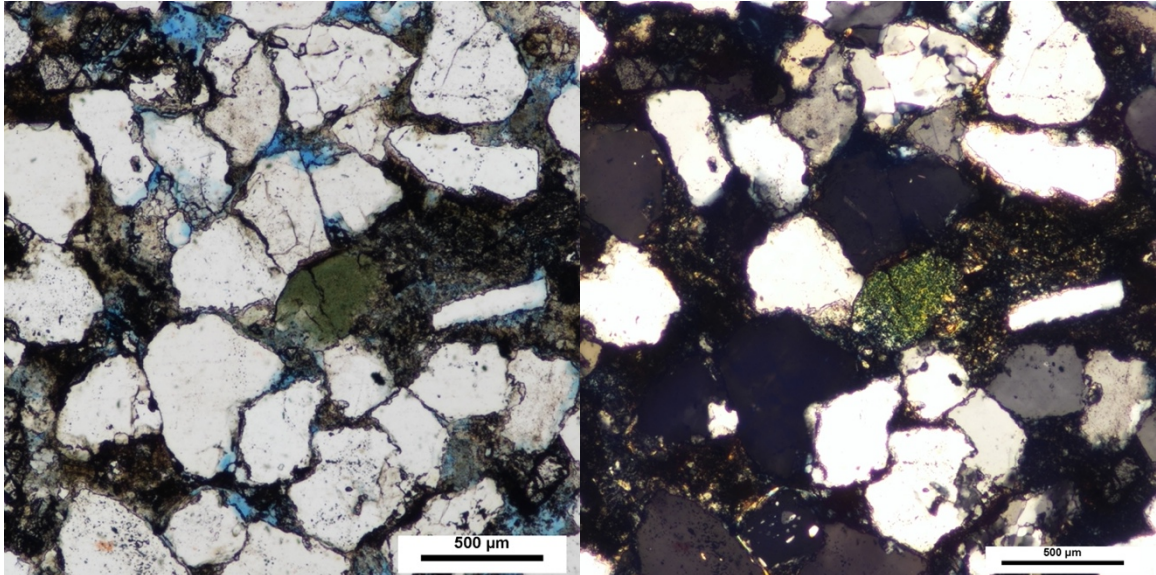


Figure 2.19: Sample JFM63 in PPL (left) and XPL (right). Sample from the Massive sands of the lower Tuscaloosa. Depth ranging from 2555 m – 2556 m (8383ft – 8385 ft). Some sandstones from the Massive sands did contained glauconite, however, the amounts were very low in comparison to those of the upper Tuscaloosa and the Pilot sands.

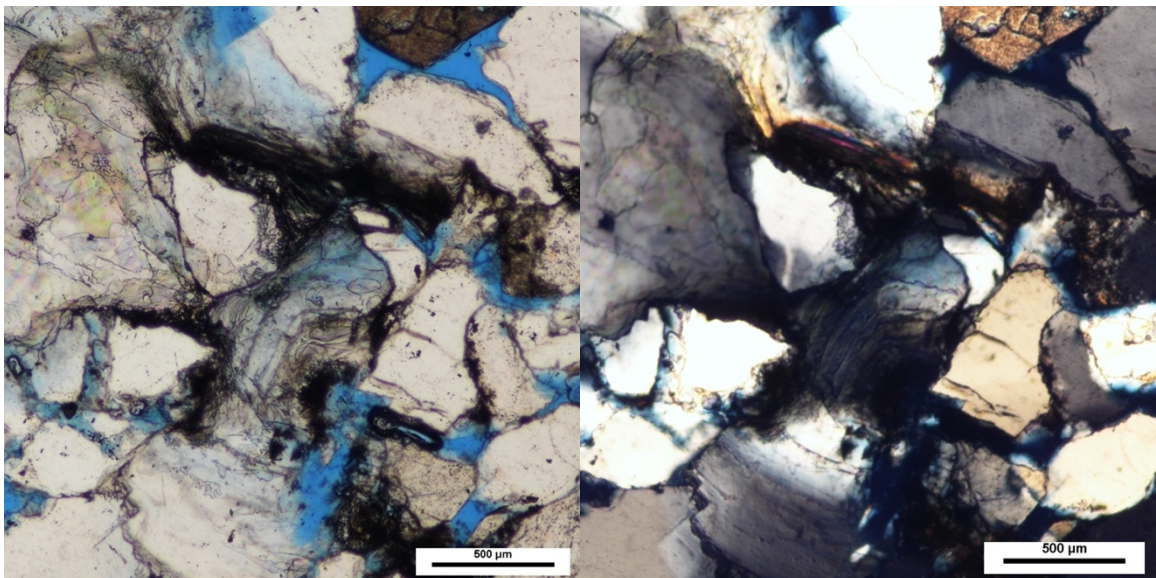


Figure 2.20: Sample JFM66 in PPL (left) and XPL (right). Sample from the Massive sands of the lower Tuscaloosa. Depth ranging from 2556 m – 2558 m (8389 ft – 8391 ft).

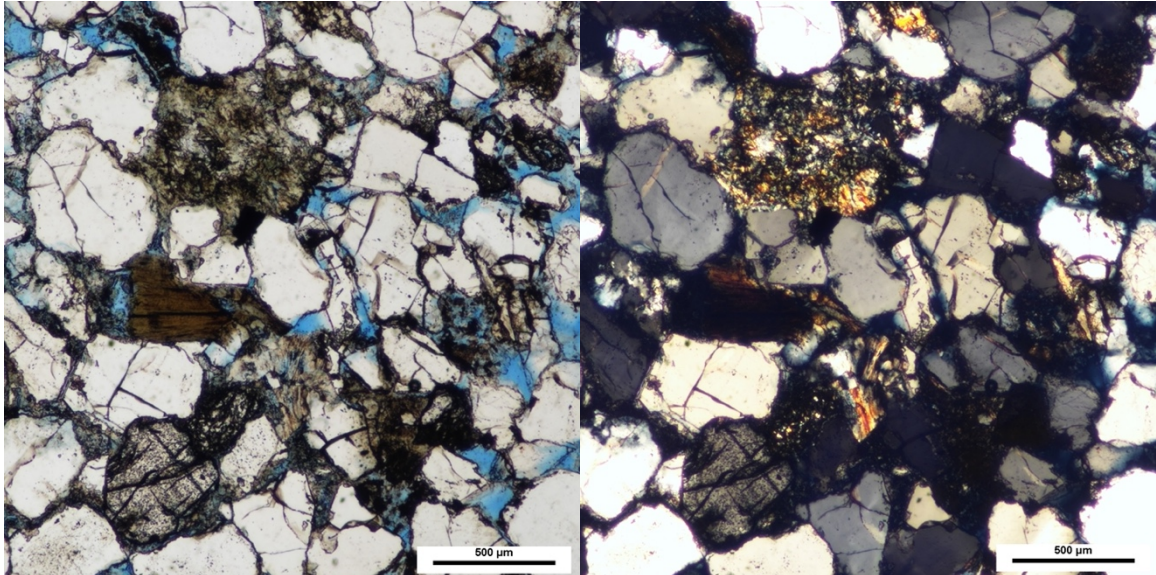


Figure 2.21: Sample JFM68 in PPL (left) and XPL (right). Sample from the Massive sands of the lower Tuscaloosa. Depth ranging from 2558 m – 2559 m (8395 ft – 8397 ft).

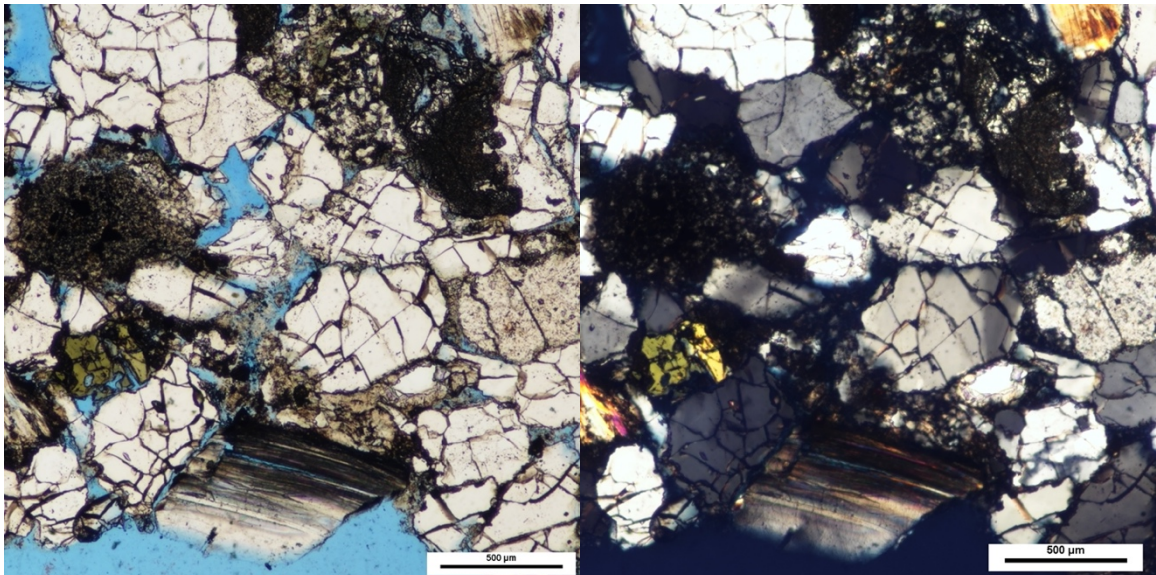


Figure 2.22: Sample JFM73 in PPL (left) and XPL (right). Sample from the Massive sands of the lower Tuscaloosa. Depth ranging from 2561 m – 2562 m (8403 ft – 8405 ft).

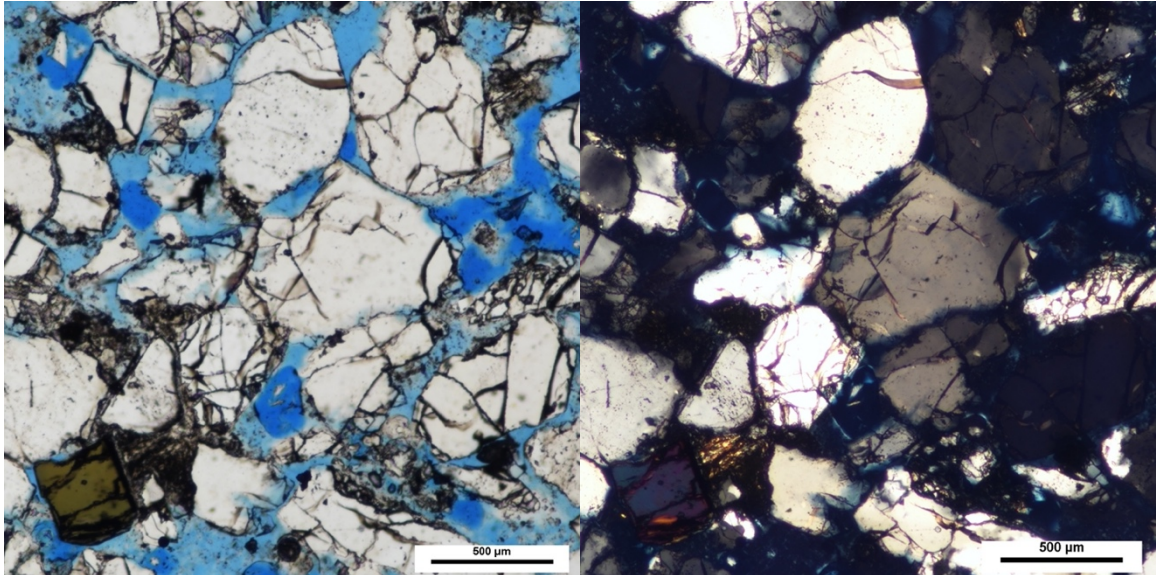


Figure 2.23: Sample JFM80 in PPL (left) and XPL (right). Sample from the Massive sands of the lower Tuscaloosa. Depth ranging from 2566 m (8417 ft – 8419 ft).

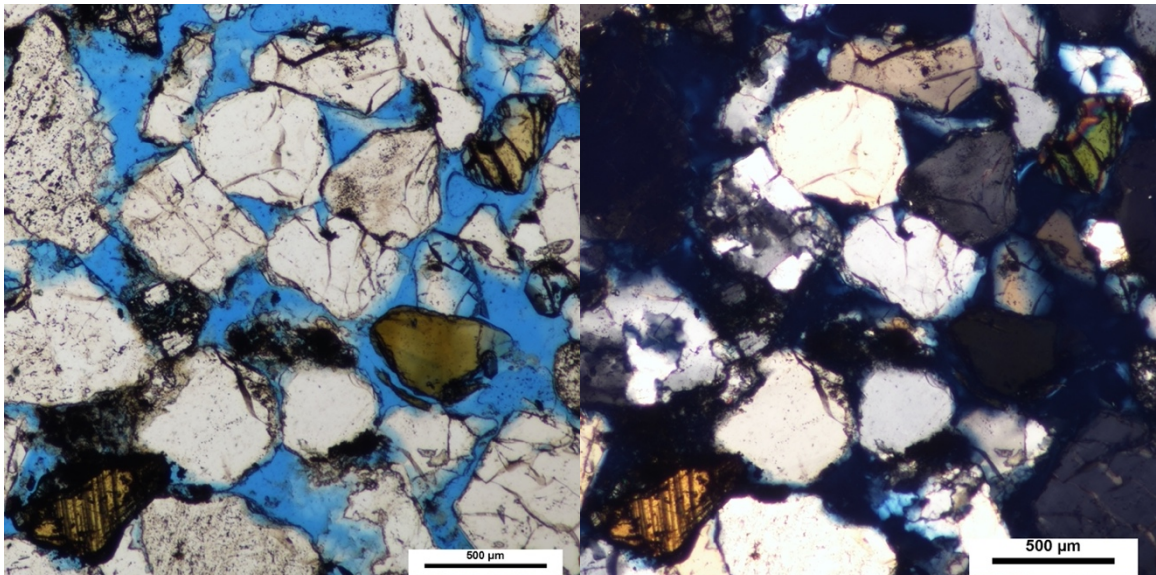


Figure 2.24: Sample JFM86 in PPL (left) and XPL (right). Sample from the Massive sands of the lower Tuscaloosa. Depth ranging from 2569 m 2570 m (8431 ft – 8434 ft).

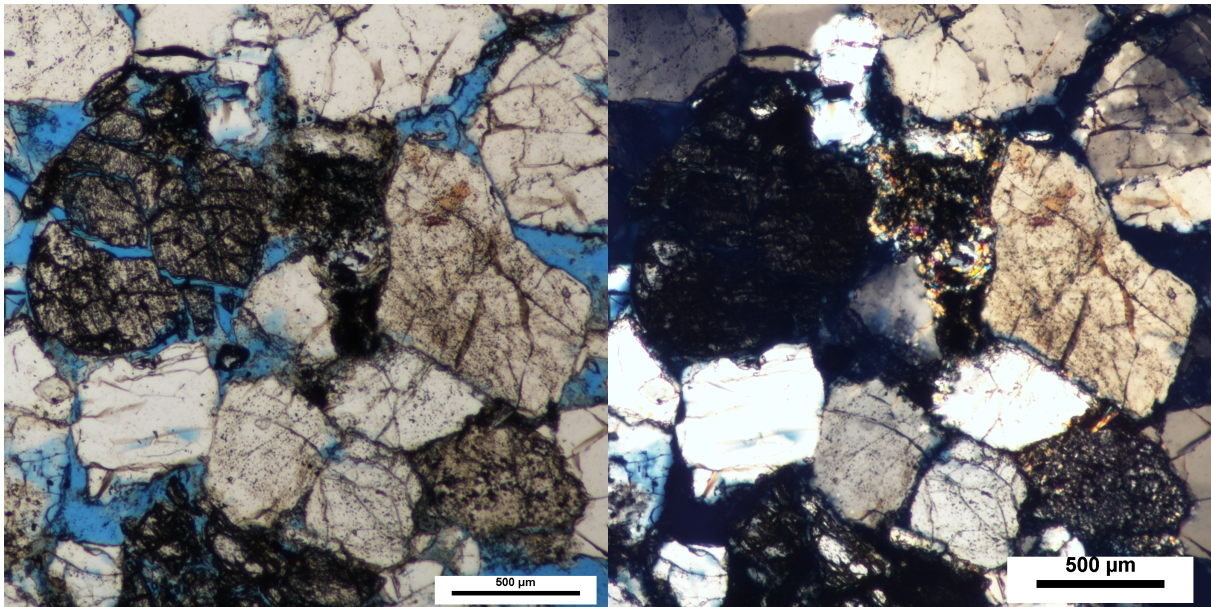
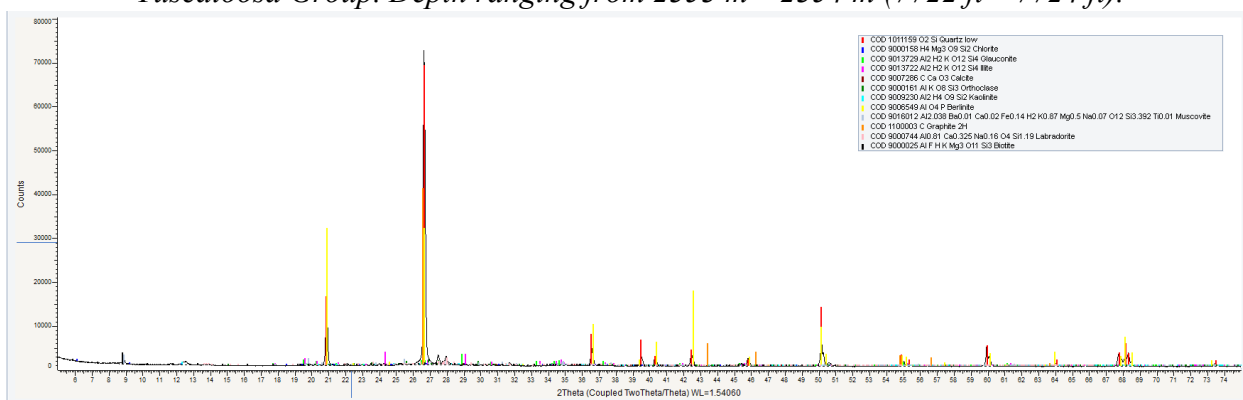
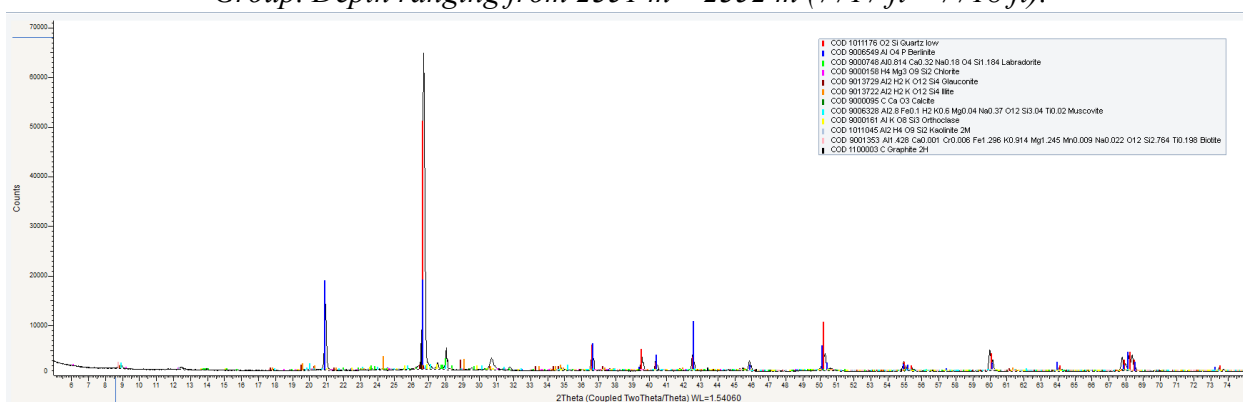
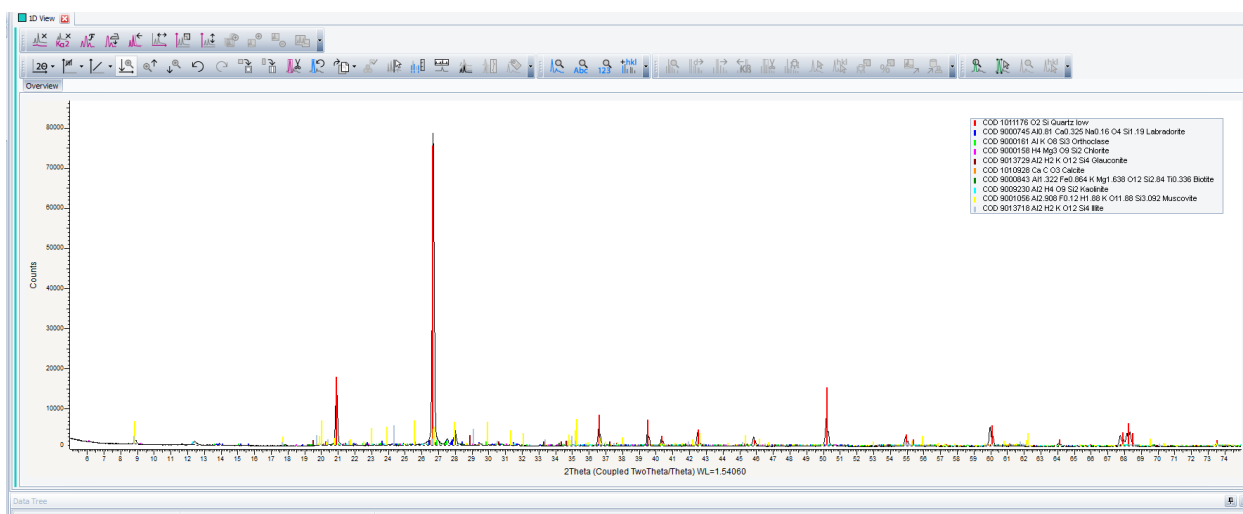


Figure 2.25: Sample JFM88 in PPL (left) and XPL (right). Sample from the Massive sands of the lower Tuscaloosa. Depth ranging from 2570 m – 2571 m (8433 ft – 8435 ft).

Appendix
Part 3: XRD Data and Graphs

Sample ID	Depth (ft)	Qtz	Cl	Glt	Ill	Cal	Ms	Or	Kao	Lab	Bt	AlPO ₄	G
JFM13	7717-7718	95.88	0.47	3.78	6.37	0.44	8.41	0.93	1.51	3.27	1.88	41.66	21.31
JFM19	7722-7724	62.22	0.42	3.65	4.99	0.14	2.12	1.54	0.6	2.36	1.78	23.06	21
JFM20	7725-7726	78.75	0.46	3.73	4.31	0.09	2.09	1.71	0.73	3.45	2.07	28.45	8.13
JFM23	7731-7732	95.05	0.52	3.96	4.36	0.3	2.88	1.51	0.92	2.35	3.46	43.63	56.12
JFM28	7740-7742	85.96	0.61	4.25	4.32	0.45	2.63	2.41	1.16	2.42	3.25	49.47	52.99
JFM31	7748-7750	68.05	1.29	3.81	4.35	0.24	2.53	5.7	1.35	2.15	2.1	45.95	32.75
JFM32	7751-7752	96.53	0.35	3.59	4.19	0.39	2.49	1.39	0.57	2.24	1.96	41	13.46
JFM33	7753-7755	94.47	0.62	4.23	4.36	0.49	0.45	1.34	1.1	2.93	4.04	47.79	44.49
JFM41	7818-7820	92.23	0.45	3.87	7.48	0.06	2.08	1.46	0.76	2.45	11.21	47.44	35.93
JFM42	7822-7822	94.11	0.9	3.87	7.21	0.12	2.08	1.46	0.73	2.11	11.12	47.44	32.46
JFM47	7832-7836	96.63	1.4	3.87	9.25	2.33	11.3	6.86	0.54	1.32	11.11	45.79	21.94
JFM48	7836-7840	96.56	1.51	3.91	4.33	0.26	2.19	7	0.75	1.71	8.67	46.17	27.71
JFM52	7852-7856	89.08	1.53	4.11	4.58	0.53	11.55	7.46	0.94	2.69	11.41	48.69	37.64
JFM53	7856-7860	92	2.57	4.11	8.7	1.03	9.88	4.43	0.57	1.22	8.74	46.59	57.99
JFM55-2	7864-77868	84.98	3	4.56	0.89	0.71	7.29	5.58	2.23	2.05	3.92	48.76	17.87
JFM59	8375-8377	96.82	2.85	no match	no match	0.11	0.72	7.81	0.75	0.94	3.39	47.01	0.09
JFM63	8383-8385	93.13	2.87	no match	no match	0.72	0.98	5.93	2.17	1.07	3.99	1.89	40.39
JFM70	8397-8399	96.02	1.54	no match	no match	0.57	0.93	1	0.94	1.53	11.06	1.96	34.79
JFM80	8417-8419	41.72	0.63	no match	no match	0.35	0.92	23.64	2.13	2.4	3.52	28.81	18.96

Table 3.1: Data obtained from XRD analysis. Bulk composition of the samples was determined based on intensity percentages given by the XRD. Most of the analyzed sandstones were made up of quartz, therefore that is why the intensity of this mineral was the highest. Glauconite intensity was low even for the samples that contained a large amount based on hand sample and thin section observations.



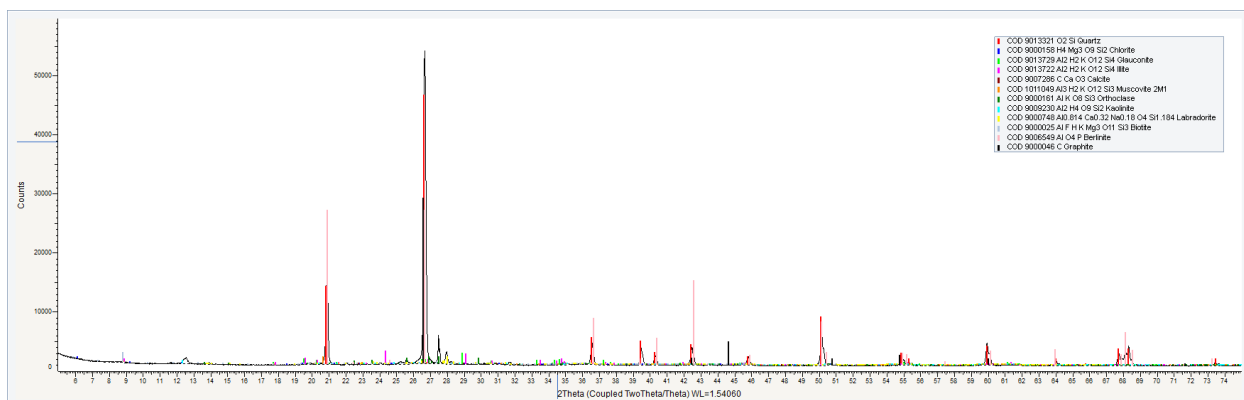


Figure 3.4: XRD graph showing the major peaks in sample JFM23 from the Pilot sands of the lower Tuscaloosa Group. Depths at 2356 m (7731 ft).

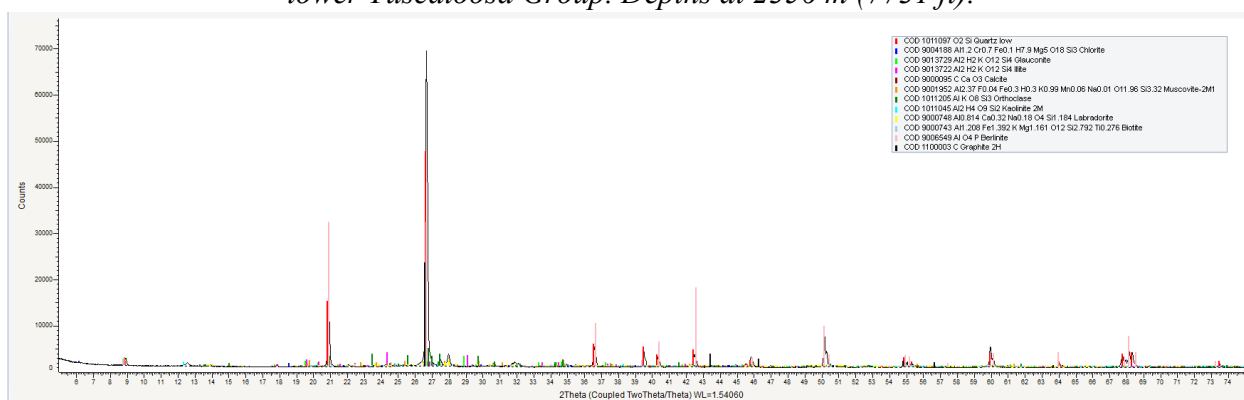


Figure 3.5: XRD graph showing the major peaks in sample JFM28 from the Pilot sands of the lower Tuscaloosa Group. Depth at 2359 m (7742 ft).

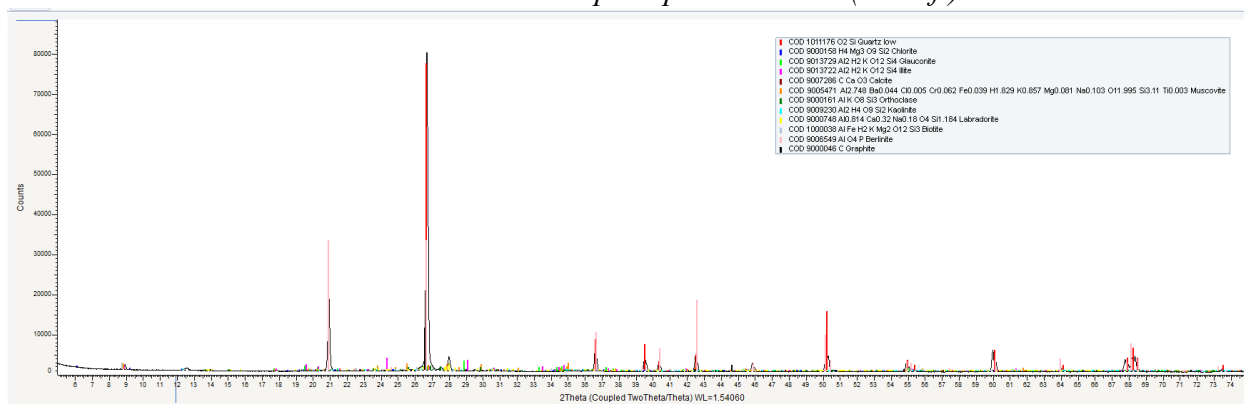


Figure 3.6: XRD graph showing the major peaks in sample JFM31 from the Pilot sands of the lower Tuscaloosa Group. Depth ranging from 2362 m - 2363 m (7751 ft – 7752 ft).

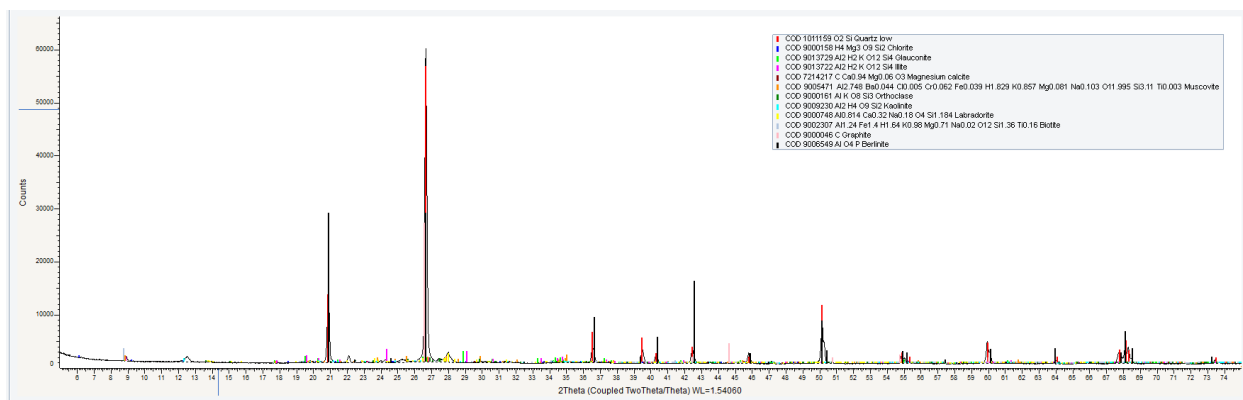


Figure 3.7: XRD graph showing the major peaks in sample JFM32 from the Pilot sands of the lower Tuscaloosa Group. Depth ranging from 2362 m – 2363 m (7751 ft – 7752 ft).

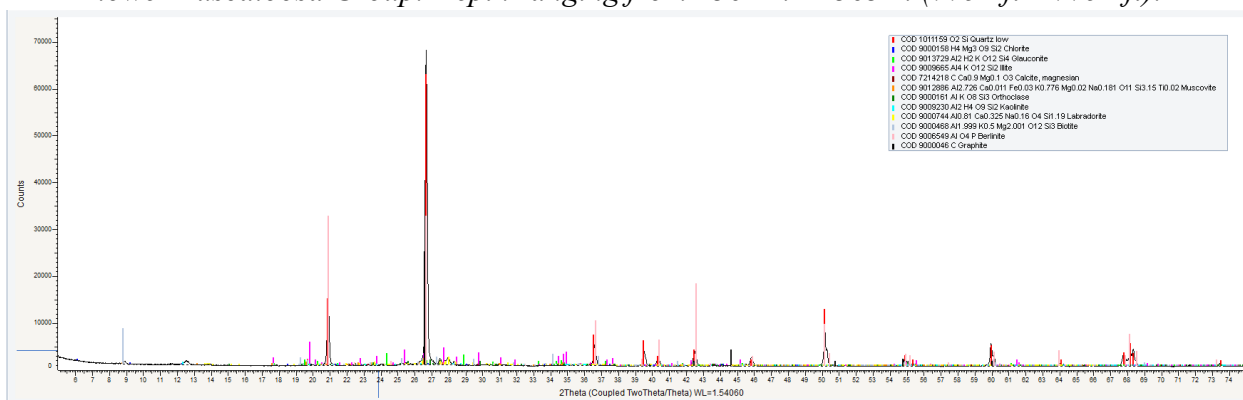


Figure 3.8: XRD graph showing the major peaks in sample JFM33 from the Pilot sands of the lower Tuscaloosa Group. Depth ranging from 2363 m – 2364 m (7753 ft – 7755 ft).

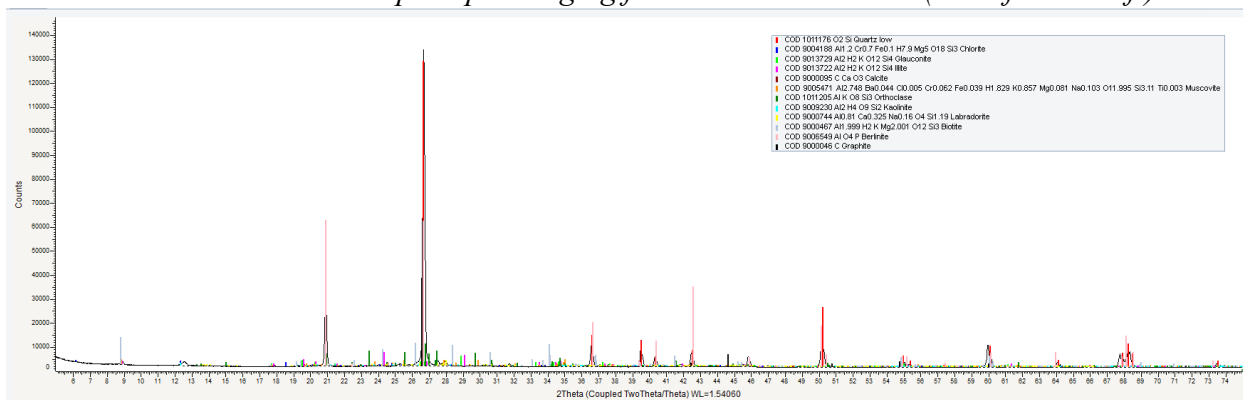


Figure 3.9: XRD graph showing the major peaks in sample JFM41 from the Pilot sands of the lower Tuscaloosa Group. Depth ranging from 2382 m – 2386 m (7818 ft – 7820 ft).

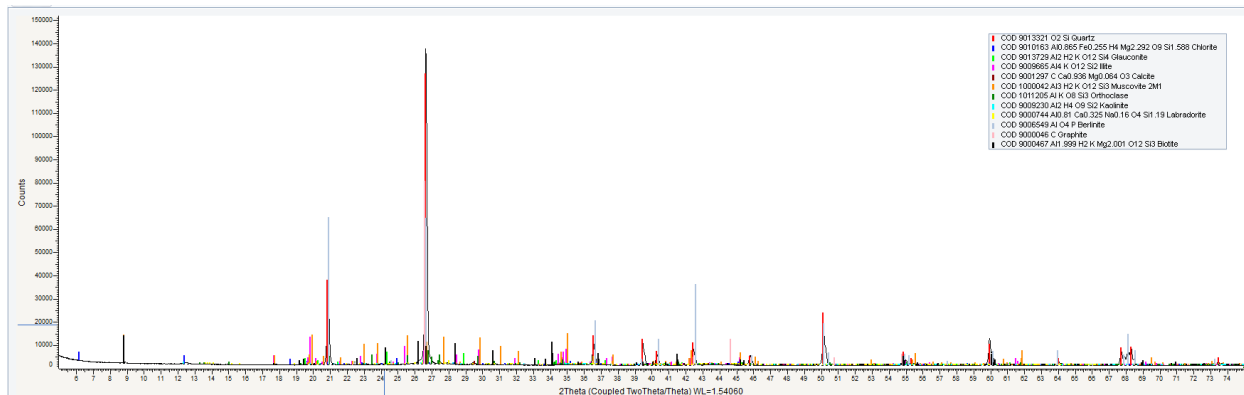


Figure 3.10: XRD graph showing the major peaks in Sample JFM42 from the Pilot sands of the lower Tuscaloosa Group. Depth at 2384 m (7822 ft).

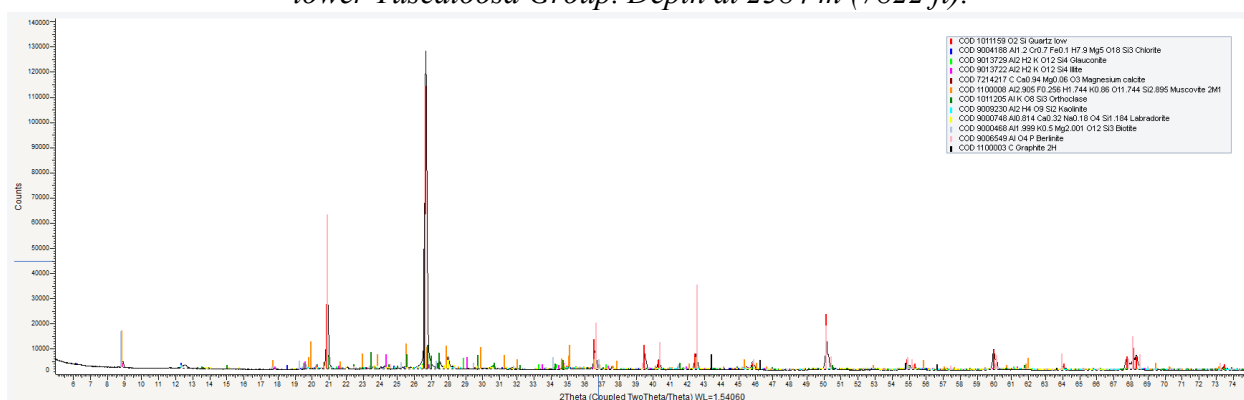


Figure 3.11: XRD graph showing the major peaks in sample JFM48 from the Pilot sands of the lower Tuscaloosa Group. Depth ranging from 2388 m – 2390 (7836 ft – 7840 ft).

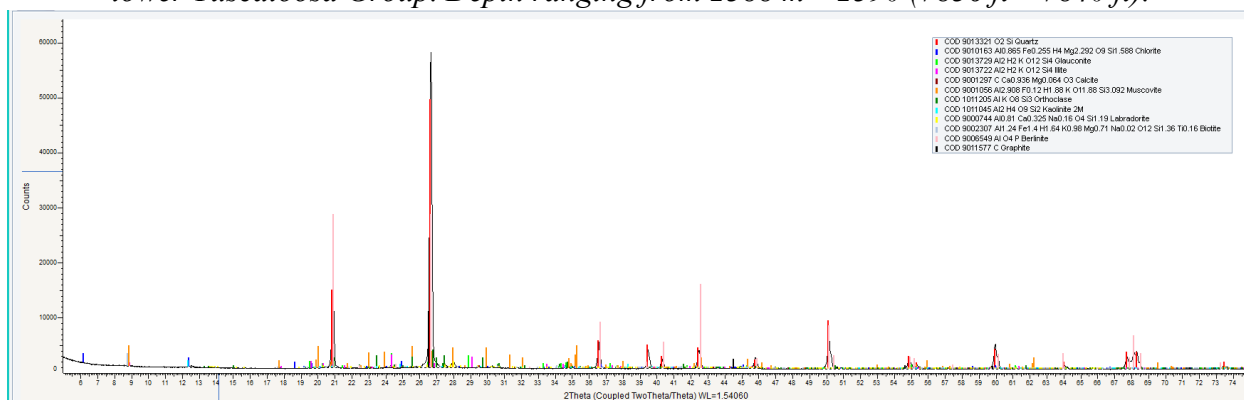


Figure 3.12: XRD graph showing the major peaks in sample JFM52 from the Pilot sands of the lower Tuscaloosa Group. Depth ranging from 2393 m – 2395 m (7852 ft – 7856 ft).

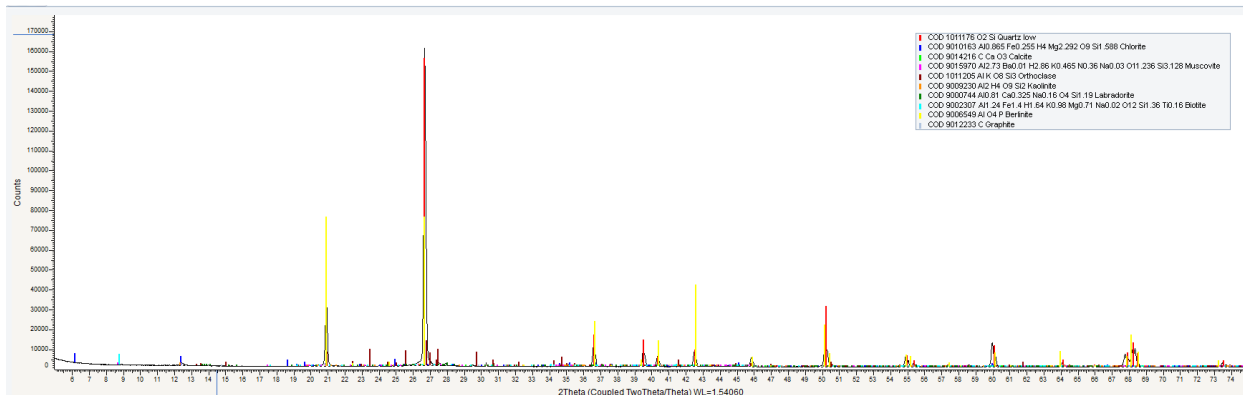


Figure 3.13: XRD graph showing the major peaks in sample JFM55-2 from the Pilot sands of the lower Tuscaloosa Group. Depth ranging from 2396 m – 2398 m (7864 ft – 7868 ft).

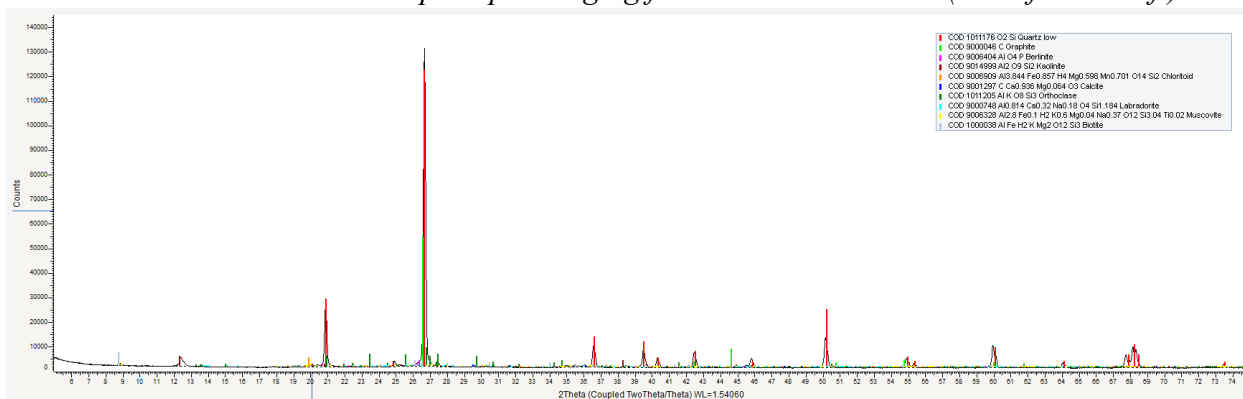


Figure 3.14: XRD graph showing the major peaks in sample JFM59 from the Pilot sands of the lower Tuscaloosa Group. Depths ranging 2555 m - 2554 m (8377 ft – 8379 ft).

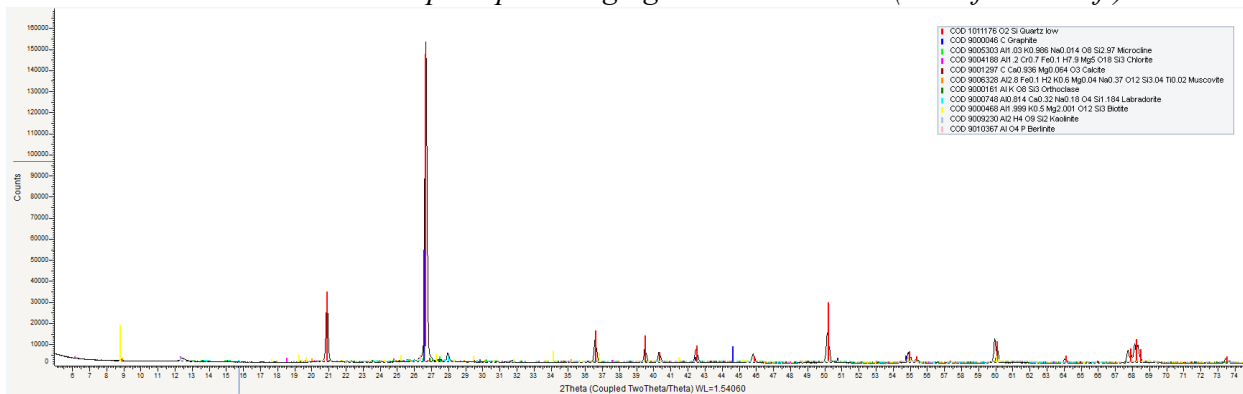


Figure 3.15: XRD graph showing the major peaks in sample JFM63 from the Massive sands of the lower Tuscaloosa Group. Depth ranging from 2555 m – 2556 m (8383ft – 8385 ft).

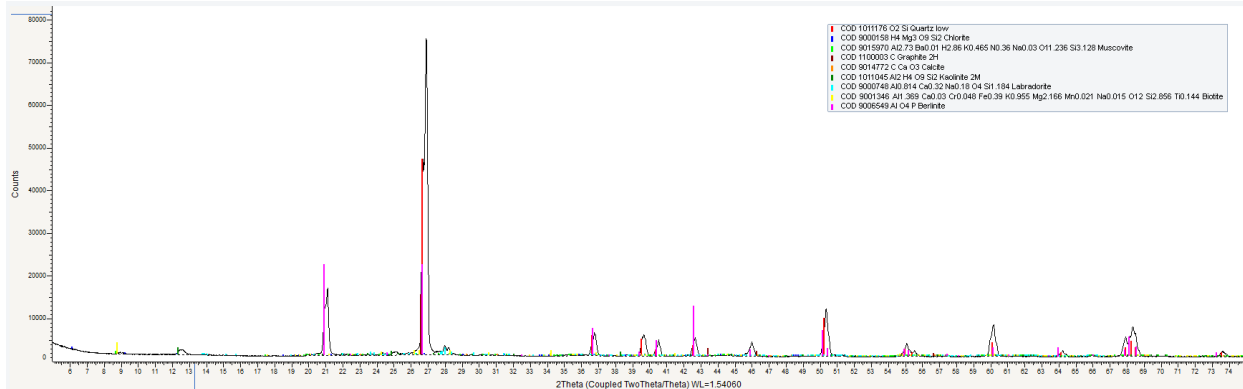


Figure 3.16: XRD graph showing the major peaks in sample JFM70 from the Massive sands of the lower Tuscaloosa Group. Depth ranging from 2561 m – 2562 m (8403 ft – 8405 ft).

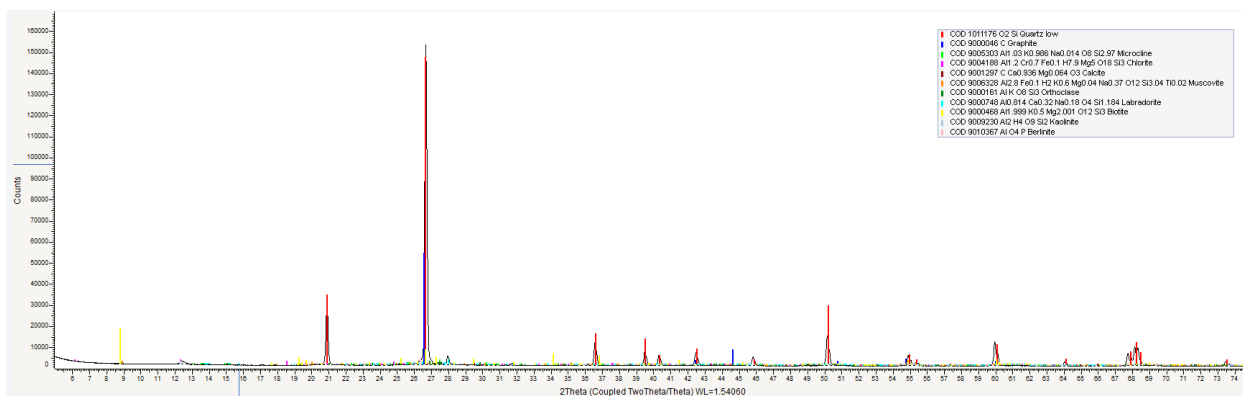


Figure 3.17: XRD graph showing the major peaks in sample JFM80 from the Massive sands of the Tuscaloosa Group. Depth ranging from 2566 m (8417 ft – 8419 ft).

Appendix
Part 4: SEM Photographs

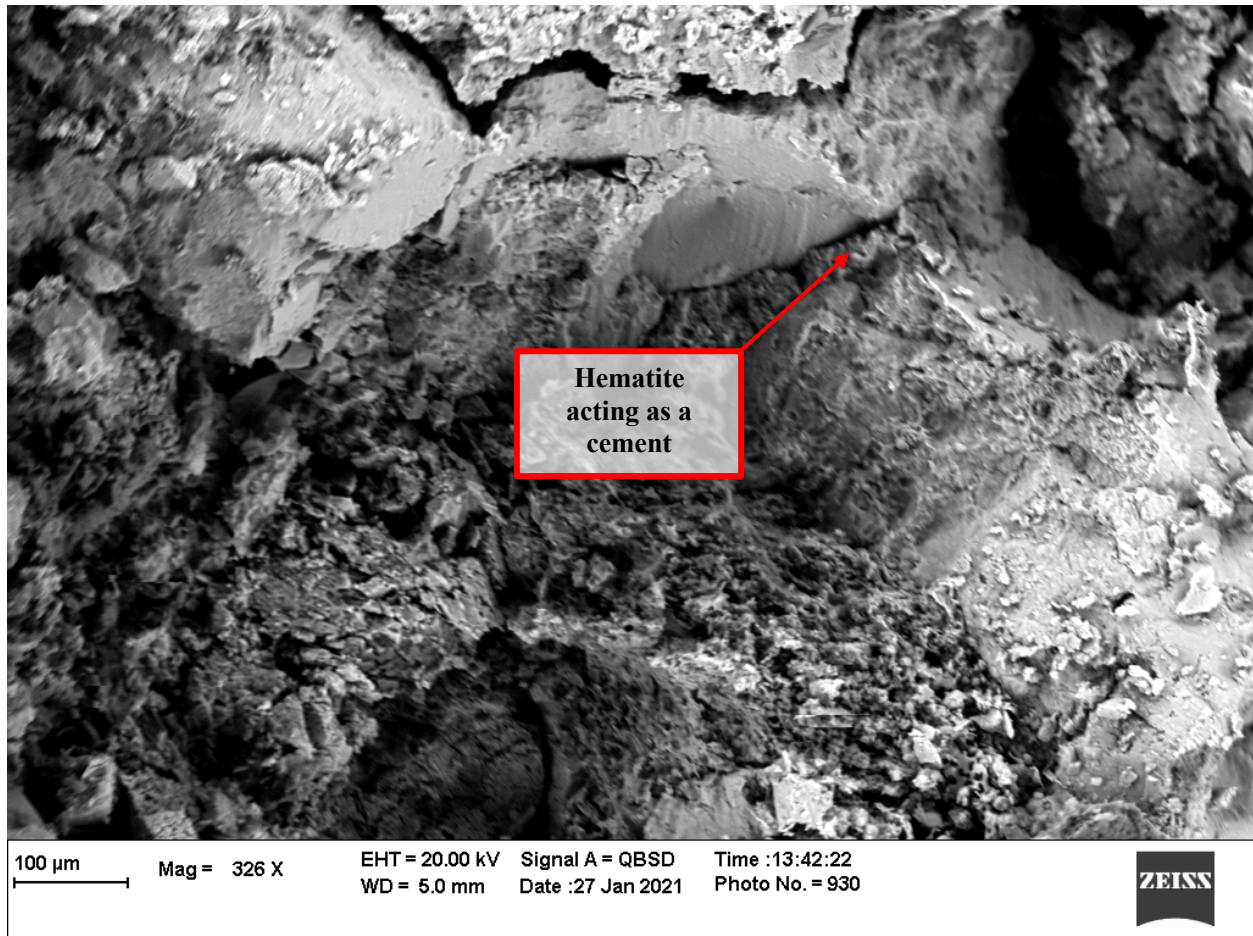


Figure 4.1: SEM image of sample JFM47 showing the cement between the grains. Based on SEM observations and thin sections, the cement between these grains was interpreted to be hematite and clays.

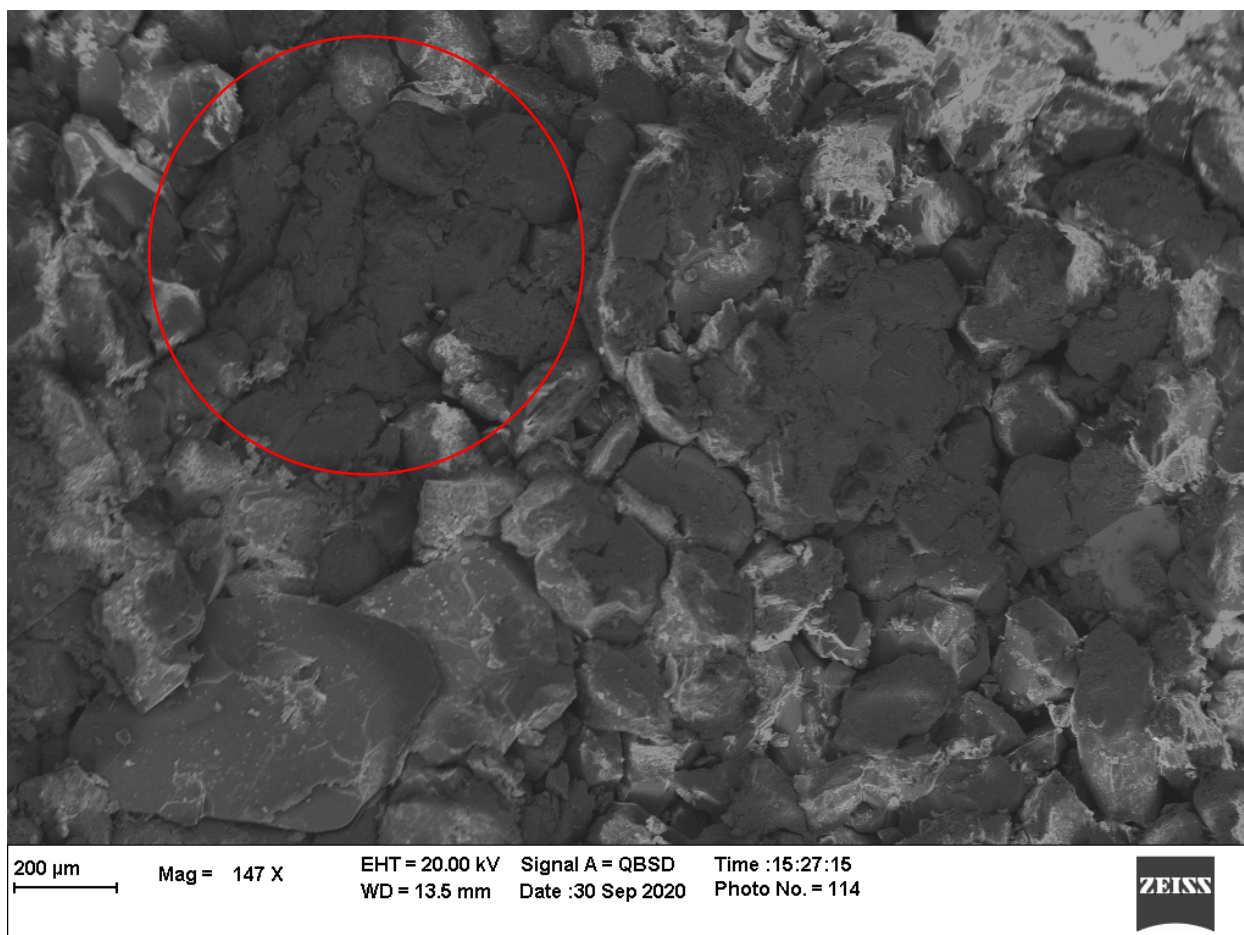


Figure 4.2: SEM image of sample JFM47 highlighting a cluster of oval shaped glauconitic grains. Depth of sample ranging from 2387 m – 2388 m (7832 ft – 7836 ft).

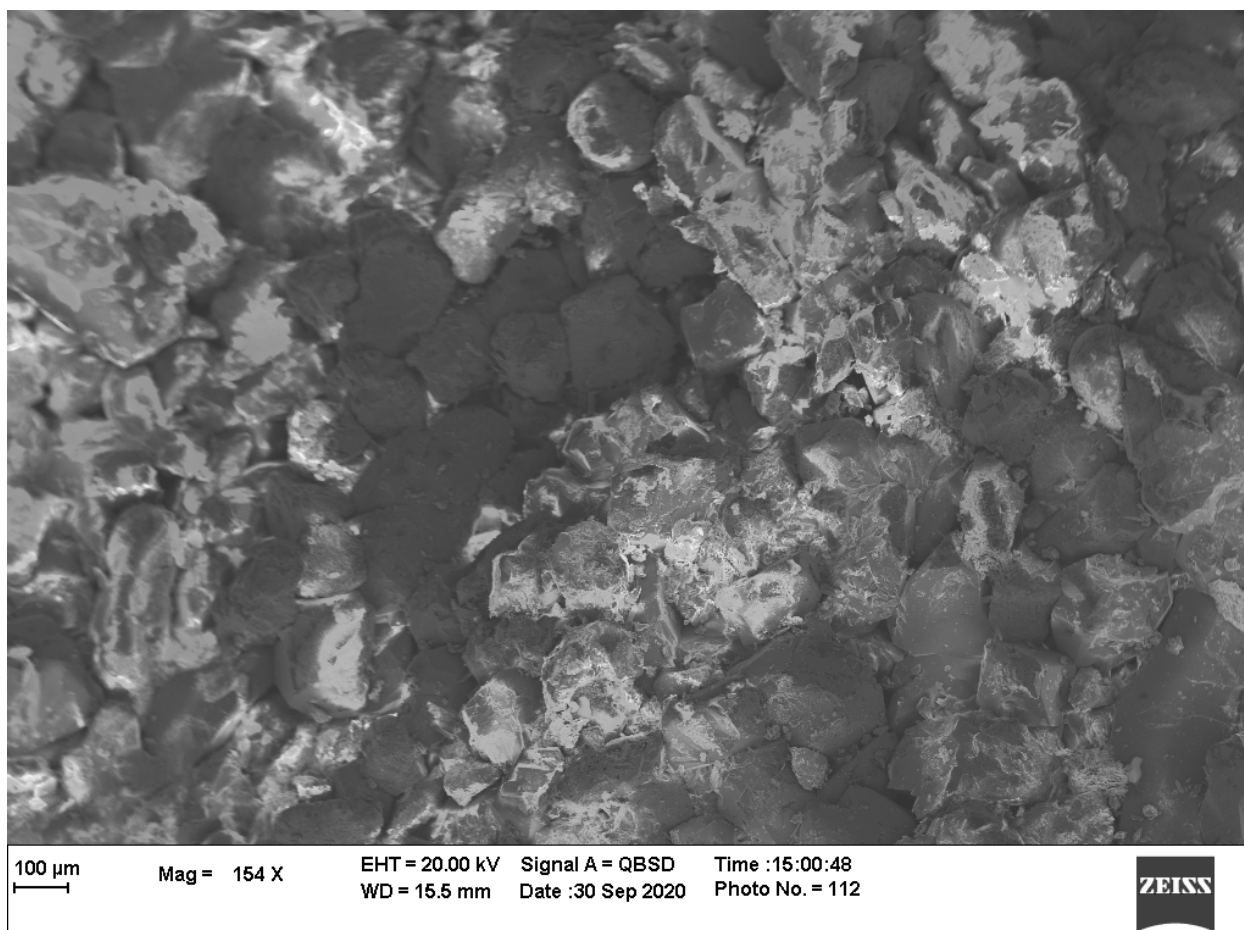


Figure 4.3: Backscattered electron (BSE) image sample JFM47. Depth of sample ranging from 2387 m – 2388 m (7832 ft – 7836 ft).

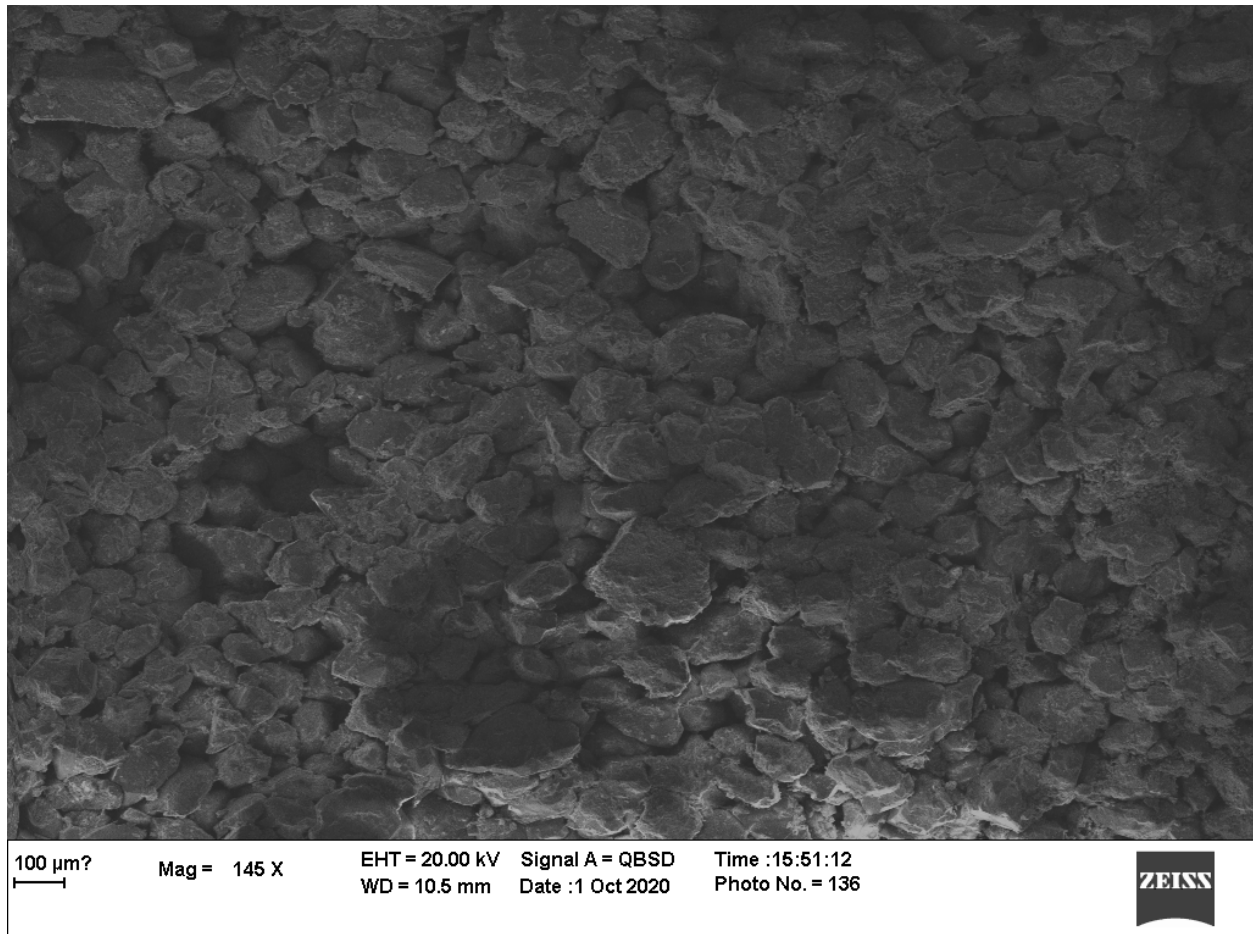


Figure 4.4: SEM image of sample JFM52 showing the topography and geometry of the shapes. Quartz grains ranged between being subangular and angular. The glauconite grains were easy to distinguish since they had a more oval shape. Depth of sample ranging from 2393 m – 2395 m (7852 ft – 7856 ft).

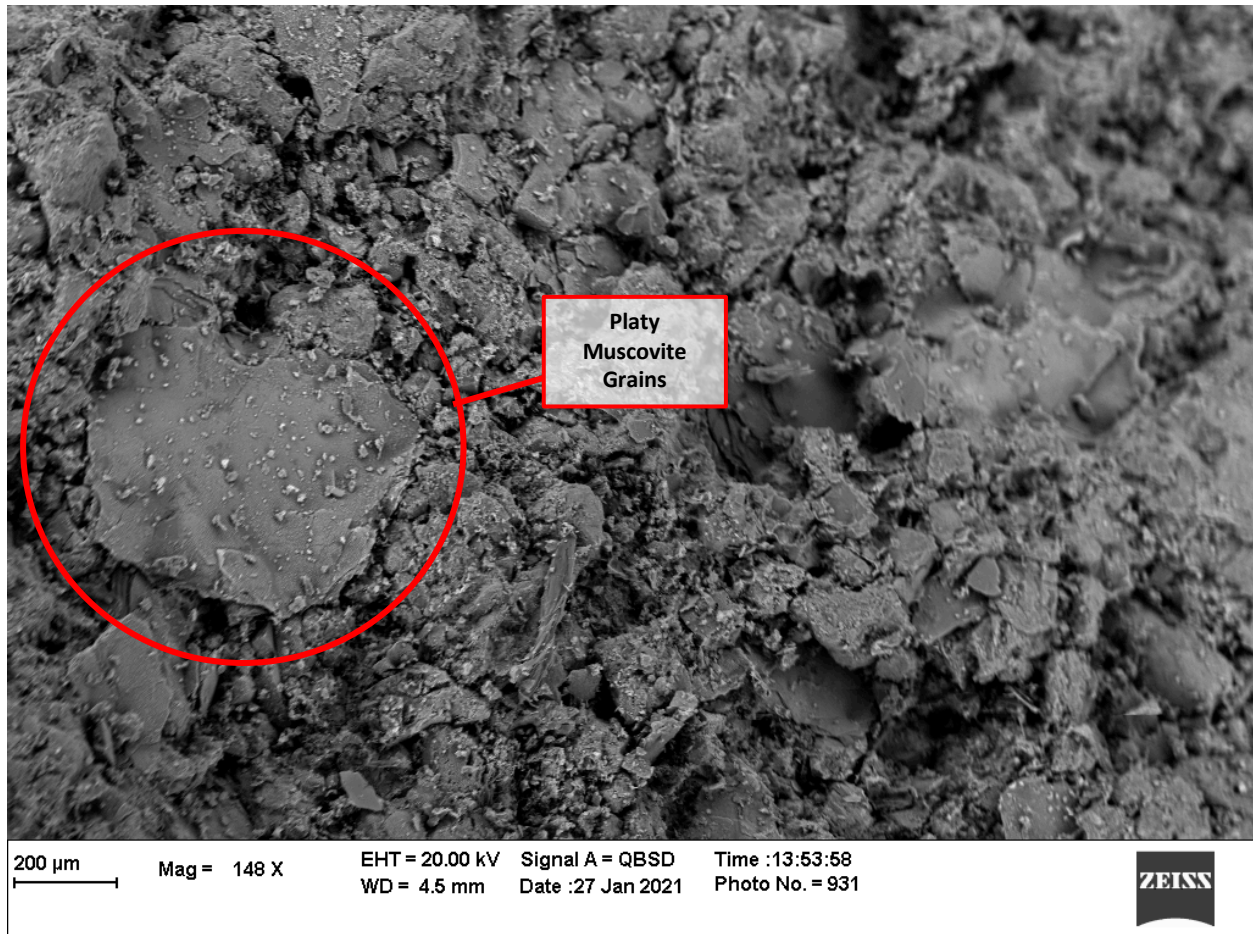


Figure 4.5: SEM image of sample JFM55-2 showing the topography of the sandstones and muscovite grains which were common throughout the entire Julian F. McGowin #1 drill core. Evidence of muscovite was found on most samples from both, the upper Tuscaloosa and the lower Tuscaloosa. Depth of sample ranging from 2396 m – 2398 m (7864 ft – 7868 ft).

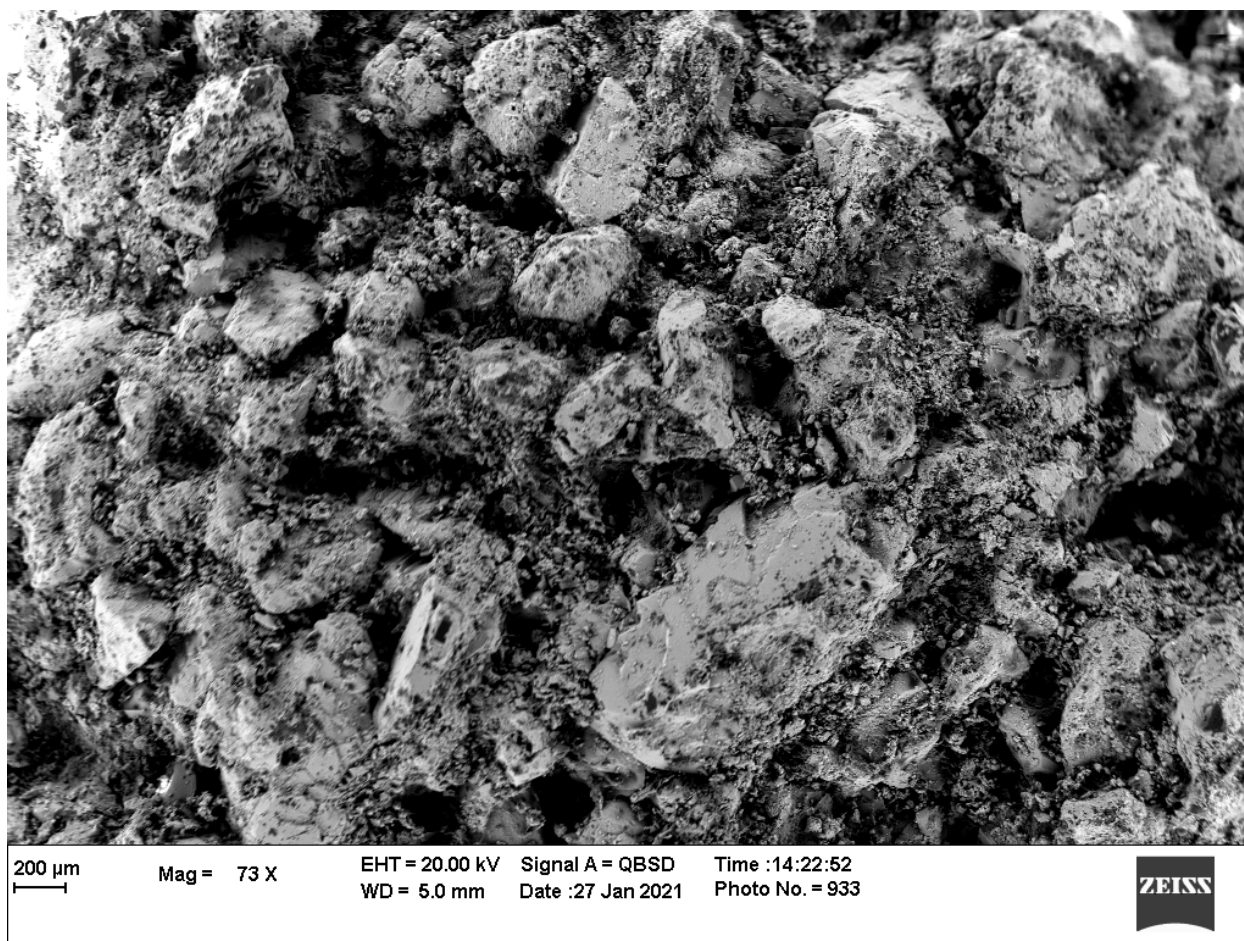


Figure 4.6: SEM image of sample JFM 73 from the Massive sands of the lower Tuscaloosa. Depth of sample ranging from 2561 m – 2562 m (8403 ft – 8405 ft).

Appendix
Part 5: Geochemical Data

Sample ID	Sample Amount (g)	Fluid (g)
Initial Build	12.63	247.35
01-000	12.63	237.55
01-001	12.63	225.55
01-002	12.63	215.05
01-003	12.63	208.55
01-004	12.63	195.55
01-005	12.63	181.83
01-006	12.63	167.28
01-007	12.63	157.5
01-008	12.63	149.92

Table 5.1: Rock-fluid ratio in Set A of the geochemical experiments as it ran. This set contained sandstones that did not contained glauconites.

Sample ID	Sample Amount (g)	Fluid (g)
Initial build	14.63	237.79
02-000	14.63	234.23
02-001	14.63	208.17
02-002	14.63	200.57
02-003	14.63	191.29
02-004	14.63	176.66
02-005	14.63	161.85
02-006	14.63	146.6
02-007	14.63	135.68
02-008	14.63	128.02

Table 5.2: Rock-fluid ratio in Set A of the geochemical experiments as it ran. This set contained sandstones that did not contained glauconites.

TEdit - thermo.tdat

File Edit View Help

thermo.tdat x

...TcO3(s)

...TcOH(s)

...TcS2(s)

...TcS3(s)

...Tenorite

...Tephroite

...Th(NO3)4*5H2

...Th(OH)4(c)

...Th(SO4)2(c)

...Th2S3

...Th2Se3

...Th7S12

...ThBr4

...ThCl4(c)

...Thenardite

...ThF4(c)

...ThF4*5/2H2O

...ThI4

...ThO2

...Thorianite

...ThS2

...Todorokite

...Torbernite

...Tremolite

...Tridymite

...Trollite

...Tsumebite

...Tyuyamunite

...U(c,alph)

...U(HPO4)2*4H2

...U(SO4)2(c)

...U3O8(c,alph)

...U3Se4

...U4O9(c)

...UCl4(c)

...UF4(c)

...UF4*5/2H2O

...UO2(am)

...UO2(NO3)2(c)

...UO2(NO3)2*2H

Mineral

Apply Undo Redo

Name: Reference:

Mole weight: g/

Molar volume: cm3/

Type:

Formula:

Status: ✔ No errors found

Species in reaction

Species	Stoichiometry	Value
H+	↕	-7
Fe++	↕	0.25
SiO2(aq)	↕	3.75
Fe+++	↕	1.25
H2O	↕	4.5
Al+++	↕	0.5
K+	↕	0.75
Mg++	↕	0.25

add delete reduce

Reaction

Glaucosite + 7 H + = .25 Fe++ + 3.75 SiO2(aq) + 1.25 Fe+++ + 4.5 H2O + .5 Al+++ + .75 K+ + .25 Mg++

Log Ks

0°C	25°C	60°C	100°C	150°C	200°C	250°C	300°C
4.5595	2.0699	-0.6483	-2.9905	-9.48045	-7.0043	-8.649	-10.4076

Figure 5.1: Thermodynamic properties used to add mineral glaucosite to the thermodynamic database of Geochemist Workbench. Properties were obtained from Blanc et al. (2015).

Main Diagram

	pH(1) Eh (V)(1)		pH(2) Eh (V)(2)		Equation	Type
FeHCO3+	3.231	0.089	0.000	0.337	208	Lower
Pyrite	3.231	1.000	3.231	0.089	212	Right
	0.000	0.337	3.231	0.089	208	Upper
	3.231	0.089	3.287	0.084	554	Upper
Siderite	3.287	0.084	3.661	0.000	559	Upper
	3.287	0.084	3.231	0.089	554	Lower
	3.231	0.089	3.231	1.000	212	Left
Glaucosite	3.287	1.000	3.287	0.084	585	Right
	3.661	0.000	3.287	0.084	559	Lower
	3.287	0.084	3.287	1.000	585	Left

Figure 5.2: Eh and pH diagram values obtained from Geochemist Workbench showing the possible formation and precipitation of different species in the activity diagram created.