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Preliminary Feasibility of Transporting and Geologically Sequestering Carbon Emissions in the Florida Pan-Handle

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PRELIMINARY FEASIBILITY OF TRANSPORTING AND GEOLOGICALLY
SEQUESTERING CARBON EMISSIONS IN THE FLORIDA PAN-HANDLE

by

Brandon Keith Poiencot

A thesis submitted to the School of Engineering in partial fulfillment of the requirements
for the degree of

Master of Science in Civil Engineering

UNIVERSITY OF NORTH FLORIDA

COLLEGE OF COMPUTING, ENGINEERING AND CONSTRUCTION

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Abstract

According to the United States Department of Energy, fossil-fueled power plants account for 78% of stationary source CO₂ emission in the United States and Canada. This has led electric utilities across the globe to research different alternatives for energy. Carbon sequestration has been identified as a bridge between fossil fuels and clean energy.

This thesis will present research results regarding the transportation costs of CO₂ and the suitability of geology in the Florida Pan-Handle for sequestration infrastructure. The thesis will utilize various evaluation tools including GIS, numerical models, and optimization models.

Analysis performed for this thesis and review of published literature produced estimated carbon storage capacities for two areas in and near the Florida Pan-Handle. These areas were labeled Disposal Area 1 and Disposal Area 3. Disposal Area 1 was estimated to contain capacity for the storage of 5.58 gigatonnes of CO₂. Disposal Area 3 was estimated to contain capacity for the storage of 2.02 gigatonnes of CO₂. Transportation scenarios were analyzed over a 25 year period and the capacities above are sufficient to store the CO₂ emissions from the Pan-Handle network of power plants for the study period.

Four transportation routing scenarios were investigated using transportation costs from the Poienkot and Brown CO₂ pipeline capital cost model. The scenarios (models) consisted of the Right-Of-Way, Solo-Funded, Piece-Wise, and Authority models. Each presents a different method for the overall funding of the Florida Pan-Handle CO₂ network and produced different total levelized and mean unit costs. The cheapest

network on a mean unit cost basis was the network for Disposal Area 1 in the Authority Model, producing a mean unit cost of \$0.64 per tonne of CO₂.

Chapter 1

INTRODUCTION

Greenhouse gases (GHGs) present in the atmosphere contribute to the trapping of radiant heat from the sun in the Earth's atmosphere, also known as the greenhouse effect. Carbon dioxide (CO₂) is the GHG of greatest interest because CO₂ is the most prevalent GHG (DOE, 2010). CO₂ is released into the atmosphere from manmade and natural sources. Manmade sources of CO₂ are mainly emitted from the burning of various fossil fuels for power generation, transportation, and numerous industrial activities (DOE, 2010). Focus lately has been directed at reducing the CO₂ emissions from power generation facilities. One technology currently under research, development, and testing is carbon capture and storage (CCS), or carbon sequestration.

Much of the technology and methods required for CCS has been used for over 30 years by the oil industry for enhanced oil recovery (EOR) practices (Esposito et al, 2010). The CCS process involves capturing CO₂ from the source, transporting the CO₂ in a supercritical or fluid phase to a storage location, and injecting the supercritical or fluid CO₂ into a saline aquifer, existing oil fields, depleted natural gas fields, or thin-nonmineable coal seams (Benson & Cook, 2005). The emission sources this thesis focuses upon are fossil fuel power plants which account for 78% of stationary source CO₂ emissions in the United States and Canada (DOE, 2011). According to 2005 Environmental Protection Agency (EPA) data, there are 136 large and small power plants

in Florida which are fueled by fossil fuels. In total, Florida power plants accounted for 143 million tonnes of CO₂ emissions in 2007 (EPA, 2011).

Saline aquifers contain a majority of the potential sequestration capacity in the Southeastern United States representing approximately 92% of the total (DOE, 2010). Oil and gas reservoirs do exist in Florida but are not considered in this thesis because they are found much deeper than suitable saline aquifers and their sequestration capacity is more limited. Also, coal seam sequestration is not considered because there are limited opportunities in Florida (Pugh et al, 2008). The U.S. Department of Energy has identified possible formations for saline aquifer storage in Florida. Some preliminary detailed work has been completed in evaluating these potential storage repository zones (Roberts-Ashby, 2010). Transportation of the CO₂ is also an issue due to the great distances that can separate sources from their corresponding geologic sinks. A transportation network is required to make any large deployment of CCS technology a reality in Florida. The University of North Florida (UNF) has been investigating these issues in Florida since May 2010 using data collection, computer sequestration modeling, and transportation optimization modeling (Poencot and Brown, 2011). It should be noted that this report will focus on the transportation costs associated with CCS in Florida and does not include the costs for capture, compression, injection, storage or monitoring.

The purpose of this paper is to assess the feasibility of CCS for the Florida Pan-Handle by presenting the results of CCS transportation and storage research, including the development of a CO₂ pipeline transportation model, a comparison of the Poencot/Brown cost model to other published CO₂ transportation cost models, cost analysis of different CO₂ transportation network deployment scenarios using linear

optimization, storage zone characterization, and numerical simulation of CO₂ sequestration in a saline aquifer. Florida is a state that is heavily dependent on fossil fuels for electricity generation with nearly 97% of generators in the state producing carbon emissions (EPA, 2011). While CCS is not a permanent solution to the world's GHG problems, the technology does provide a bridge between the world's current reliance on fossil fuel generated electricity and that of diversified clean energy production. This thesis is a step towards proving the preliminary feasibility of CCS in the Florida Pan-Handle.

1.1 Technology Overview

Carbon capture and storage is a technological innovation whereby carbon dioxide off-gas is captured, separated from other gases, concentrated, compressed, and then injected into underground repositories. Here the carbon dioxide is sequestered or stored for hundreds to thousands of years, effectively reducing the carbon footprint of the industrial emitter. In 2005, 83% of Florida's electrical energy was produced by fossil fuels while in 2010 the percentage was almost 89% (EIA, 2009). The continuing use of fossil fuels, in Florida, may depend upon finding suitable subsurface sequestration repositories in Florida and connecting them to an optimized network of pipelines and primary CO₂ sources.

According to the Intergovernmental Panel on Climate Change (IPCC), storage of CO₂ in geologic formations includes four primary storage repository categories: saline aquifers, existing oil fields, depleted natural gas fields, and thin-nonmineable coal seams (Benson & Cook, 2005). The capacity of each of these repository categories to sequester

CO₂ is an important planning variable to be considered during feasibility-level investigations of potential projects (Koide et al., 1992; Bradshaw et al., 2007). Deep saline aquifers appear to offer the highest potential capacity of the four primary options (Bachu et al., 1994; Van der Meer, 1995; Obdam et al., 2003; Herzog, 2009). In Florida, saline aquifers are the most likely storage option (DOE, 2010). According to the United States Department of Energy (DOE, 2010), the estimated capacity of oil/gas fields is relatively small by comparison (e.g., 100 times less) and their geographic distribution is rather limited. A typical CCS saline aquifer storage project will undergo several operational changes over time with the injected CO₂ ultimately becoming completely dissolved in the aquifer fluid. The various operation phases include site characterization, initial active injection, post-injection, and long-term monitoring. During the project lifecycle, there are significant changes in the state of injected CO₂ with it starting as a free-phase, becoming residually-trapped, being dissolved, and ultimately being precipitated as a mineral. The relative time scales for each process are different with residual trapping likely a decadal time scale, dissolution over hundreds of years, or more likely in saline waters, thousands of years and mineralization over even longer periods. During active operations, when liquid or supercritical CO₂ is being injected into a repository, the CO₂ will be highly mobile as a pure separate phase and concentrated aqueous phase (Bachu & Adams, 2003). Carbon dioxide is a highly compressible fluid compared to water and its density radically increases from 300 to 800 kg/m³ at pressure ranging from 10 to 25 MPa (Han & McPherson, 2009). Since liquid or supercritical CO₂ has a density less than the typical density of the saline repository fluid (Sharqawy et al., 2010), it will be buoyant, tending to rise within the formation (MIT, 2010) until it

intercepts a competent confining unit (primary seal) where it may spread laterally until it will become trapped (Flett et al., 2005). In some cases, depending upon formation dip, the supercritical CO₂ may migrate updip along the confining unit. The feasibility of any type of system will require the design and planning of a transportation system and suitable storage repositories.

Chapter 2

STUDY AREA

The study area consists mainly of the Florida Pan-Handle, or western Florida. A network comprises of sources and sinks. This chapter identifies the sources for the proposed Florida Pan-Handle network, which are fossil fuel power plants. Also identified are the sinks, which are the proposed CO₂ disposal areas. The CO₂ will be stored in saline aquifers and the general geology of each area is discussed.

2.1 Florida Emission Sources

The first task in developing an optimal CO₂ pipeline transportation network for Florida is to identify the location and magnitude of the largest sources of CO₂ within the state. Florida has 136 primary sources of CO₂ inventoried by the EPA. For the initial model development effort (Poencot & Brown, 2011), the 40 largest sources of CO₂ were identified and summarized. These 40 sources comprise over 90% of the 2005 total CO₂ emissions for Florida. Poencot & Brown (2012) later updated these 40 sources with 2007 CO₂ emission data from DOE (2011). The list of 40 sources is included in Appendix A. Because this thesis focuses on the pan-handle area of Florida, the list of sources was narrowed down to those in and around the Pan-Handle. The 13 sources along with a map identification number, location in UTM 1983 (meters) horizontal grid coordinates, and the respective annual CO₂ emissions for 2007 are listed in Table 1. Each of the 13 sources is also shown on Figure 1 along with two potential CO₂ repositories discussed later in this thesis. Also note that the power plant ID numbering is consistent with the

original 40 sources from other publications (Poencot and Brown, 2011; Poencot & Brown 2012).

Table 1. Florida Pan-Handle CO₂ Emission Sources

Map ID	Plant Name	Northing	Easting	Annual CO₂ Emission (Mt)
1	Crystal River	3204678.076	334313.2099	14.53
3	St Johns River Power Park	3366685.069	447107.3266	9.38
4	Seminole	3289401.62	438698.3555	8.95
6	Crist	3398084.815	-97895.92908	6.62
10	Northside Generating Station	3365145.497	446936.553	4.46
13	Lansing Smith	3357948.163	47642.89122	3.44
22	Deerhaven Generating Station	3292844.025	365772.0841	1.58
26	Cedar Bay Generating Company LP	3365693.624	441618.5065	1.28
32	S O Purdom	3341056.505	191654.8001	0.64
33	Brandy Branch	3354692.44	408803.1779	0.63
37	Arvah B Hopkins	3373808.201	173480.9335	0.52
38	Scholz	3399359.3847	127519.0930	0.52
39	Putnam	3277742.366	443310.436	0.50

2.2 Geologic Storage Areas

2.2.1 Storage Zone Characterization

With the sources (supply nodes) identified, the CCS repository or demand locations are identified next. The locations of the various repositories were based upon the available geology, location of existing emission sources, and institutional concerns regarding possible CO₂ releases (Lewicki et al, 2007). Based upon the existing research, Florida has ample potential CCS repositories including depleted oil/gas fields, unminable coal seams, and deep, saline aquifers (Cole, 1942; Chen, 1965; Babcock, 1969; Vernon, 1970; Puri & Winston, 1974; Raymond & Copeland, 1988; Rupert, 1991; Yamamoto et al, 2009). Of the four primary disposal alternatives, saline aquifers present the best opportunity to store large quantities of CO₂ safely (DOE, 2008; DOE, 2010).

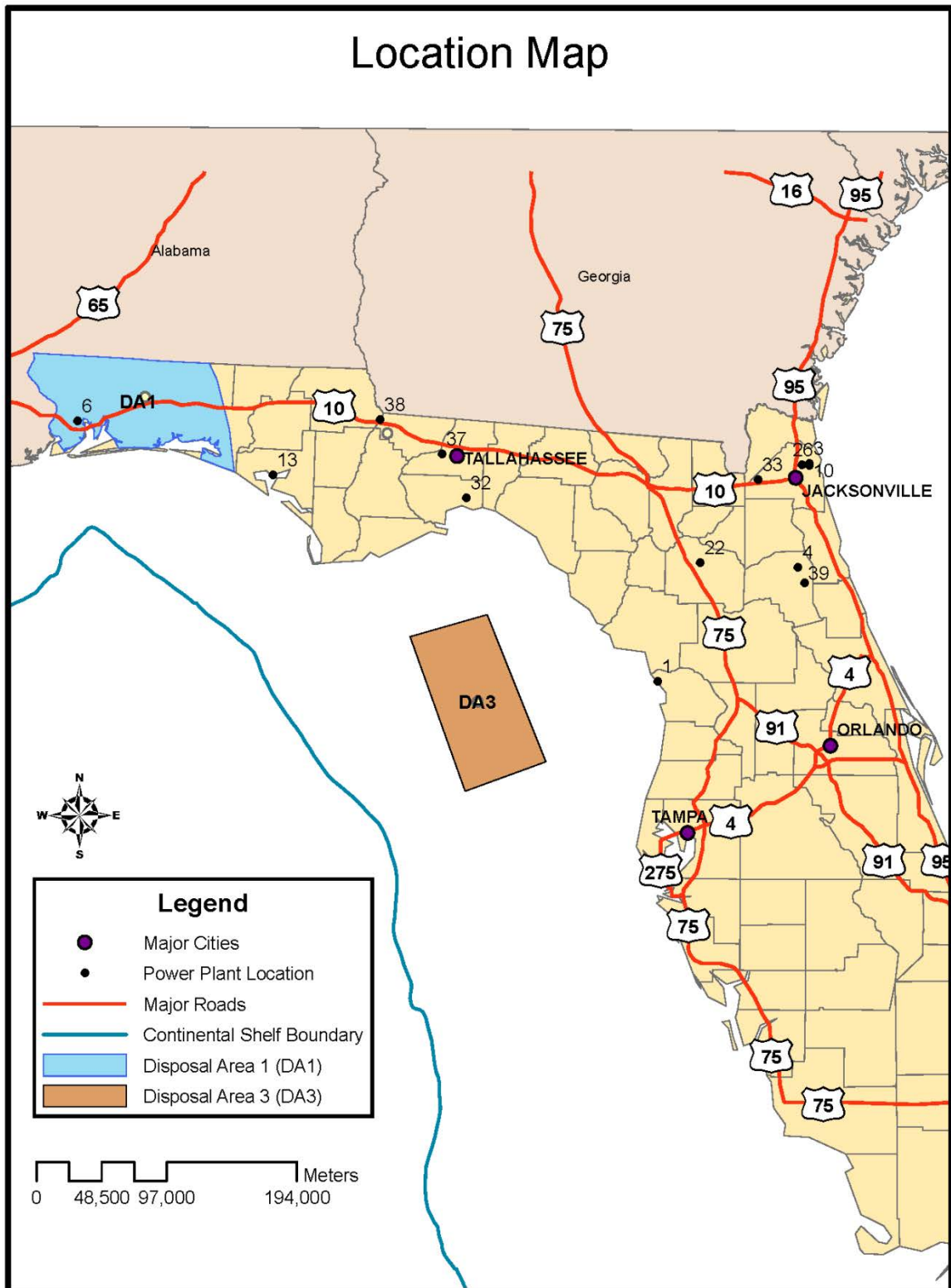


Figure 1. Study Area Location Map

Building upon the existing research, this thesis has chosen two separate saline aquifer CCS repository sites (see Figure 1) distributed throughout the Florida Pan-Handle. Each of the 2 sites represents a portion of an identified CO₂ disposal/repository site outlined in the “2010 Carbon Sequestration Atlas of the United States and Canada” (DOE, 2010). Each of these two sites is discussed herein. Figure 2 presents the overall saline aquifer sequestration potential for the southeastern United States, as defined by DOE in the Carbon Atlas (DOE, 2010).

The Florida panhandle contains ample potential capacity for carbon sequestration within the Upper Cretaceous Zone, specifically the Tuscaloosa Formation. This formation is present in several Gulf Coast states and is estimated to have a “low” estimate capacity

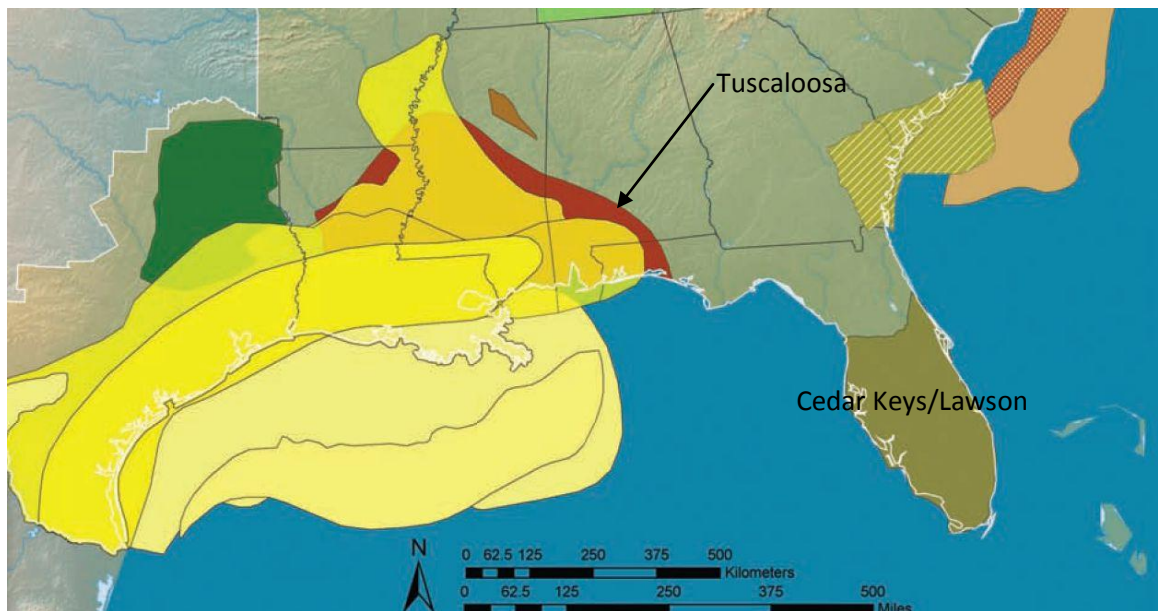


Figure 2. Southeastern United States Geologic Sequestration Potential (DOE, 2010)

of at least 5 gigatonnes (Gt) according to the (DOE, 2010). Disposal Area 1 (DA1) consists of the western Pan-Handle. Disposal Area 3 (DA3) is located off-shore of the

Pan-Handle in the Gulf of Mexico. Not much data exists to characterize this region however; preliminary assessment was completed by Poiencot and Brown (2011 & 2012), where geologic information was extrapolated offshore under the assumption that similar geology exists from the peninsula of Florida to the extents of the Florida shelf. Characterization of DA3 will be carried over from the initial studies and included here as an offshore, low impact alternative.

2.2.1.1 Selma Group

The Selma Group in the area of Cedar Keys, Florida is mainly white chalk with some chalky limestone (Cole, 1942). Pugh et al. (2008) describe the Selma in the area of Bay County as comprising of marls, clay, limestones, and interbedded sands and identify the Selma Group as a primary seal for CCS activities in the Florida Pan-Handle.

2.2.1.2 Eutaw Formation

In the area around Plant Scholtz (number 38 on Figure 1), the Eutaw Formation consists of hard, dark gray shales, some chalk and sands while in northern Jackson County, Florida the Eutaw contained much more sand and sandstone and the shale were micaceous (Cole, 1942). The Eutaw is also identified in the Coastal Province of Alabama as genetically related in sedimentary cycle as the Tuscaloosa where the Eutaw consists mainly of estuarine, inner-shelf marine and open bay sands and fine clastics (Raymond & Copeland, 1988). Pugh et al. (2008) identify the Eutaw formation as a candidate for CO₂ storage in the Florida Pan-Handle.

2.2.1.3 Tuscaloosa Group

In the area of Cedar Keys, Florida the Tuscaloosa consists dominantly of red, light red, brown or mottled shales with interbedded sandstones while in northern Jackson County, Florida, the Tuscaloosa is dominantly sand and sandstone interbedded with shales (Cole, 1942; Rupert, 1991). The Tuscaloosa is generally sub-divided in the upper, middle, and lower members however as far as Gulf County, Florida, only the lower member exists (Rupert, 1991). The general lithology in the area of Gulf, County consists of light-colored sands and interbedded calcareous and glauconitic sands and shales (Rupert, 1991). Raymond and Copeland state in the Coastal Plain Province of Alabama, the Tuscaloosa Group comprises mainly fossiliferous, nearshore, marine clastics (Raymond & Copeland, 1988). In eastern-most Alabama, the formation is typically poorly sorted kaolinitic, arkosic sand and gravel interbedded yellowish-orange to reddish-green mottled kaolinitic clay. Thickness of the Tuscaloosa Formation ranges anywhere from 100 to 400 meters (Raymond & Copeland, 1988). The United States Department of Energy describes the proposed storage reservoir at Southern Company Plant Daniel in Mississippi as a “massive sandstone that is a thick, regionally extensive, porous and permeable coastal to deltaic-marine sandstone at the base of the lower Tuscaloosa” (DOE, 2010). According to the report, the Lower Tuscaloosa in this area is overlain by a thick section of 90 to 140 meters of shales and mudrocks that were deposited as sea level rose during a marine transgression. This deposit of shales and mudrocks is identified as the middle Tuscaloosa. Carbon sequestration activities utilizing the Lower Tuscaloosa for storage may utilize the Middle Tuscaloosa as a potentially effective seal (Pugh et al.

2008). This thesis will focus on a combination of the Eutaw Formation and Upper Tuscaloosa for CO₂ storage.

2.2.1.4 Cedar Keys/Lawson

The offshore repository (DA3) would inject CO₂ into the Cedar Keys/Lawson Dolomite formations. The USDOE estimates that the entire Cedar Keys/Lawson Dolomite formations capable of storing CO₂ have a “low” estimate capacity of approximately 11 Gt (DOE, 2010). For initial studies, the capacity of DA3 was estimated by the area-weighted share of the total estimated low capacity or 1 Gt. According to Chen (1965), the Cedar Keys Formation is widely spread across peninsular Florida and spreads into the Pan-Handle. In Brevard County, Florida, the top of the Cedar Keys Formation ranges from approximately 670 meters NGVD to 914 meters NGVD below land surface. The formation consists of dolomite and evaporates with a minor amount of limestone. Gypsum commonly fills pore spaces within the dolomite beds and occurs as thin irregular streaks or seams in the dolomite. The Lawson Formation is generally found at the base of the Cedar Keys Formation. The Lawson is comprised mainly of pure, clean, very light brown and fine crystalline dolomite and/or chalky dolomitic limestone (Chen, 1965).

Chapter 3

STORAGE CAPACITY

Important in assessing the feasibility of CCS for the Florida Pan-Handle is determining the available storage capacity of the proposed storage areas. Methods outlined by USDOE (2010) and Roberts-Ashby (2010) utilize existing oil and gas geophysical explorations to populate the storage equation used by the National Energy Technology Laboratory. This chapter outlines the process for estimating the storage capacity.

3.1 Storage Capacity Estimation

In conjunction with technical staff from Southern Company, the research effort compiled a series of pertinent geophysical and lithological logs for the purposes of developing a geological model to aid with estimating repository capacity. Wells were chosen if they had a bulk density, borehole compensated sonic, or dual induction geophysical logs. These logs provide a relatively simple method to determine the porosity of the formations in question based upon published standards. In order to determine the capacity of the formation, the volumetric equation for capacity estimation for saline formations was used. This formula is defined in National Energy Technology Laboratory (NETL) Carbon Sequestration Atlas for the United States and Canada (DOE, 2010) as follows:

$$G_{CO_2} = Ah_g \text{ tot } E \quad (1)$$

G_{CO_2} - Carbon mass capable of being stored (kg);

A - Geographic area of the Disposal Area (m^2);

h_g - Gross thickness of the injection formation (m);

ρ_{tot} - Average porosity of the injection formation;

ρ_{CO_2} – Density that the CO₂ would be at given the pressure and temperature of the formation (kg/m³); and,

E – Storage efficiency factor (Typically 1 to 4%).

ArcGIS coverages obtained from NETL depicted the general areas of suitable saline aquifer formations for CCS across the United States. ArcGIS polygons were created around each area of interest in Florida and used to determine the geographic area of each of the proposed repository/disposal sites. The area of Disposal Area 1 (DA1) was created from a much larger coverage which spanned most of Alabama, Mississippi and the Florida Pan-handle, as shown previously in Figure 2. The overall coverage was edited to only include the portions that existed within the boundary of Florida. Disposal Area 3 (DA3) is an offshore area that is believed to share geologic characteristics with the Florida peninsula, as previously mentioned in this report. The polygon size for DA3 was arbitrarily selected. The original estimate for capacity for this site was approximately 1 Gt (Poencot & Brown, 2011). For this thesis, a revised capacity estimate was determined for DA1 by using the ArcGIS polygon, storage zone thickness estimates, estimated porosities, estimated storage efficiencies, and assuming in-place CO₂ densities. The capacity estimate for DA3 was determined from data provided by the USDOE (2010), Roberts-Ashby (2010), and Poencot and Brown (2012).

Well logs used in conjunction with existing cross section and lithologic data were needed to determine the depths of the repository/disposal zone. This information was

required to determine an overall cross-section for DA1, as well as the total thickness of the various storage zones but also in formations, such as the Tuscaloosa, was required to determine the percentage of the formation that was available for sequestration given that much of the Tuscaloosa contains shale stringers. This analysis was accomplished by matching up the limited lithological well logs available to corresponding geophysical well logs. It should be noted that storage zone thickness shown on tables in this report generally indicates “total” sandstone stringer zone thicknesses rather than one continuous geologic zone. Corresponding figures report the total formation thickness including both shale and sandstone. Each well log interpretation is presented in detail in Appendix B.

3.1.1 Average Porosity

In order to calculate the average porosity of the injection formations, geophysical logs and the corresponding Schlumberger conversion graphs were used, similar to the methods used by Roberts-Ashby (2010). An average porosity value was obtained for each well and an average of these values was calculated in order to determine the average porosity of the injection formations. Tables listing the well log data and corresponding porosity values are included in Appendix C. Temperature and pressure data from the well logs were used when available or given a conservative estimate when not available.

3.1.2 Storage Efficiency

Storage efficiency relates to the ratio of available storage in a disposal area and the amount of storage area occupied by injected CO₂. Supercritical CO₂ is less viscous and less dense than the brine found in saline aquifers. Subsequently the injected CO₂ does not displace resident brine in a plug-flow fashion (Okwen, 2009). Instead the CO₂ migrates to the top of the brine as it is injected, forming a layer of CO₂ at the top of the

confined formation (Nordbotten et al, 2006). It is important to calculate the storage efficiency to obtain accurate estimates of sequestration capacity within saline aquifers. Okwen et al. (2009) developed an analytical solution to determining the storage efficiency of saline storage reservoirs. The Okwen model focuses on initial active injection times when the primary trapping mechanisms for CO₂ are stratigraphic and structural trapping, or when the CO₂ is most mobile. Okwen et al. (2009) identify the importance of CO₂ buoyancy to storage efficiency, defined as epsilon (ε) below, and use the dimensionless group as defined below.

$$= \frac{2\pi\Delta\rho g k \lambda_b B^2}{Q_{well}} \quad (2)$$

Δ – difference in density of injected CO₂ and native brine (kg/m³)

g – gravitational acceleration constant (m/s²)

k – intrinsic permeability

λ_b – brine mobility equal to the relative permeability of the brine divided by the viscosity of the brine, $k_{r,b}/\mu_b$

B – thickness of aquifer

Q_{well} – injection rate of CO₂

Once importance of CO₂ buoyancy () is quantified, the storage efficiency calculation can continue. The following efficiency equations are presented by Okwen et al. (2009) and each is used depending on the value of for the proposed storage area.

$$\epsilon \approx (1 - S_R) \frac{1}{\lambda}; \quad 0 \leq < 0.5 \quad (3)$$

$$\epsilon \approx \frac{2(1-S_R)}{(0.0324\lambda - 0.0952) + (0.1778\lambda + 5.9682)^{1/2} + 1.6962\lambda - 3.0472}; \quad 0.5 \leq \lambda \leq 50 \quad (4)$$

S_R – residual brine saturation following displacement of brine by CO_2

λ – ratio of CO_2 mobility to brine mobility, $\lambda_{\text{CO}_2}/\lambda_b$

ϵ - storage efficiency

The calculated ϵ value for DA1 was approximately 0.95, meaning buoyancy would in fact affect the CO_2 plume. Table 2 presents the parameters and calculated values of ϵ , for DA1, for varying values of residual brine saturation (S_R). The residual brine saturation is not a readily definable term, therefore in following the methods of Okwen et al. (2009), a range of values was used. The calculation is presented in further detail in Appendix D.

Table 2. Storage Efficiency Parameters

	$S_r = 0$	$S_r = 0.15$	$S_r = 0.30$	$S_r = 0.45$
λ_c	12496.88	12496.88	12496.88	12496.88
λ_b	1361.90	1361.90	1361.90	1361.90
λ	9.18	9.18	9.18	9.18
ϵ	0.10	0.08	0.07	0.05

As mentioned previously, storage efficiency values typically range from 1 to 4% (NETL, 2007). The results of the above analysis show efficiency values of 5 to 10%. While higher than the commonly accepted values, they are not unreasonable due to the presence of the shale stringers within the proposed storage zones. These shale stringers could cause the injected CO_2 to stack in different zones and utilize more of the available storage space. It is also worth noting that other published studies have produced values within

range and sometimes higher for storage efficiencies (Van der Meer, 1995; Okwen et al, 2009). The efficiencies and their interaction with the shale stringers within DA1 were analyzed using numerical modeling, which is discussed later in this chapter.

3.1.3 Storage Capacity

Disposal Area 1 had an abundance of high quality well logs to choose from. In the end thirteen wells were chosen for this thesis, seven for a west to east cross section and six for a north to south cross section. Figure 3 is a location map of the borings used in this study and presents the cross-section paths. The cross-sections are presented in Figure 4 and Figure 5. The scale on the cross-sections is exaggerated for clarity, showing the vertical axis in meters and the horizontal axis in kilometers. While formation dip may appear steep in the figures, the maximum dip calculated between two well logs for the Tuscaloosa formation was 1.46%.

Disposal Area 3 was considered as an alternative to DA1 because of its location offshore in the Gulf of Mexico. Unfortunately the offshore location also provided a lack of available data on the geology of that area. This was addressed by using information gathered for the Florida Peninsula and reviewing literature on the geology off the coast of Florida that was closest to this repository, then estimating the capacity based off of this information. This method will not give a highly accurate estimate of the true capacity of DA3, but it is the best estimate obtainable with the information available. The estimated geologic sequestration capacities for each of the two Florida Pan-handle areas are shown on Table 3. The capacities for DA1 with varying storage efficiencies are presented in Table 4.

Table 3. Geologic Sequestration Capacities for the Florida Pan-Handle

Disposal Area	Area (m ²)	Thickness (m) ¹	Porosity	Density (kg/m ³)	Capacity at 1% E (Gt)	Capacity at 4% E (Gt)
DA1	8.39 X 10 ⁹	104.0	0.18	842.75	1.40	5.58
DA3	7.47 X 10 ⁹	162.5	0.23	725.0	2.02	8.09

Note 1: Thickness represent combined thickness of sandstone stringer zones.

Table 4. Geologic Sequestration Capacities for Disposal Area 1 with Varying Storage Efficiencies

Disposal Area	Capacity at $\epsilon = .01$ (Gt)	Capacity at $\epsilon = .04$ (Gt)	Capacity at $\epsilon = .05$ (Gt)	Capacity at $\epsilon = .07$ (Gt)	Capacity at $\epsilon = .08$ (Gt)	Capacity at $\epsilon = .10$ (Gt)
DA1	1.40	5.58	7.00	9.80	11.21	14.01

3.2 Numerical Modeling

In an effort to analyze the effect of the shale stringers present in DA1 and further validate storage efficiency values, numerical modeling was performed. The software package used to conduct the analysis was UTCHEM-9.0. Research completed by University of Texas produced UTCHEM, a 3-D, multicomponent, multiphase, compositional model of chemical flooding processes which accounts for complex phase behavior, chemical and physical transformations and heterogeneous porous media properties, and uses advanced concepts in high-order numerical accuracy and dispersion control and vector and parallel processing (University of Texas, 2000, p. 1-1). The code was originally designed for simulating enhanced oil recovery but has since also been used to simulate multi-phase flow in aquifers at contaminated sites. Therefore, it is an ideal code to use for CCS simulations (Brown, 2011). The UTCHEM code provides the ability to model the migratory behavior of the CO₂ plume over time under different storage efficiency factors, assess the effects of shale stringers, and estimate the surface area of the CO₂ plume.

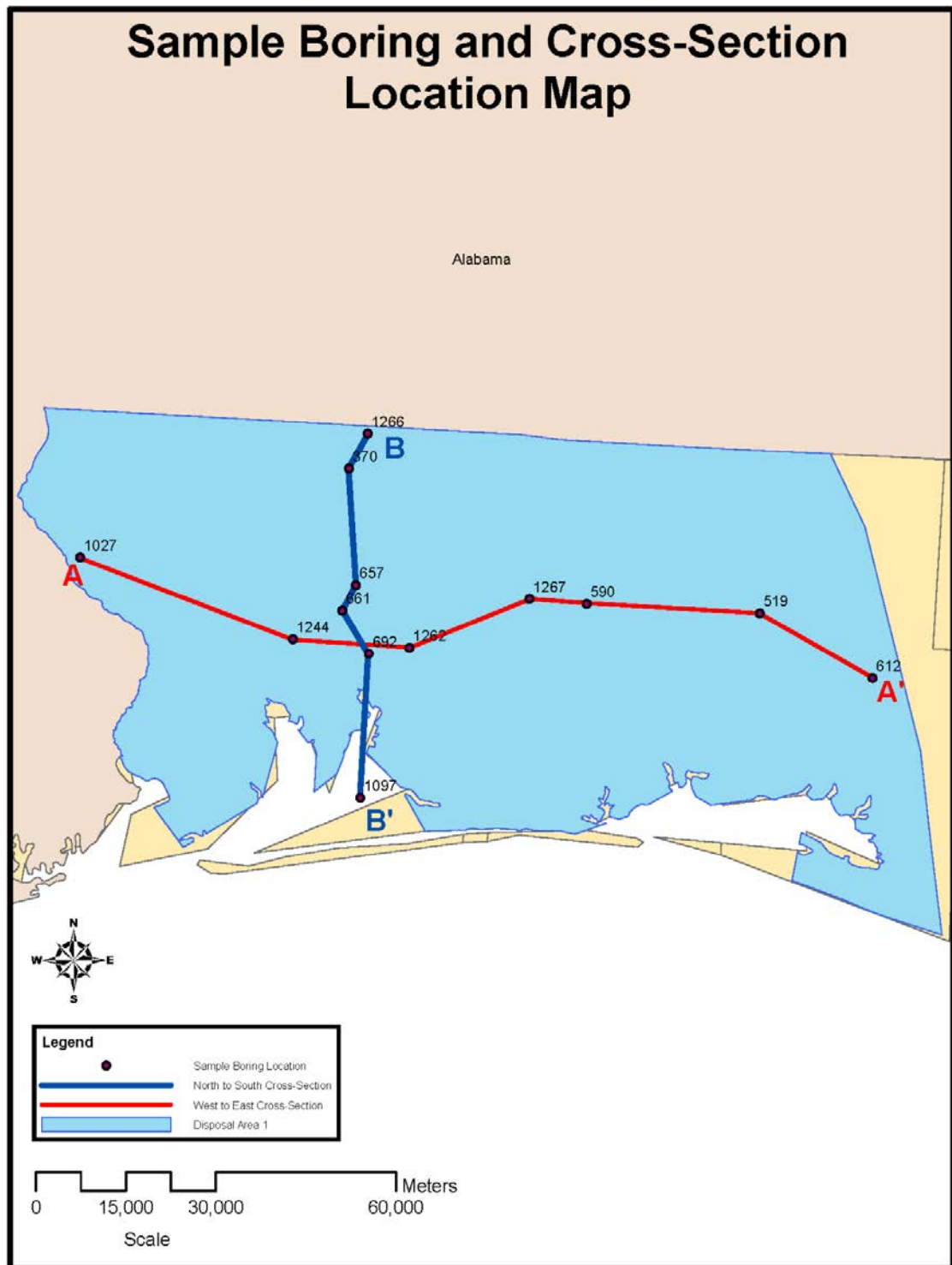


Figure 3. Sample Borings and Cross-Section Location Map

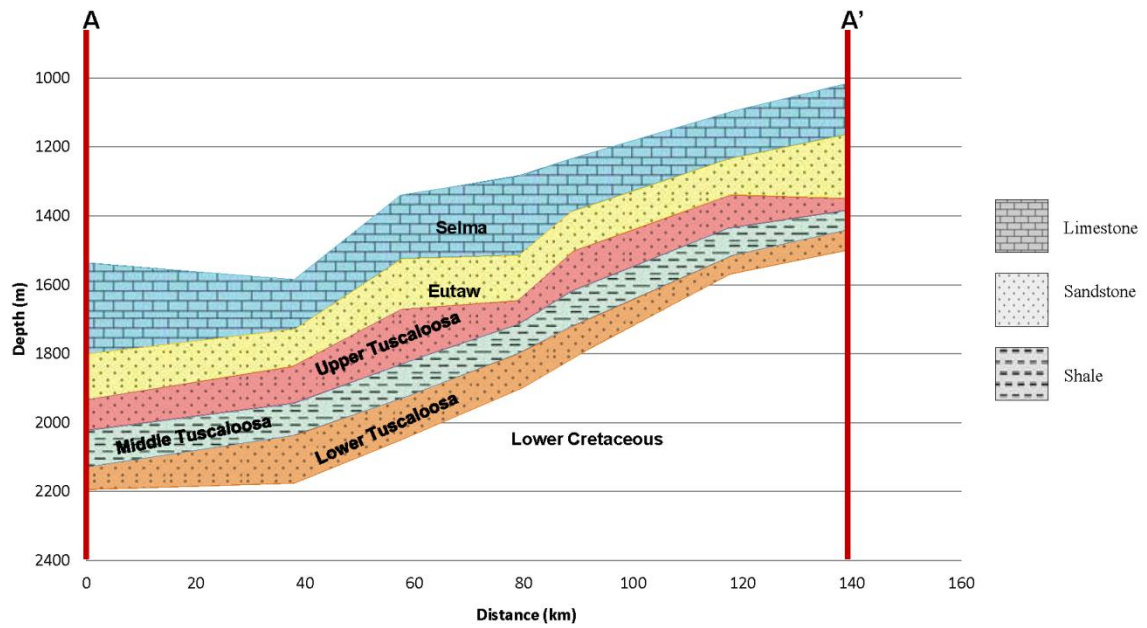


Figure 4. Disposal Area 1 West-East Cross-Section

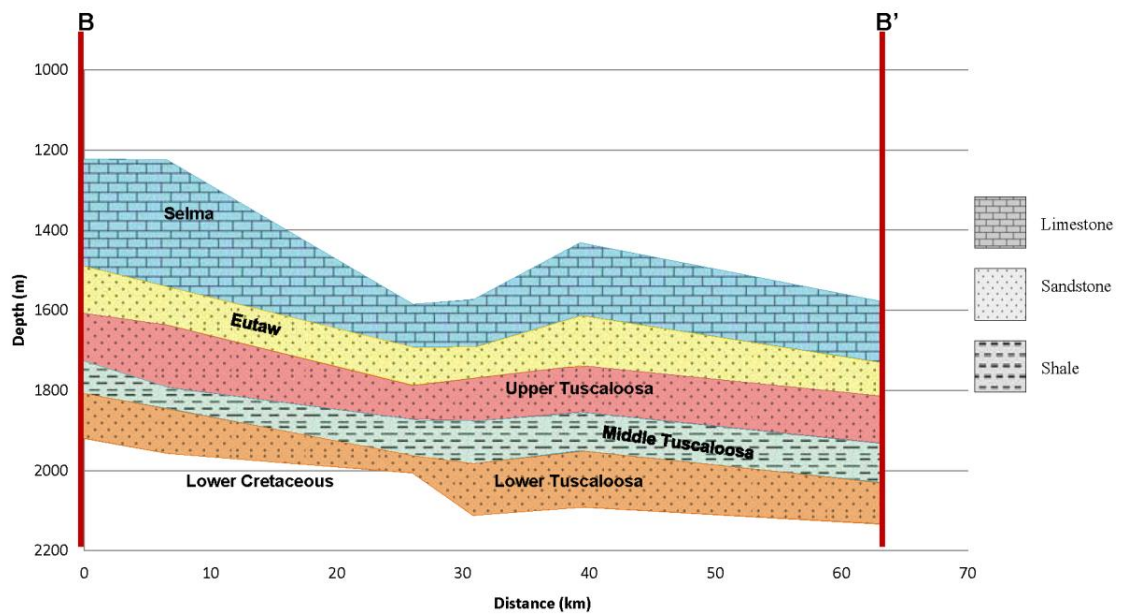


Figure 5. Disposal Area 1 North-South Cross-Section

Brown (2011) provided a model which was originally created to provide analysis in the creation of graphical planning envelopes for estimating the surface footprint of CO₂ injected into saline aquifers. A robust 3-dimensional finite difference model was created in UTCHEM and different injection scenarios were analyzed. The Brown (2011) model provided a “type-aquifer” to use as the foundation and revised for analysis of DA1. The model simulated a storage zone 100 meters thick and 500 meters long. Details of the original and revised models are provided in Appendix E.

The purpose for modeling DA1 was to analyze the effect of the shale stringers present in the Eutaw and Tuscaloosa formations in the Florida Pan-Handle. Porosity, temperature, pressure, and intrinsic permeability values were changed to match the data for DA1. The stringers were modeled by changing the permeability of particular layers of cells within the storage reservoir. Eight simulations in total were performed with varying percentages of shale versus sand. Four variations of shale percentage were applied to the model; 0, 25, 50, and 75%. For each variation of shale content, two values of hydraulic conductivity for the sandstone were used, 5 and 50 milidarcys (mD), in order to cover the commonly accepted range of hydraulic conductivities for sand/sandstone (Fetter, 2001). One value of hydraulic conductivity, 0.01 mD, was used for shale (Fetter, 2001). Each model run simulated a 180 day injection period and produced a 3-dimensional contour depicting the distribution of injected CO₂ within the aquifer.

One model simulation from Brown (2011) was replicated to portray an exaggerated case of how supercritical CO₂ is expected to behave in a sand aquifer with a very high, 5,000 mD, hydraulic conductivity. Figure 6 presents the results from this case. Notice how the CO₂, shown in variations of green, immediately migrates to the top of the

aquifer and begins to spread in a thin layer along the top. The higher concentrations are near the top of the formation.

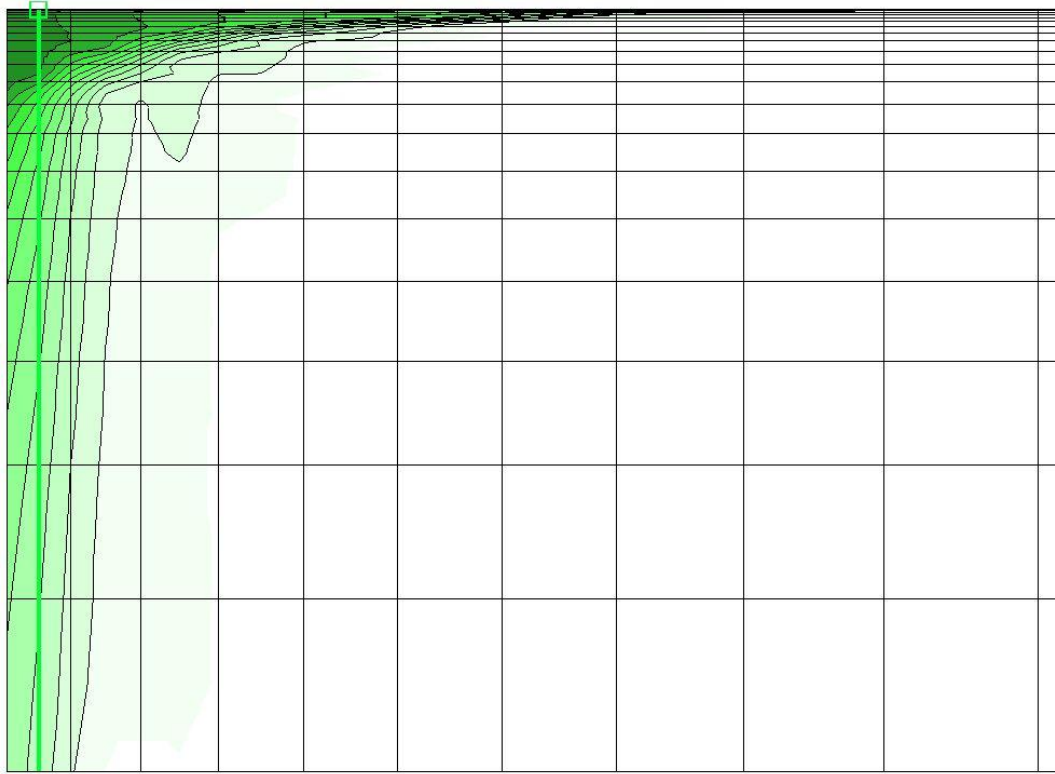


Figure 6. CO₂ Plume at 5,000mD Hydraulic Conductivity (Brown, 2011)

The expectation for DA1, was that the shale stringers would succeed in trapping the CO₂ in “stacked” layers, improving the storage efficiency. Also included in the process, the estimated percentage of shale contained in DA1 was calculated from the geologic characterizations. DA1 was estimated to have approximately 56% shale. All model results are provided in Appendix E, while the 0% and 50% shale simulations are presented and discussed below. The results from the 0% simulations provide comparison between shale stringers and no shale stringers for DA1.

Figure 7 and Figure 8 present the results from the simulations with 0% shale and 5 and 50 mD hydraulic conductivity, respectively. Notice the CO₂ behavior is similar to that of Figure 6; however the CO₂ migration is not as rapid. After 180 days, plenty of CO₂ remains around the injection point, but much has migrated to the top of the aquifer. Figure 9 and 10 present the results from the simulations with 50% shale and 5 and 50mD hydraulic conductivity, respectively. In these figures the contrast in hydraulic conductivity between the sand and shale is apparent. The CO₂ indeed is trapped in “stacked” layers.

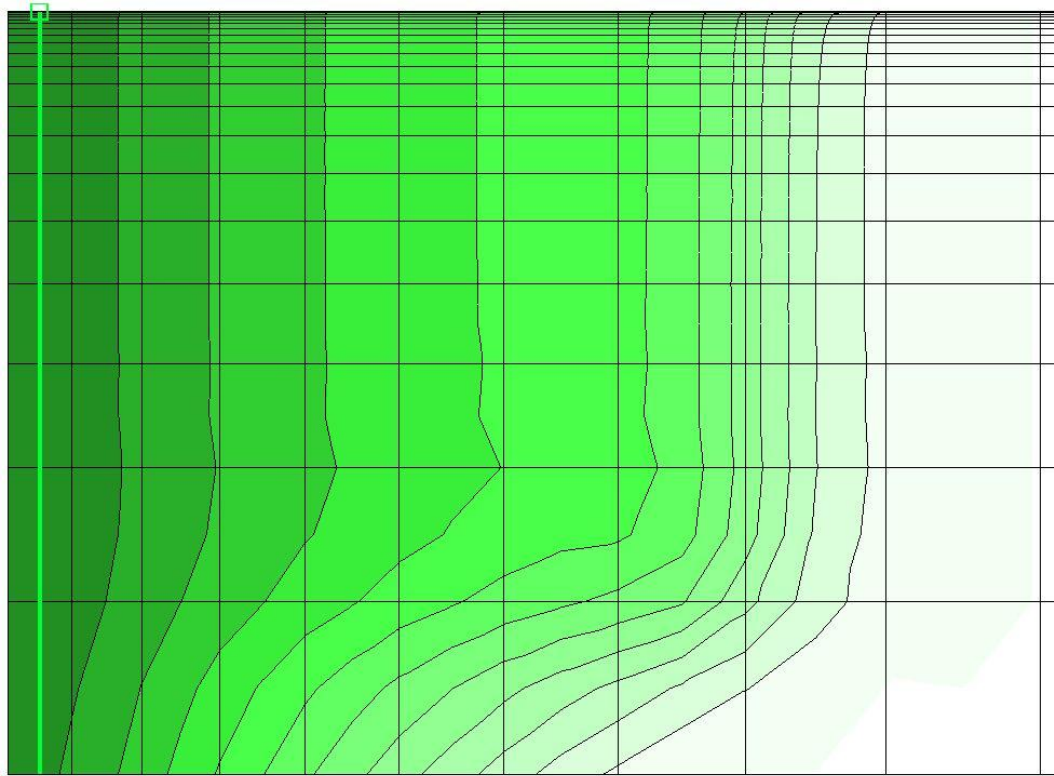


Figure 7. CO₂ Plume Injected into Aquifer with 0% Shale at 5mD

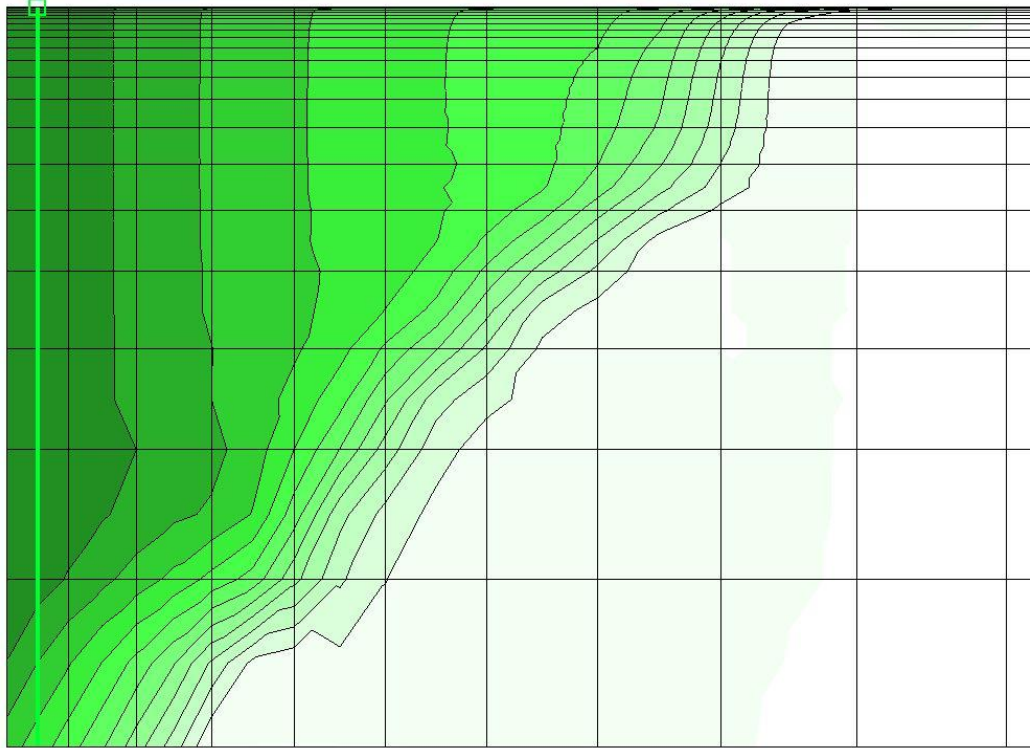


Figure 8. CO2 Plume Injected into Aquifer with 0% Shale at 50mD

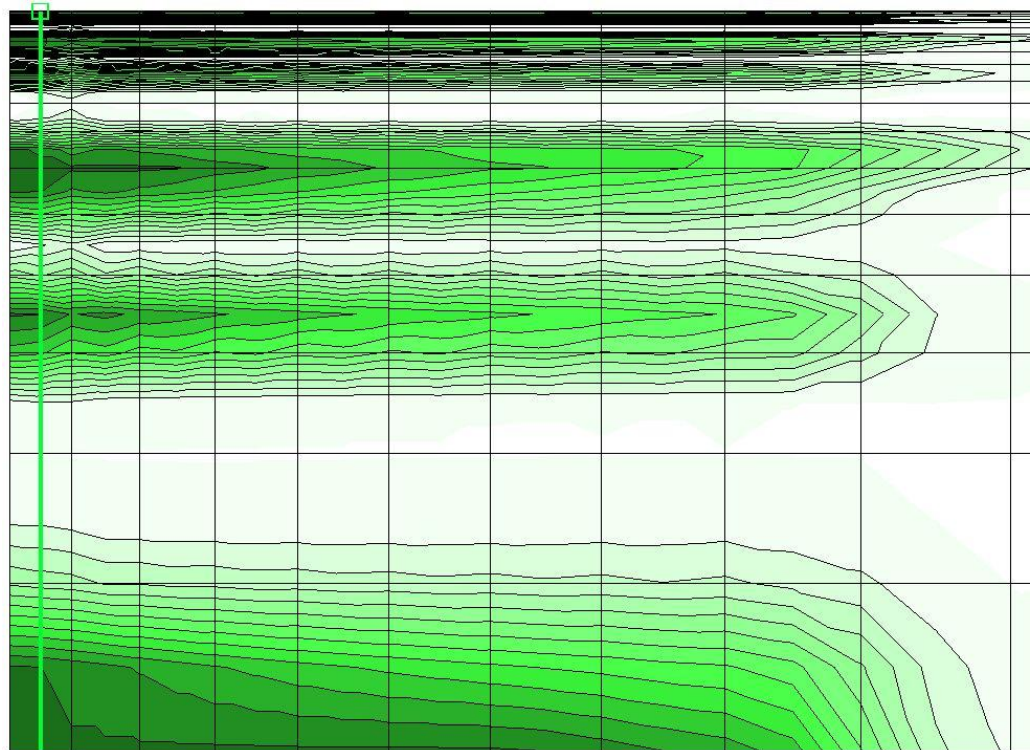


Figure 9. CO2 Plume Injected into Aquifer with 50% Shale at 5mD

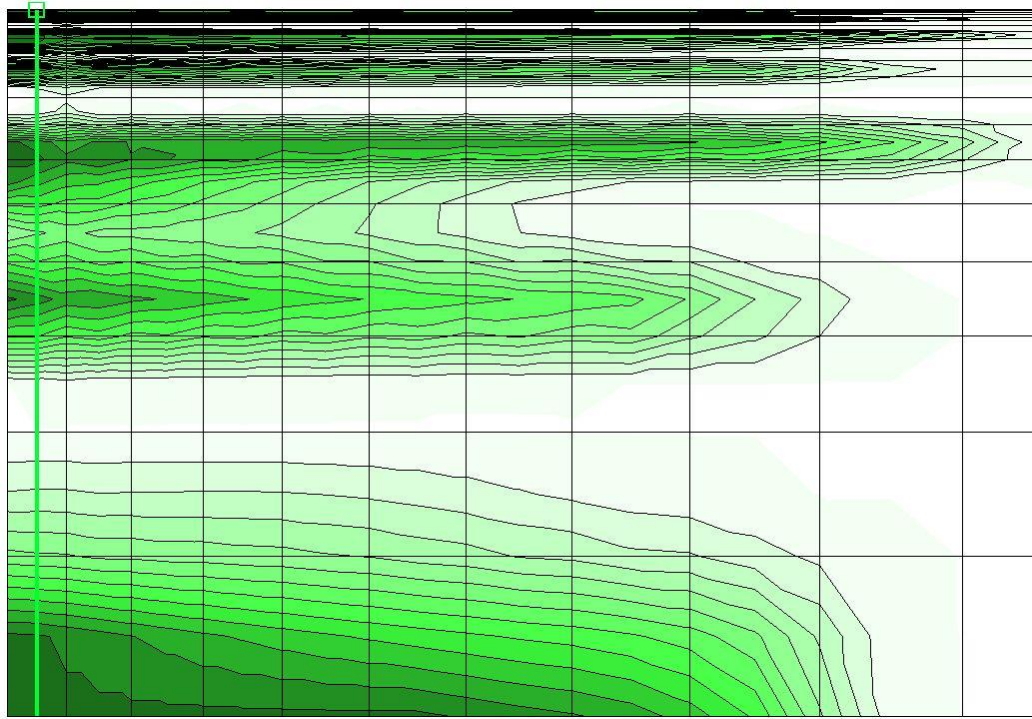


Figure 10. CO₂ Plumes Injected into Aquifer with 50% Shale at 50mD

Of note is the difference in CO₂ migration from simply changing the hydraulic conductivity of the sand. In Figure 7 and Figure 8, there is a noticeable difference in the plume shape between 5mD and 50mD. The addition of the shale stringers, changes the behavior of the CO₂ even more. The CO₂, in these simulations remains in the areas of sand and slowly works its way through the shale. From a qualitative perspective, the aquifers modeled in Figure 9 and Figure 10 appear to be more efficient at trapping CO₂ than those without the shale. The CO₂ does migrate horizontally as in any other simulation however this lateral movement is achieved in multiple layers of the repository as opposed to the CO₂ collecting near the surface. Higher concentrations of the supercritical CO₂ remain distributed throughout the aquifer. Judging by the results of the numerical modeling, higher values of storage efficiency may be warranted. The Okwen et al. (2009) model, discussed earlier, produced efficiencies ranging between 5 and 10%.

The lower end of the Okwen range is applicable to DA1 but 10% or larger seems too high considering the model results and based upon the other literature estimates. To remain conservative while including results from the numerical modeling, a storage efficiency value of 4% was used for DA1 while analyzing transportation scenarios.

Chapter 4

CARBON DIOXIDE TRANSPORTATION ANALYSIS

Once the CO₂ sources and sinks were indentified, a pipeline network model was developed. Poencot and Brown (2011) developed a feasibility-level pipeline cost model as the first step in developing the network model and later applied the cost estimates to different pipeline routing scenarios (Poencot & Brown 2011; Poencot & Brown 2012).

4.1 Transportation Costs

Poencot and Brown (2011) reviewed a number of different cost models from sources such as Heddle et al. (2003), McCoy (2008), Bakken & Von Streng Velken (2008), and Zhang et al. (2006). These sources were chosen because they focused solely on the transport portion of CCS. Heddle et al. developed a simple linear model that includes capital cost and annual operation and maintenance (O&M) costs (Heddle et al., 2003). McCoy (2008) developed a model that provides for regional cost differences as well as further resolution of cost factors such as pipe materials, labor, real estate, permitting, design and construction management. Total capital cost of a pipeline is made up of four key categories; material cost, labor cost, right-of-way (ROW) cost and miscellaneous cost (Liu & Gallagher, 2010). After reviewing the literature, Poencot and Brown (2011) chose the McCoy (2008) cost model to adapt for their study. The specific details of the model development are presented in Poencot and Brown (2011) while the equation and parameters are included below.

$$\begin{aligned}
\text{[Total Annual Cost = } & [[\omega_m \times \beta_m \times L^{a6m} \times (D \times 39.38)^{a7m} \times CF] + [\omega_L \times \beta_L \times L^{a6L} \times (D \times 39.38)^{a7L} \times CF] + \\
& [\omega_{RE} \times \beta_{RE} \times L^{a6RE} \times (D \times 39.38)^{a7RE} \times CF] + [\omega_{MS} \times \beta_{MS} \times L^{a6MS} \times (D \times 39.38)^{a7MS} \times CF] + \\
& [0.0088 \times \epsilon_2 \times L] \times \alpha]
\end{aligned}
\tag{5}$$

Where ω_m , ω_L , ω_{RE} , and ω_{MS} are cost adjustment coefficients to convert April 2004 costs to March 2010 costs and are $\omega_m = 1.18$, $\omega_L = 1.15$, $\omega_{RE} = 1.05$, and $\omega_{MS} = 1.26$; β_m , β_L , β_{RE} , and β_{MS} are cost coefficients for materials, labor, real estate, and miscellaneous (e.g., design, permitting, construction management) in 2004 dollars and are $\beta_m = 1,534.62$, $\beta_L = 30,690.22$, $\beta_{RE} = 8,912.51$, and $\beta_{MS} = 33,265.96$; L is the least-cost pipeline route length in kilometers; D is the pipeline diameter in meters and is a function of flow rate (see Poiencot & Brown, 2011); CF is a capital cost factor of 0.067574 assuming a 5% discount rate used to annualize the initial pipeline capital construction cost; ϵ_2 is CO_2 mass flow rate in tonnes per year; α is a factor to adjust costs for underwater construction, it is 1.75 for underwater projects and 1.0 for land pipeline projects; $a6_m$, $a6_L$, $a6_{RE}$, and $a6_{MS}$ are model pipeline length power exponents for materials, labor, real estate, and miscellaneous and are $a6_m = 0.901$, $a6_L = 0.82$, $a6_{RE} = 1.049$, and $a6_{MS} = 0.783$; and, $a7_m$, $a7_L$, $a7_{RE}$, and $a7_{MS}$ are model pipeline diameter power exponents for materials, labor, real estate, and miscellaneous and are $a7_m = 1.59$, $a7_L = 0.94$, $a7_{RE} = 0.403$, and $a7_{MS} = 0.791$. The new cost model for Florida is intended for use as a planning tool to be used in feasibility-level studies. It is applicable for use in Florida or other in other areas of similar flat topography.

For this thesis, the Poiencot and Brown model was validated against the previously referenced pipeline transportation models. UNF also conducted further validation against other recent CCS transportation models published by Liu and Gallagher (2010), McCollum and Ogden (2006), Ogden et al. (2004) and Parker (2004).

Liu & Gallagher (2010) provide an engineering-economic assessment for CO₂ pipeline transportation in China, utilizing methods outlined by McCollum and Ogden (2006). McCollum and Ogden (2006) took an average of a number of published cost models including Heddle et al. (2003), Ogden et al. (2004), and Parker (2004), after applying common bases to those models. A comparison of various model estimates from McCollum and Ogden (2006) is recreated in Figure 11 and includes the McCoy (2008), Poienkot and Brown (2011) and Liu and Gallagher (2010) cost models. The years for each model correspond to the costs used in each model. As shown in Figure 11, the Poienkot and Brown (2011) model falls within range of the previously published cost models.

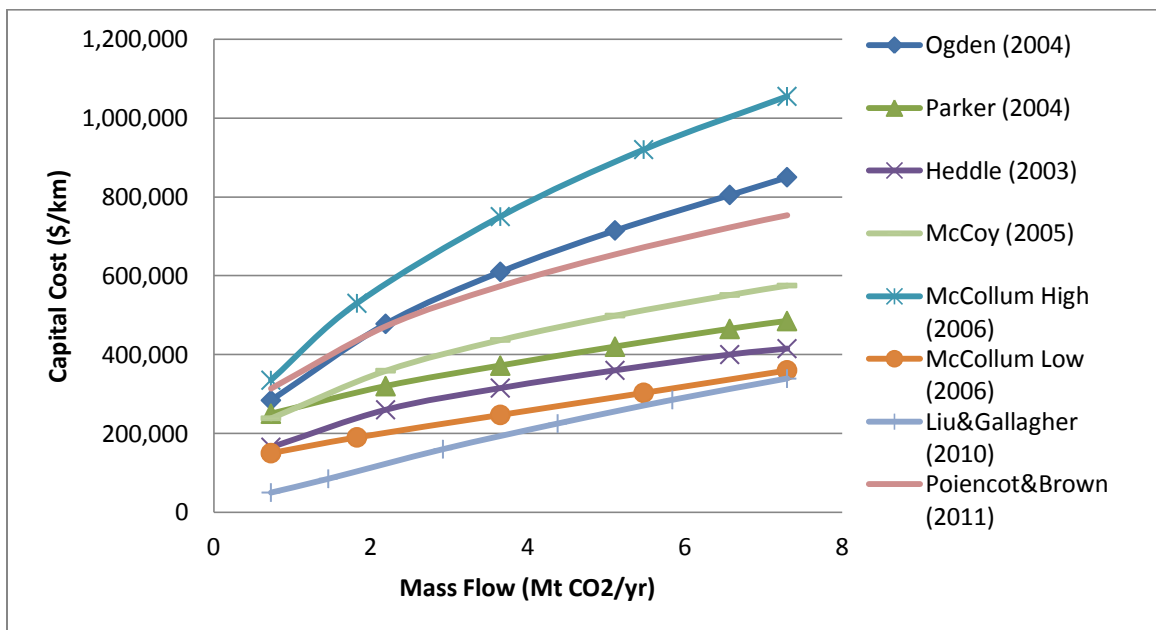


Figure 11. CO₂ Pipeline Capital Cost Model Comparison

The various published models used in validation testing for this thesis were also recently reviewed by Essandou-Yeddu and Gulen (2009). They determined that the

various models use historical natural gas pipeline costs, which for the scale considered here were last constructed in the 1990s, to develop their respective cost equations. The models do well in predicting the capital costs for pipelines constructed in the past but falter when predicting the costs for more recent CO₂ pipelines (Essandou-Yeddu & Gulen, 2009). To remedy this situation, Essandou-Yeddu and Gulen (2009) provide a method for utilizing cost escalation factors for each of the models. Figure 11 compares all reviewed cost models before escalation factors were applied. In this case, the Poiencot and Brown (2011) model falls within the upper limits of the cost range provided by the other published cost models. Using the methods prescribed by Essandou-Yeddu and Gulen (2009) in conjunction with published cost factors from Lewis (2010), the estimated costs from each of the published models was escalated to March 2010 costs. The results including the cost escalation factors are displayed in Figure 12. Once the costs were escalated, the Poiencot and Brown (2011) model costs resulted in estimates fourth lowest of all the models but near the middle of the cost range, indicating the model is suitable for feasibility-level studies in Florida.

Another important factor in the transportation cost analysis is the O&M costs for the pipeline network. Pipeline O&M costs can include depreciation, amortization, financial, maintenance, materials, fuel, power, labor, administration and miscellaneous (Liu & Gallagher, 2010). Poiencot & Brown, through literature review, developed a reasonable mean O&M cost of 0.0088 \$/tonne CO₂/kilometer. Further analysis showed differing methods in the estimation of O&M for a CO₂ pipeline. Ogden (2006) and Liu and Gallagher (2010) estimate O&M as a percentage of the total capital cost of the pipeline, 4% and 3% respectively. Heddle et al. (2003) and McCoy (2008) apply a value

of \$3,100 per kilometer and \$3,250 per kilometer of pipe respectively. Parker (2004) and McCollum and Ogden (2006) did not calculate O&M values. To compare the O&M values, all dollar amounts were escalated to March 2010 dollars using the Essandou-Yeddu and Gulen (2009) composite escalation factors as described earlier. Figure 13 displays a comparison of the different O&M values for each model in 2010 dollars. The results from this comparison are similar to the capital cost comparisons in that, Liu and Gallagher (2010) provide a low estimate, Ogden (2006) a high estimate and the Poiencot and Brown (2011) values are somewhere in the middle. The differences in the estimates lie in the methods used to calculate the O&M values. The Heddle (2003) and McCoy (2008) values rely only on length of pipe. The Ogden (2006) and Liu and Gallagher (2010) estimations rely on capital cost and therefore are affected by the same factors as capital costs, i.e. diameter, length, etc. The Poiencot and Brown (2011) estimates are based on capacity and length, making the values similar to the Ogden (2006) and Liu and Gallagher (2010) estimates and within range of the two models. Notice the behavior of the Poiencot and Brown (2011) estimate is more linear as opposed to the other models. Another deficiency identified in this thesis is the fact that the original Poiencot and Brown (2011) estimate relied only on pipeline length, not taking into account pipe diameter or capacity. Ogden (2004) and Liu and Gallagher (2010) estimate pipeline O&M costs as a percentage of the capital cost, 4% and 3% respectively. Poiencot and Brown (2012) later proposed to calculate O&M as 6% of the capital cost. Figure 14 presents a revised O&M cost comparison.

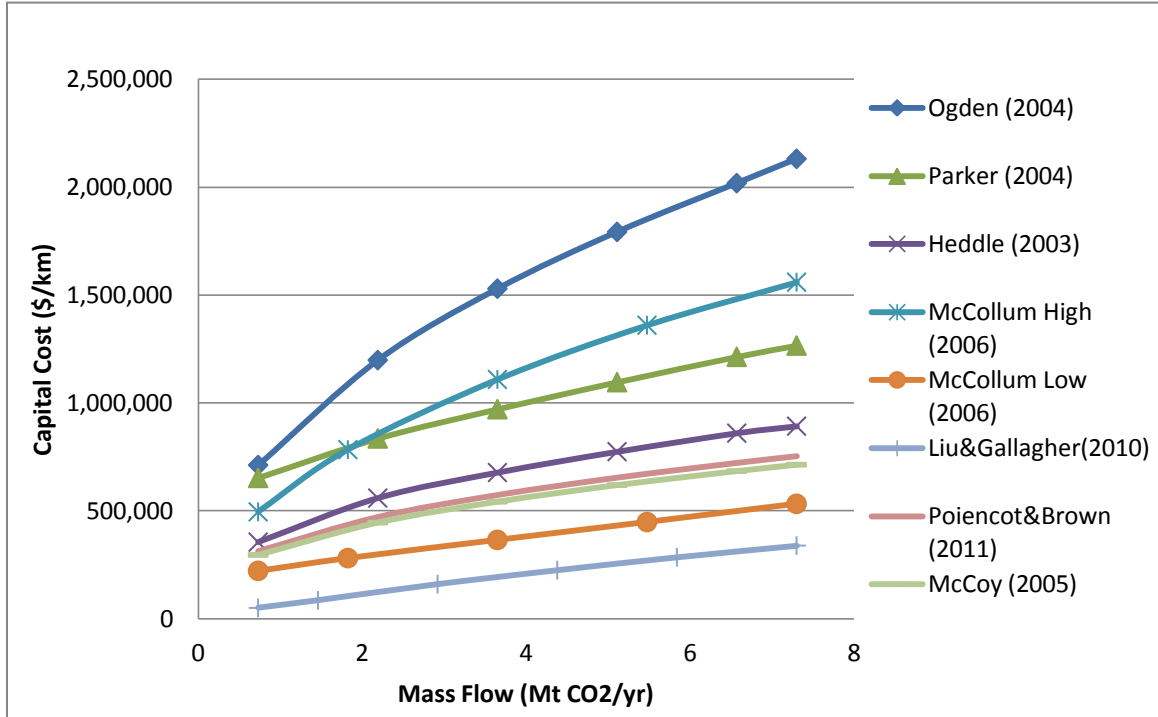


Figure 12. CO₂ Capital Cost Model Comparison – Escalated Costs

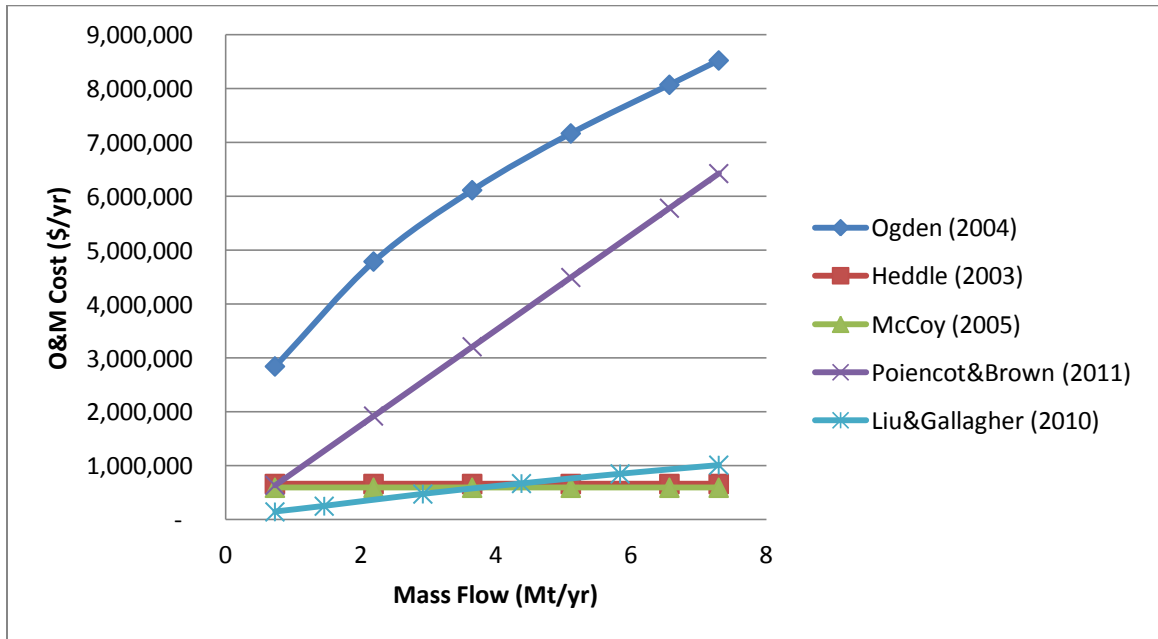


Figure 13. Operation and Maintenance Cost Model Comparison

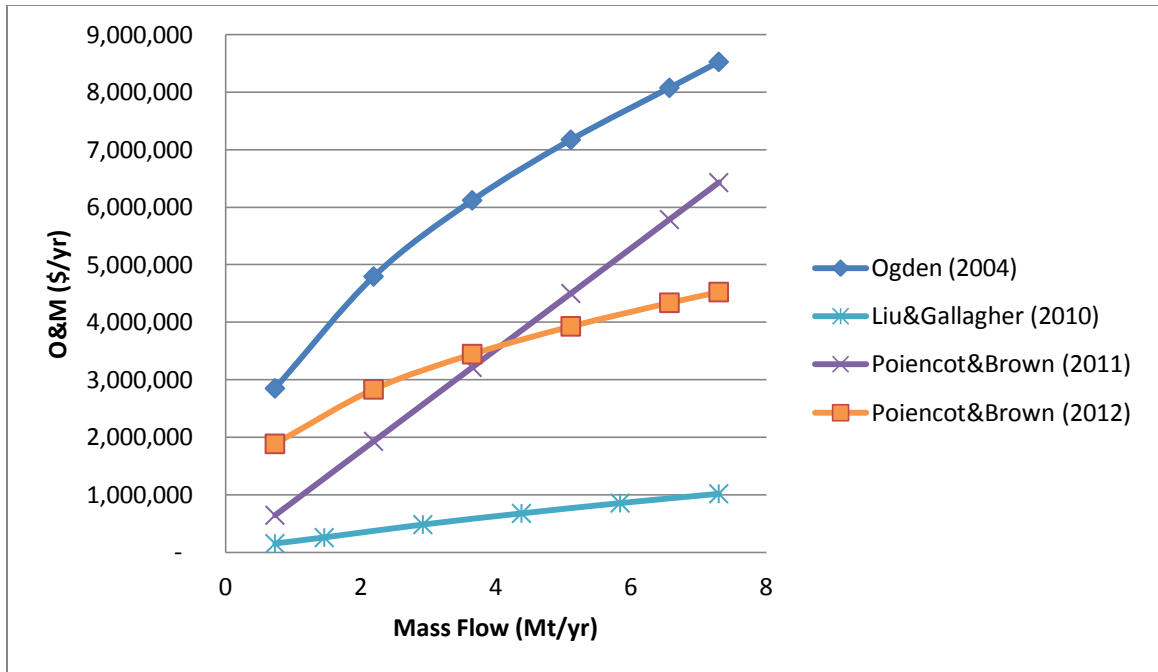


Figure 14. Revised Operation and Maintenance Cost Model Comparison

As previously mentioned, the capital cost is calculated based on materials, labor, and right-of-way factors and is a function of pipeline length and capacity. Estimating O&M as a function of capital cost is reasonable considering that actual pipeline O&M costs can include depreciation, amortization, financial, maintenance, materials, fuel, power, labor, administration, and miscellaneous costs (Liu & Gallagher 2010). Therefore, based upon the model validation testing, the revised Poencot and Brown (2012) O&M model is reasonable. Carbon dioxide transportation deployment scenarios included in this thesis use the revised Poencot and Brown (2012) model for cost determinations.

4.2 Transport Scenarios

4.2.1 Preliminary Research

Initially, Poencot and Brown (2011) focused on a simple statewide transport model using straight line distance from each source to each sink. This method was not

constrained by geography, real estate limitations, institutional concerns or practical engineering considerations regarding pipeline ROW selection (Poencot & Brown, 2011). Later, this method was updated to a more “real-world” scenario using interstate and highway right-of-way (ROW) paths (Poencot & Brown 2012). The measured distances and pipeline sizes for these networks were used to calculate the capital and O&M costs for the network and a least-cost transport optimization model was run using Microsoft Excel SolverTM. This model is discussed below. The basic model equation and model constraints are included herein:

$$[Minimize \sum F_{ijk} \times X_{SiDjk} = Total Cost] \quad (6)$$

Where X is the annual CO₂ pipeline transportation cost (\$/tonne CO₂) from CO₂ supply node S_i (from i = 1 to 13) to demand node or repository D_j (from j = 1 to 2) at Time Year k (from k = 1 to 25 years) and F_{ijk} is the CO₂ flow through that pathway in tonnes CO₂/year during Year k.

$$[Subject to Constraint 1 \sum_1^{26} F_{ijk} \leq Capacity D_j] \text{ Summed from 1:26} \quad (7)$$

each Year

$$[Subject to Constraint 2 \sum_1^{26} F_{ijk} \leq Emission Supply from S_i] \quad (8)$$

$$[Subject to Constraint 3 \sum_1^{26} F_{ijk} \geq 0] \quad (9)$$

4.2.2 Regional Networks

The purpose of this thesis is to focus on the Florida Pan-Handle. The preliminary research discussed earlier, was applied in more detail to DA1 and DA3 with a more regional emphasis. A statewide “authority model” was also used in this report in order to

compare the changes in costs due to the revised O&M estimation and demonstrate the effectiveness of DA1 and DA3 as statewide repositories. All pipeline networks will follow major highway and interstate right-of-ways (ROW).

4.2.2.1 The Right-of-Way Model

Figure 15 displays an example of the Right-of-Way Model. This model assumes that all of the proposed disposal areas are permitted and operational at once. Each source is connected to each disposal area and the associated unit costs for each path are calculated. The transport optimization model developed by Poiencot and Brown (2011) was then used to determine the least-cost path for transporting CO₂ from each source to each disposal area over a 25 year period and calculate the associated levelized costs.

Transport Optimization was performed for the Right-of-Way Model over a 25 year period in one year increments. The optimization model determined the cheapest route to transport and store CO₂ from each source. As storage areas filled, flow was rerouted along the next cheapest route. Figure 16 presents the results of the transport optimization in spider diagram format. According to the analysis, there is plenty of capacity for the 25 year study period. DA1 and DA3 still have 83% and 82% capacity remaining respectively after 25 years. The total levelized cost for the regional network was \$5.44 per tonne per year.



Figure 15. Right-Of-Way Model Collection Network



Figure 16. Right-Of-Way Model Results

4.2.2.2 The Solo-Funded Model

The Solo-funded model is an “every-man-for-himself” approach where each plant will fund its own pipeline to the disposal area. This model differs from the Right-of-Way Model in that transport optimization was not performed. Instead a simple comparison of unit costs to the other models was analyzed. Also different from the Right-of-Way Model, only one disposal area is available for storage. While not a realistic approach to developing a regional network, this model is significant because it can provide preliminary cost estimates for different phases of network construction when very few plants will be connected to the regional network. Table 5 presents the unit costs for the Solo-Funded Model for each disposal area, along with the mean unit cost for each disposal area. Disposal Area 1 provided the lowest mean unit cost of \$12.24 per tonne per year. The total levelized cost for DA1 was \$5.66 per tonne per year.

4.2.2.3 The Piece-wise Model

The Piece-wise Model is a cost sharing model based upon the ROW distances used in the Right-of-Way Model. This model assumes only one disposal area is available to store CO₂. Power plants which fall into the top 25 will fund the network while the smaller plants, 25 through 40, will simply pay to connect to the system. The unit costs for each source were calculated for each disposal area and compared to the other models. This model is significant because it provides a preliminary cost sharing scenario applicable to the planning of a regional network.

Table 6 presents the unit costs for the Piece-wise Model for each disposal area, along with the mean unit cost for each. Disposal Area 1 provides the network with the lowest mean unit cost of \$1.11 per tonne per year. The total levelized cost for DA1 was \$1.15 per tonne per year.

Table 5. Solo-Funded Model Unit Costs

Map ID	Plant Name	2007 Annual CO₂ Emissions (Mt)	DA1 Total Unit Cost/tonne CO₂	DA3 Total Unit Cost/tonne CO₂
1	Crystal River	14.530	\$ 4.24	\$ 3.43
3	St Johns River Power Park	9.384	\$ 4.99	\$ 6.01
4	Seminole	8.948	\$ 4.67	\$ 5.33
6	Crist	6.621	\$ 1.05	\$ 10.77
10	Northside Generating Station	4.459	\$ 7.40	\$ 8.92
13	Lansing Smith	3.436	\$ 3.09	\$ 14.14
22	Deerhaven Generating Station	1.582	\$ 13.38	\$ 14.64
26	Cedar Bay Generating Company LP	1.284	\$ 15.47	\$ 18.67
32	S O Purdom	0.638	\$ 15.95	\$ 36.38
33	Brandy Branch	0.630	\$ 24.84	\$ 31.70
37	Arvah B Hopkins	0.525	\$ 16.66	\$ 43.69
38	Scholz	0.519	\$ 13.90	\$ 46.56
39	Putnam	0.495	\$ 33.54	\$ 38.21
Mean Total Unit Cost (\$/tonne CO₂)			\$ 12.24	\$ 21.42
Total Levelized Cost (\$/tonne CO₂)			\$ 5.66	\$ 8.86

Table 6. Piece-Wise Model Unit Costs

Map ID	Plant Name	2007 Annual CO₂ Emissions (Mt)	DA1 Total Unit Cost/tonne CO₂	DA3 Total Unit Cost/tonne CO₂
1	Crystal River	14.530	\$ 1.30	\$ 0.74
3	St Johns River Power Park	9.384	\$ 0.04	\$ 1.25
4	Seminole	8.948	\$ 2.13	\$ 1.76
6	Crist	6.621	\$ 1.00	\$ 2.17
10	Northside Generating Station	4.459	\$ 0.95	\$ 0.77
13	Lansing Smith	3.436	\$ 1.72	\$ 4.62
22	Deerhaven Generating Station	1.582	\$ 1.61	\$ 1.20
26	Cedar Bay Generating Company LP	1.284	\$ 0.04	\$ 0.04
32	S O Purdom	0.638	\$ 2.69	\$ 2.77
33	Brandy Branch	0.630	\$ 0.28	\$ 0.29
37	Arvah B Hopkins	0.525	\$ 0.84	\$ 0.86
38	Scholz	0.519	\$ 0.40	\$ 0.41
39	Putnam	0.495	\$ 1.43	\$ 1.47
Mean Total Unit Cost (\$/tonne CO₂)			\$ 1.11	\$ 1.41
Total Levelized Cost (\$/tonne CO₂)			\$ 1.15	\$ 1.45

4.2.2.4 The Authority Model

The Authority Model operates as an authority run statewide network. This authority would completely fund the construction and operation of a statewide network connecting all of the top 40 power plants to a single disposal area. The capital costs and O&M costs for the entire network would be financed and charged to each user on a cost per tonne basis. This model differs from the Right-of-Way, Solo-Funded, and Piece-wise Models because the unit costs are based on the percentage of CO₂ each plant is supplying

the system. The purpose of analyzing the Authority scenario is to compare the costs from Poencot and Brown (2012) with the new costs incorporating the revised O&M calculation. Disposal Areas 1 and 3 were used for the comparison to Poencot and Brown (2012). Smaller Regional Authority Models were also created and analyzed for the Florida Pan-Handle. Figure 17 and Figure 18 display the Regional Authority Model networks for DA1 and DA3 respectively. Table 7 presents the unit costs for the regional DA1 and DA3 networks.

Table 8 compares the unit costs for the statewide DA1 and DA3 networks with those from Poencot and Brown (2012). The unit costs increased from Poencot & Brown by 6.4% for DA1 and 6.0% for DA3. Figure 19 is a scatter plot comparing the O&M costs from each study. While the O&M unit costs using the new calculation are typically lower than previously estimated, the trend lines are similar to those in Figure 14.

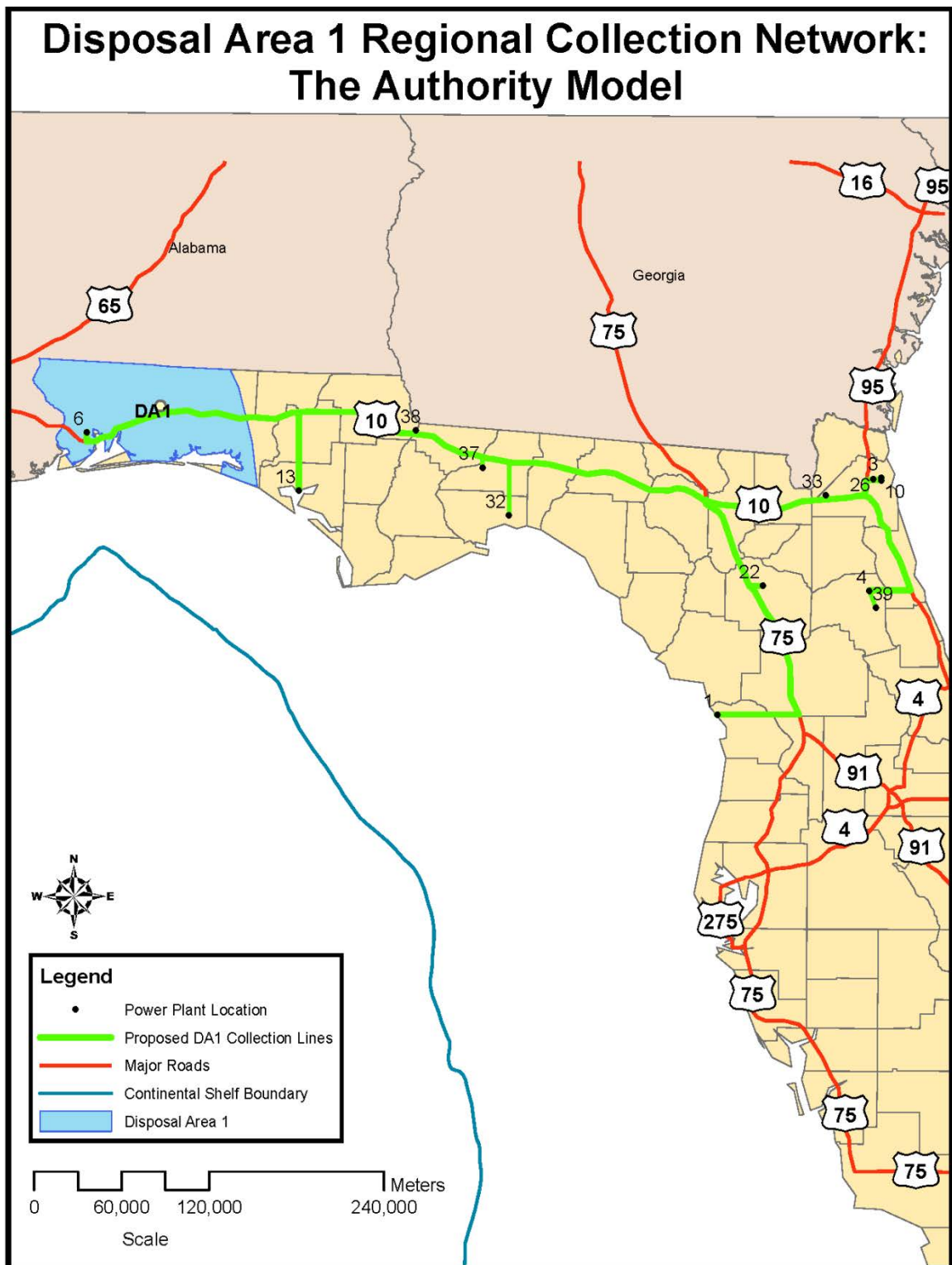


Figure 17. Authority Model: Disposal Area 1 Collection Network

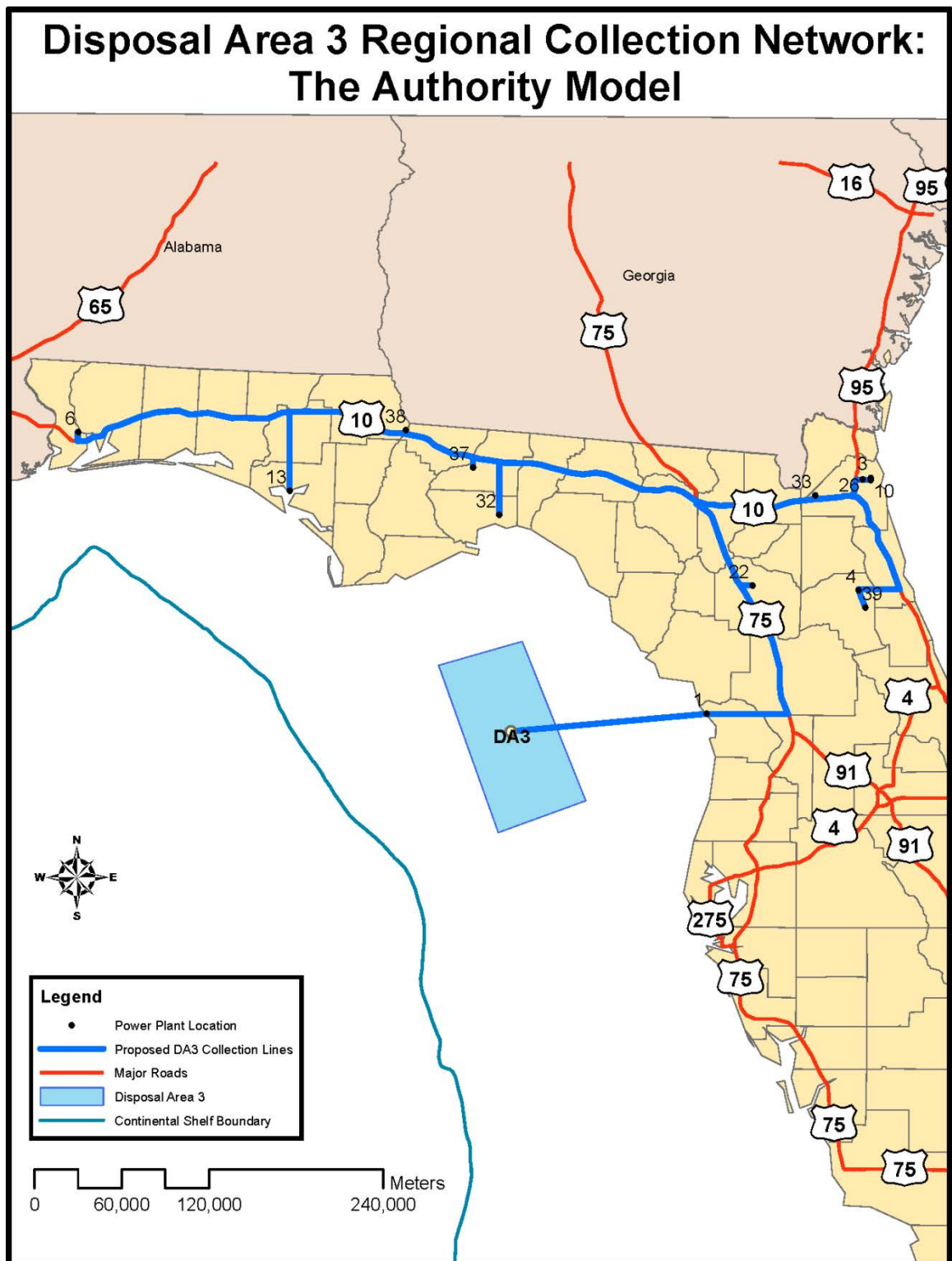


Figure 18. Authority Model: Disposal Area 3 Collection Network

Table 7. Authority Model Unit Costs

Map ID	Plant Name	DA1 Total Unit Annual Cost/tonne CO₂	DA3 Total Unit Annual Cost/tonne CO₂
1	Crystal River	\$ 2.27	\$ 2.62
3	St Johns River Power Park	\$ 1.47	\$ 1.69
4	Seminole	\$ 1.40	\$ 1.62
6	Crist	\$ 1.03	\$ 1.20
10	Northside Generating Station	\$ 0.70	\$ 0.80
13	Lansing Smith	\$ 0.54	\$ 0.62
22	Deerhaven Generating Station	\$ 0.25	\$ 0.29
26	Cedar Bay Generating Company LP	\$ 0.20	\$ 0.23
32	S O Purdom	\$ 0.10	\$ 0.12
33	Brandy Branch	\$ 0.10	\$ 0.11
37	Arvah B Hopkins	\$ 0.08	\$ 0.09
38	Scholz	\$ 0.08	\$ 0.09
39	Putnam	\$ 0.08	\$ 0.09
Mean Total Unit Cost (\$/tonne CO₂)		\$ 0.64	\$ 0.74

Table 8. Authority Model Unit Cost Comparison

Map ID	Plant Name	Poencot & Brown (2011)		Poencot & Brown (2012)	
		DA1 Total Unit Annual Cost/tonne CO₂	DA3 Total Unit Annual Cost/tonne CO₂	DA1 Total Unit Annual Cost/tonne CO₂	DA3 Total Unit Annual Cost/tonne CO₂
1	Crystal River	\$ 1.35	\$ 1.44	\$ 2.26	\$ 2.40
3	St Johns River Power Park	\$ 0.87	\$ 0.93	\$ 1.46	\$ 1.55
4	Seminole	\$ 0.83	\$ 0.89	\$ 1.39	\$ 1.48
6	Crist	\$ 0.62	\$ 0.66	\$ 1.03	\$ 1.09
10	Northside Generating Station	\$ 0.42	\$ 0.44	\$ 0.69	\$ 0.74
13	Lansing Smith	\$ 0.32	\$ 0.34	\$ 0.53	\$ 0.57
22	Deerhaven Generating Station	\$ 0.15	\$ 0.16	\$ 0.25	\$ 0.26
26	Cedar Bay Generating Company LP	\$ 0.12	\$ 0.13	\$ 0.20	\$ 0.21
32	S O Purdom	\$ 0.06	\$ 0.06	\$ 0.10	\$ 0.11
33	Brandy Branch	\$ 0.06	\$ 0.06	\$ 0.10	\$ 0.10
37	Arvah B Hopkins	\$ 0.05	\$ 0.05	\$ 0.08	\$ 0.09
38	Scholz	\$ 0.05	\$ 0.05	\$ 0.08	\$ 0.09
39	Putnam	\$ 0.05	\$ 0.05	\$ 0.08	\$ 0.08
Mean Total Unit Cost (\$/tonne CO ₂)		\$ 0.38	\$ 0.40	\$ 0.64	\$ 0.67

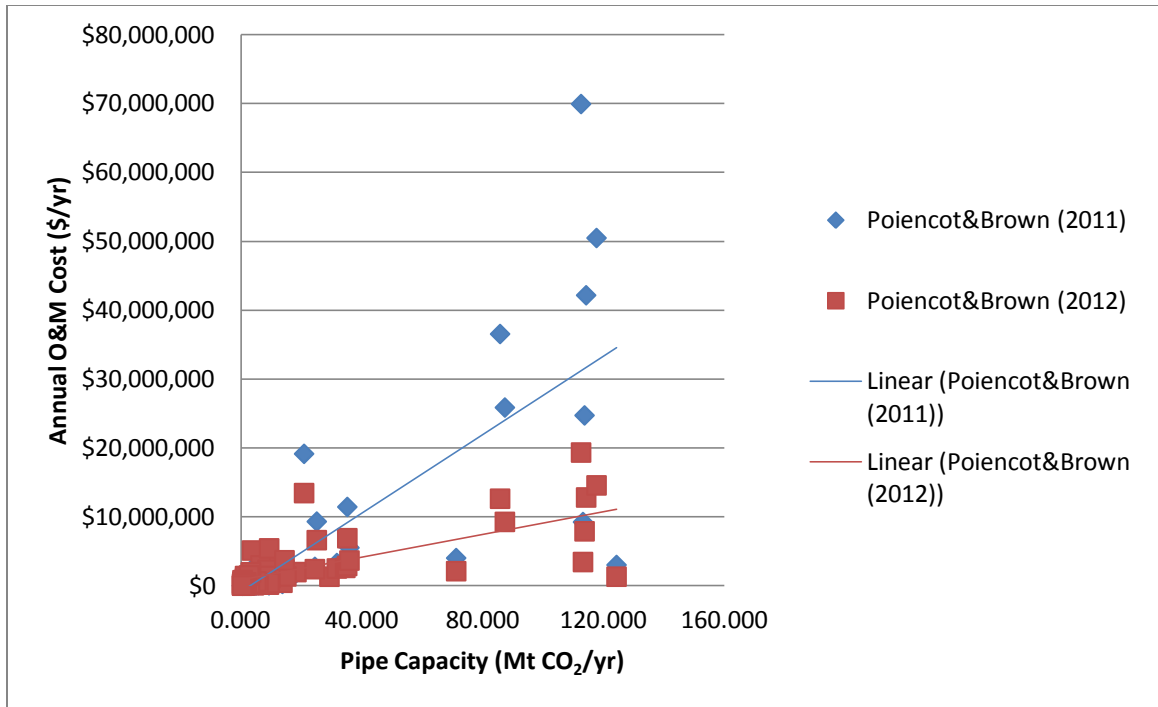


Figure 19. Operation and Maintenance Scatter Plot

Chapter 5

DISCUSSION AND CONCLUSION

This thesis has presented the results of storage capacity estimation and transportation cost analysis for CCS activities in the Florida Pan-Handle. Chapter 5 discusses the results presented and makes conclusions regarding the preliminary feasibility of transporting and geologically sequestering carbon emissions in the Florida Pan-Handle.

5.1 Discussion

Previously published information from DOE and research efforts by Roberts-Ashby (2010) has shown the potential for CCS in Florida. This thesis attempted to present the feasibility of potential storage zones in the Florida Pan-Handle and a pipeline network to transport CO₂ from sources in and around the Pan-Handle to the proposed storage sites. The results show the potential costs to be in the realm of other published investigations around the world. From a transport perspective, the quickest and most efficient solution may be the authority model. Because of the large initial capital cost to construct such a network, even a regional network, a toll road type authority would need to provide initial funding to connect as many sources as possible to help offset that initial cost.

DOE presented an initial estimate as to the amount of storage capacity available in Florida. This thesis confirms not only the validity of the initial estimates but also that they may be conservative. Again, the results presented here are preliminary and are based on oil and gas exploratory drilling logs. Some of the logs are old and difficult to

read. Also these logs were not originally used for the purpose of geologic sequestration so the parameters needed to characterize a CO₂ storage area were not necessarily collected. A more accurate analysis of the proposed storage areas would need to be completed including new borings taking measurements meant specifically for carbon sequestration, such as accurate readings of native brine temperature and salinity. The majority of the reviewed logs for this thesis only included data on the drilling mud as opposed to the native brine. This holds especially true in the case of Disposal Area 3, where no well logging geophysics have been performed. While DA3 was a more expensive option from a transportation perspective, it remains a low-impact location. Low-impact in that development of DA3 would be free of land acquisition, property rights, and human impacts in the event of a release. The relative ease of acquiring ROW, zoning, permits, etc could be offset with DA3 and is another area which would benefit from further investigation.

The development of carbon sequestration in the Florida Pan-Handle, or anywhere, will depend greatly on economics, regulation, and demand. The main incentive pushing the R&D efforts of utilities across the country is the proposals presented in the 110th Congress to lower CO₂ emissions to 1990 levels by 2030 (Esposito et al., 2010). The ultimate decision on the feasibility of CCS or enhanced oil recovery technology will depend on the number of coal plants needing either of these technologies. The commercial deployment of CCS/EOR will require coal-fired utilities and other CO₂ emitters to develop a business model for how CCS/EOR operations will be managed (Esposito et al., 2010). Many factors will play into the development of a business model including the criteria presented within this report along with regulatory framework,

availability of risk mitigation, and the desire to be vertically integrated (Esposito et al., 2010). The size of the system or population of sources would decide between saline aquifer storage and EOR. A larger number of sources would justify a regional network with aquifer storage while a smaller population of sources would be more suitable for EOR.

Jay Field, is one of the few oil fields in Florida that could potentially be a candidate for EOR; however more investigation is needed for those fields. The depth at which Jay Field is found produces uncertainty regarding the injection of CO₂ and the overall cost of drilling new wells if that is required.

Another factor in the feasibility of CCS is the shift from coal to natural gas and renewable energy sources. Using natural gas as a fossil fuel in power plants or using renewable sources results in lower emissions overall. Electric utilities may find that retooling their technology could be more cost effective.

5.2 Conclusion

The potential to implement a regional CO₂ sequestration infrastructure exists in Florida, warranting further analysis. This report presented a preliminary look at the transportation and storage capability in Florida. Areas of this study will require further investigations including a full-fledged feasibility study, as well as planning, permitting, and socioeconomic considerations in order to reach a definitive answer.

Appendix A
Carbon Dioxide Emission Sources

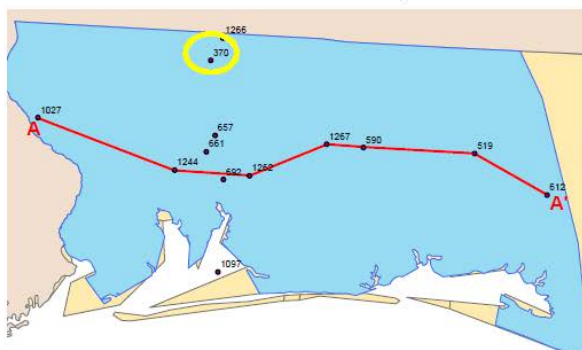
40 Largest Sources of CO₂ Emissions in Florida (2007)

Map ID	Plant/Facility Name	Northing	Easting	Annual CO₂ Emissions (tonnes)
1	Crystal River	3204678.1	334313.21	14,530,258
2	Big Bend	3075217.2	361725.59	9,498,430
3	St Johns River Power Park	3366685.1	447107.33	9,384,220
4	Seminole	3289401.6	438698.36	8,947,766
5	Martin	2992447.2	543356.54	8,023,112
6	Crist	3398084.8	-97895.929	6,621,180
7	Stanton Energy Center	3150786.7	483497.41	5,890,437
8	Manatee	3054258.7	367211.87	5,205,981
9	Sanford	3190513.2	468238.35	4,767,698
10	Northside Generating Station	3365145.5	446936.55	4,459,034
11	Fort Myers	2953081.9	422095.77	3,765,060
12	Turkey Point	2813351.3	567289.72	3,447,477
13	Lansing Smith	3357948.2	47642.891	3,435,570
14	C D McIntosh Jr	3106509.9	409058.51	3,135,822
15	H L Culbreath Bayside	3087736.7	359949.38	3,033,718
16	Hines Energy Complex	3074087.8	414350.29	3,010,012
17	Anclote	3118924.3	324414.88	2,800,194
18	Lauderdale	2883472.1	580187.57	2,218,068
19	Port Everglades	2885457.2	587476.5	2,202,415
20	Indiantown Cogeneration LP	2990880.9	548162.48	1,856,566
21	Polk	3067530.7	402444.71	1,853,968
22	Deerhaven Generating Station	3292844	365772.08	1,581,549
23	Cape Canaveral	3149224.6	523083.25	1,470,463

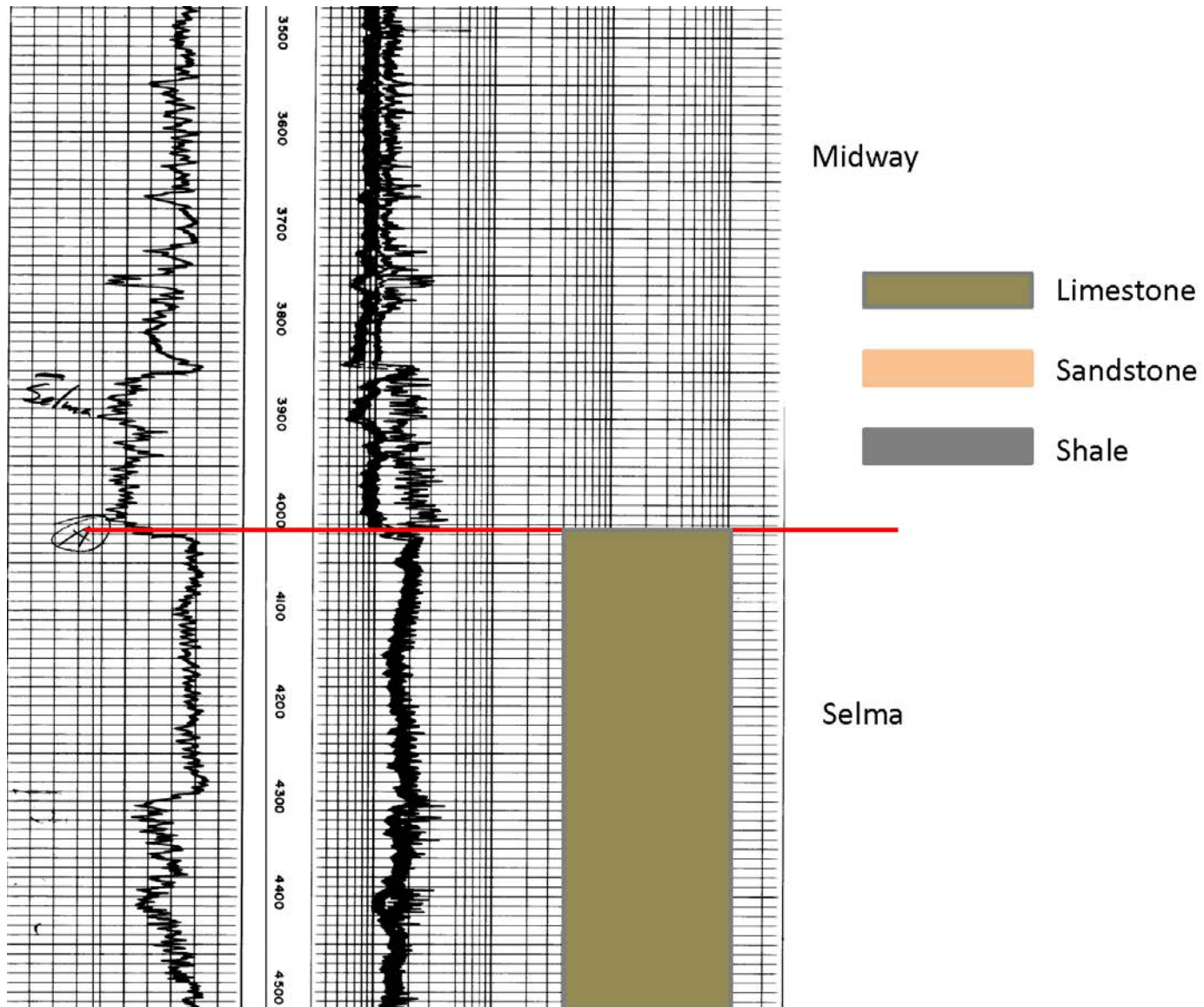
24	P L Bartow	3082867.6	342353.21	1,425,979
25	Riviera	2960791.1	594173.51	1,369,759
26	Cedar Bay Generating Company LP	3365693.6	441618.51	1,283,795
27	Curtis H Stanton Energy Center	3151285.1	483605.77	1,031,593
28	Osprey Energy Center	3103281.6	420562.98	910,493
29	Central Power & Lime	3162445.1	360123.38	766,241
30	Wheelabrator North Broward	2907830	584050.88	715,719
31	Wheelabrator South Broward	2883538.3	580157.15	707,480
32	S O Purdom	3341056.5	191654.8	638,142
33	Brandy Branch	3354692.4	408803.18	629,567
34	Shady Hills Generating Station	3138790.3	347216.72	603,715
35	Cane Island	3127936.4	447728	596,860
36	Intercession City	3126436.6	446191.23	541,897
37	Arvah B Hopkins	3373808.2	173480.93	524,922
38	Scholz	3399359.4	127519.09	519,116
39	Putnam	3277742.4	443310.44	495,412
40	Miami Dade County Resource Recovery Fac	2857602.5	564510.41	456,887

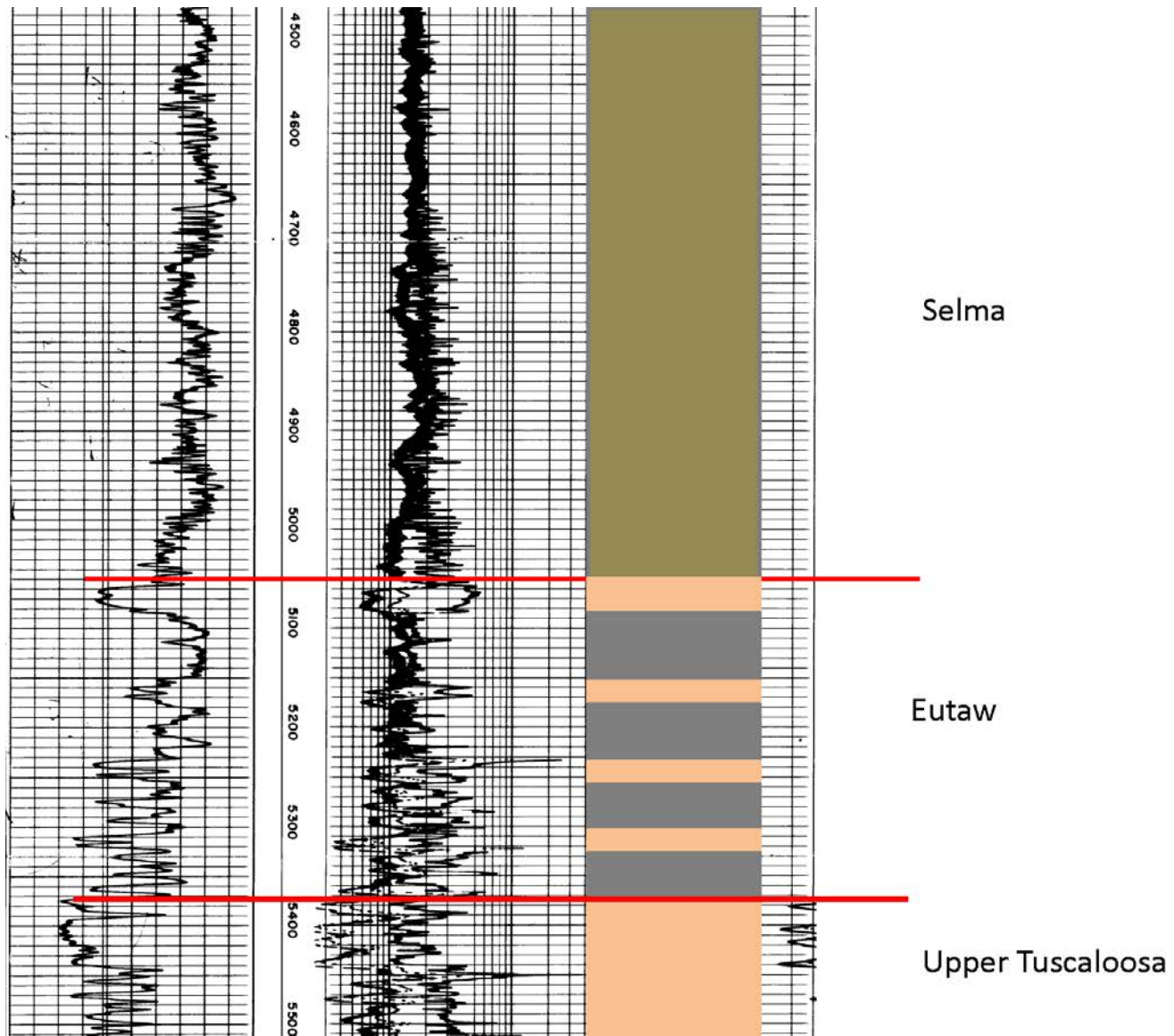
Appendix B
Geophysical Logs and Interpretations

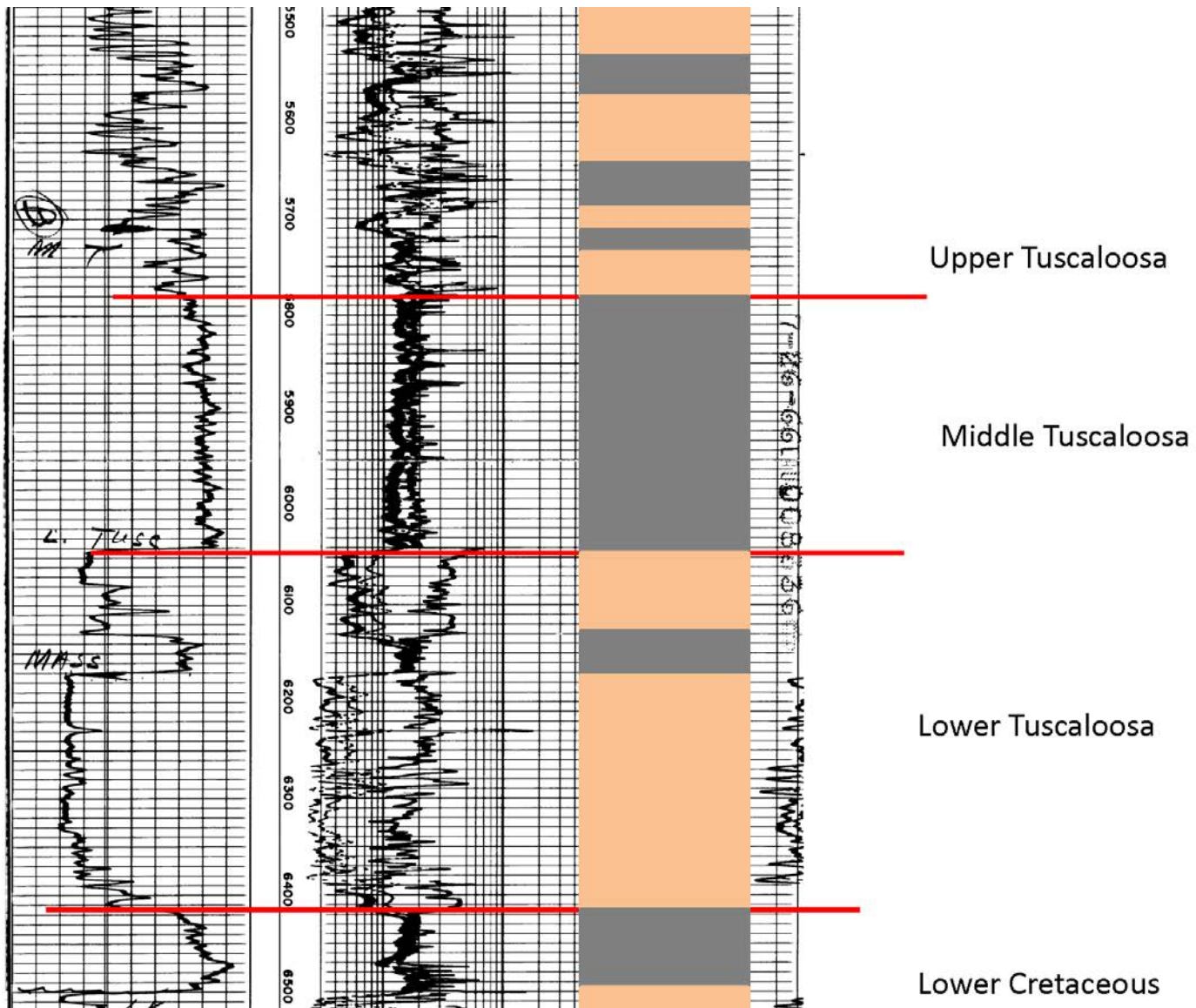
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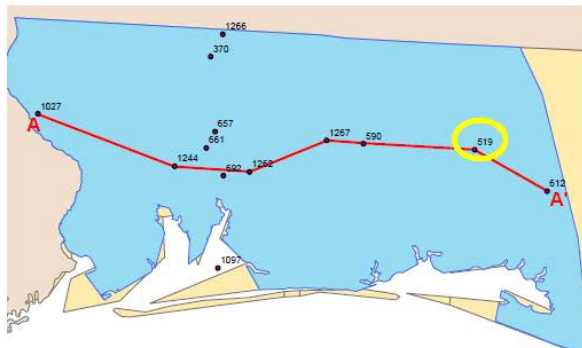
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COMPANY TEXACO, INC. WELL #1 T. R. MILLER FIELD WILDCAT COUNTY SANTA ROSA STATE FLORIDA LOCATION 1980' NSL & 990' EWL OF SEC 32 Sec. 32 Twp. 5N Rge. 28W		COMPANY TEXACO, INC. WELL #1 T. R. MILLER FIELD WILDCAT COUNTY SANTA ROSA STATE FLORIDA LOCATION 1980' NSL & 990' EWL OF SEC 32 Sec. 32 Twp. 5N Rge. 28W	
Date 6/4/66 Run No. ONE Depth-Driller 2530 Depth-Logger 2532 Btm. Log Interval 2528 Top Log Interval 2528 Casing-Driller 16" @ 78 Casing-Logger 78 Bit Size 15"		Date 6/19/66 Run No. TWO Depth-Driller 10550 Depth-Logger 10549 Btm. Log Interval 10545 Top Log Interval 10545 Casing-Driller 16" @ 78 Casing-Logger 78 Bit Size 15"	
Permanent Datum: GROUND LEVEL Log Measured From RKB DS. 18.75 Ft. Above Perm. Datum Drilling Measured From RKB		Permanent Datum: GROUND LEVEL Log Measured From RKB DS. 18.75 Ft. Above Perm. Datum Drilling Measured From RKB	
Dens. 9.3 pH 3.8 Fluid Loss 30 ml Source of Sample FLOW LINE R _{sh} @ Meas. Temp. 3.19 @ 85°F R _{mf} @ Meas. Temp. 3.30 @ 71°F R _{ms} @ Meas. Temp. 3.74 @ 71°F Source R _{sh} M Source R _{mf} M Source R _{ms} M		Dens. 9.7 pH 9.2 Fluid Loss 45 ml Source of Sample MUD TANK R _{sh} @ Meas. Temp. 1.48 @ 96°F R _{mf} @ Meas. Temp. 1.30 @ 95°F R _{ms} @ Meas. Temp. 1.62 @ 88°F Source R _{sh} M Source R _{mf} M Source R _{ms} M	
Time Since Circ. 2 HOURS Max. Rec. Temp. 100°F Equip. Location 7007 LRL Recorded By GAMERILL Witnessed By HUNT		Time Since Circ. 3 HOURS Max. Rec. Temp. 205°F Equip. Location 7007 LRL Recorded By GAMERILL Witnessed By KINLEY	
REMARKS SERVICE ORDER #D8336			
Changes in Mud Type or Additional Samples			
Date	Sample No.	Type Log	Scale Changes
Depth-Driller			Scale Up Hole
Depth-Logger			Scale Down Hole
Type Fluid in Hole			
Dens.	Visc.		
pH	Fluid Loss		
Source of Sample			
R _{sh} @ Meas. Temp.	@ °F	Run No.	Tool Type
R _{mf} @ Meas. Temp.	@ °F	ONE	IIL
R _{ms} @ Meas. Temp.	@ °F	TWO	IIL
Source: R _{sh}	R _{ms}	THREE	IIL
R _{sh} @ BHT	@ °F	FOUR	IIL
R _{mf} @ BHT	@ °F		
R _{ms} @ BHT	@ °F		
C.D. USED	S.O. = 1.5"	RUN #1	RUN #2
Equip. Used	Cart. No.	B-25	B-25
	Panel No.	A-52	A-63
	Sonde No.	B-22	B-22
	AP No.	D-414	D-70
	BBR =	1.0	1.0
NOTE: RUN #1 IS 20MV SCALE; OTHER RUNS ARE 15MV SCALE			
NOTE: RUN #1 CONTAINS 2" & 5" FILM; SUBSEQUENT RUNS ARE 1" & 5" FILM			
Check one, filling in blanks where applicable: <input checked="" type="checkbox"/> Surface determined sonde errors used for ILM and ILD. <input type="checkbox"/> ILM and ILD sonde errors corrected for _____ inch <input type="checkbox"/> barehole signal at R _{sh} = _____ <input type="checkbox"/> ILM and ILD zeros set in hole at depth of _____ feet.			



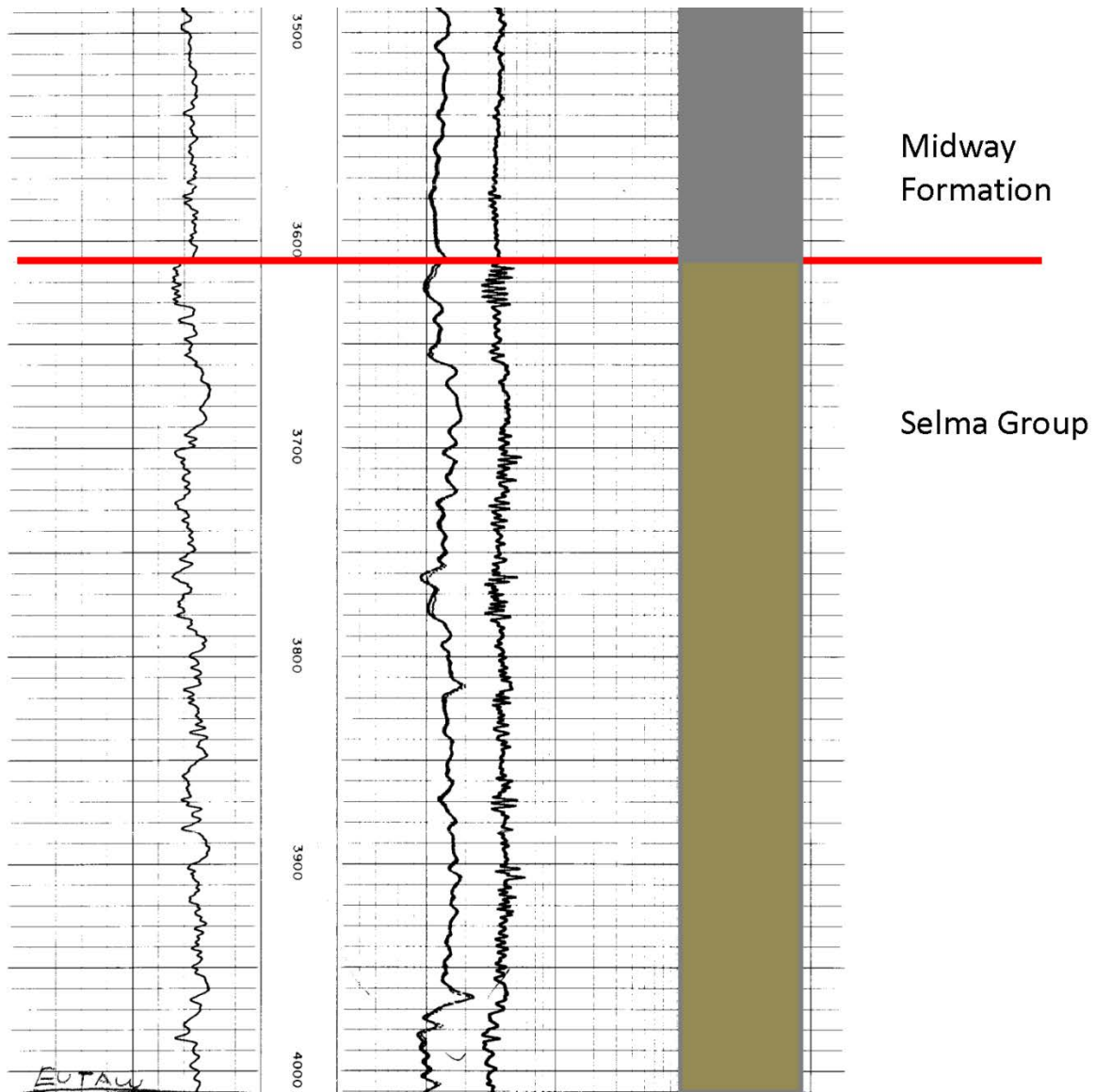


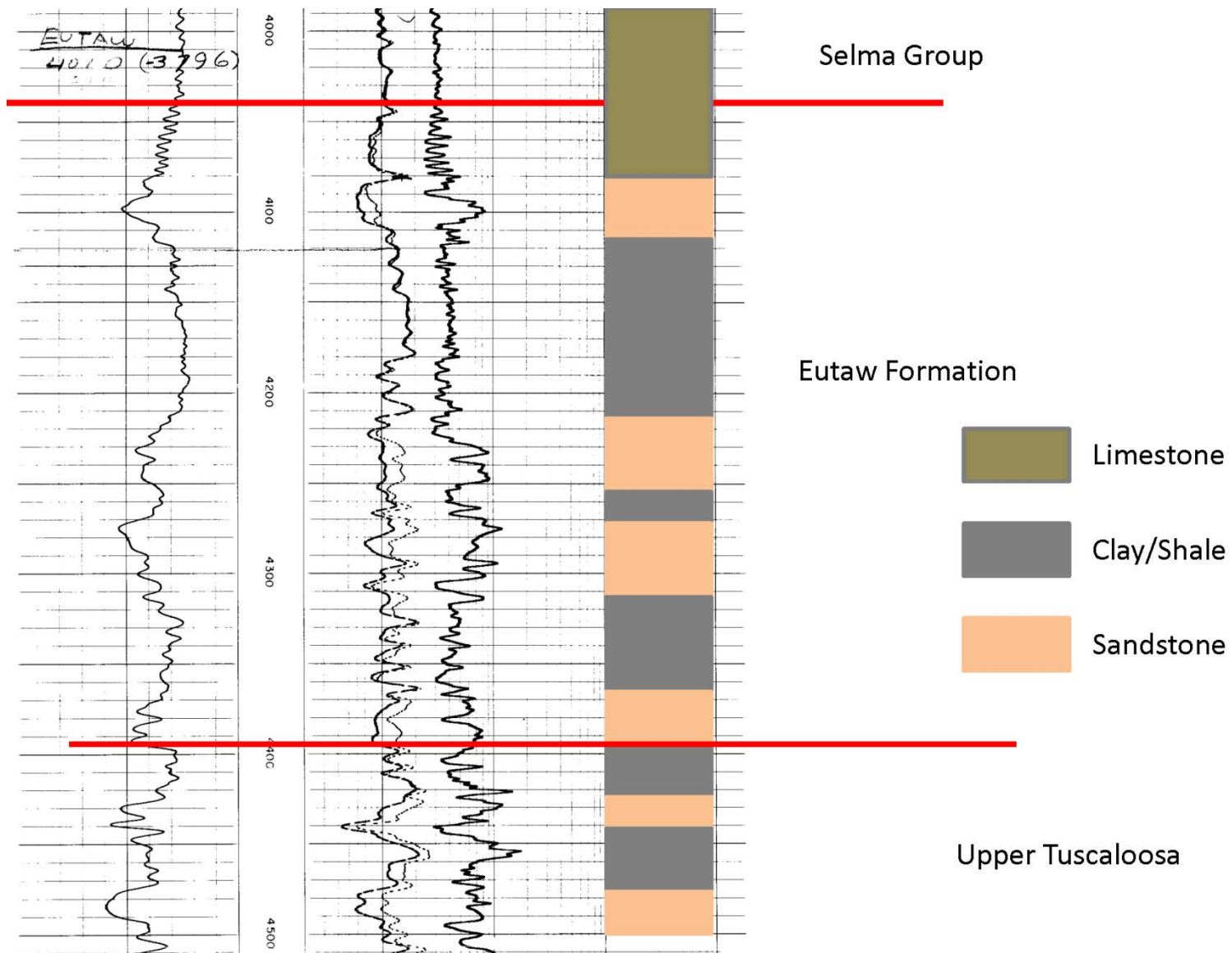


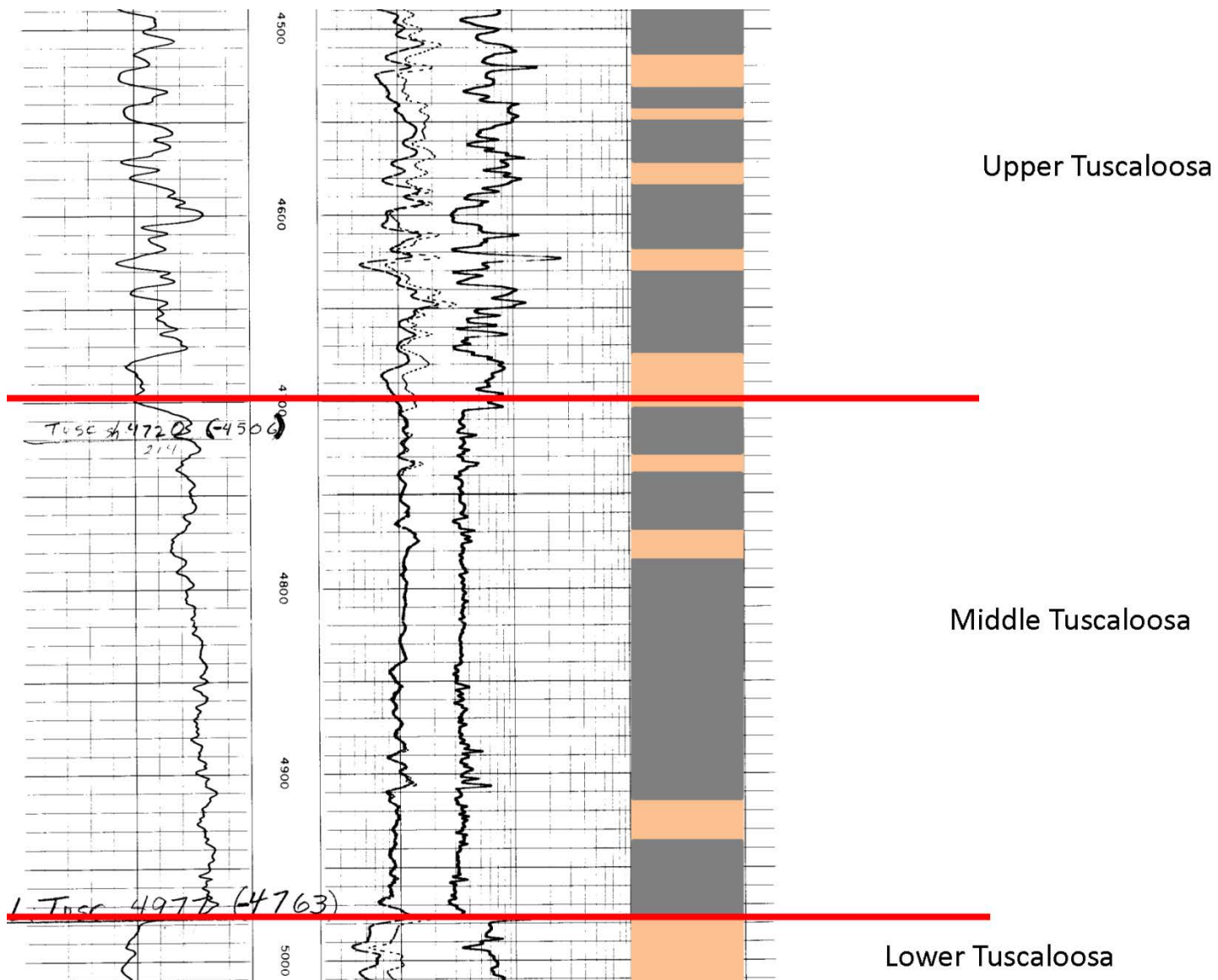
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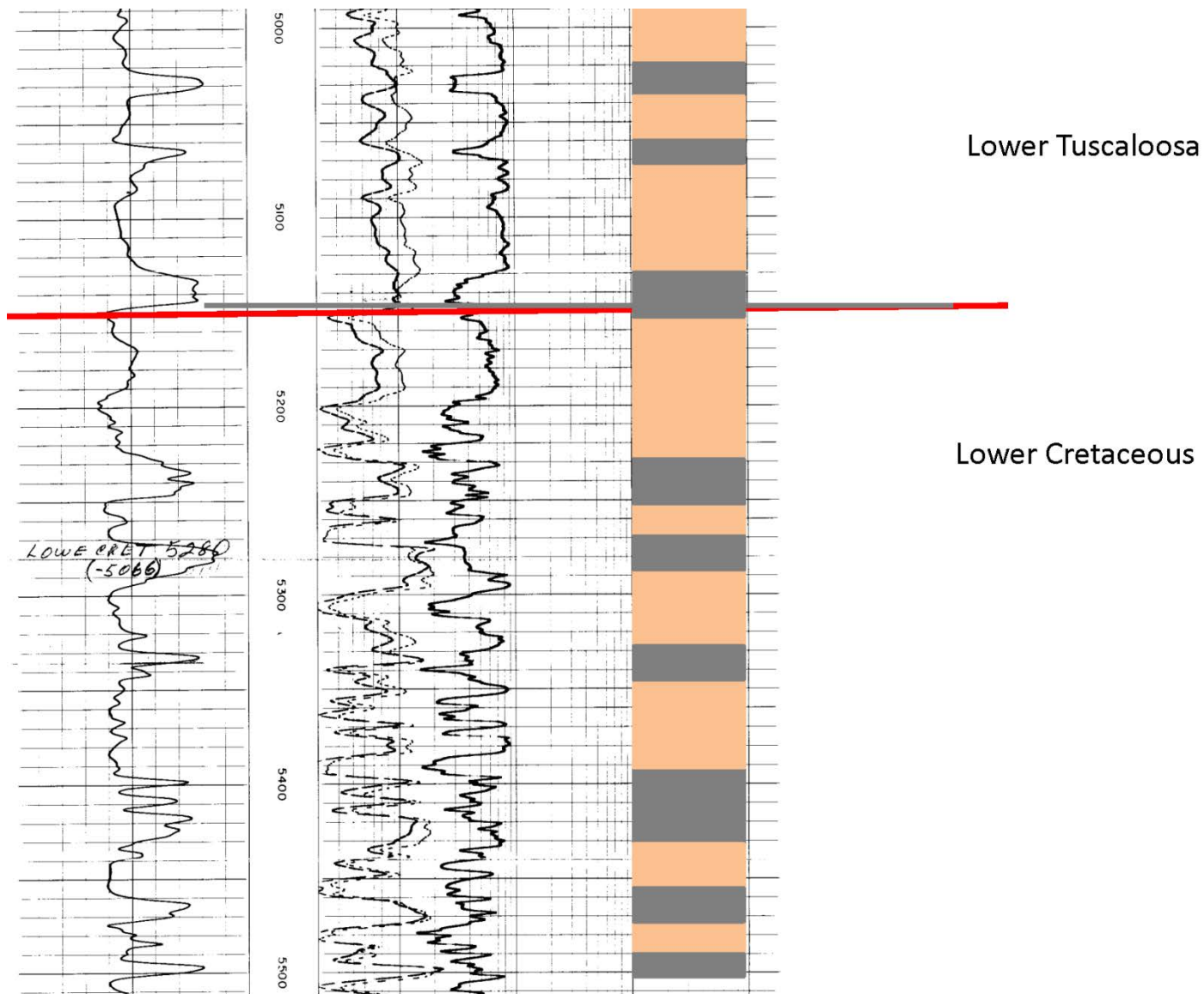


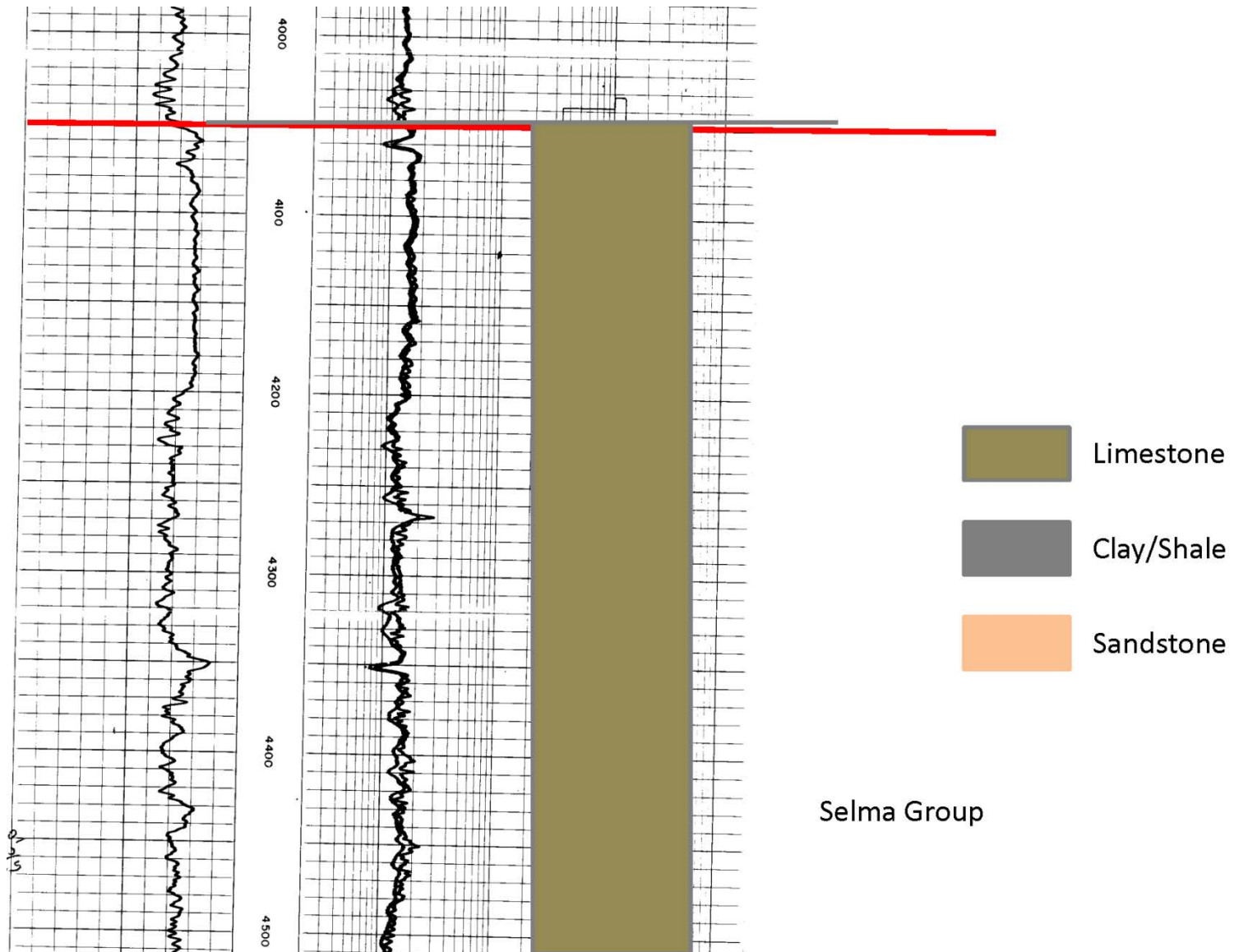
SCHLUMBERGER DUAL INDUCTION - LATEROLOG		COUNTY: WALTON FIELD or LOCATION: WILDCAT WELL: BRADY BELCHER COMPANY: COASTAL PROD. CO.	
COMPANY: COASTAL PRODUCTION COMPANY WELL: BRADY BELCHER WELL #1 FIELD: WILDCAT COUNTY: WALTON LOCATION: 1320 FNI & 1665 FMI OF SEC. 9. STATE: FLORIDA Other Services:		COMPANY: COASTAL PROD. CO. WELL: BRADY BELCHER WELL #1 FIELD: WILDCAT COUNTY: WALTON LOCATION: 1320 FNI & 1665 FMI OF SEC. 9. STATE: FLORIDA Other Services:	
Permanent Datum: CL 195 Log Measured From: KB 195 Drilling Measured From: KB 195		Date: 10/6/71 Run No.: ONE Depth - Driller: 17038 Depth - Logger: 17038 Bm. Log Interval: 17037 Top Log Interval: 17037 Casing - Driller: 10 1/2 @ 3103 Casing - Logger: 3117 Bit Size: 9 5/8 Type Fluid in Hole: INCO VC-10 Type Fluid in Hole: INCO VC-10	
Date: 10/6/71 Run No.: ONE Depth - Driller: 17038 Depth - Logger: 17038 Bm. Log Interval: 17037 Top Log Interval: 17037 Casing - Driller: 10 1/2 @ 3103 Casing - Logger: 3117 Bit Size: 9 5/8 Type Fluid in Hole: INCO VC-10 Type Fluid in Hole: INCO VC-10		Date: 10/10/71 Run No.: TWO Depth - Driller: 17038 Depth - Logger: 17038 Bm. Log Interval: 17037 Top Log Interval: 17037 Casing - Driller: 10 1/2 @ 3103 Casing - Logger: 3117 Bit Size: 9 5/8 Type Fluid in Hole: INCO VC-10 Type Fluid in Hole: INCO VC-10	
Dens. 9.5 Visc. 37 pH 9.9 Fluid Loss 12.0 ml Source of Sample: MUD TANK R _{sh} @ Meas. Temp. 1.70 @ 108F 2.17 @ 77F R _{mt} @ Meas. Temp. 1.81 @ 80F 1.78 @ 92F R _{ms} @ Meas. Temp. 3.29 @ 74F 3.15 @ 74F Source R _{mt} / R _{ms} 0.92 @ 190F 0.85 @ 192F R _{sh} @ BHT 190 192 R _{mt} @ BHT 190 192 R _{ms} @ BHT 190 192		Dens. 9.5 Visc. 34 pH 16.4 Fluid Loss 15.4 ml Source of Sample: MUD TANK R _{sh} @ Meas. Temp. 1.70 @ 108F 2.17 @ 77F R _{mt} @ Meas. Temp. 1.81 @ 80F 1.78 @ 92F R _{ms} @ Meas. Temp. 3.29 @ 74F 3.15 @ 74F Source R _{mt} / R _{ms} 0.92 @ 190F 0.85 @ 192F R _{sh} @ BHT 190 192 R _{mt} @ BHT 190 192 R _{ms} @ BHT 190 192	
REMARKS Changes in Mud Type or Additional Samples Date Sample No. Type Log Depth Scale Changes Scale Up Hole Scale Down Hole Depth - Driller Type Fluid in Hole Dens. Visc. pH Fluid Loss ml Source of Sample R _{sh} @ Meas. Temp. @ @ @ R _{mt} @ Meas. Temp. @ @ @ R _{ms} @ Meas. Temp. @ @ @ Source R _{mt} / R _{ms} R _{sh} @ BHT @ @ @ R _{mt} @ BHT @ @ @ R _{ms} @ BHT @ @ @ Run No.: ONE TWO C.D.: YES YES S.O.: 1.5" 1.5" Equip. PANEL No.: DIP C 219 C 219 Used: CART. No.: DIC B 143 B 113 SONDE No.: DIS DB 47 DB 69 IAP No.: MMP B 172 B 172 S.B.R.: 1.0 1.0 NOTE RUN #2: TOOL OFF BOTTOM @ 0430 Check one, filling in blanks where applicable: <input checked="" type="checkbox"/> Surface determined sonde errors used for ILM and ILD. <input type="checkbox"/> ILM and ILD sonde errors corrected for inch borehole signal at R _m = <input type="checkbox"/> ILM and ILD zeros set in hole at depth of feet.			

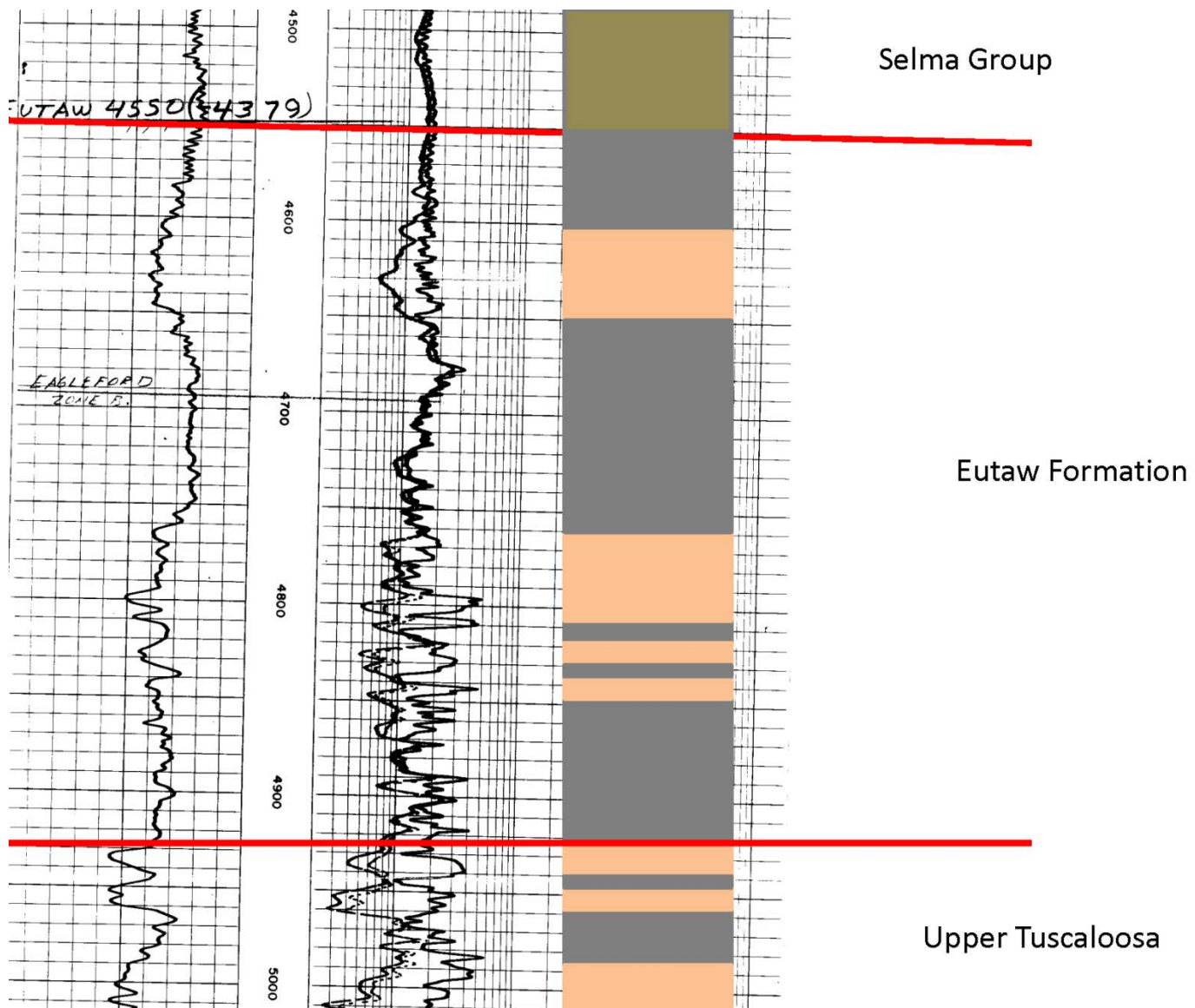


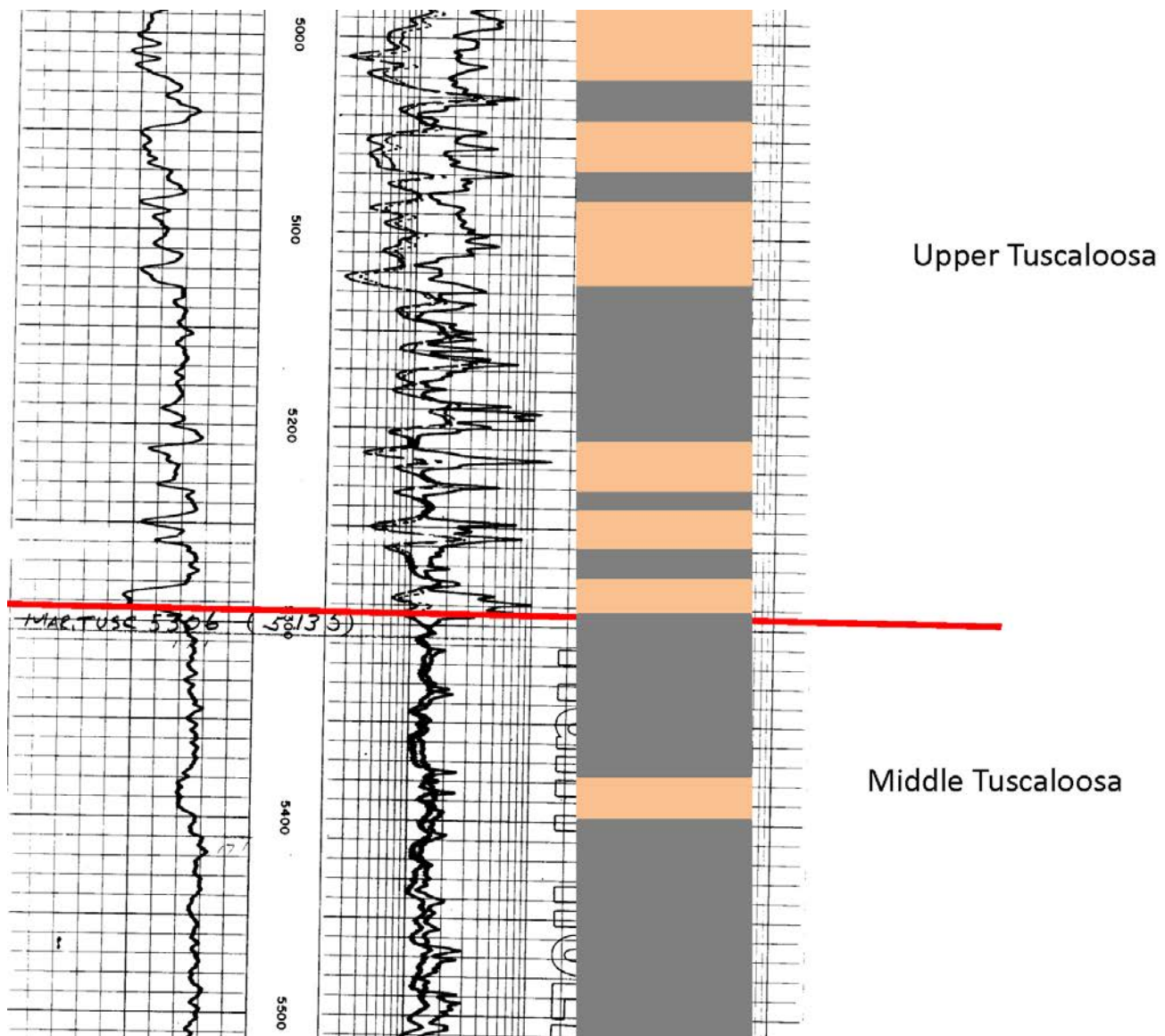


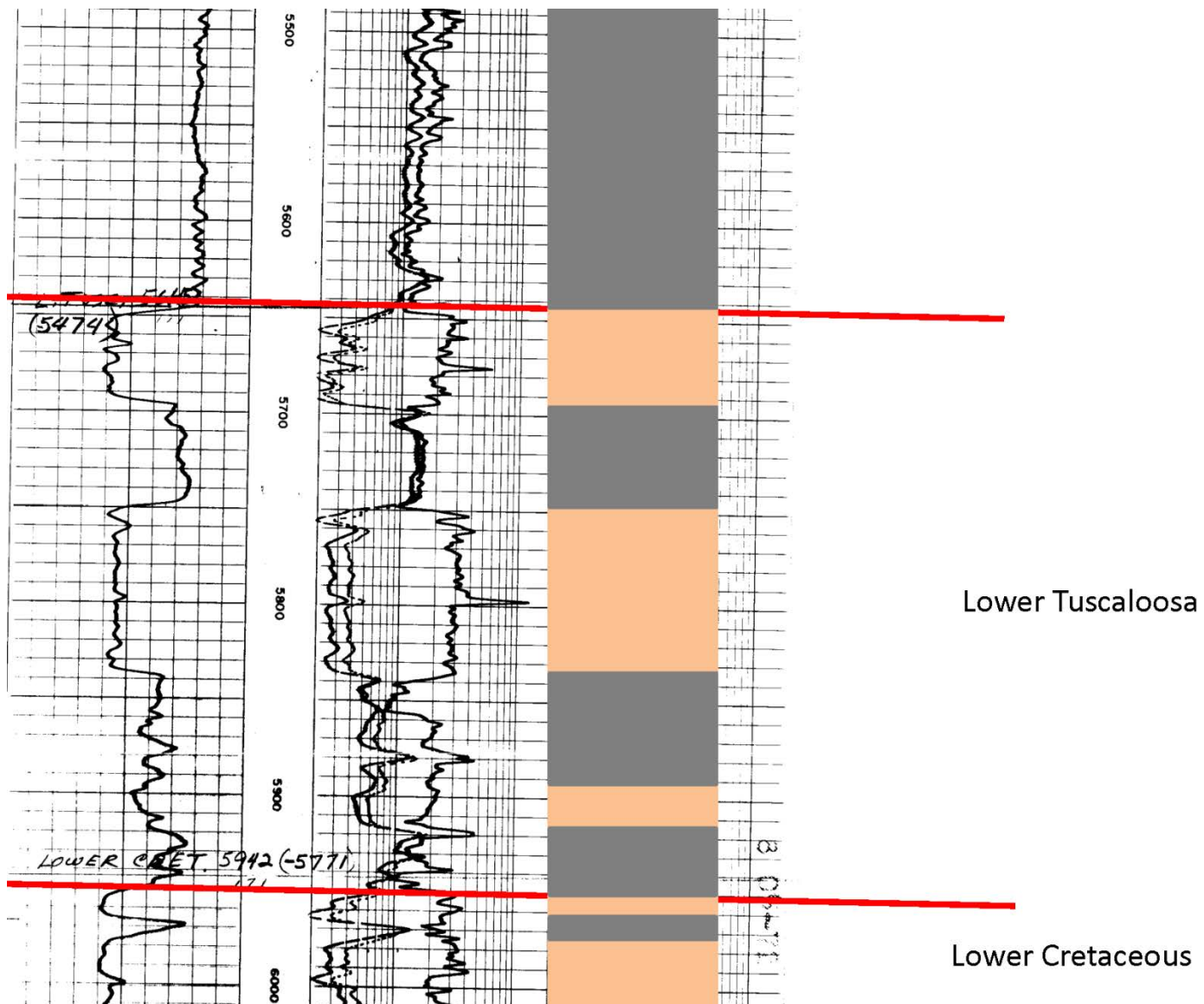




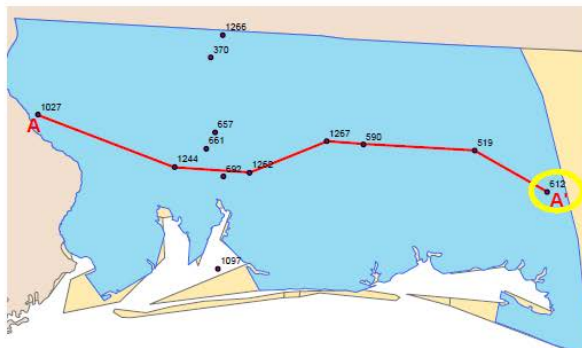




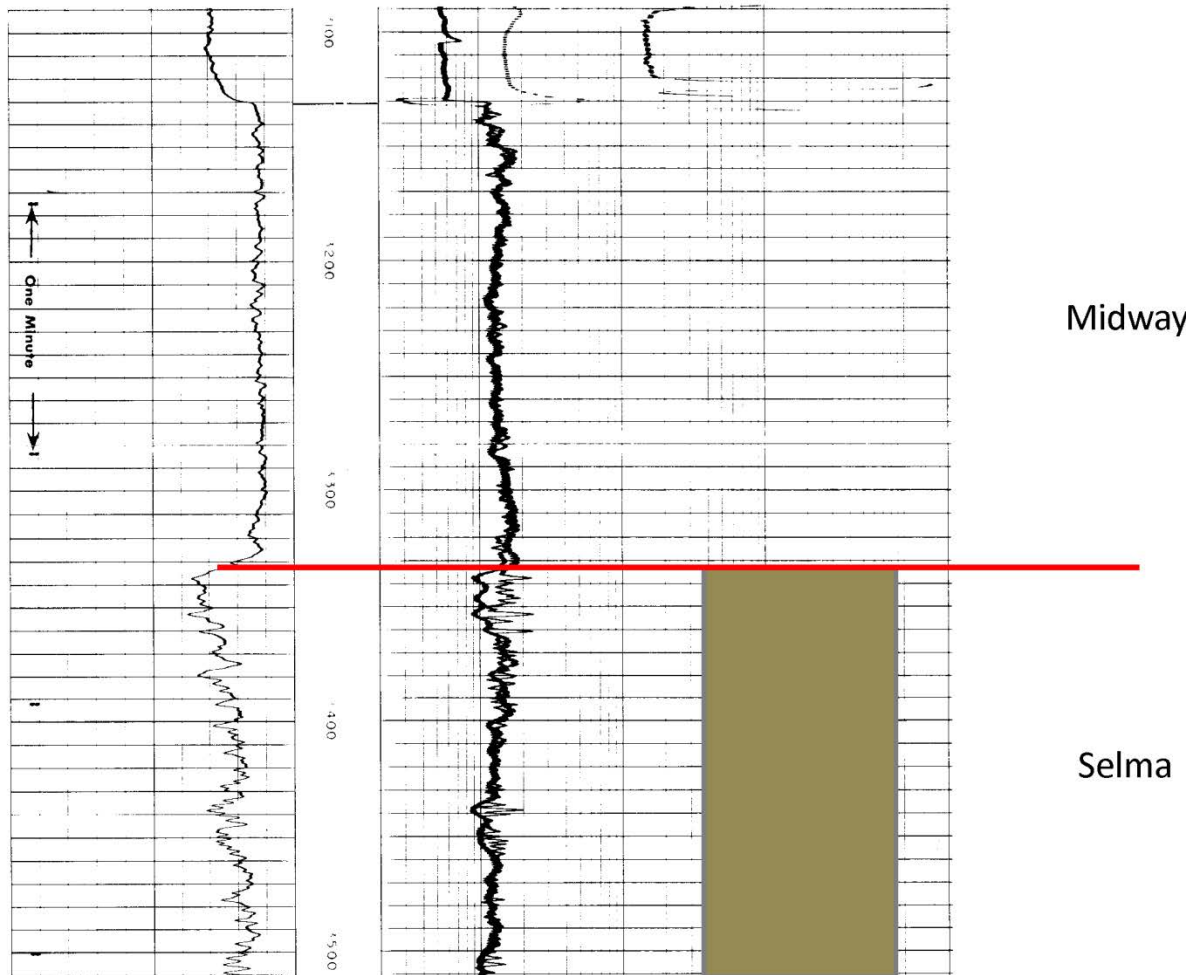


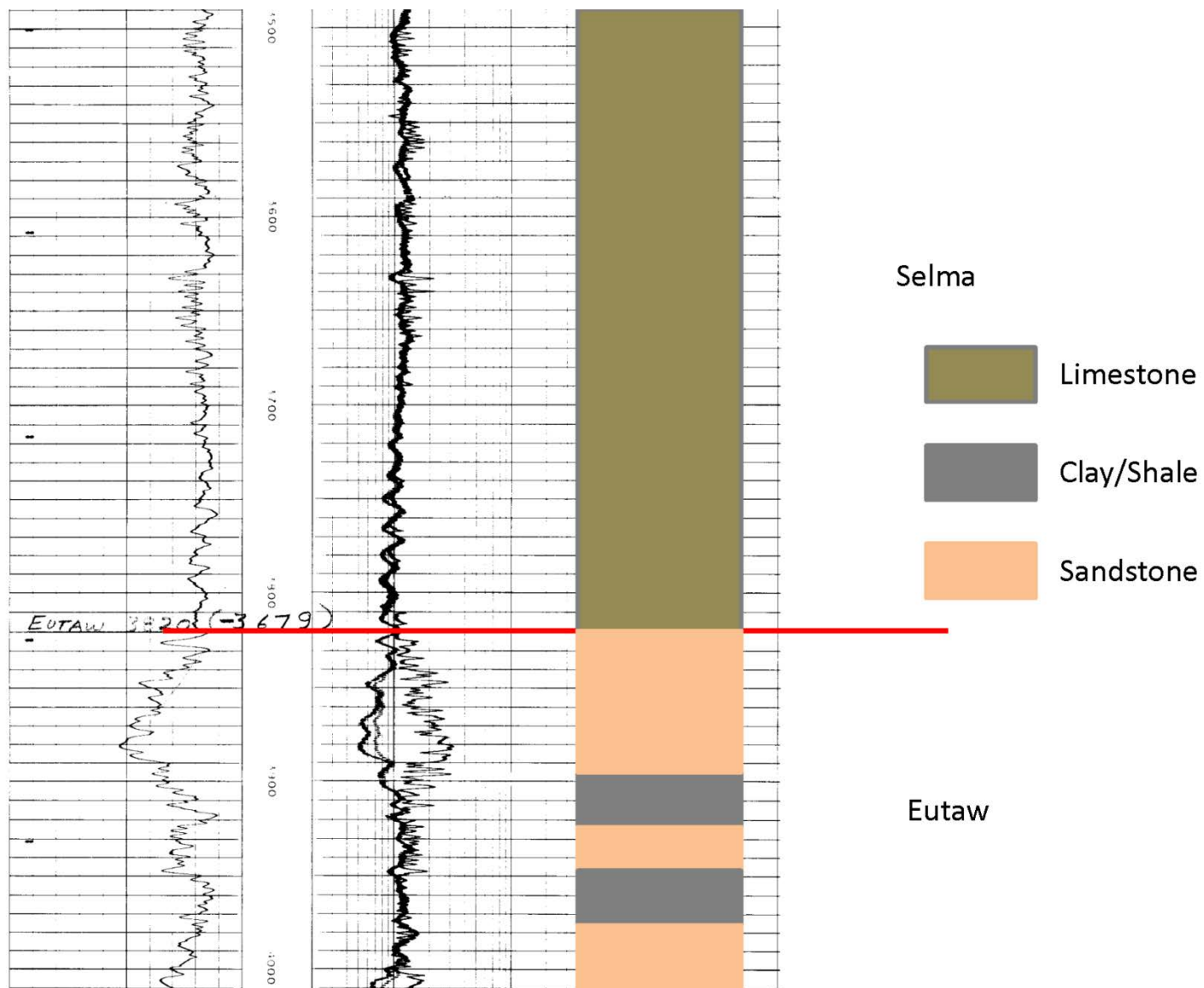


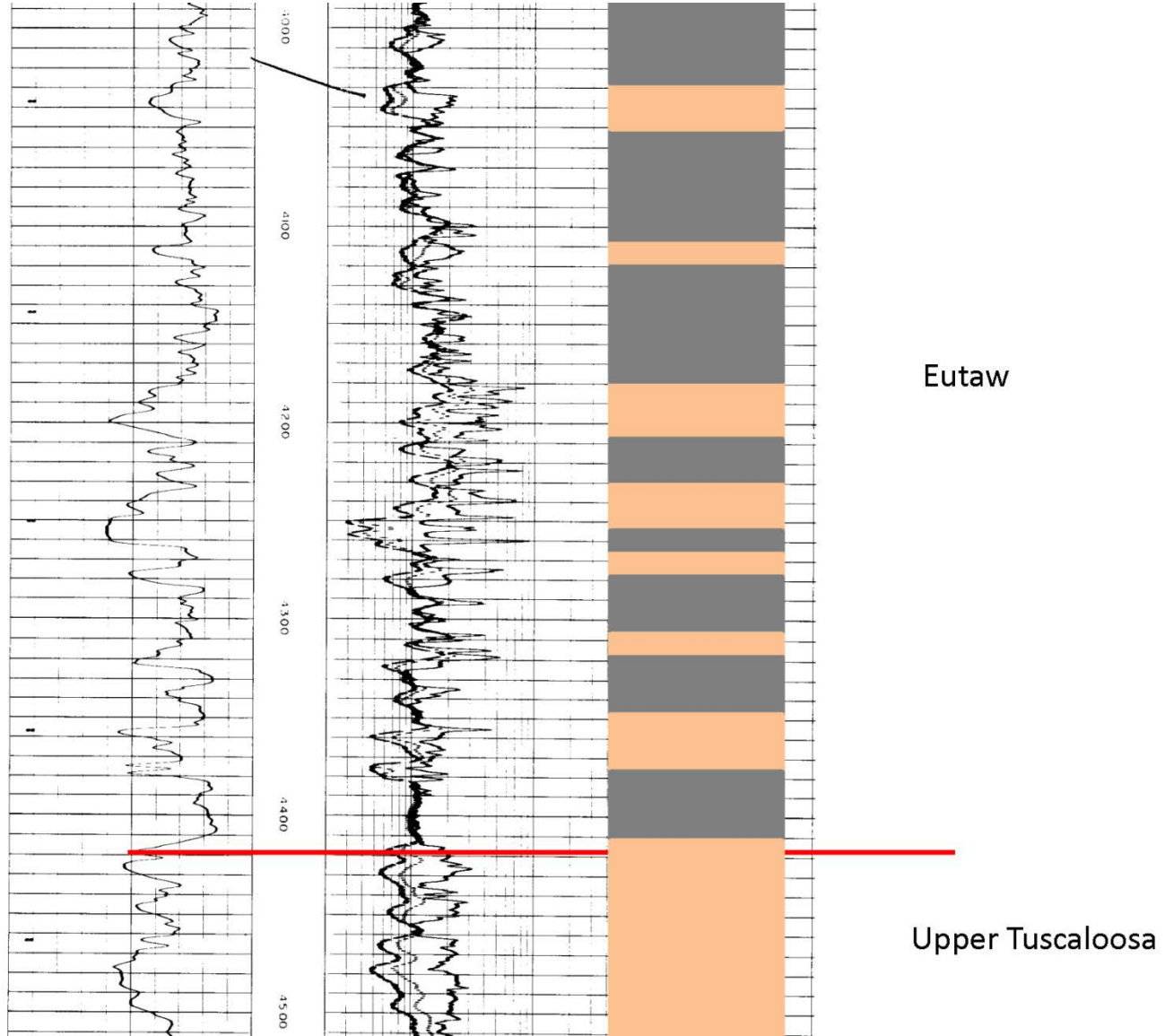
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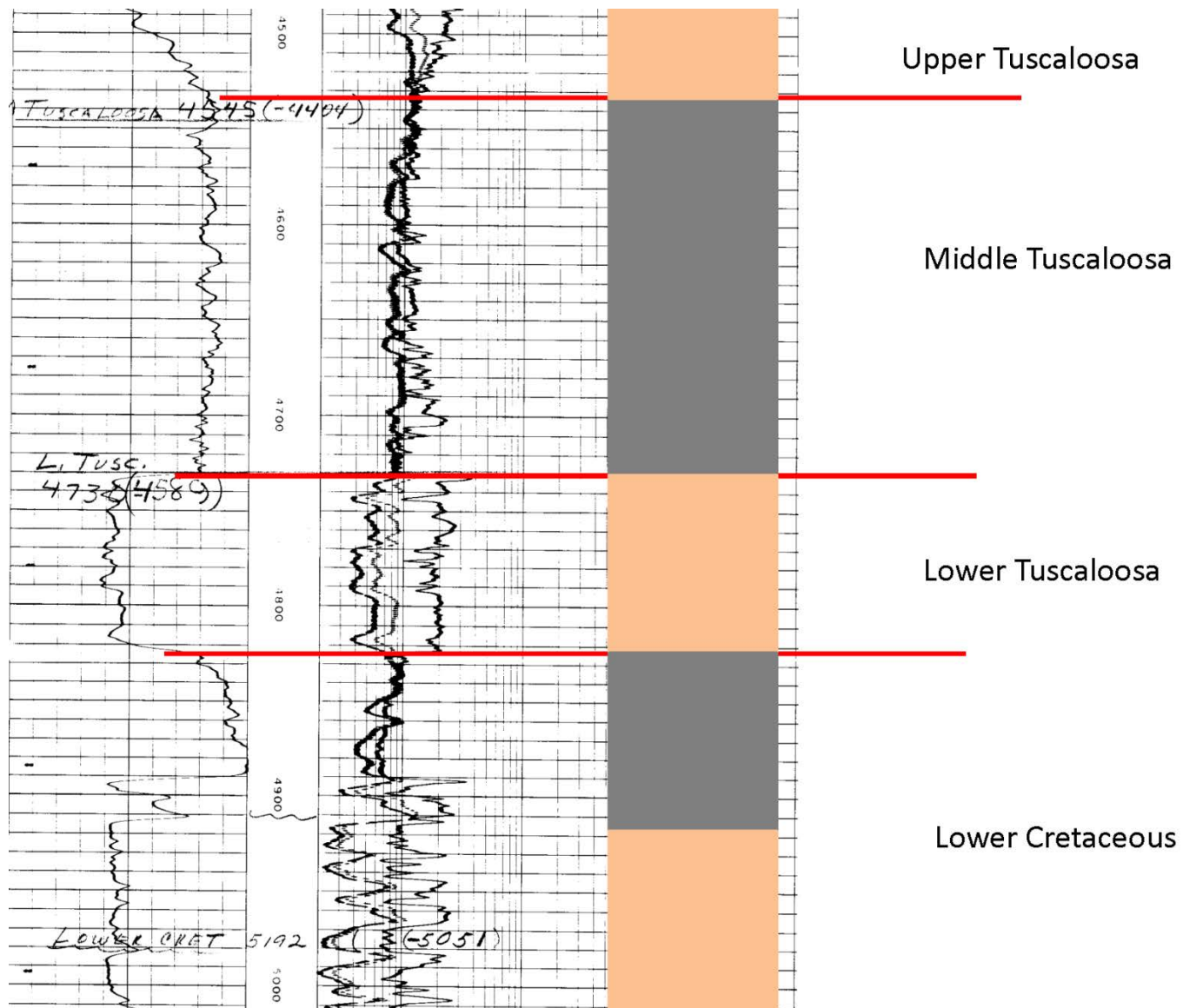


Presser Atlas <i>Drill Production</i> <i>Special Log</i>	
HLT NO. F-434 COMPANY McCHILLOCH OIL - I.D.S. - RUDMAN WELL # 1-24 INDIAN CREEK RANCH INC. FIELD WILKAT COUNTY WATSON STATE FLORIDA LOCATION 1223' FSL. 1289' PFL SEC. 24 TWP. 2N RGE. 19W Other Services: BHC - AL - GR T T INT SWS	
Permanent Datum: C.L. Elev. 118.5 Log Measured from: K.B. 23.5 ft. Above Permanent Datum Drilling Measured from: K.B.	
Date: 9-19-72 Run No. 0-12 Depth-Driller: 11.343 Depth-Logger: 11.348 Bottom Logged Interval: 11.348 Top Logged Interval: 3131 Casing-Driller: 9.5/86 3131 Casing-Logger: 3131 Bit Size: 8 3/4 Type Fluid in Hole: MUD - CHEM	
Density and Viscosity: 9.6 35 pH and Fluid Loss: 9.5 14.0cc Source of Sample: CJR Rm @ Meas. Temp.: 1.55 @ 76 Rmf @ Meas. Temp.: 1.17 @ 75 Rmc @ Meas. Temp.: 1.95 @ 75 Source of Rmf and Rmc: C Rm @ BHT: 5.5 @ 210 Time Since Circ: 5.485 Max. Rec. Temp. Deg. F.: 210 Studio No. and Location: 60731RL Recorded by: MOORE Witnessed by: MR. BERRY JAYLOR	
REMARKS:	
Run No. ONE S.D. No. 23909 Tool No. 455 Elev. No. 455 Parcel No. 27254 Conv. Set 24360	
Changes in Mud Type or Additional Samples Date Sample No. Type Log Depth Scale Up Hole Scale Down Hole Depth-Driller Type Fluid in Hole Dens. Visc. pH Fluid Loss cc cc Source of Sample Rm @ Meas. Temp. @ F @ F Run No. Tool Type Pad Type Tool Position Other Rmf @ Meas. Temp. @ F @ F ONE 1592 P-125 CENT S.O. = 1 Rmc @ Meas. Temp. @ F @ F Source Rmf Rmc Rm @ BHT @ F @ F Rmf @ BHT @ F @ F Rmc @ BHT @ F @ F	

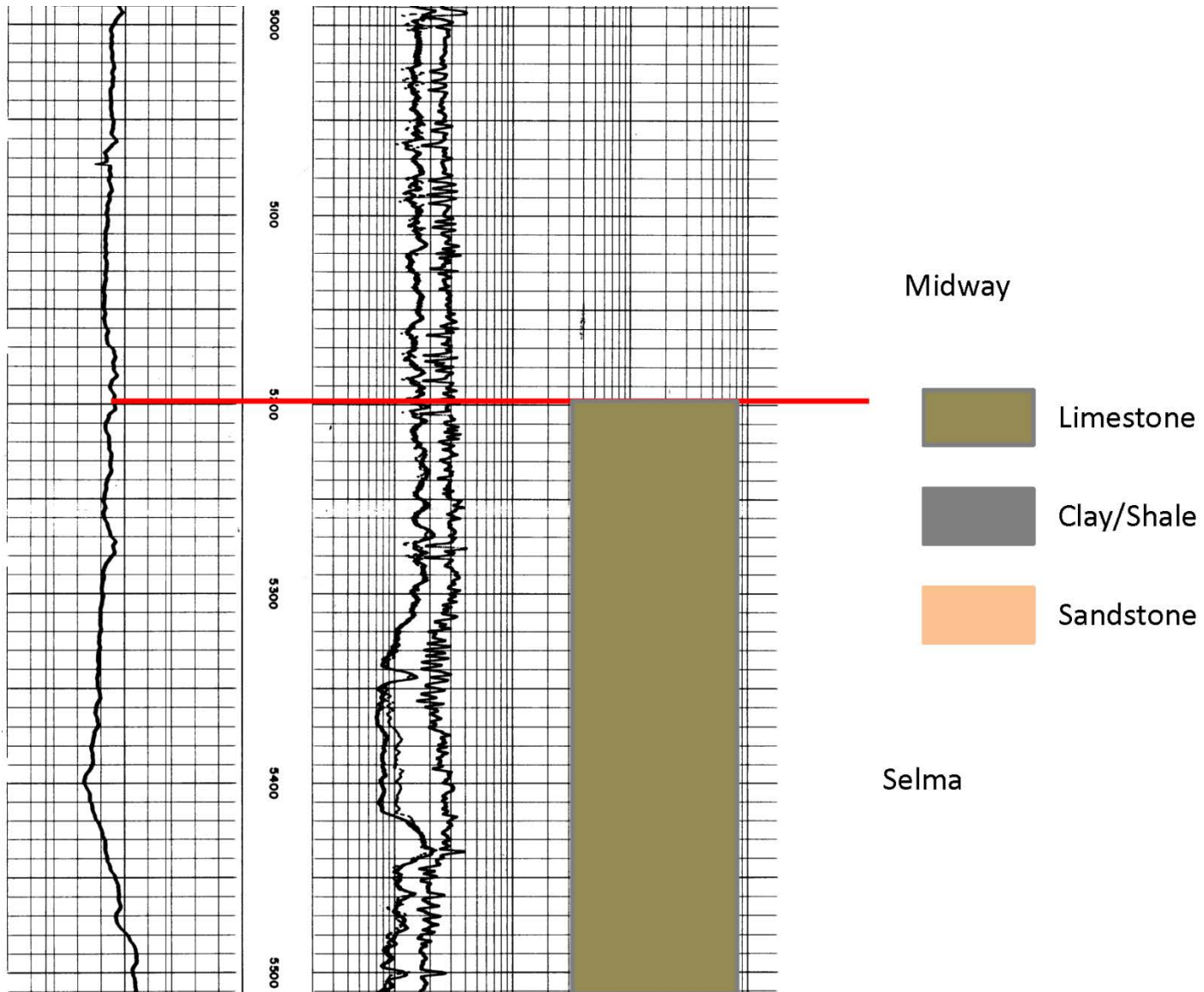


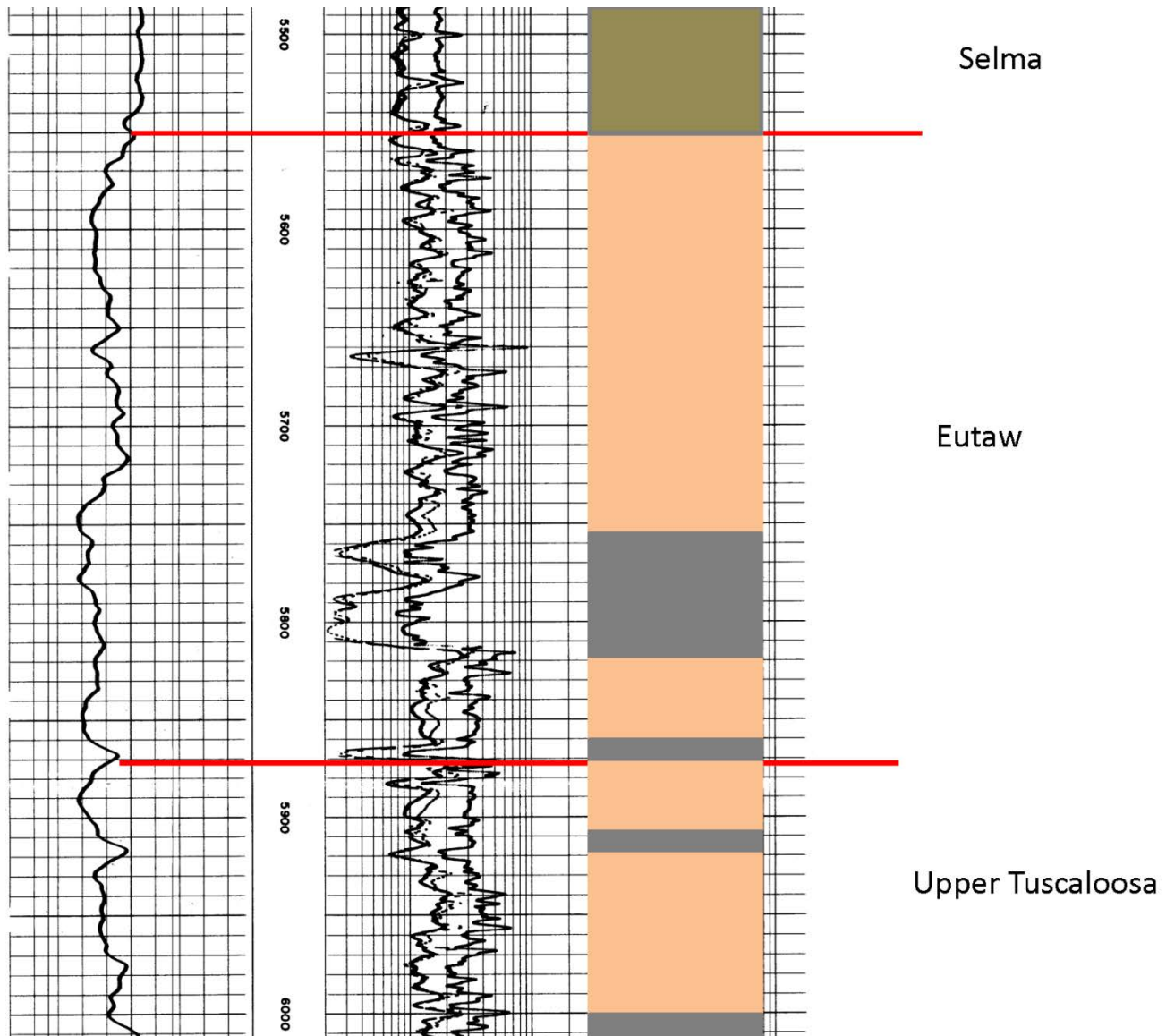


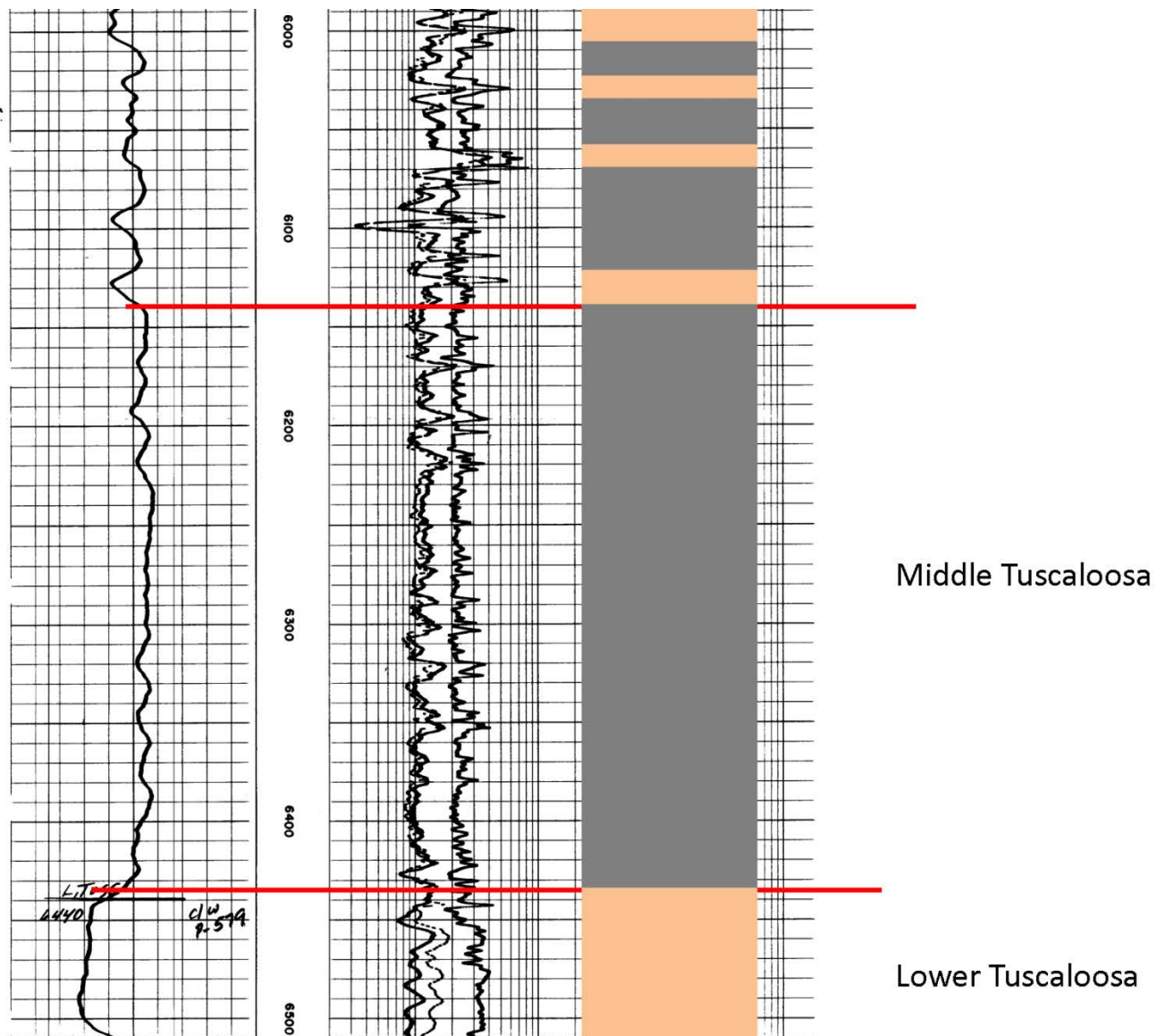


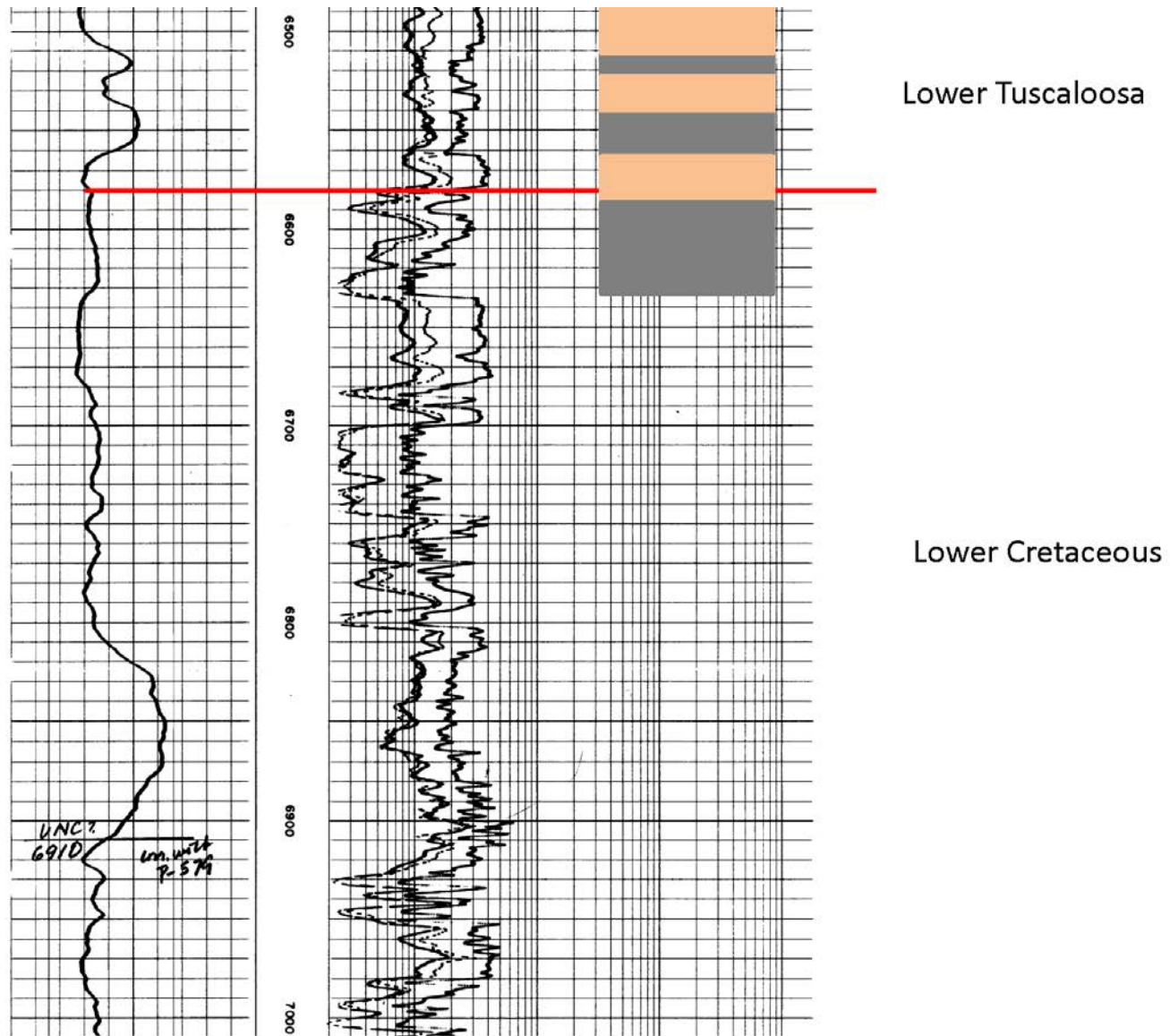


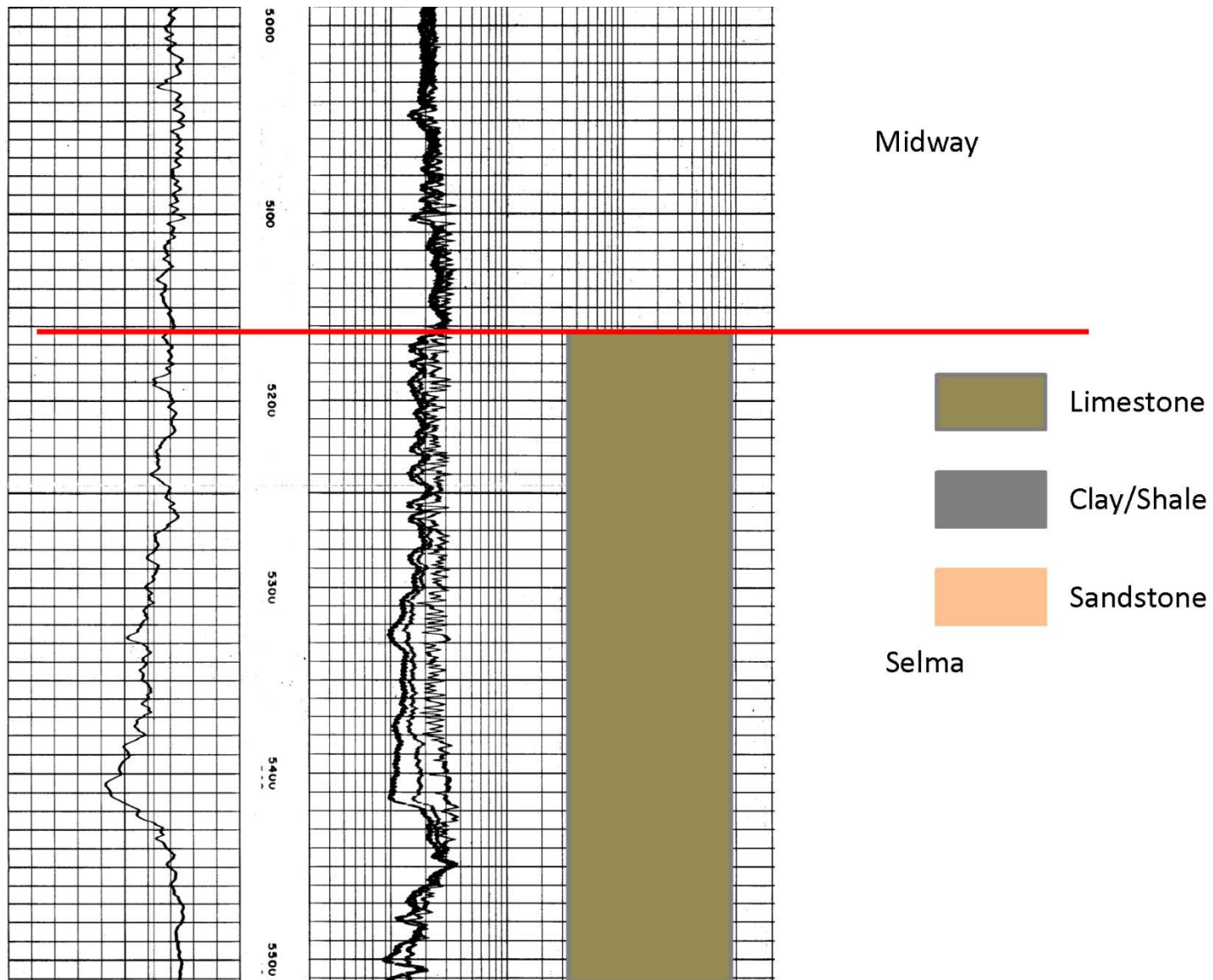
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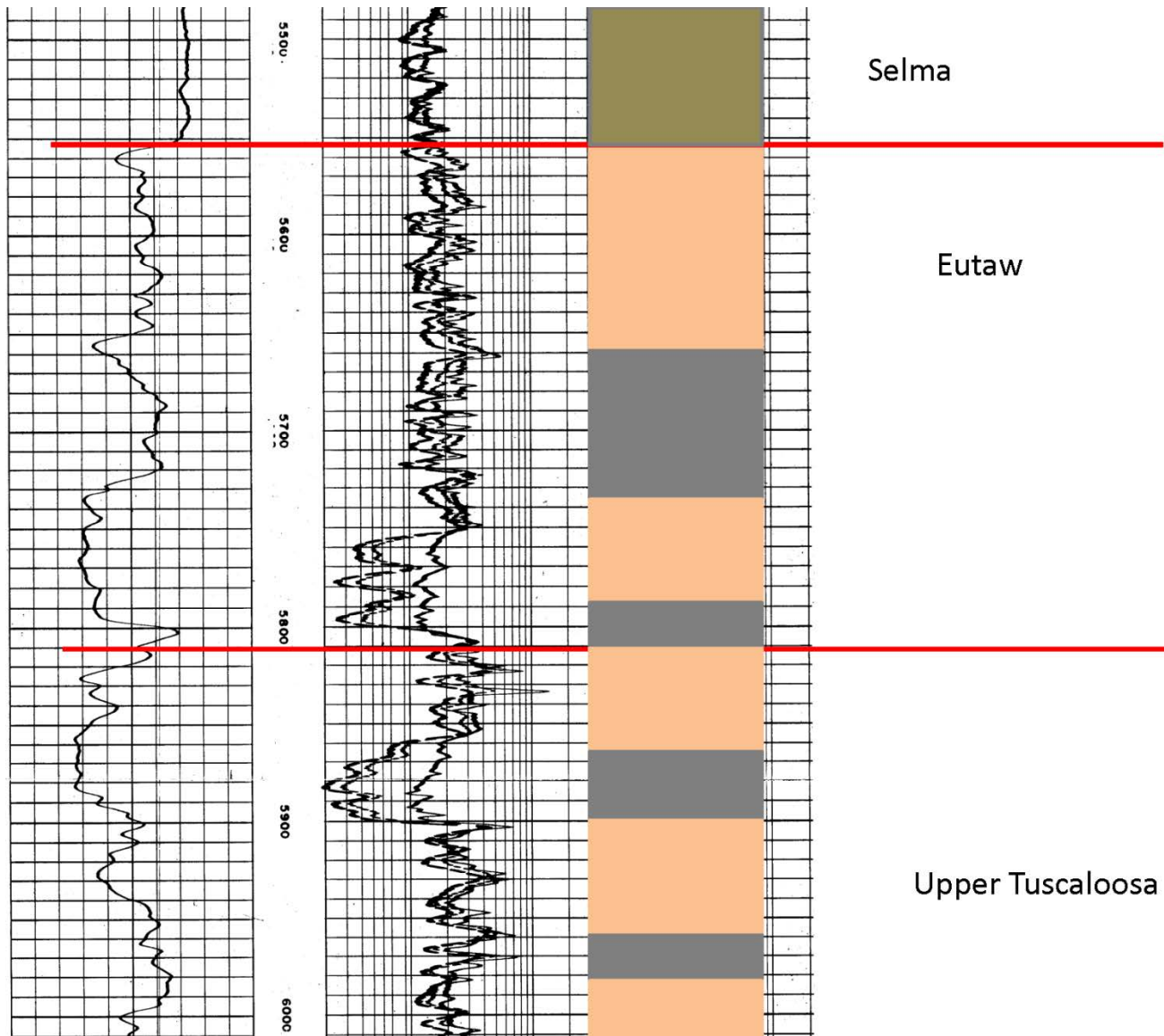


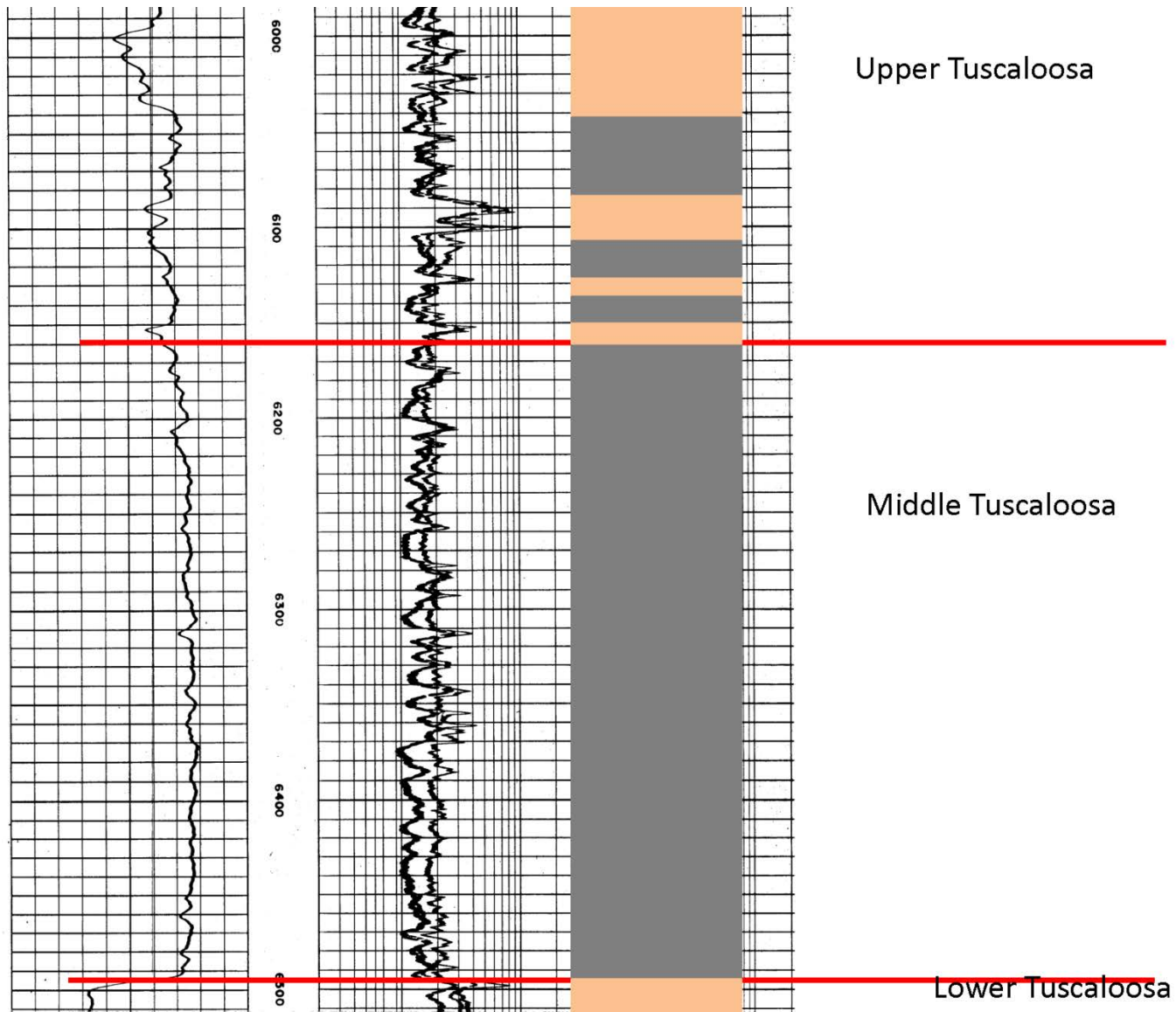


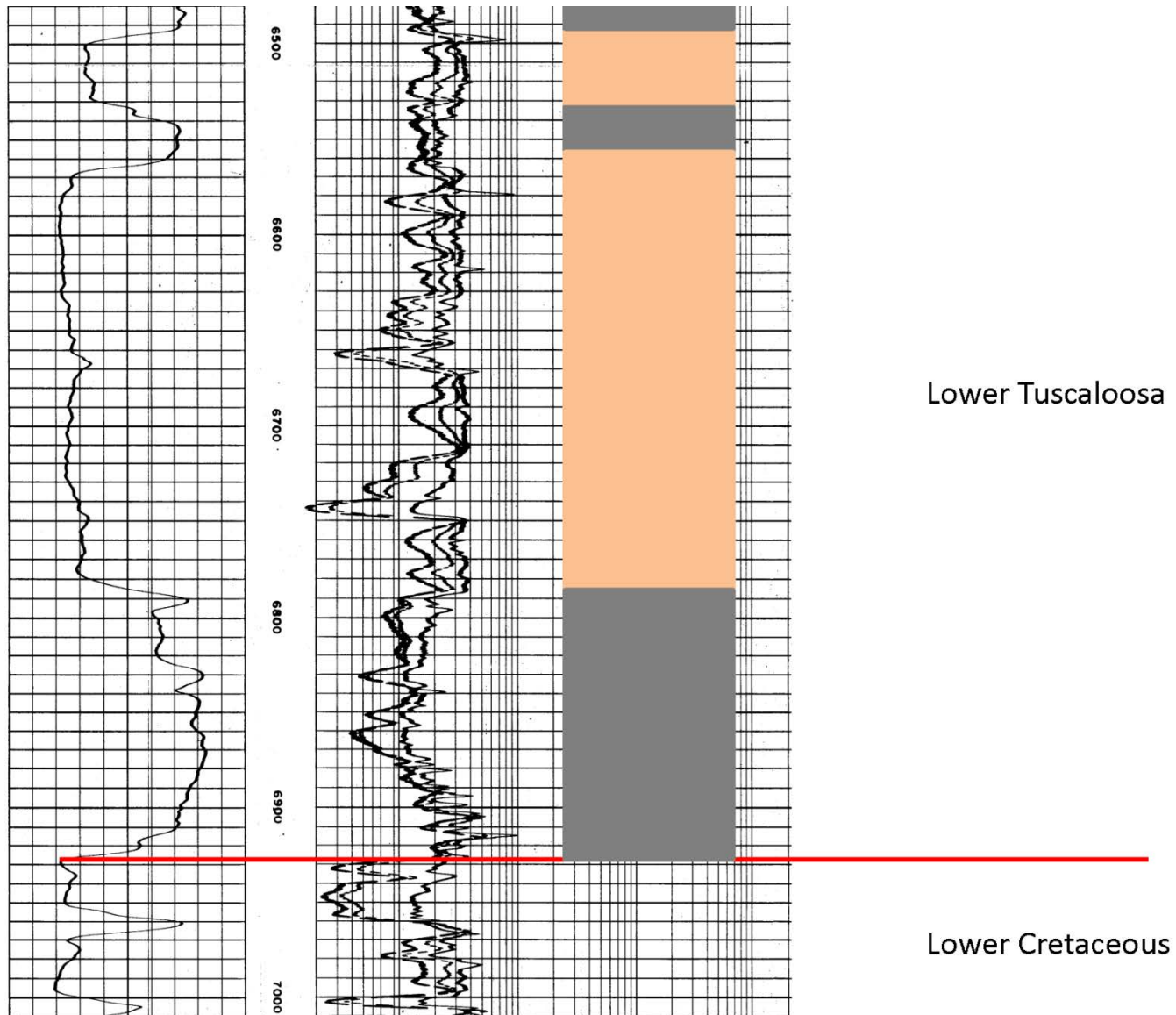




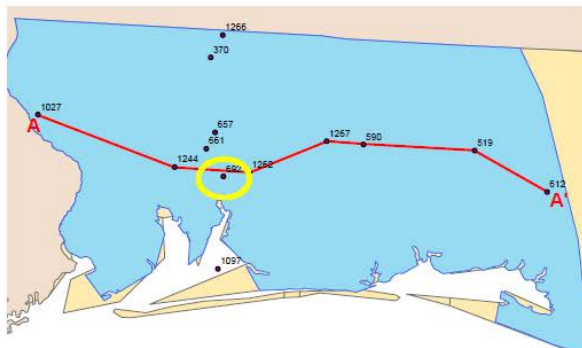




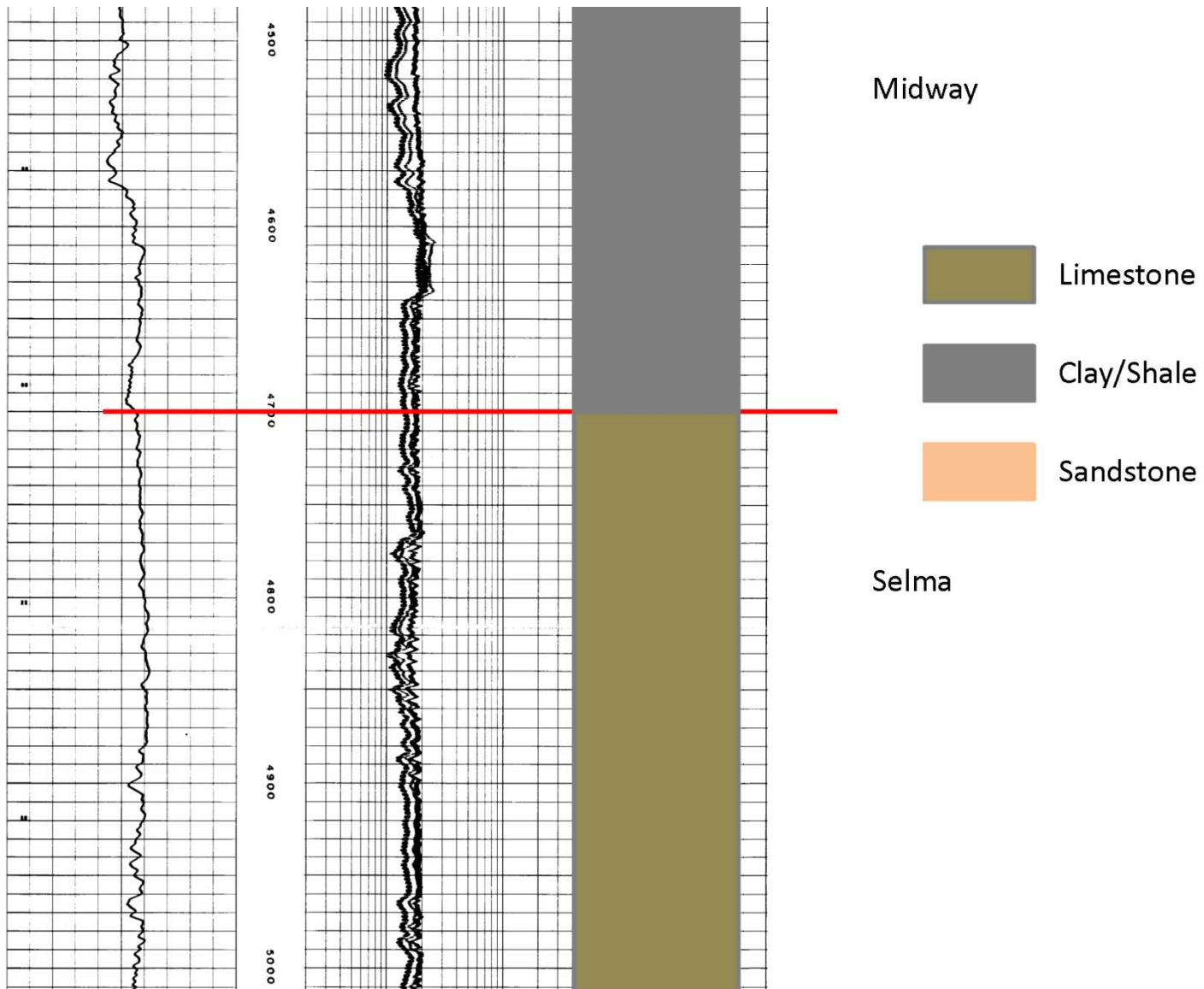


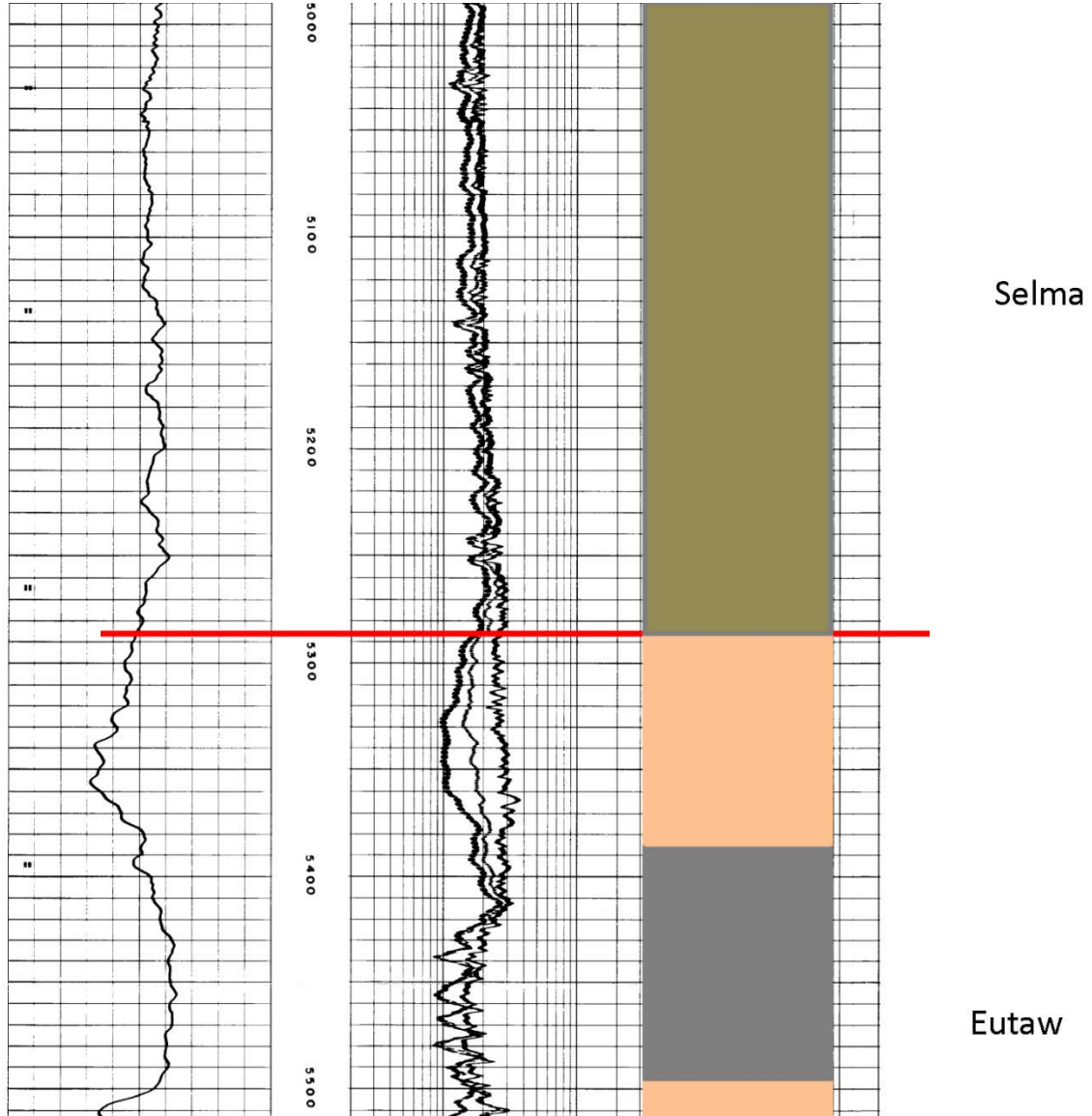


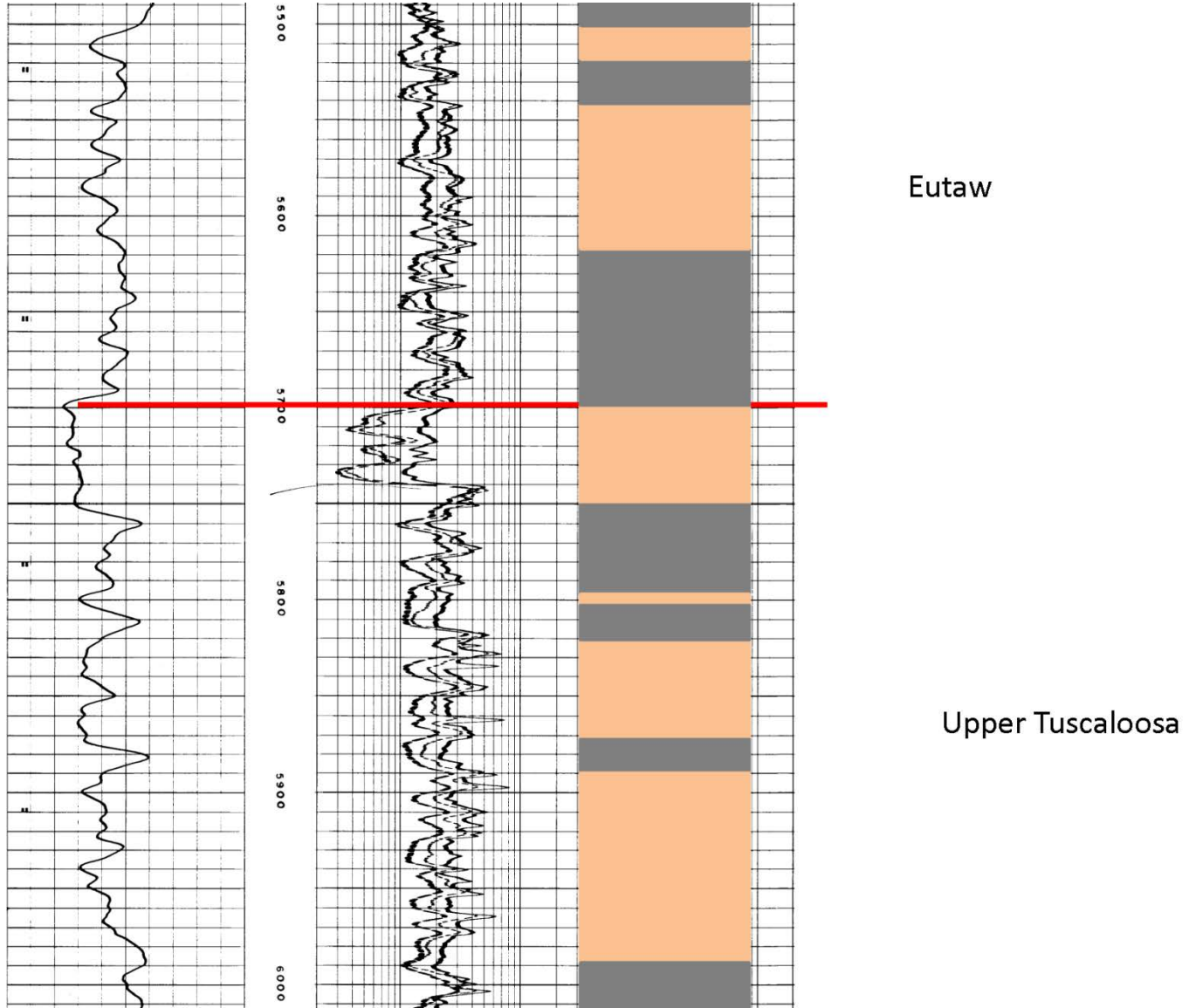
Disposal Area #1 P#692 Standard Potential Resistivity

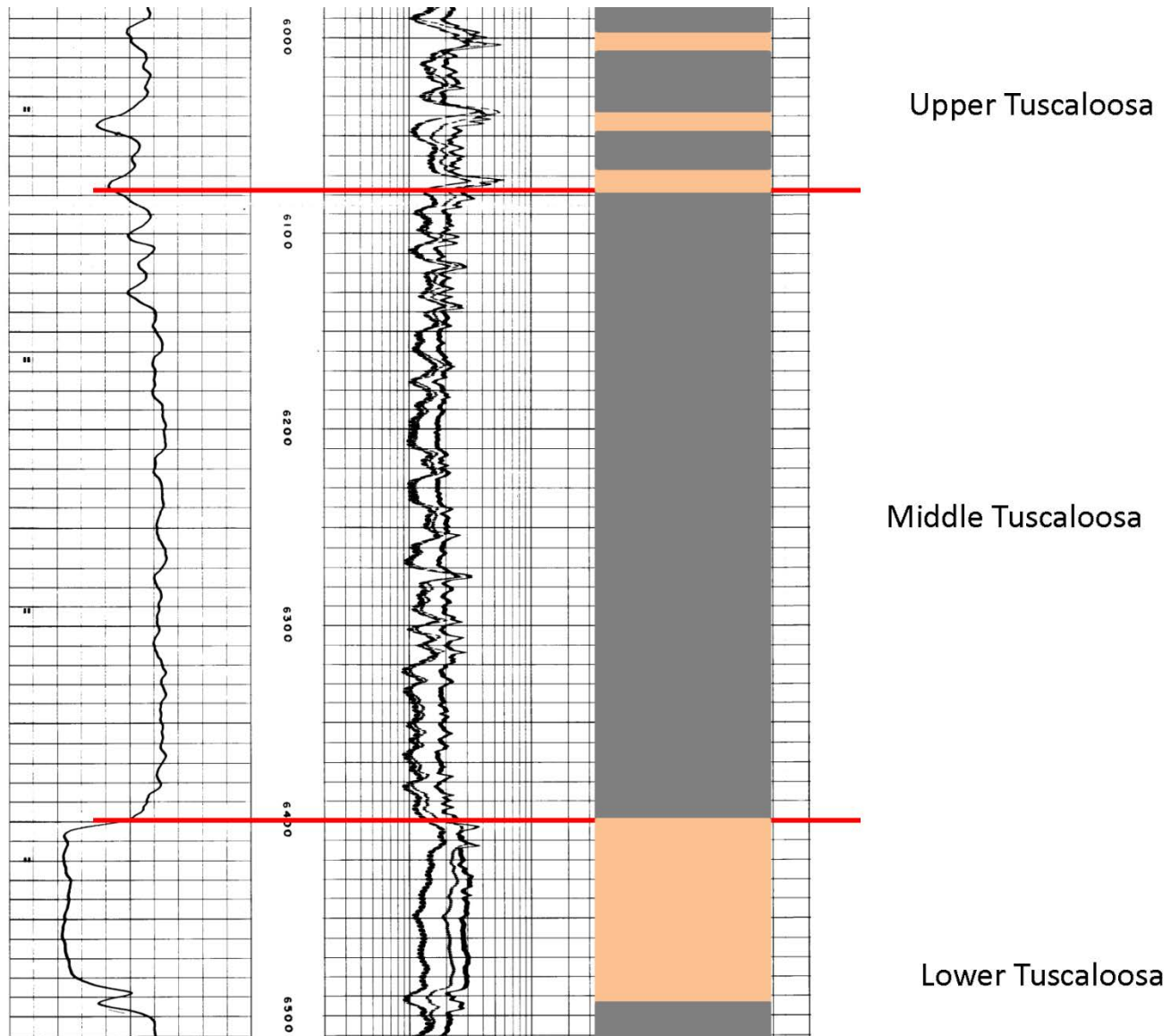


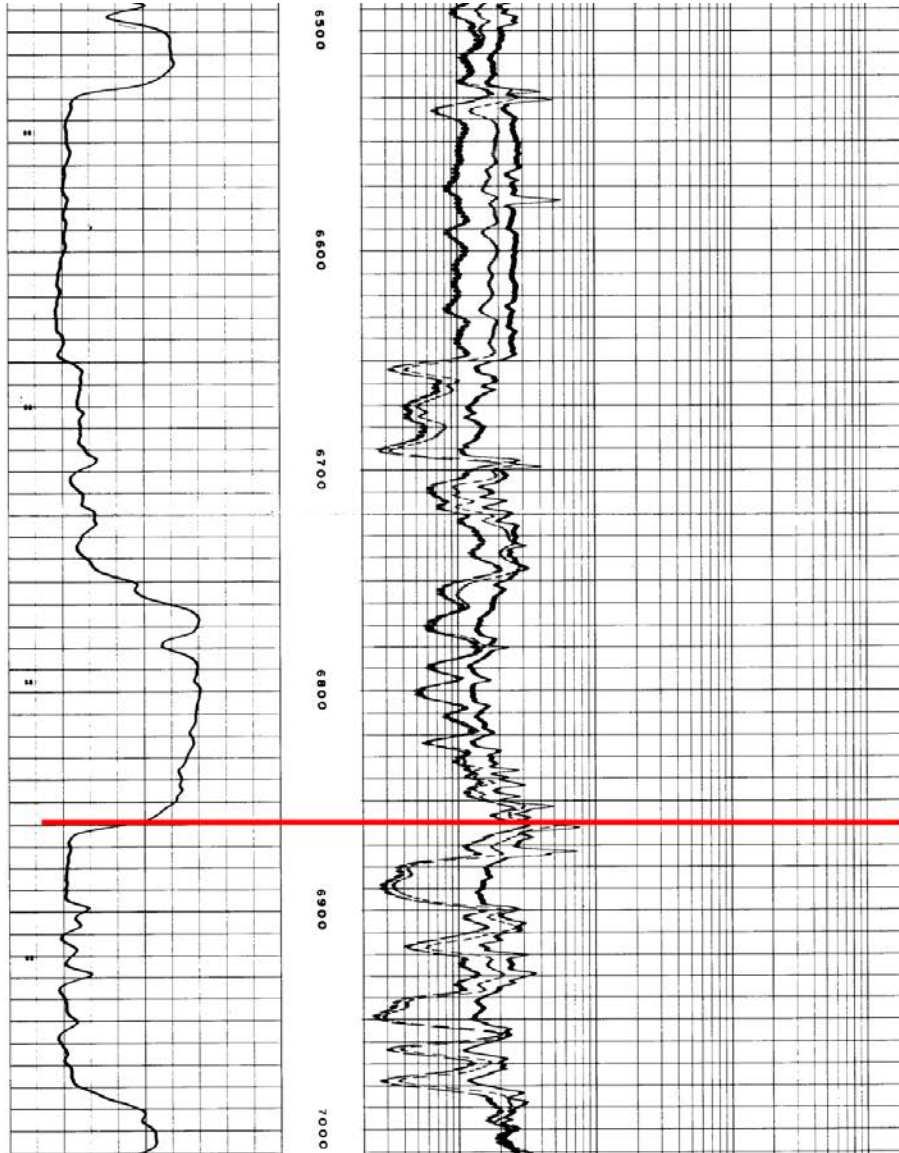
Dresser Atlas <i>Geophysical Services</i> Geophysical Services RECEIVED		FILE NO. F-681 COMPANY BELCO PETROLEUM CORPORATION WELL NO. 1 W. S. WILCOX FIELD WILCOX COUNTY SANTA ROSA STATE FLORIDA LOCATION: 734' FSL & 930' FEL SEC 23 TWP 2 N RGE 28 W DATE DEC 17 1973 APR# 401320670000	
Permanent Datum G. L. Log Measured from K. B. Drilling Measured from K. B.		Elev. 25.4 Fl. Above Permanent Datum 23.5 GL 23.4	
Date 9-18-73 Run No. ONE Depth-Driller 3887 Depth-Logger 3087 Bottom Logged Interval 3085 Top Logged Interval 99 Casing-Driller 16" @ 1135 Casing-Logger 99 Bit Size 15"		11-23-73 P.W.O. 16,967 16,960 16,962 3857 16" @ 1135 3857 9.78 TO 16.437 GEL-CAUCHI-CHEM-GEL	
Density and Viscosity 8.8 40 pH and Fluid Loss 9.0 21.26 Source of Sample TANK Rm @ Meas. Temp. 2.57 @ 97 Rmt @ Meas. Temp. 3.0 @ 97 Rmc @ Meas. Temp. 2.1 @ 97 Source of Rmt and Rmc C Rm @ BHT 2.7 @ 114 Time Since Circ. 6 HRS. Max. Rec. Temp. Deg. F. 114 Equip. No. and Location HI-6006 LRI HI-6008 LAUREL Witnessed By POLAR TENNANT		10.2 50 11.0 11.36 TANK 0.85 @ 75 0.58 @ 75 0.97 @ 75 0.28 @ 266 18 HRS. 266 HI-6006 LRI HI-6008 LAUREL	
REMARKS WITNESSES RUN 1 - BENNETT, OWINGS WITNESSES RUN 2 - BENNETT, MILTON MARCHETT, KENDRICK.			
Equipment Used Run No. ONE TWO S.O. 41532 41726 Tool No. 138 825 Elec. No. 138 825 Panel No. 24387 24187 C.S. 120 100		Scale Changes Type Log Depth Scale Up Hole Scale Down Hole	
Changes in Mud Type or Additional Samples Date Sample No. Depth-Driller Type Fluid in Hole		Equipment Data Run No. Tool Type Pad Type Tool Position Other ONE 1502 P S.O. 1" TWO 1502 P S.O. 2"	
Dens. Visc. pH Fluid Loss cc cc Source of Sample Rm @ Meas. Temp. @ *F @ *F Rmt @ Meas. Temp. @ *F @ *F Rmc @ Meas. Temp. @ *F @ *F Source Rmt, Rmc Rm @ BHT @ *F @ *F Rmt @ BHT @ *F @ *F Rmc @ BHT @ *F @ *F			











Lower Tuscaloosa

Lower Cretaceous

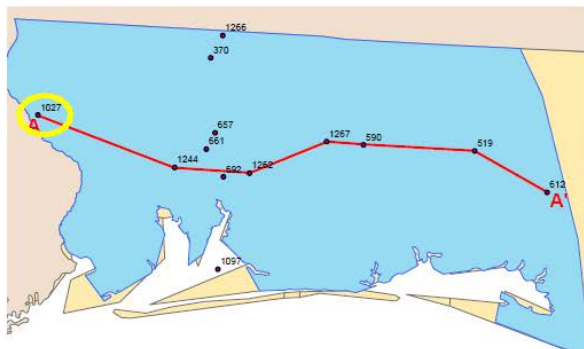
Disposal Area #1

P#1027

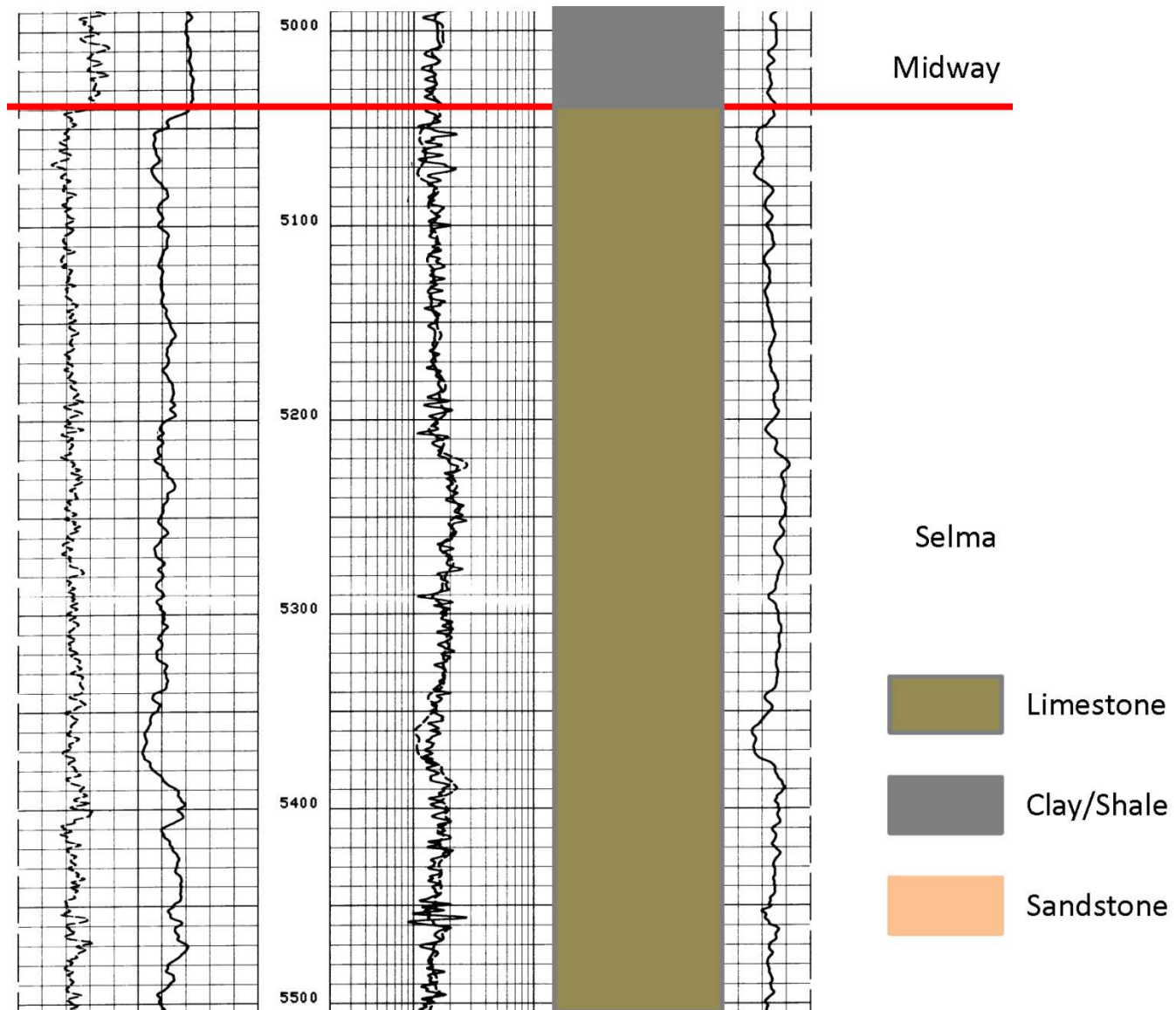
Standard Potential

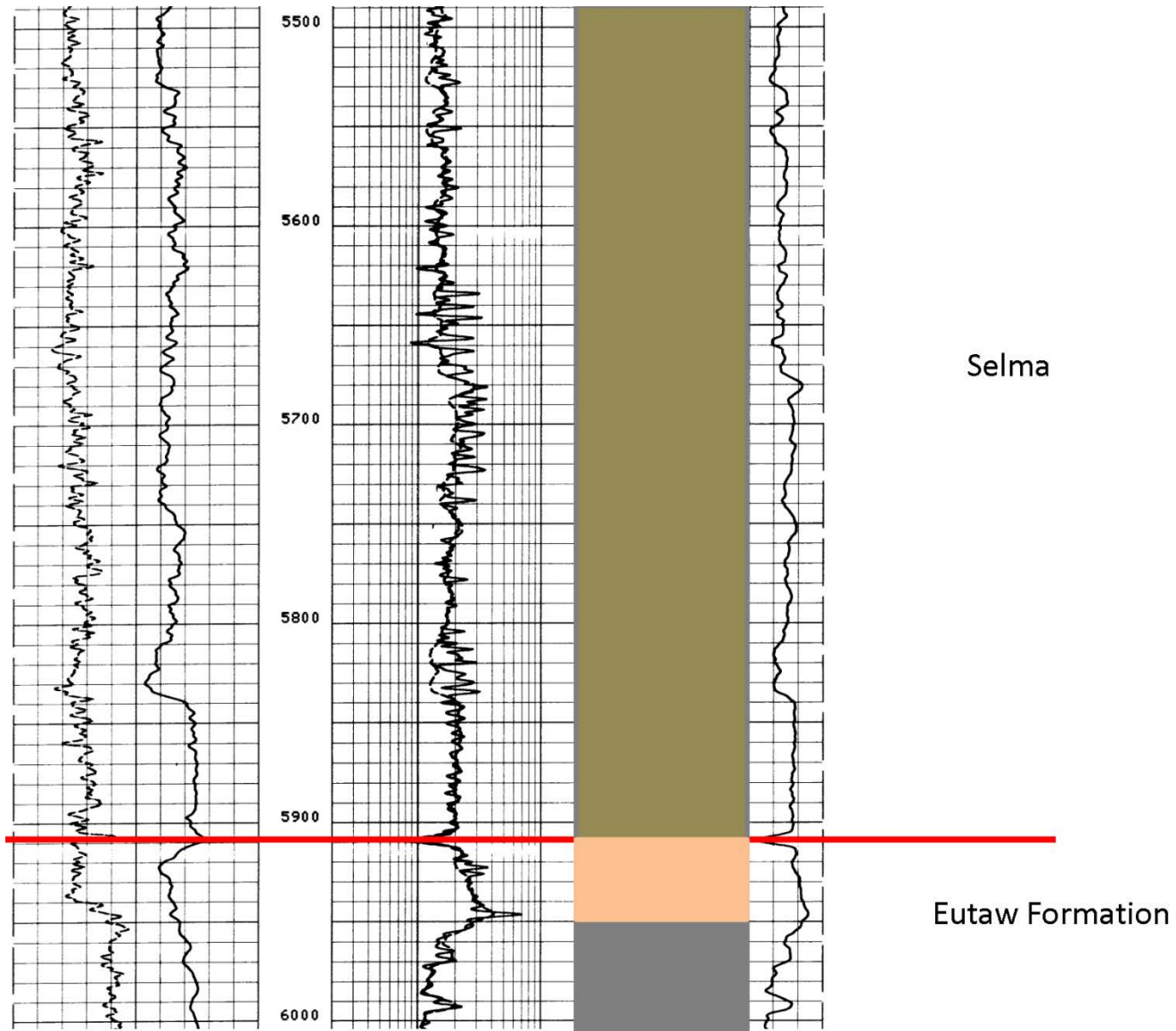
Gamma

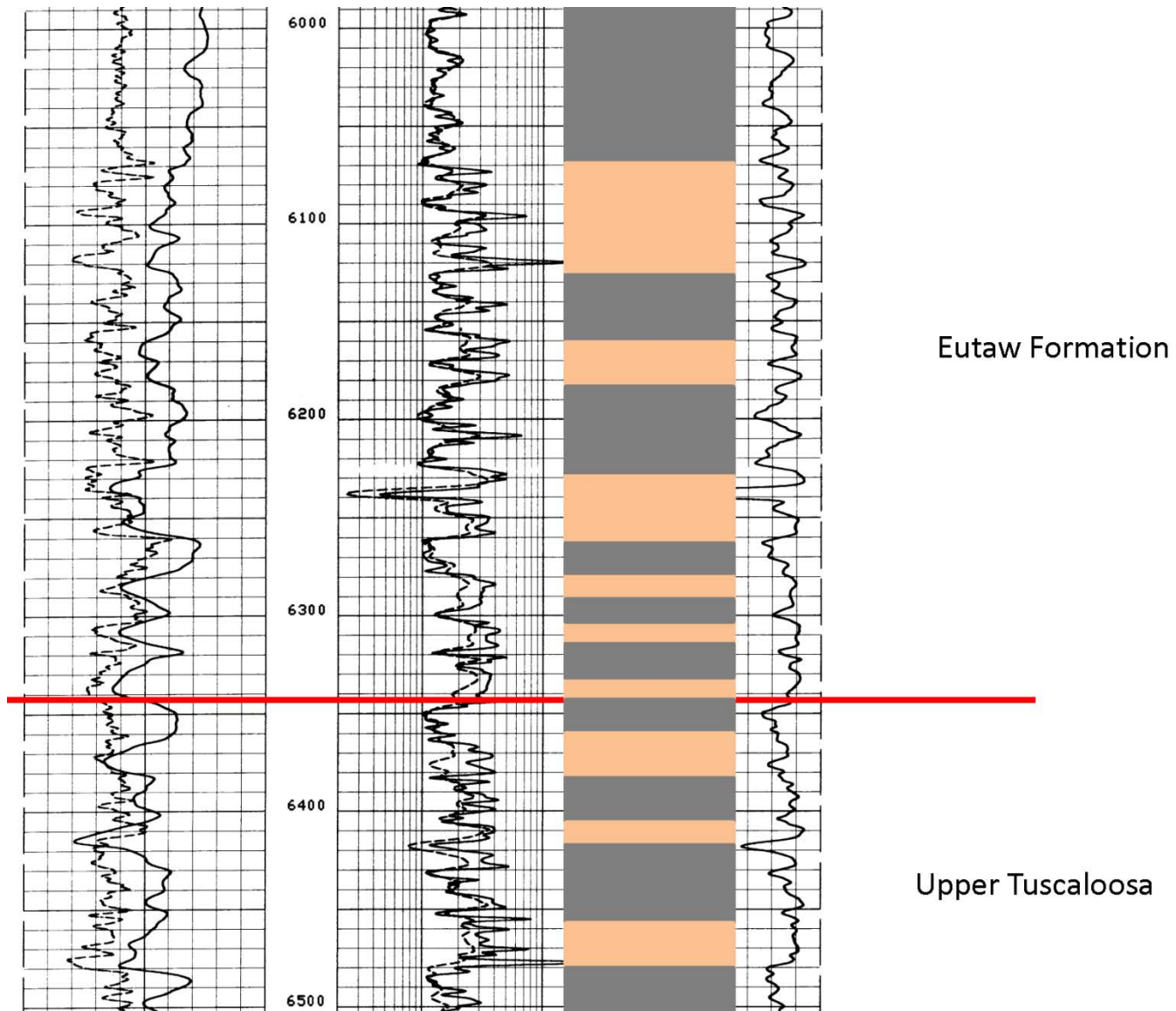
Resistivity

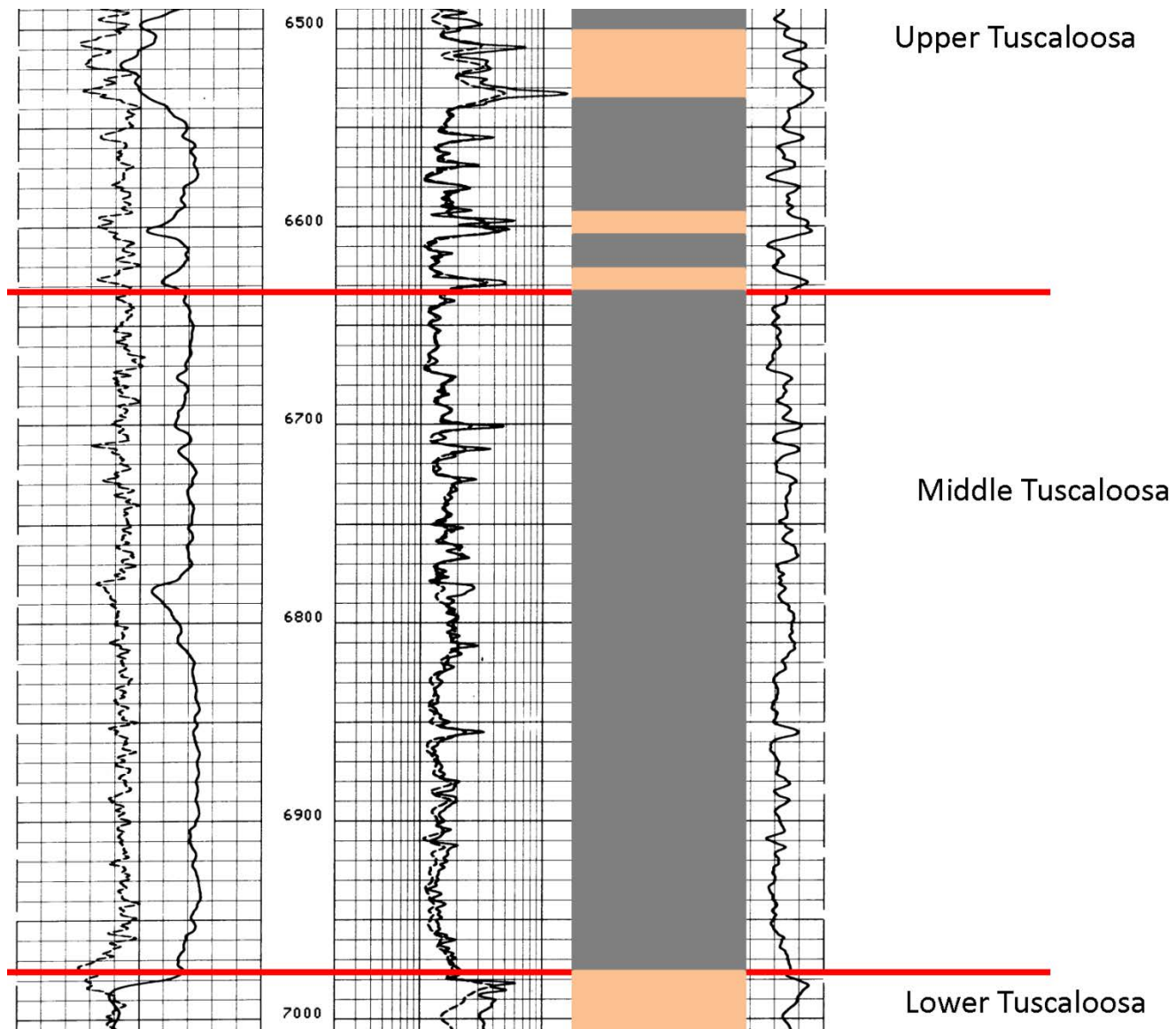


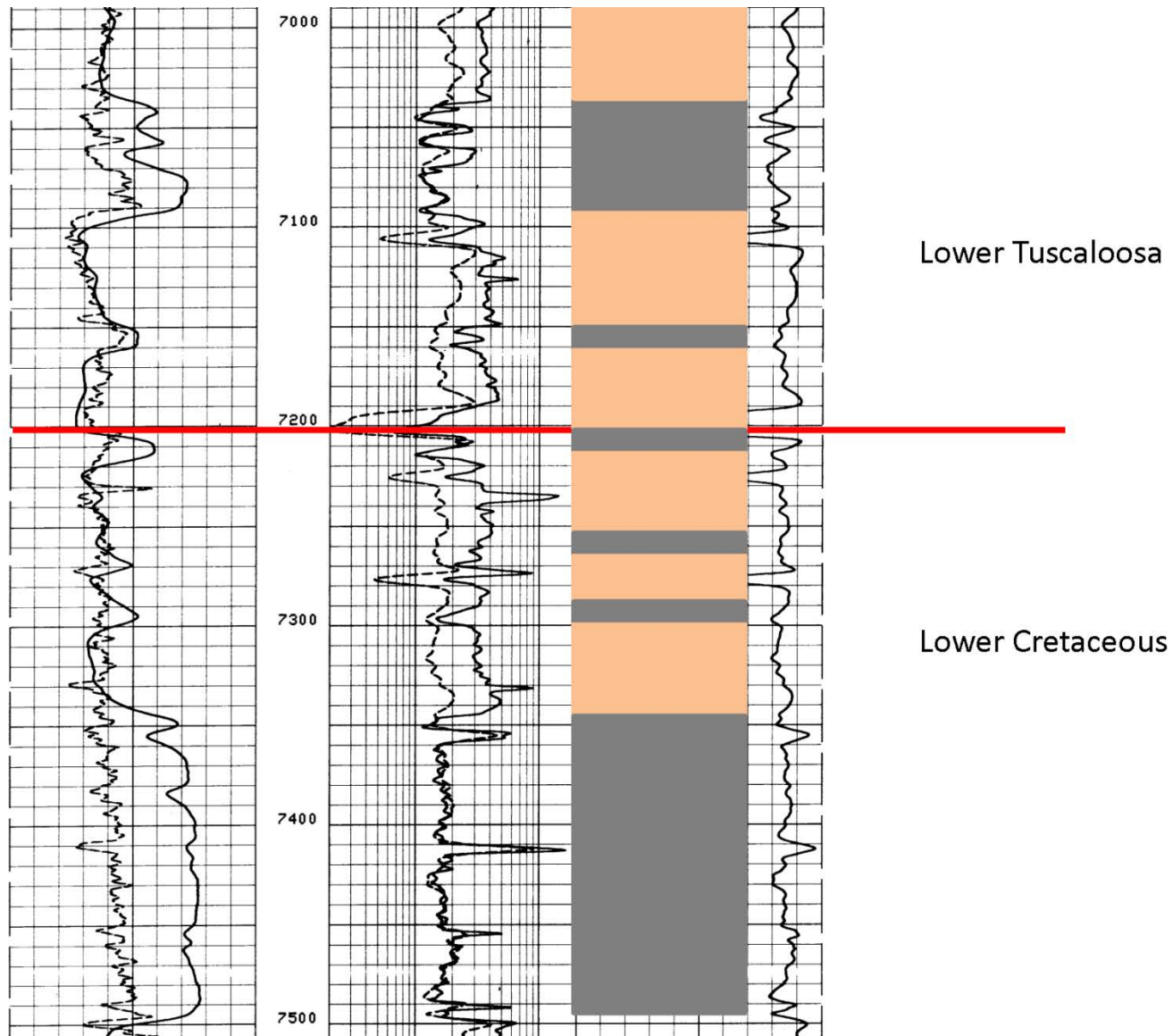
1027 Schlumberger		DUAL INDUCTION-SFL																																																																																																															
COUNTY: ESCAMBIA, FLORIDA FIELD: BAY SPRINGS AREA LOCATION: SEC. 2-3N-38W WELL: #1 LAFORESTIA 2-1																																																																																																																	
COMPANY: CHEVRON U.S.A., INC. WELL: #1 LAFORESTIA 2-1 FIELD: BAY SPRINGS AREA COUNTY: ESCAMBIA STATE: FLORIDA																																																																																																																	
LOCATION: ADI SERIAL NO. 2 REC. 2 TWP. 3N RANGE. 3W		FILE #2458 DATE: 11/14/81 TIME: 12:01 P.M.																																																																																																															
PERMANENT DOWN: GROUND LEVEL LOG MEASURED FROM: RKE DRILLING MEASURED FROM: RKE		Elev. 223 34 ft. Above Perm. Datum Elev. K.B. 257 D.F. 256 G.L. 223																																																																																																															
<table border="1"> <tr> <th>Run No.</th> <th>ONE</th> <th>TWO</th> <th>THREE</th> <th>FOUR</th> </tr> <tr> <td>Depth-Driller</td> <td>600</td> <td>4528</td> <td>16427</td> <td>17950</td> </tr> <tr> <td>Depth-Logger (GAL)</td> <td>607</td> <td>4528</td> <td>16428</td> <td>17946</td> </tr> <tr> <td>Top Log Interval</td> <td>601</td> <td>4522</td> <td>16422</td> <td>17946</td> </tr> <tr> <td>Bottom Log Interval</td> <td>301</td> <td>201</td> <td>13780</td> <td>16402</td> </tr> <tr> <td>Core-Driller</td> <td>301</td> <td>201</td> <td>13780</td> <td>16402</td> </tr> <tr> <td>Core-Logger</td> <td>301</td> <td>201</td> <td>13780</td> <td>16402</td> </tr> <tr> <td>Bit Size</td> <td>12"</td> <td>12"</td> <td>12"</td> <td>12"</td> </tr> <tr> <td>Type Fluid in Hole</td> <td>GEI</td> <td>GEI</td> <td>GEI</td> <td>GEI</td> </tr> <tr> <td>Dens. Visc.</td> <td>8.31</td> <td>9.1</td> <td>9.2</td> <td>14.1</td> </tr> <tr> <td>Fluid Loss</td> <td>10.5</td> <td>18</td> <td>24</td> <td>10.5</td> </tr> <tr> <td>Source of Sample</td> <td>GEI</td> <td>CLRC</td> <td>CLRC</td> <td>CLRC</td> </tr> <tr> <td>Run @ Meas. Temp.</td> <td>1.22</td> <td>1.22</td> <td>1.22</td> <td>1.22</td> </tr> <tr> <td>Run @ Meas. Temp.</td> <td>1.22</td> <td>1.22</td> <td>1.22</td> <td>1.22</td> </tr> <tr> <td>Time @ Meas. Temp.</td> <td>1.36</td> <td>1.36</td> <td>1.36</td> <td>1.36</td> </tr> <tr> <td>Source Ref. Rnc</td> <td>M</td> <td>M</td> <td>M</td> <td>M</td> </tr> <tr> <td>Rm @ BHT</td> <td>11.30</td> <td>11.30</td> <td>11.30</td> <td>11.30</td> </tr> <tr> <td>Circulation Stopper</td> <td>11.30</td> <td>11.30</td> <td>11.30</td> <td>11.30</td> </tr> <tr> <td>Max Rec. Temp.</td> <td>1500</td> <td>1500</td> <td>1500</td> <td>1500</td> </tr> <tr> <td>Equip. Location</td> <td>8012</td> <td>8012</td> <td>8012</td> <td>8012</td> </tr> <tr> <td>Received By</td> <td>ENTRE</td> <td>ENTRE</td> <td>ENTRE</td> <td>ENTRE</td> </tr> <tr> <td>Witnessed By</td> <td>ENTRE</td> <td>ENTRE</td> <td>ENTRE</td> <td>ENTRE</td> </tr> </table>				Run No.	ONE	TWO	THREE	FOUR	Depth-Driller	600	4528	16427	17950	Depth-Logger (GAL)	607	4528	16428	17946	Top Log Interval	601	4522	16422	17946	Bottom Log Interval	301	201	13780	16402	Core-Driller	301	201	13780	16402	Core-Logger	301	201	13780	16402	Bit Size	12"	12"	12"	12"	Type Fluid in Hole	GEI	GEI	GEI	GEI	Dens. Visc.	8.31	9.1	9.2	14.1	Fluid Loss	10.5	18	24	10.5	Source of Sample	GEI	CLRC	CLRC	CLRC	Run @ Meas. Temp.	1.22	1.22	1.22	1.22	Run @ Meas. Temp.	1.22	1.22	1.22	1.22	Time @ Meas. Temp.	1.36	1.36	1.36	1.36	Source Ref. Rnc	M	M	M	M	Rm @ BHT	11.30	11.30	11.30	11.30	Circulation Stopper	11.30	11.30	11.30	11.30	Max Rec. Temp.	1500	1500	1500	1500	Equip. Location	8012	8012	8012	8012	Received By	ENTRE	ENTRE	ENTRE	ENTRE	Witnessed By	ENTRE	ENTRE	ENTRE	ENTRE
Run No.	ONE	TWO	THREE	FOUR																																																																																																													
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Witnessed By	ENTRE	ENTRE	ENTRE	ENTRE																																																																																																													
FOLD HERE The well name, location and borehole reference data were furnished by the customer.																																																																																																																	
Run No. ONE TWO THREE FOUR Service Order No. 202726 202801 202748 157118 Fluid Level FULL FULL FULL FULL Speed F.P.M. 200 60 30 30 Salinity ppm. cl 400 1700 2600 2500		SCALE CHANGES Type Log DEPTH Scale Up Hole Scale Down Hole Type Log DEPTH Scale Up Hole Scale Down Hole																																																																																																															
EQUIPMENT DATA Panel 35 21 58 31 Cartridge 574 135 175 131 Sonde 589 143 595 143 Memorizer Panel CSU CSU CSU CSU Centralizer Type CSU FIN FIN FIN Stand-off - Inches 1 1 1 1 G.R. Panel - 27 83 27 G.R. Cart. 2617		REMARKS RUN #3 SONIC PANEL - 352 SONIC CART. - 1221 SONIC SONDE - 1392 RUN #4 SONIC PANEL - 348 SONIC CART. - 363 SONIC SONDE - 69																																																																																																															
CALIBRATION DATA SBR SEE SEF SEE SLL ILM Sonde Error CALIB. CALIB. CALIB. CALIB. ILM Sonde Error SUMMARY SUMMARY SUMMARY SUMMARY S.E. Set In Hole - Depth S.E. Corr. - Hole Size G.R. Background G.R. Source T.C. - Cal.		LOGGING DATA SBR SEE SEF SEE SLL ILM Sonde Error Log CALIB. CALIB. CALIB. CALIB. ILM Sonde Error Log SUMMARY SUMMARY SUMMARY SUMMARY G.R. Scale per 100 Div. G.R. - T.C. Log																																																																																																															



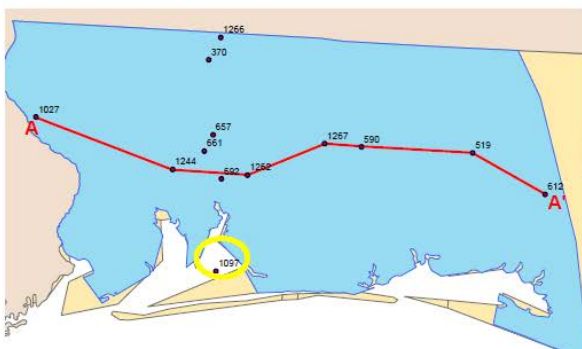




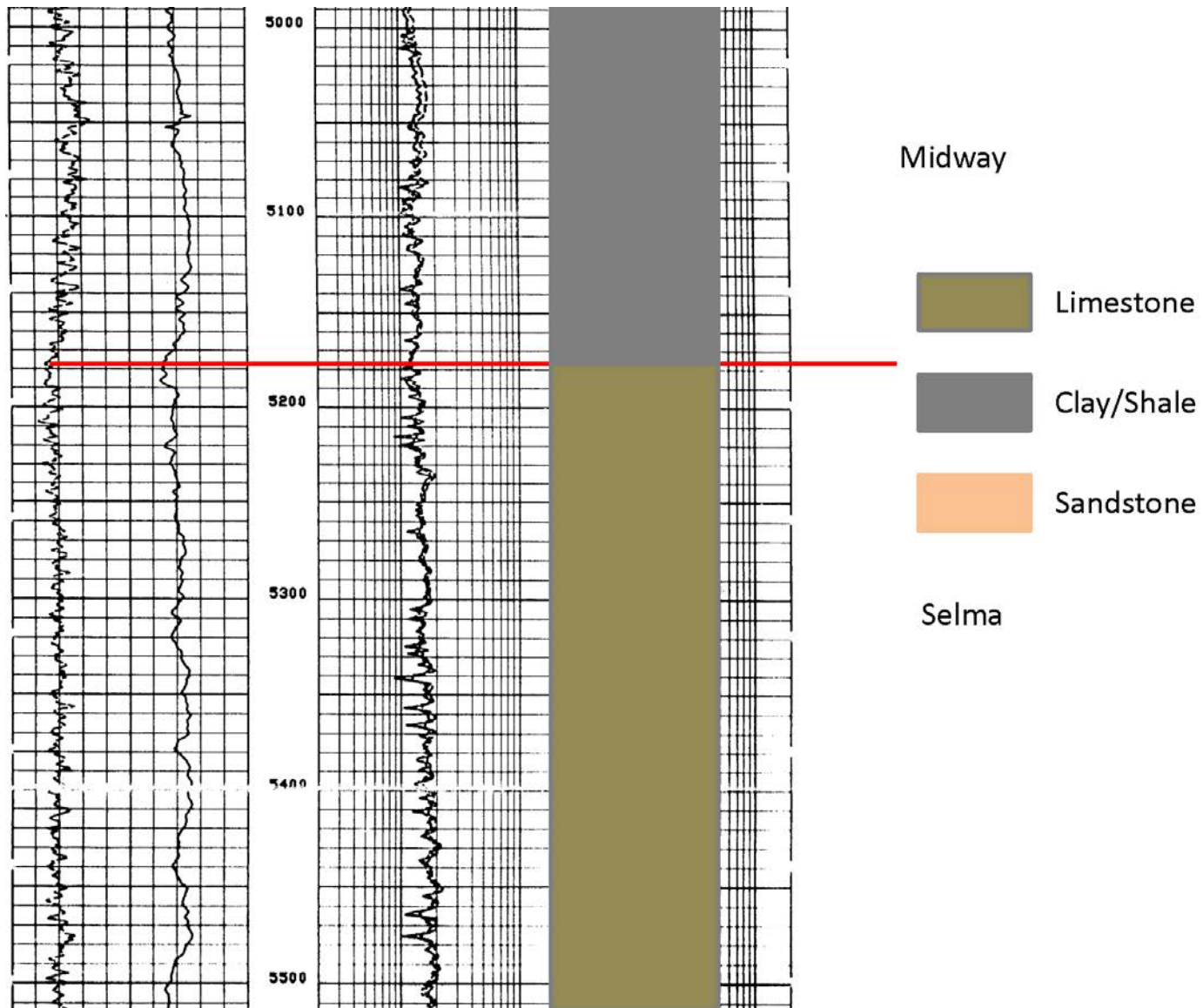


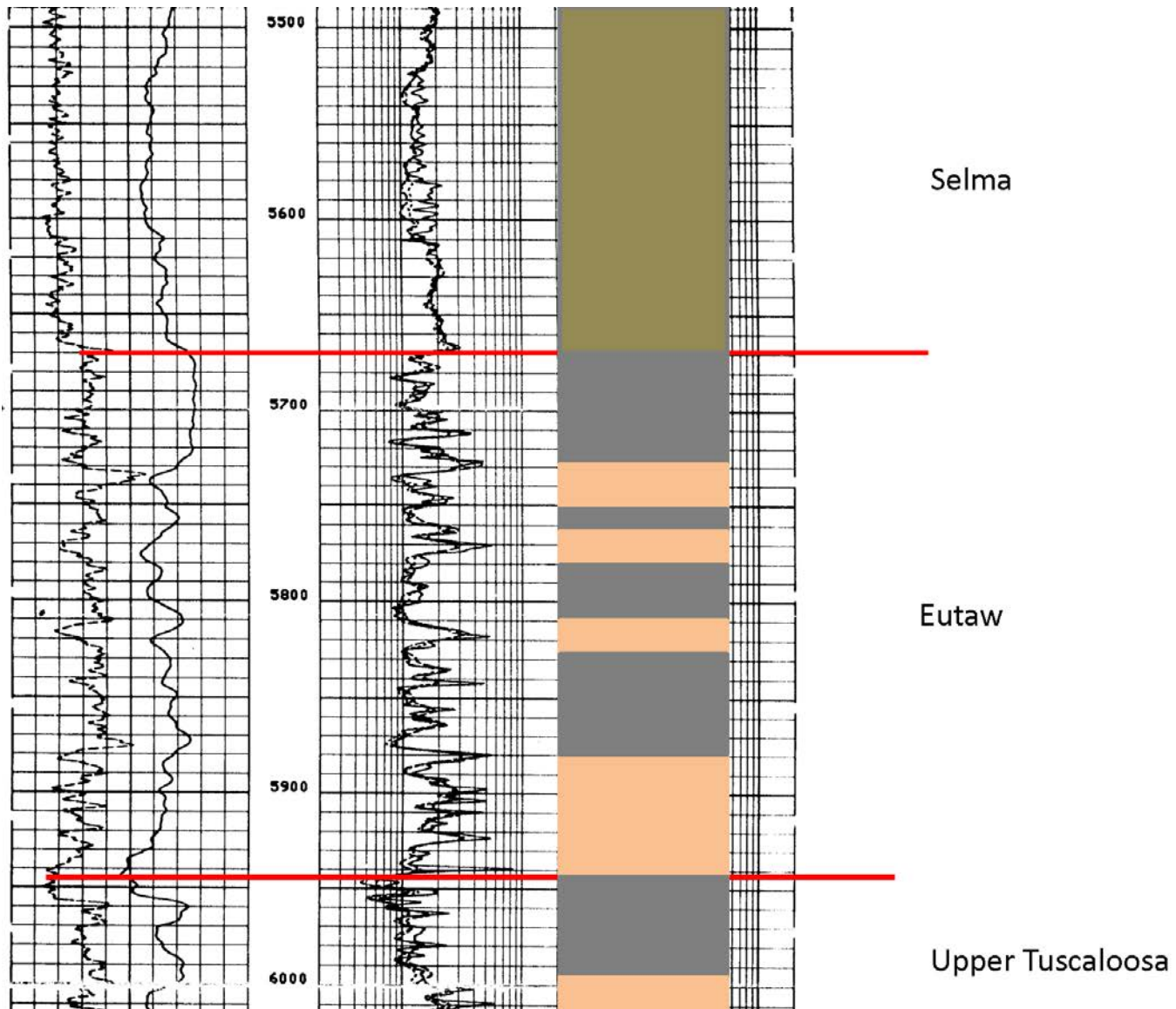


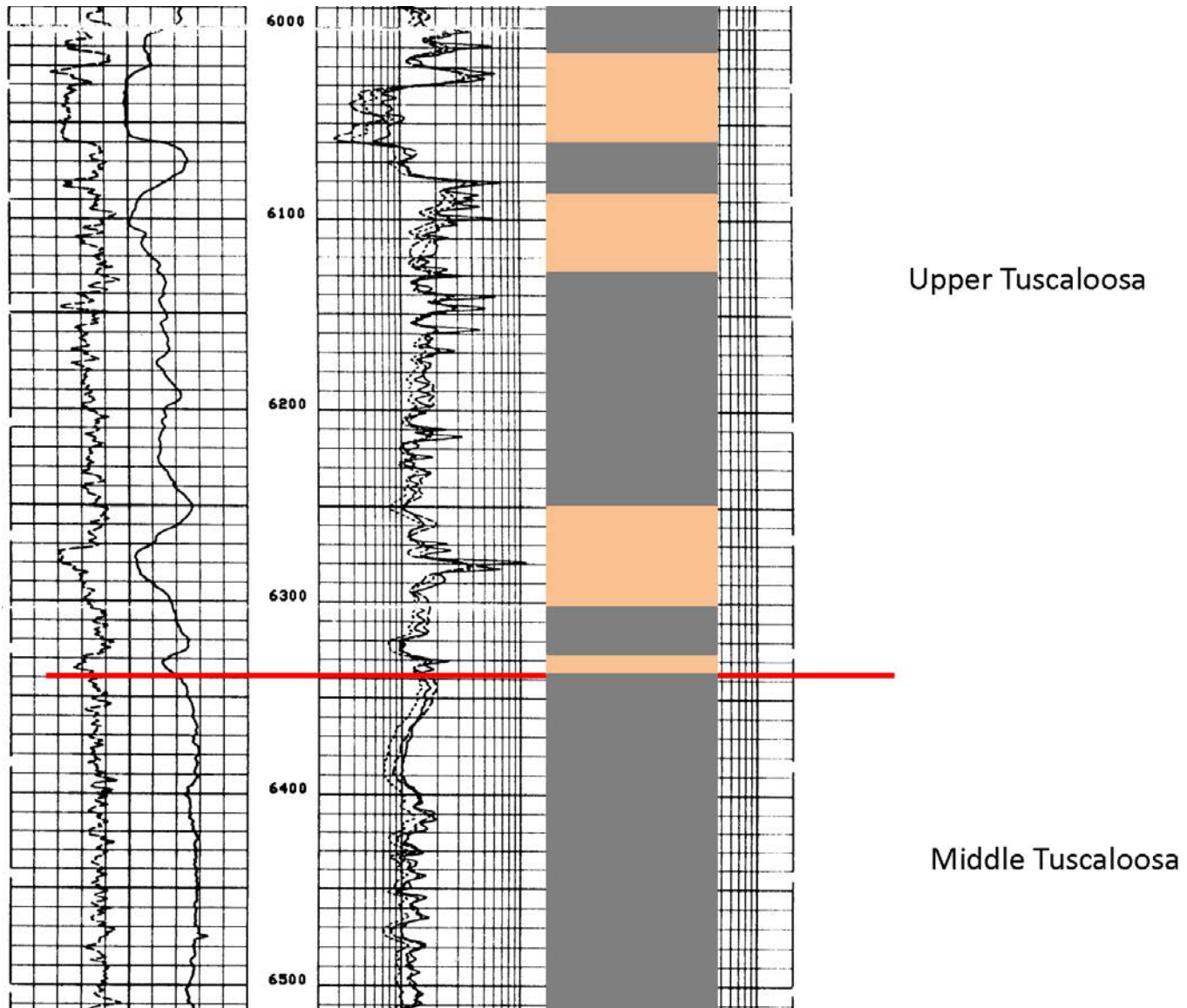
Disposal Area #1 P#1097 Standard Potential Gamma Resistivity

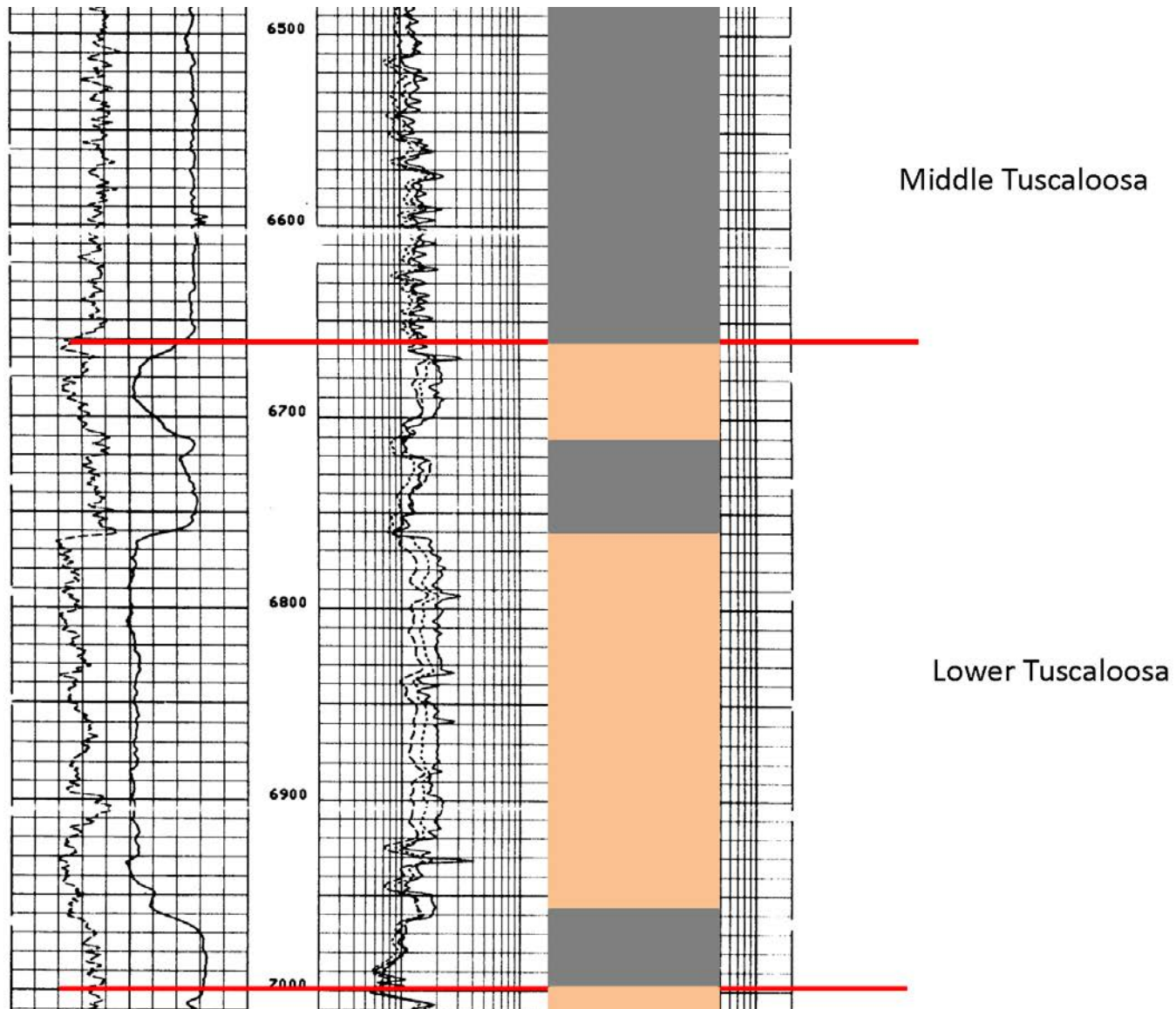


WELL LOG Schlumberger		PRODUCTION SET SHEET	
COMPANY: GETTY OIL COMPANY WELL: #1 STATE LEASE 2338 FIELD: MCLEIST BAY PROSPECT COUNTY: SANTA ROSA STATE FLORIDA LOCATION: 1-25-28W WELL: #1 STATE LEASE 2338 COMPANY: GETTY OIL COMPANY		2" log 7D	
Date: 6/06/83 Run No: 2010 Depth-Driller: 2010 Depth-Logger: 2004 Top Log Interval: 30' @ 327' - 20' @ 2007 Coring-Driller: 322 Coring-Logger: 322 Bit Size: 8 1/2" Type Fluid in Hole: 15% Den. Visc: 9.4 12.0 pH: 9.4 12.0 Fluid Loss: 2.59 @ 95' 10.88 @ 88' 0.38 @ 84' 0.32 @ 80' 0.32 @ 76' 0.32 @ 72' 0.32 @ 68' 0.32 @ 64' 0.32 @ 60' 0.32 @ 56' 0.32 @ 52' 0.32 @ 48' 0.32 @ 44' 0.32 @ 40' 0.32 @ 36' 0.32 @ 32' 0.32 @ 28' 0.32 @ 24' 0.32 @ 20' 0.32 @ 16' 0.32 @ 12' 0.32 @ 8' 0.32 @ 4' 0.32 @ 0' 0.32 @ Source of Sample: 2.44 @ 31' F 10.62 @ 230' F Recorder on Bottom: 0.32 Recorder on Surface: 0.32 Recorder on Location: 0.32 Recorder on Time: 0.32 Recorder on Temperature: 0.32 Recorder on Pressure: 0.32 Recorder on Humidity: 0.32 Recorder on Wind: 0.32 Recorder on Rain: 0.32 Recorder on Clouds: 0.32 Recorder on Visibility: 0.32 Recorder on Air Quality: 0.32 Recorder on Water Quality: 0.32 Recorder on Soil Quality: 0.32 Recorder on Vegetation: 0.32 Recorder on Wildlife: 0.32 Recorder on Human Activity: 0.32 Recorder on Other: 0.32		Date: 10/08/83 Run No: 17011 Depth-Driller: 17011 Depth-Logger: 17006 Top Log Interval: 15000 Coring-Driller: 15000 Coring-Logger: 15000 Bit Size: 8 1/2" Type Fluid in Hole: 15% Den. Visc: 9.4 12.0 pH: 9.4 12.0 Fluid Loss: 2.59 @ 95' 10.88 @ 88' 0.38 @ 84' 0.32 @ 80' 0.32 @ 76' 0.32 @ 72' 0.32 @ 68' 0.32 @ 64' 0.32 @ 60' 0.32 @ 56' 0.32 @ 52' 0.32 @ 48' 0.32 @ 44' 0.32 @ 40' 0.32 @ 36' 0.32 @ 32' 0.32 @ 28' 0.32 @ 24' 0.32 @ 20' 0.32 @ 16' 0.32 @ 12' 0.32 @ 8' 0.32 @ 4' 0.32 @ 0' 0.32 @ Source of Sample: 2.44 @ 31' F 10.62 @ 230' F Recorder on Bottom: 0.32 Recorder on Surface: 0.32 Recorder on Location: 0.32 Recorder on Time: 0.32 Recorder on Temperature: 0.32 Recorder on Pressure: 0.32 Recorder on Humidity: 0.32 Recorder on Wind: 0.32 Recorder on Rain: 0.32 Recorder on Clouds: 0.32 Recorder on Visibility: 0.32 Recorder on Air Quality: 0.32 Recorder on Water Quality: 0.32 Recorder on Soil Quality: 0.32 Recorder on Vegetation: 0.32 Recorder on Wildlife: 0.32 Recorder on Human Activity: 0.32 Recorder on Other: 0.32	



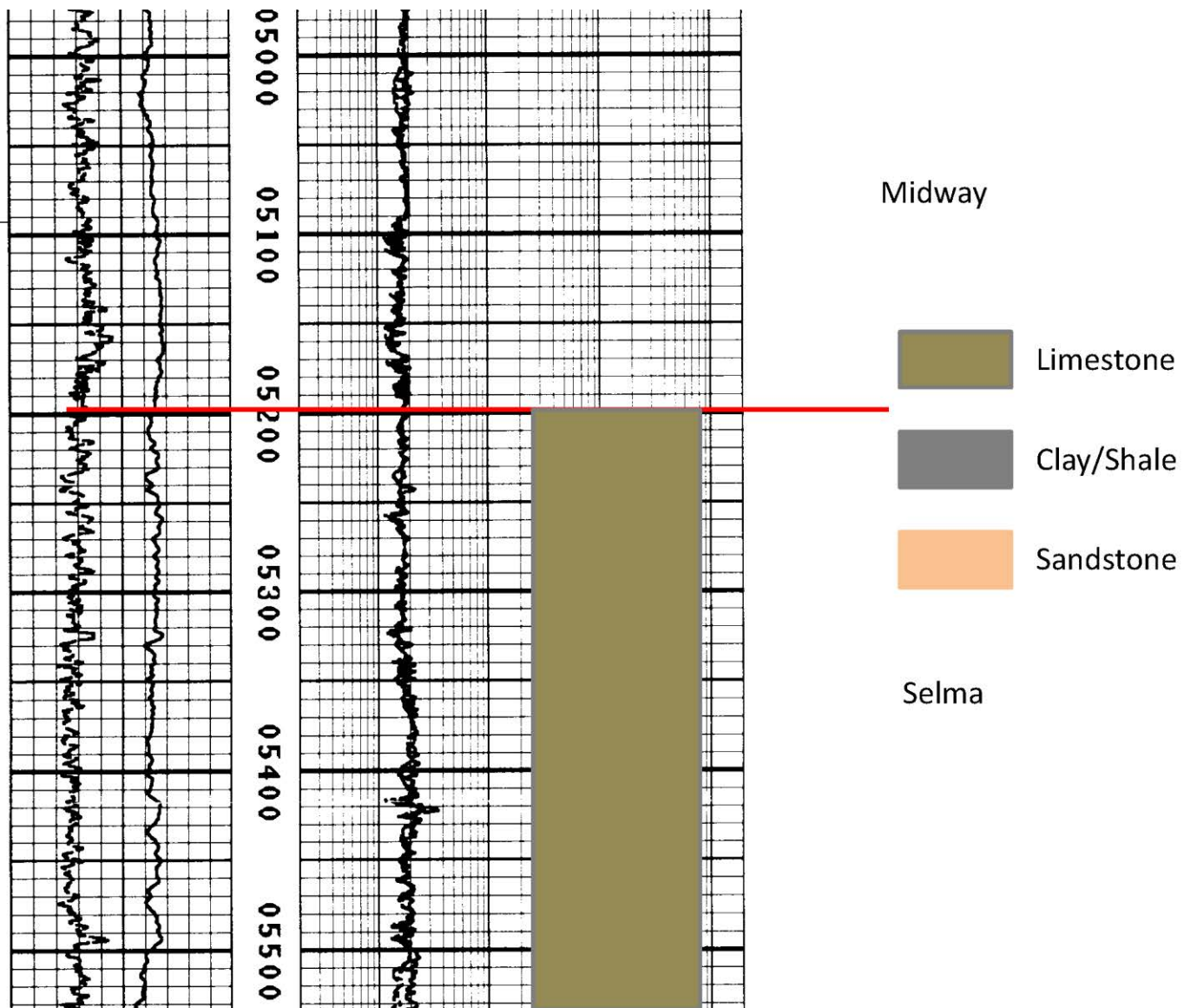


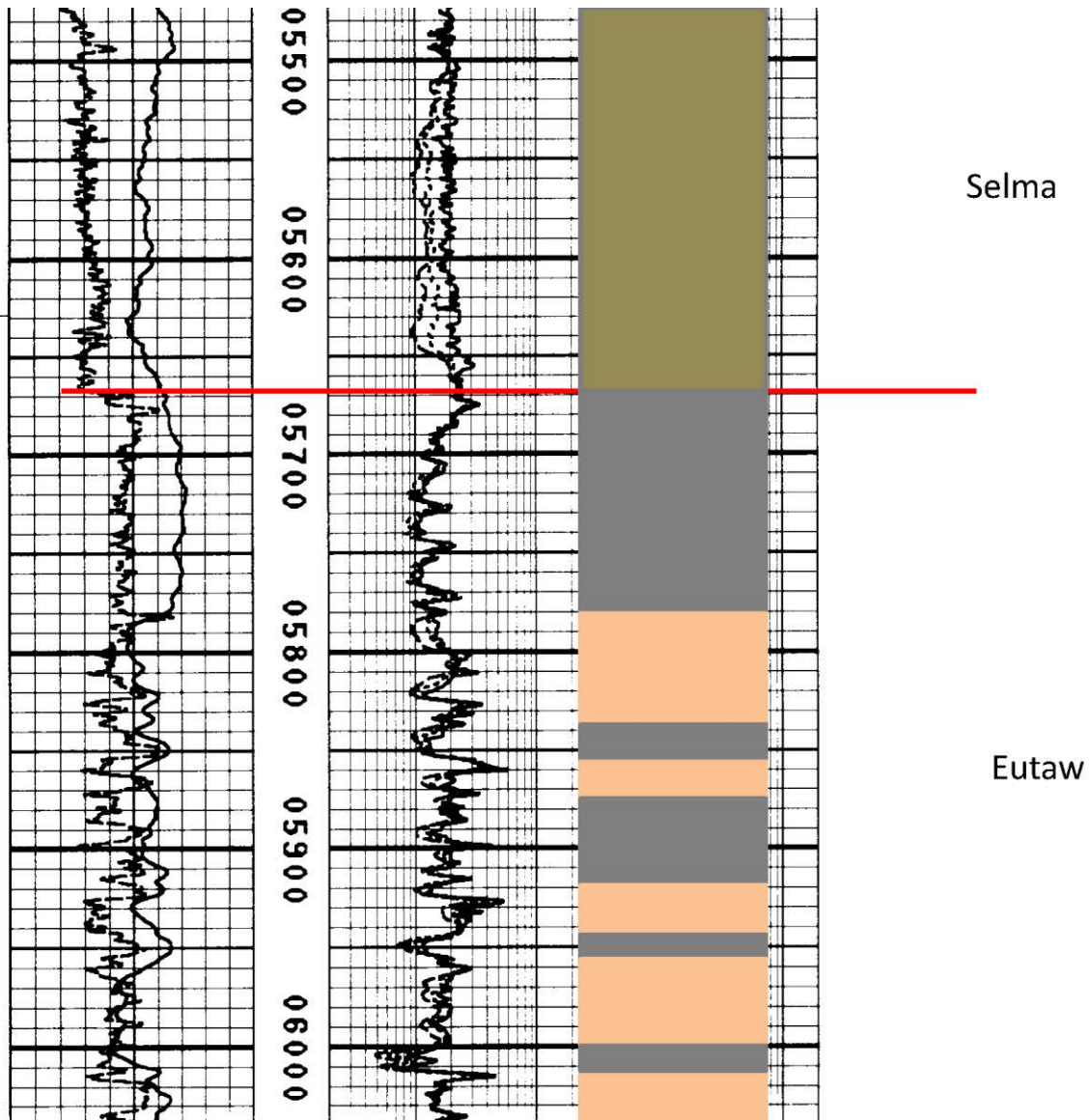


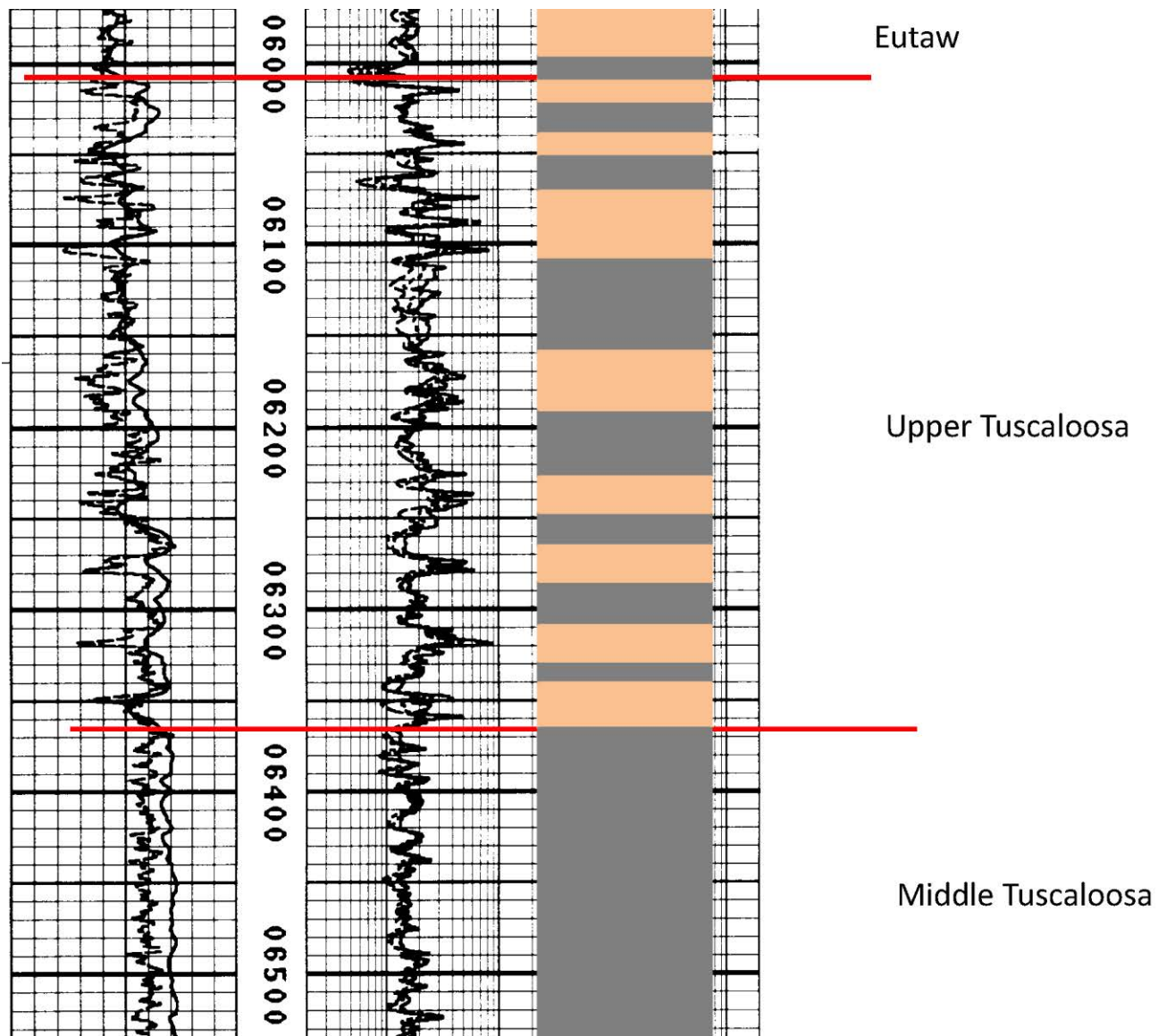


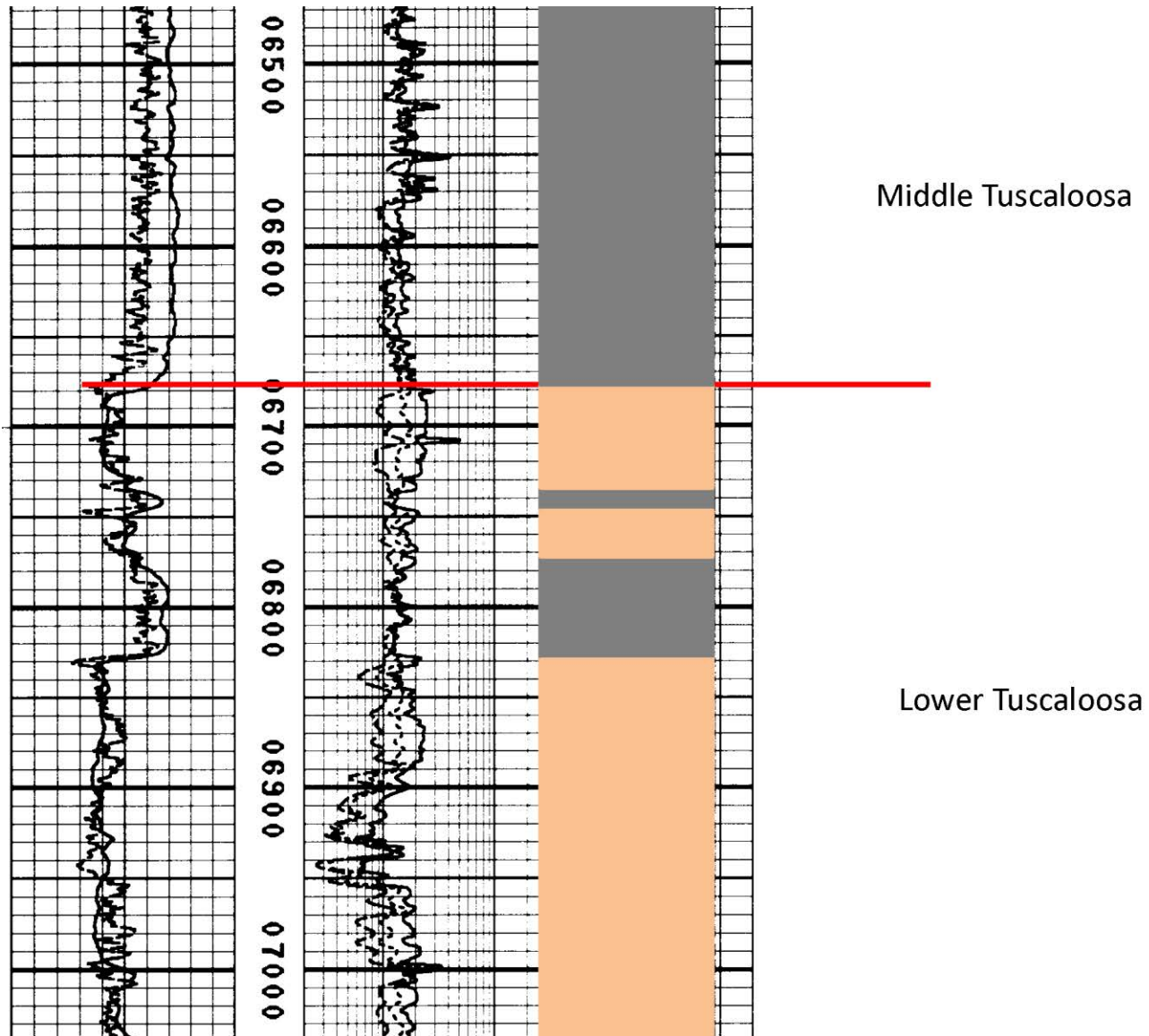
A map of the North Sea region showing a red line connecting several points. The points are labeled with numbers: 1027, 1244, 1267, 590, 519, and 512. Point 1244 is circled in yellow. The line starts at point A on the left, goes to 1027, then to 1244, then to 1267, then to 590, then to 519, and finally to 512. Other points shown on the map include 1266, 370, 657, 651, 682, 1258, 1097, and 1268. The map shows the coastline of the North Sea, with land in yellow and water in blue.

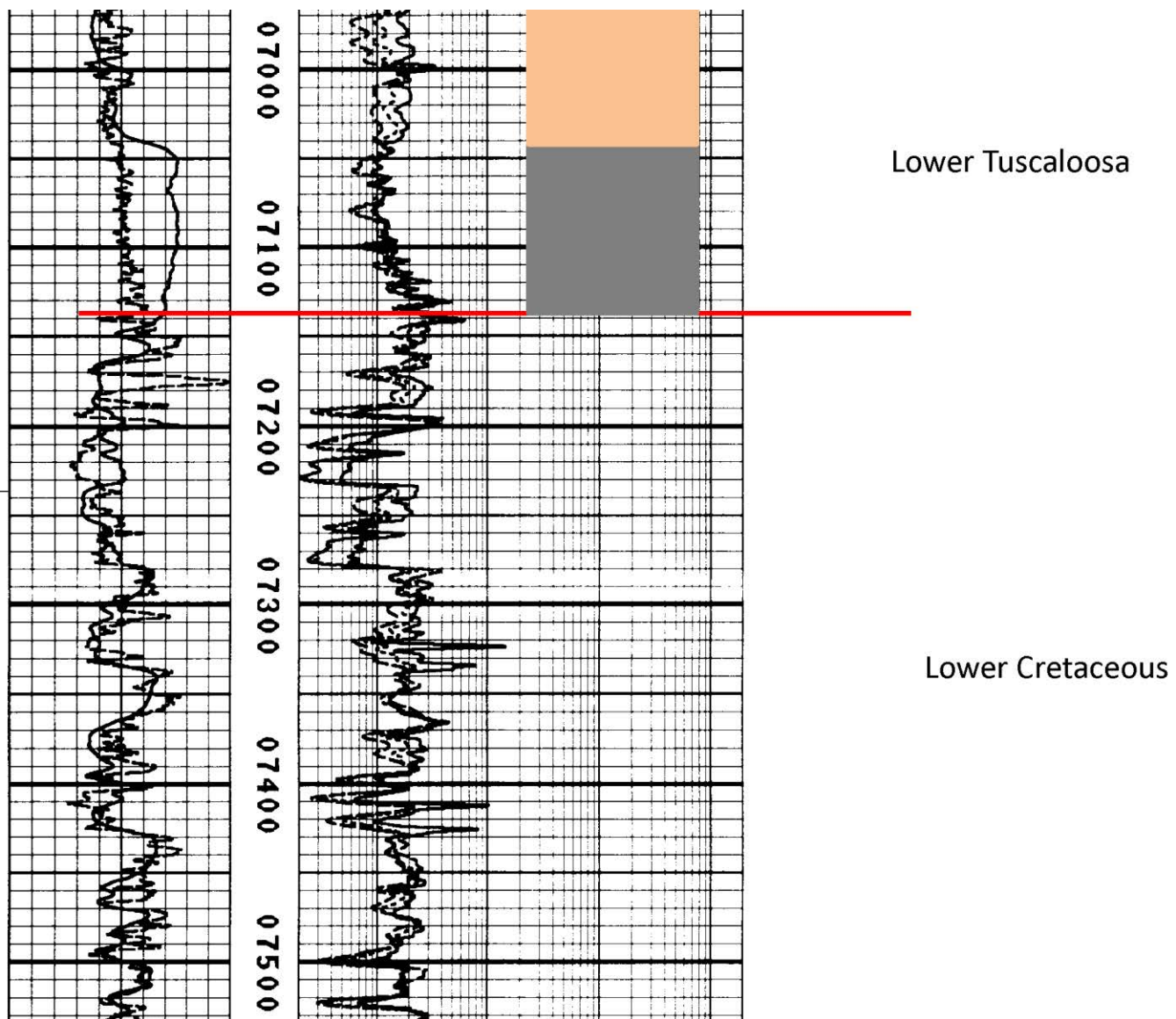
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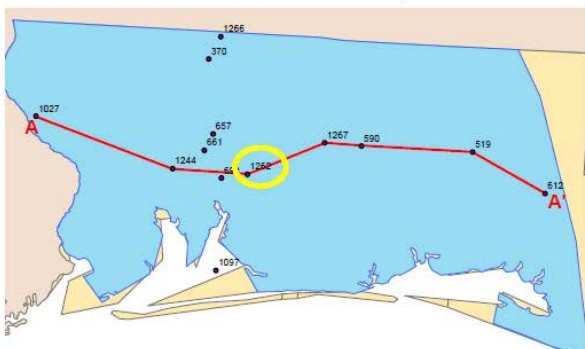




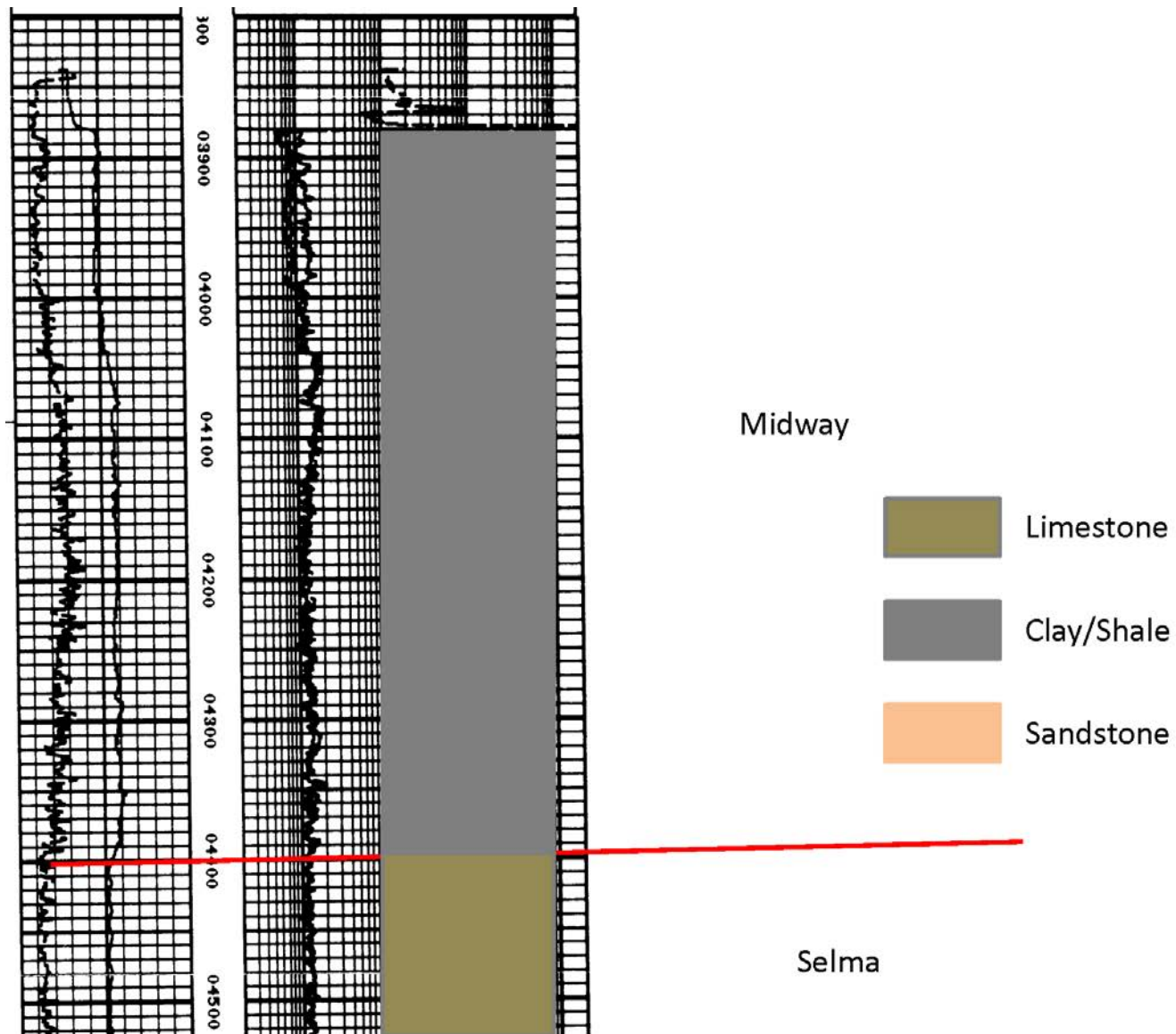


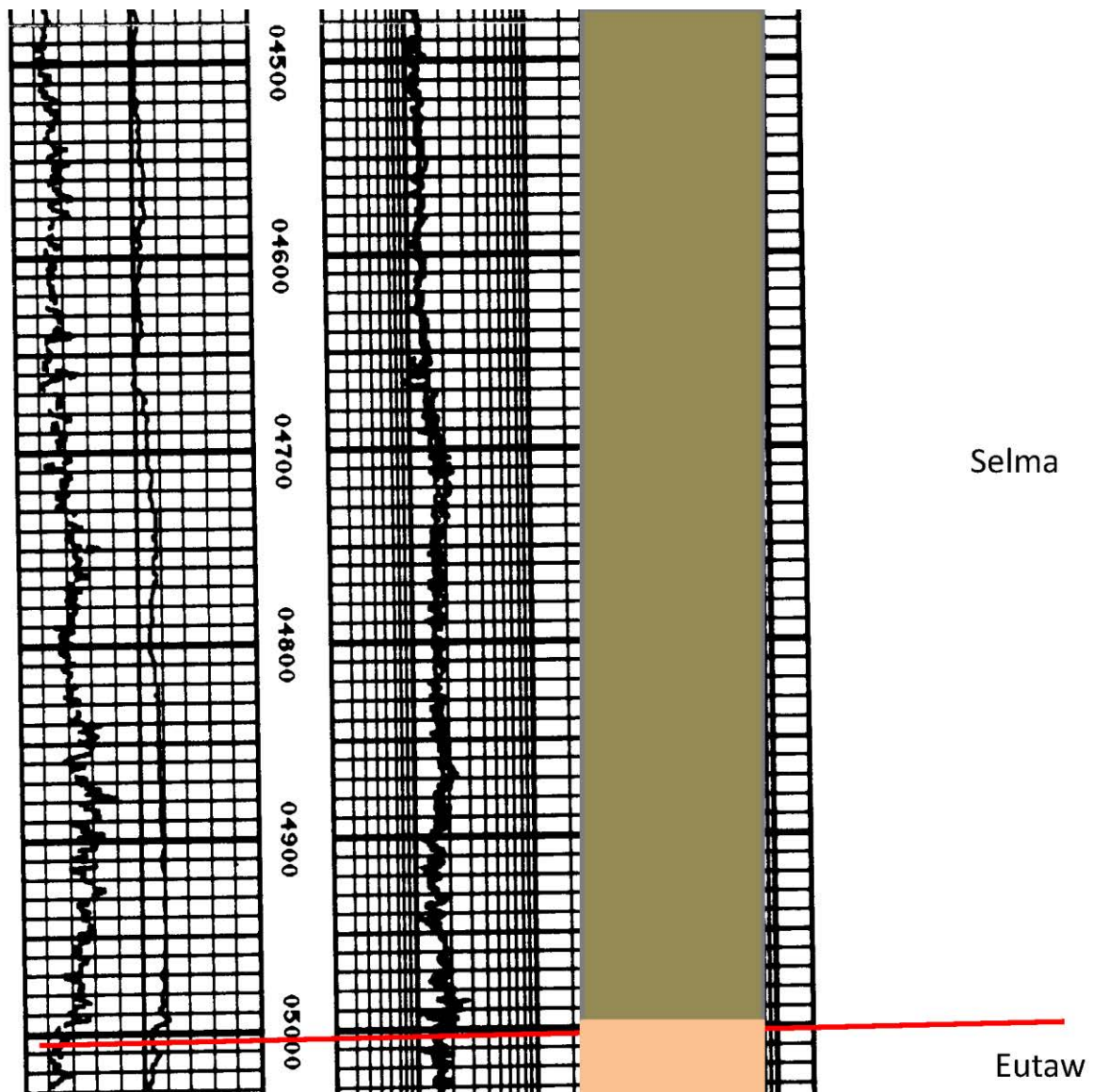


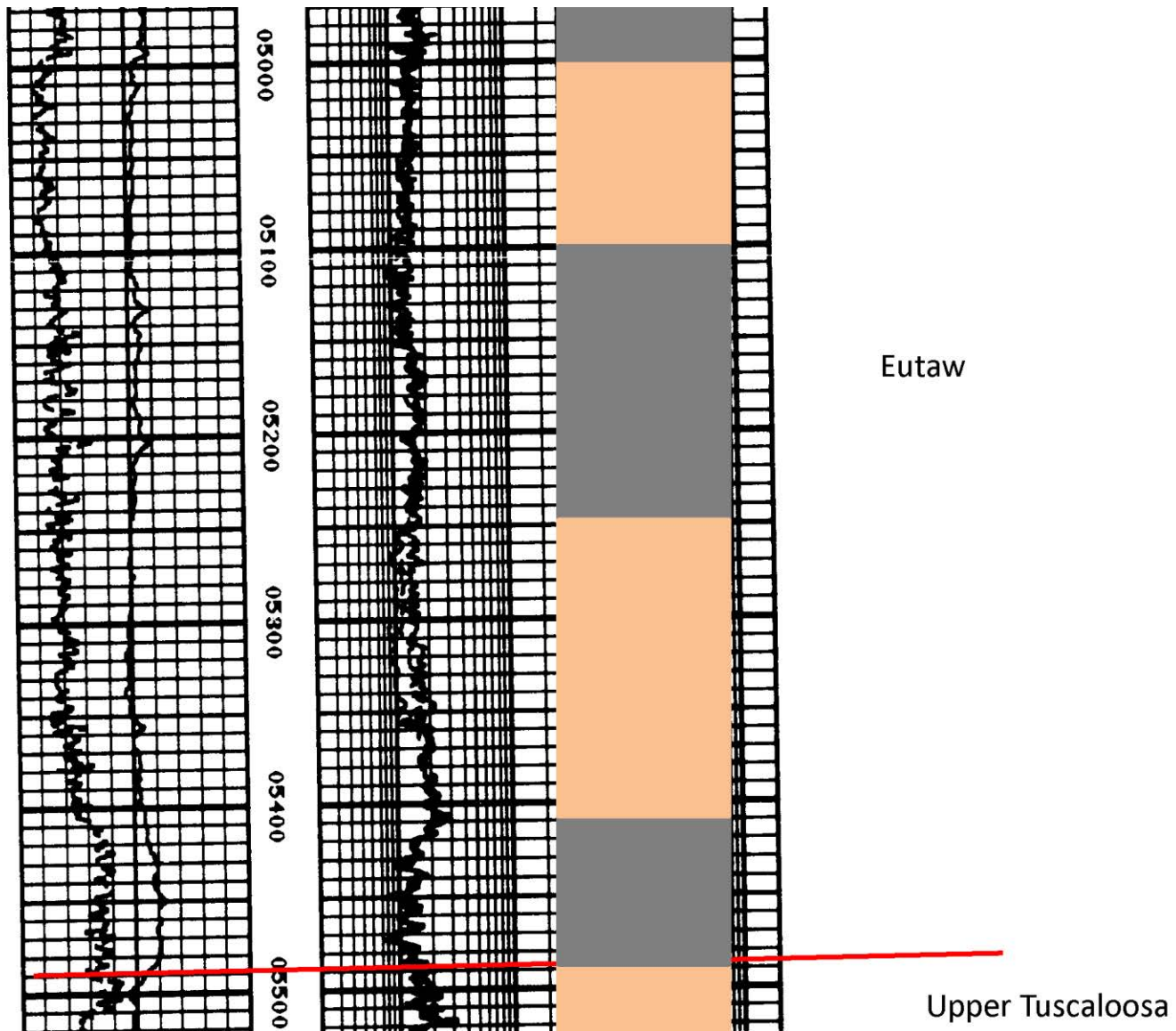
Disposal Area #1 P#1262 Gamma Standard Potential Resistivity

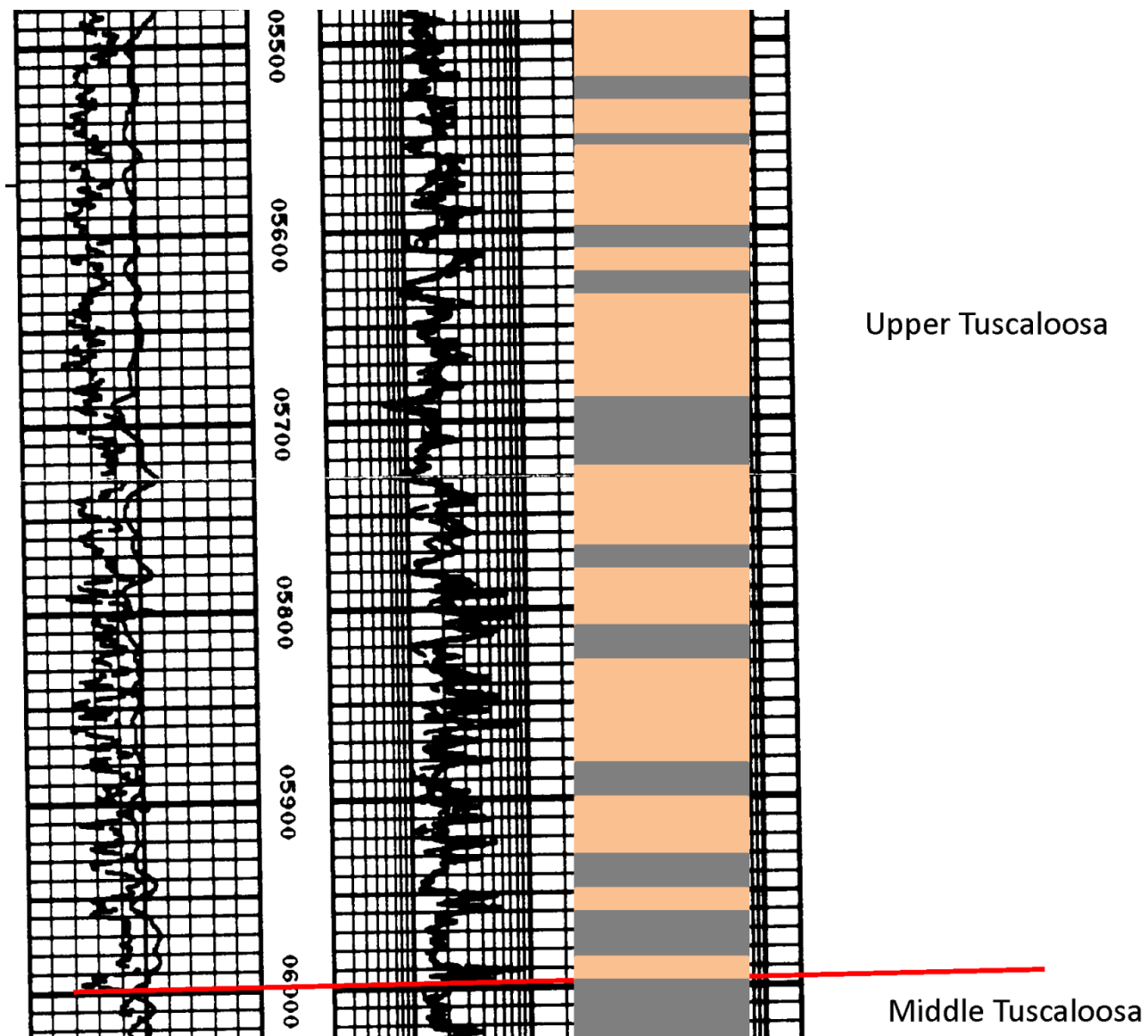


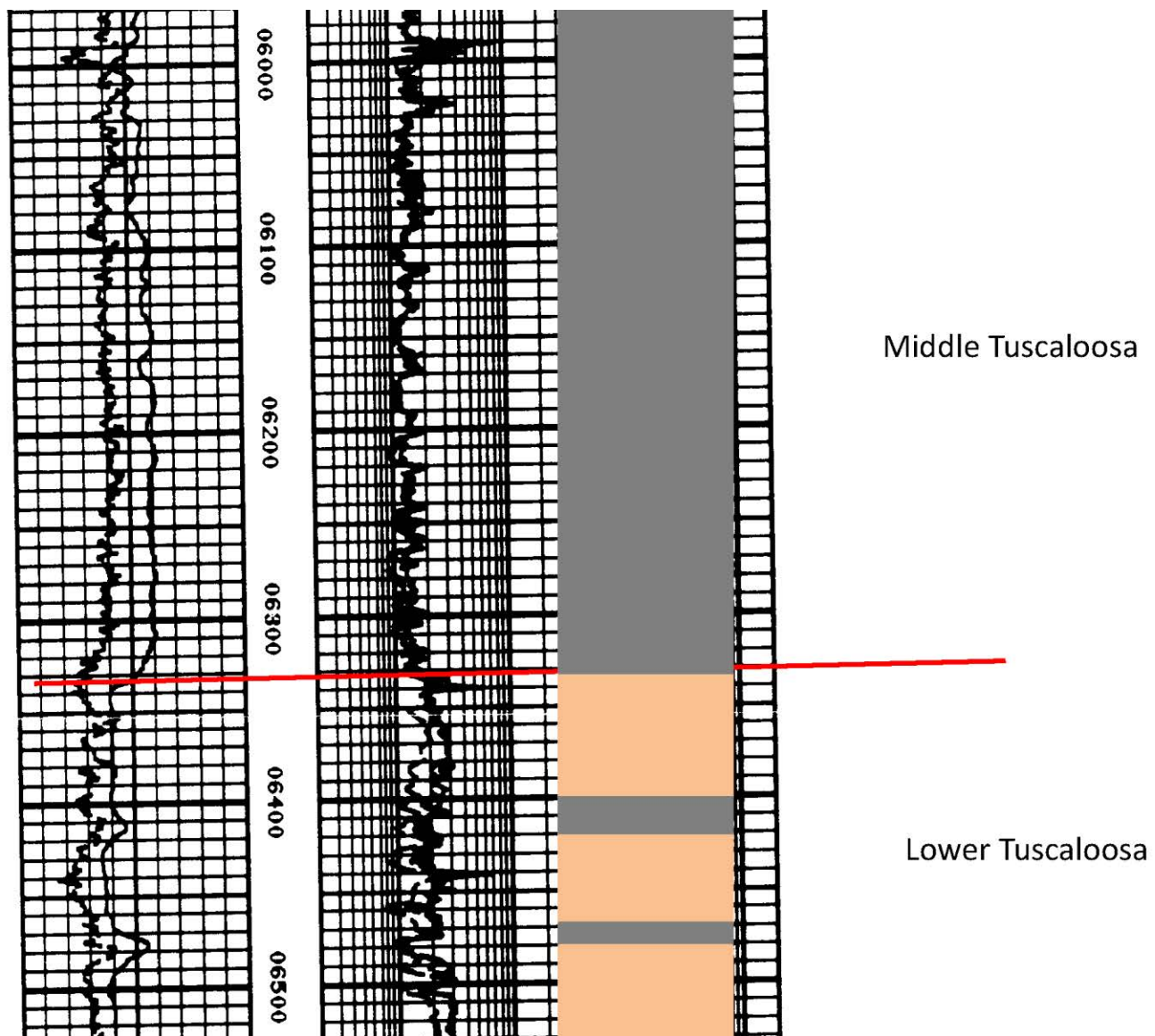
		ATLAS WIRELINE SERVICES		DRL INDUCTION FOCUSED LOC B/C ACUSTILLOC® CPMR RAY	
FILE NO. B-1419 RPT NO. 87-113-2025		COMPANY HELMERICH & FRYE, INC. WELL NO. 1 PRODUCE ESTES 26-2 FIELD MUDROT COUNTY SMITH ROSS STATE FLORIDA		LOCATION: 1128' N.E. & 128' N.E. OF SECTION SEC. 26 TWP. 2N RGE. 21W OTHER SERVICES M.C. ZOL-CR-CR UNIT	
PERCENT DRIFT LOGGING MEASURED FROM DRILLING MEASURED FROM		DATE 17 JUNE 1990		ELEVATIONS 165.8 183.7 152.3	
DATE 17 JUNE 1990		(Circular stamp: JUL 26 1990)			
SERVICE ORDER 62427 DEPTH-DRILLER 16765 DEPTH-LOGGER 15549 BOTTOM LOGGED INTERVAL 14538 TOP LOGGED INTERVAL 3890 CRUSING - DRILLER 9.5/8 CRUSING - LOGGER 3802 BIT SIZE 8 3/4 TYPE FLUID IN HOLE OPEN OIL DENSITY / VISCOSITY 10.3 9.2 9.6 PH / FLUID LOSS 9.2 SOURCE OF SAMPLE CIRC RT AT MEAS. TEMP. 0.35 RT AT MEAS. TEMP. 0.25 RT AT MEAS. TEMP. 0.63 SOURCE OF RT / RT 0.18 RT AT RT 0.18 TIME SINCE CIRCULATION 6.185 PER. REC. TEMP. DEC. F 278 & 278 EQUIP. NO. / LOC. M. 6338 RECORDED BY FETTY-JONSSON WITNESSED BY M. JAMES & J. GUN		FOLD HERE			
IN MAKING INTERPRETATIONS OF LOGS, OUR EMPLOYEES WILL GIVE CUSTOMER THE BEST FIT OF THEIR BEST JUDGMENT, BUT SINCE ALL INTERPRETATIONS ARE OPINIONS BASED ON INTERFERENCES FROM ELECTRICAL OR OTHER INTERFERENCES, WE CANNOT, AND WE DO NOT GUARANTEE THE ACCURACY OR CORRECTNESS OF ANY INTERPRETATION. WE SHALL NOT BE LIABLE OR RESPONSIBLE FOR ANY LOSS, COST, DAMAGES, OR EXPENSES WHATSOEVER INCURRED OR SUSTAINED BY THE CUSTOMER RESULTING FROM ANY INTERPRETATION MADE BY ANY OF OUR EMPLOYEES.		FOLD HERE			

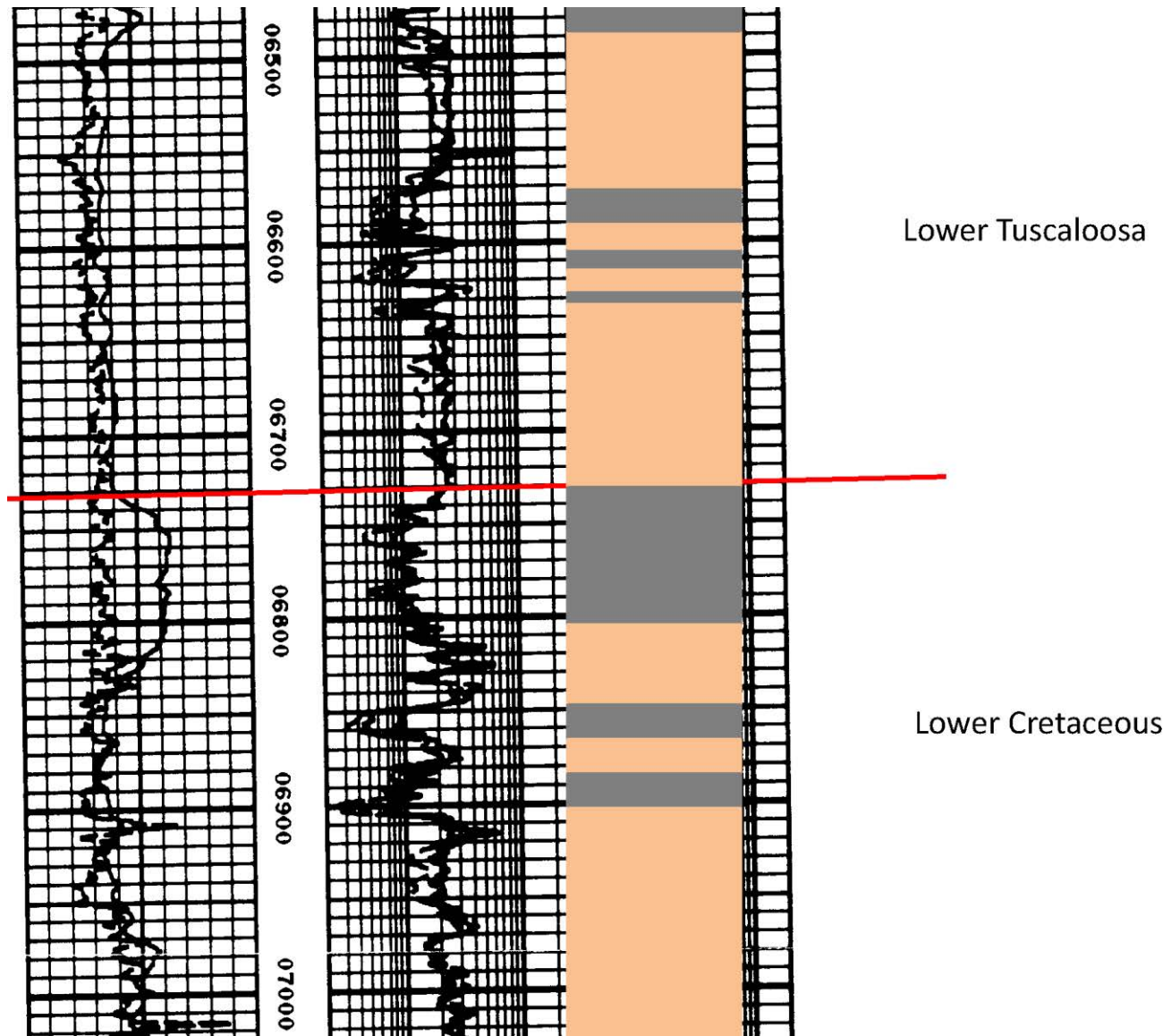




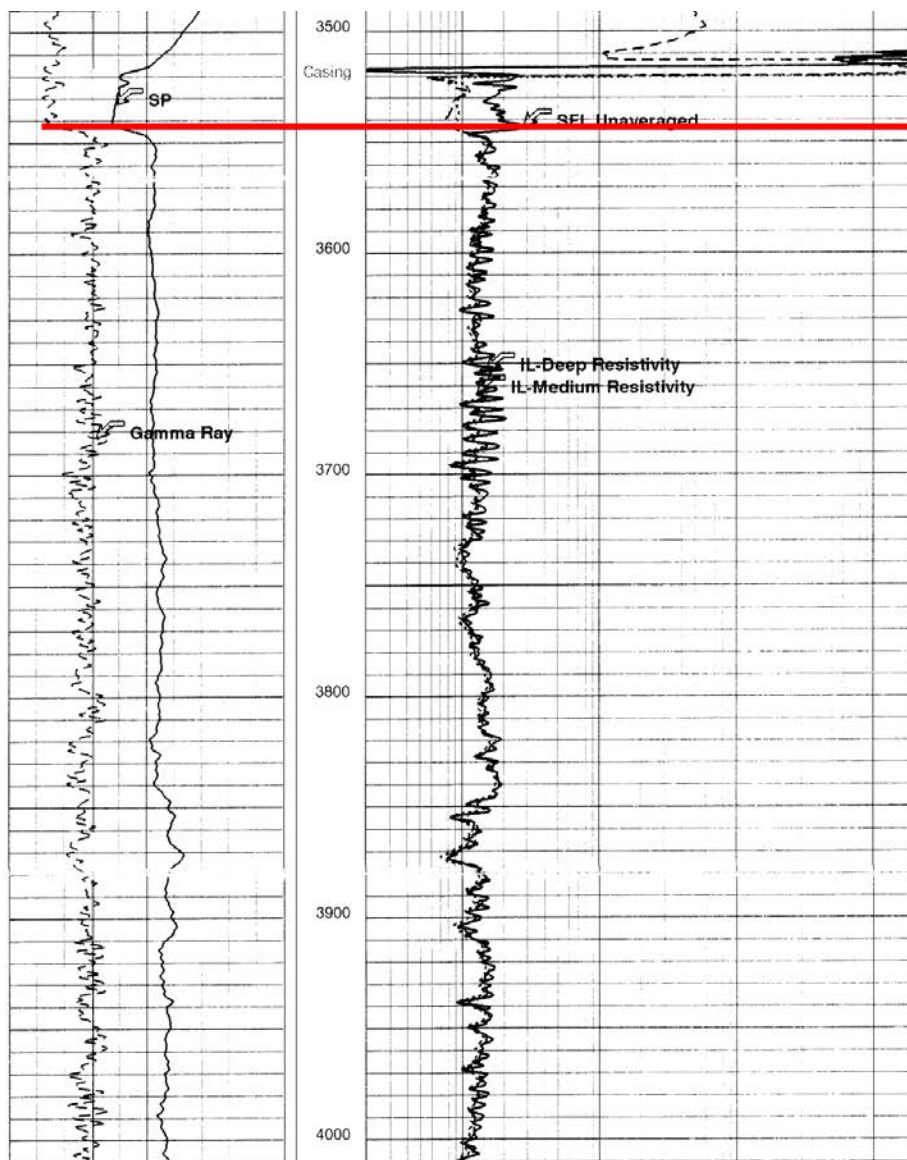






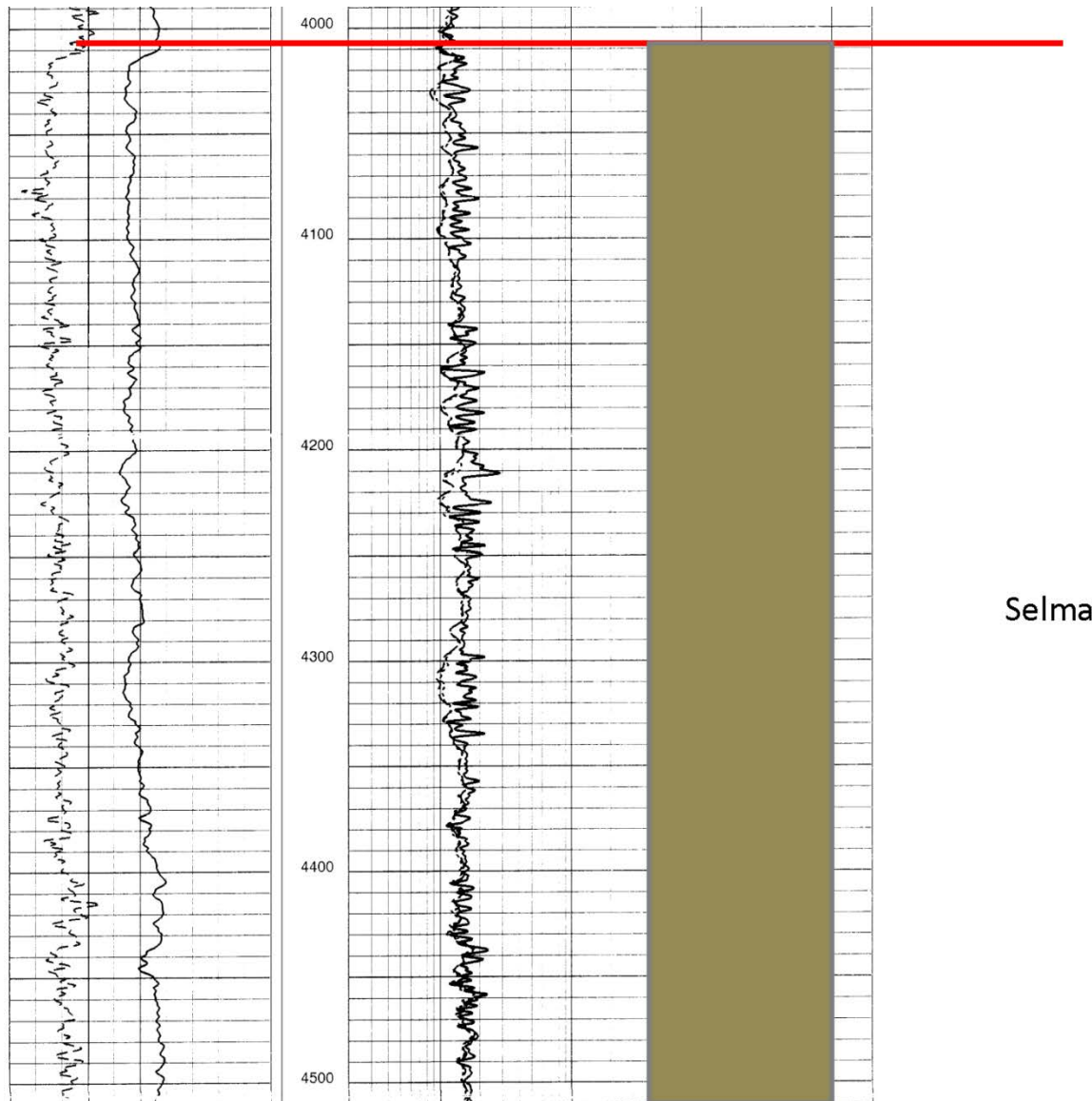


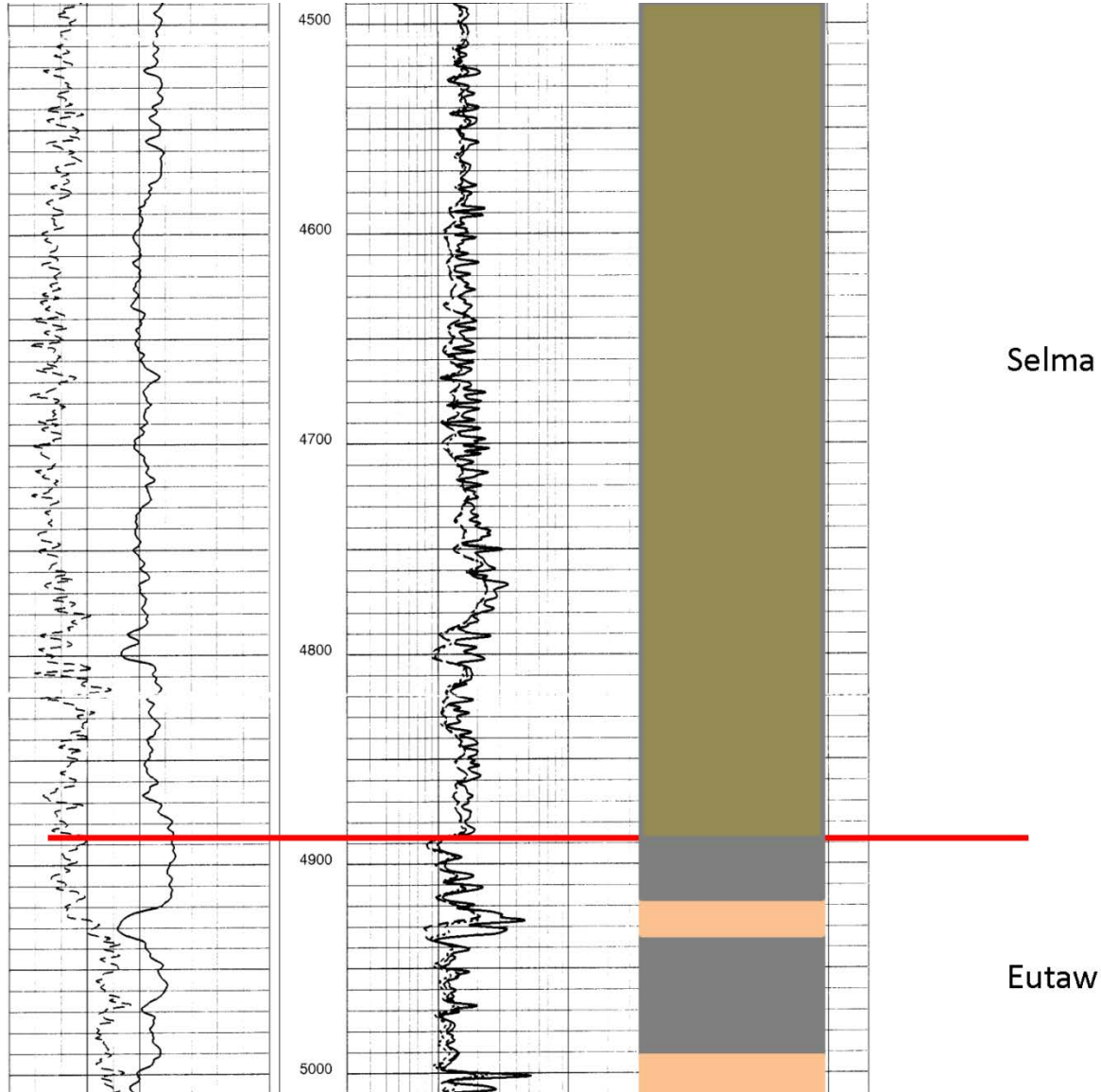
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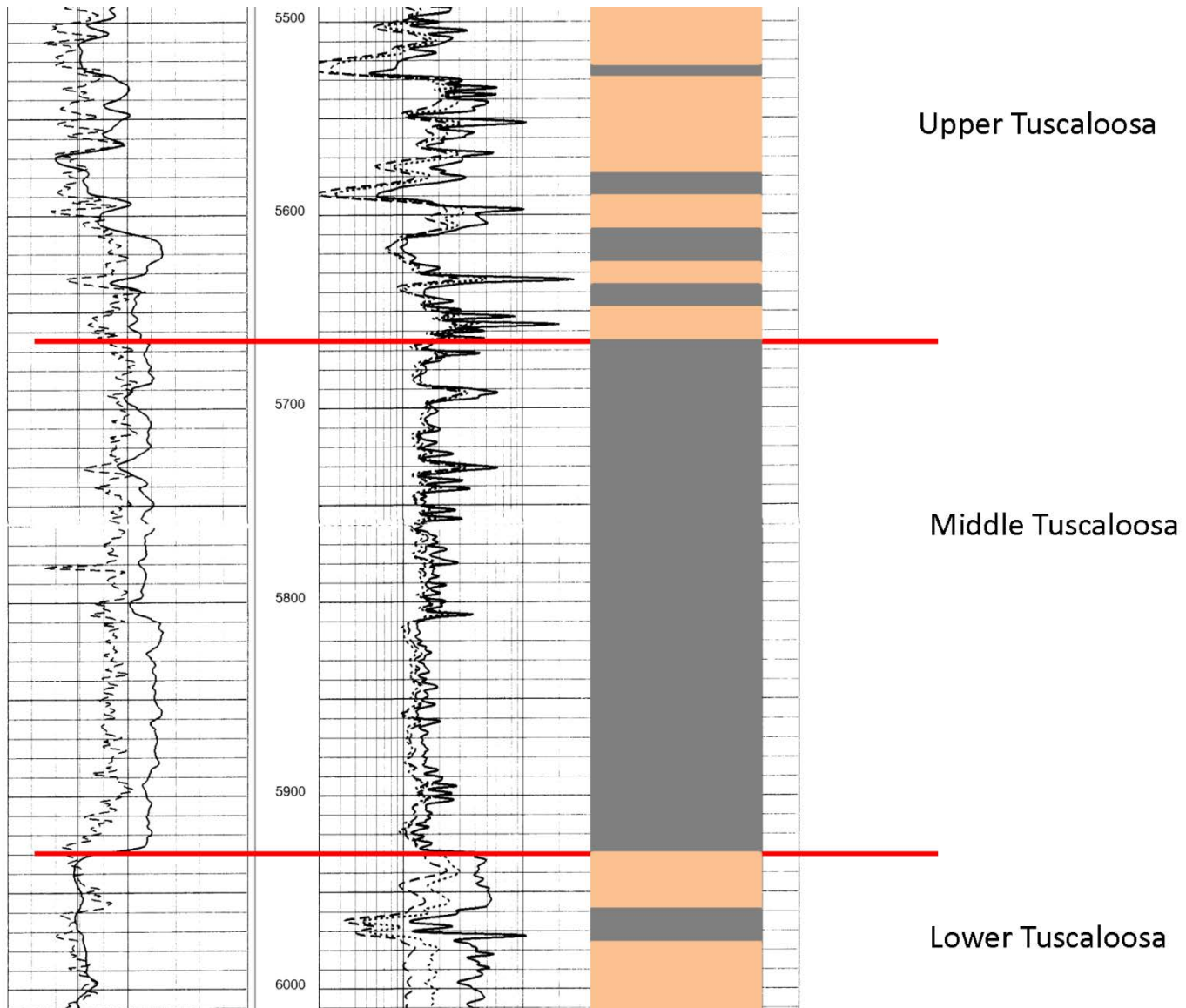
Midway

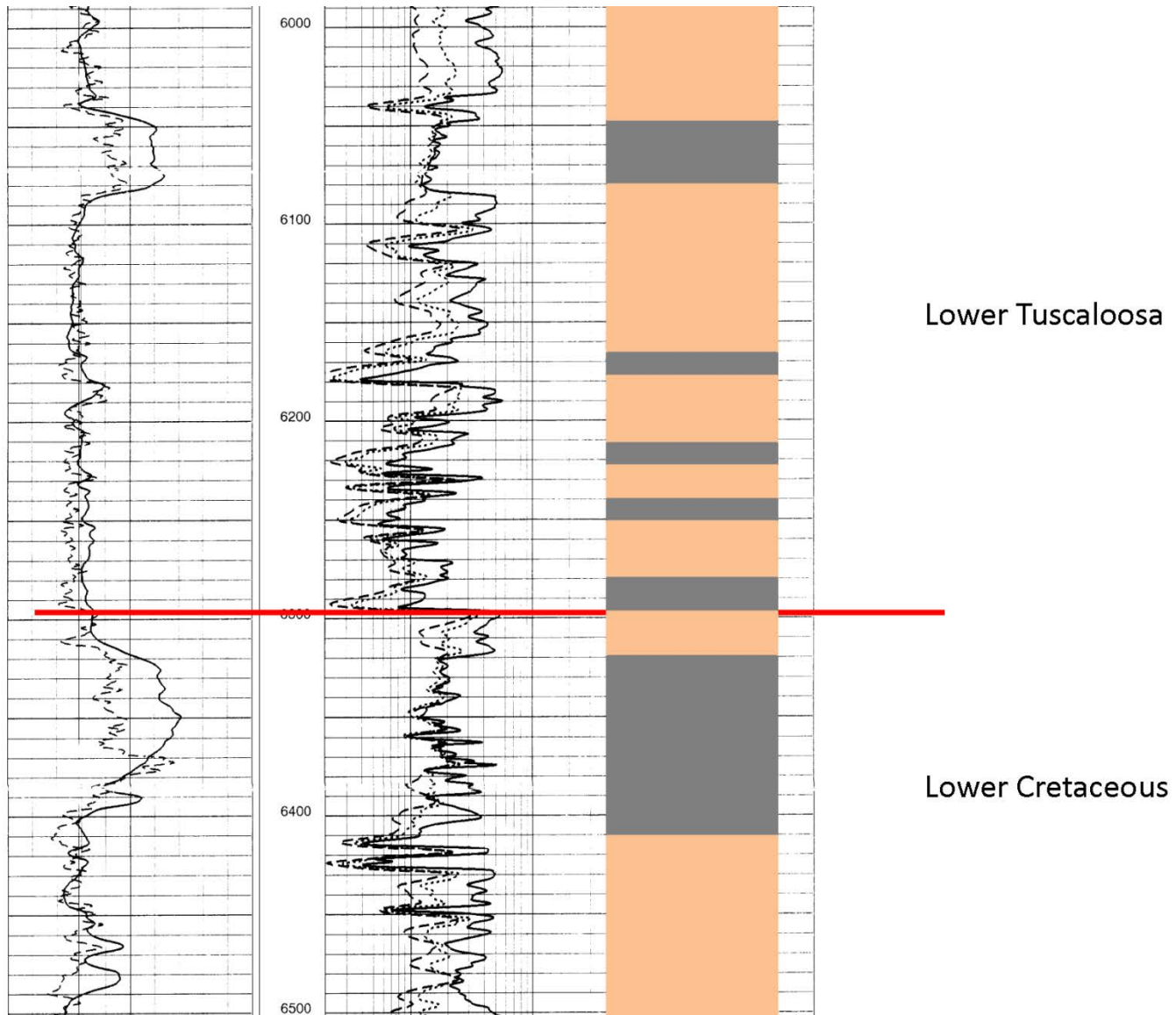






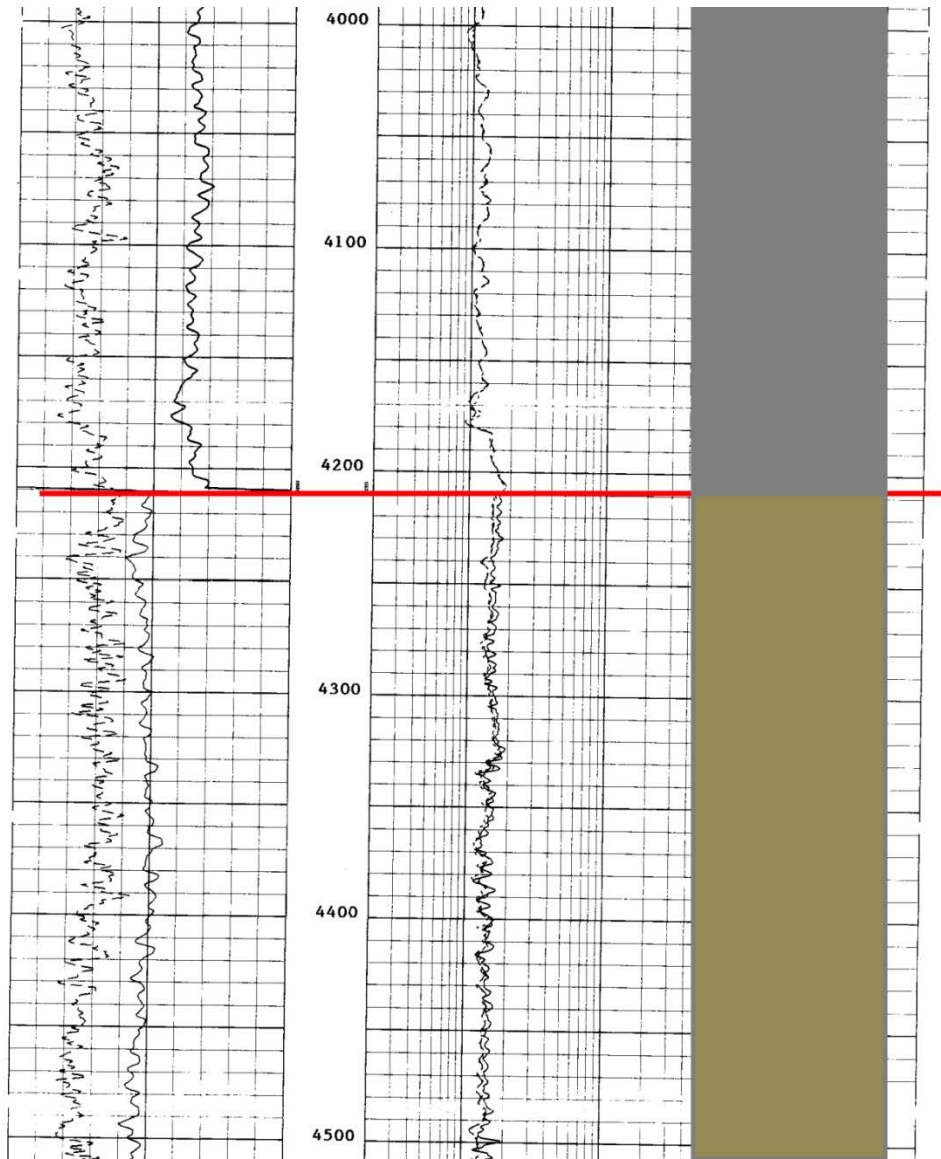






A map of the North Sea region showing a red line connecting several stations. The stations are labeled with numbers: 1027, 1244, 682, 1258, 1267, 590, 619, and B12. Station 1267 is highlighted with a yellow circle. Other stations shown include 1266, 370, 657, 661, 1097, and 612. The map also shows the coastline of the British Isles and the North Atlantic Ocean.

121



Midway



Limestone

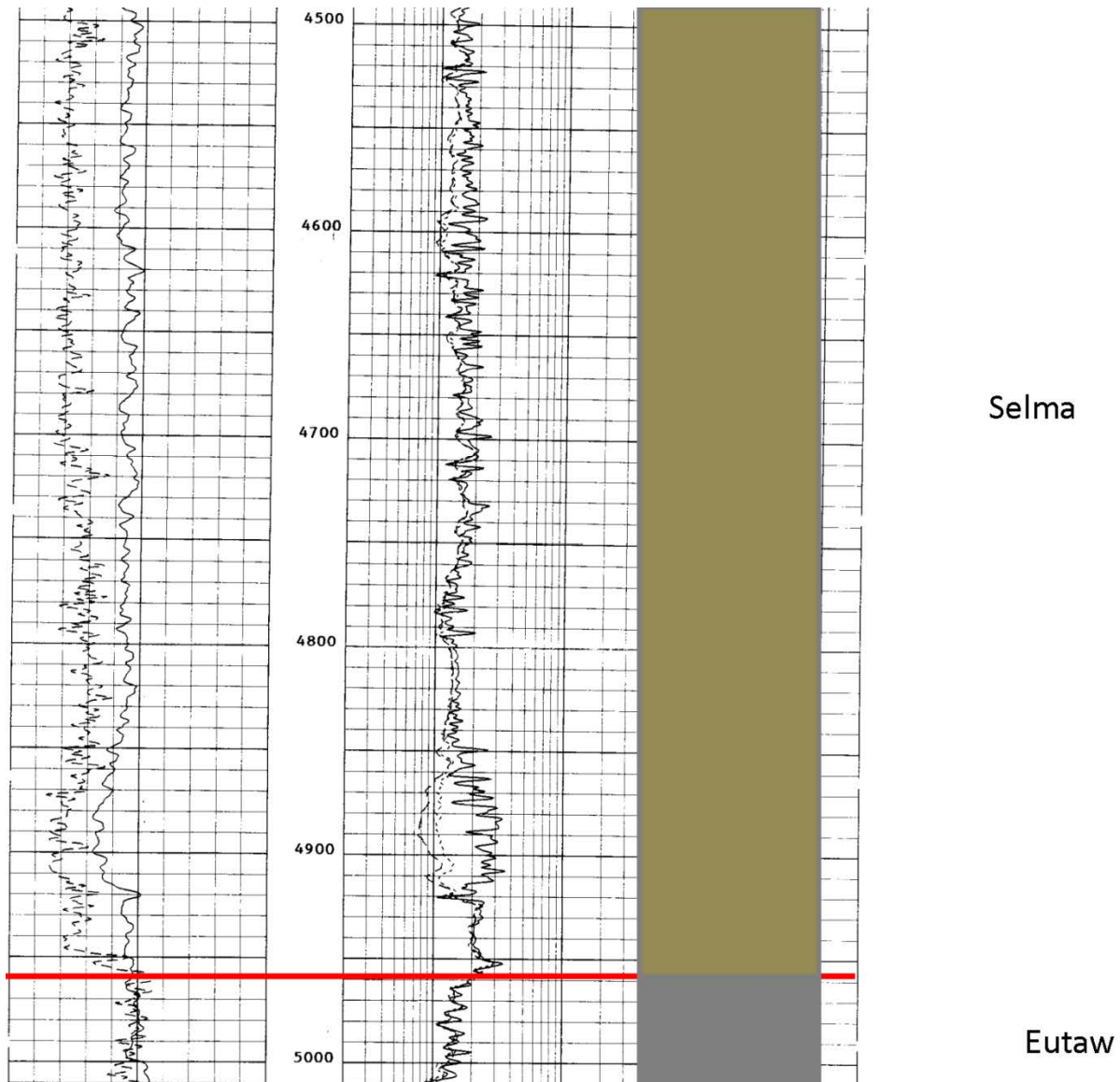


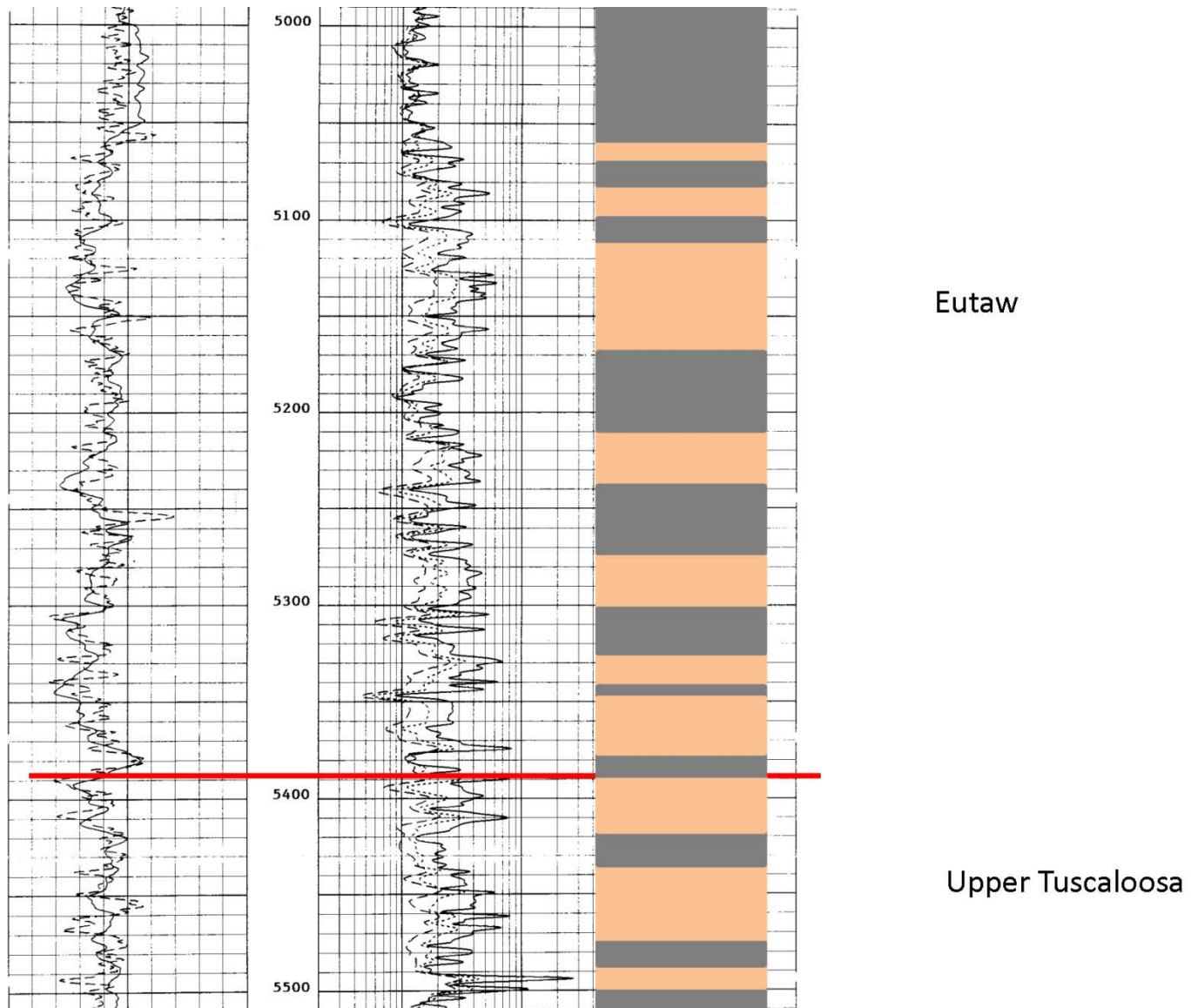
Clay/Shale

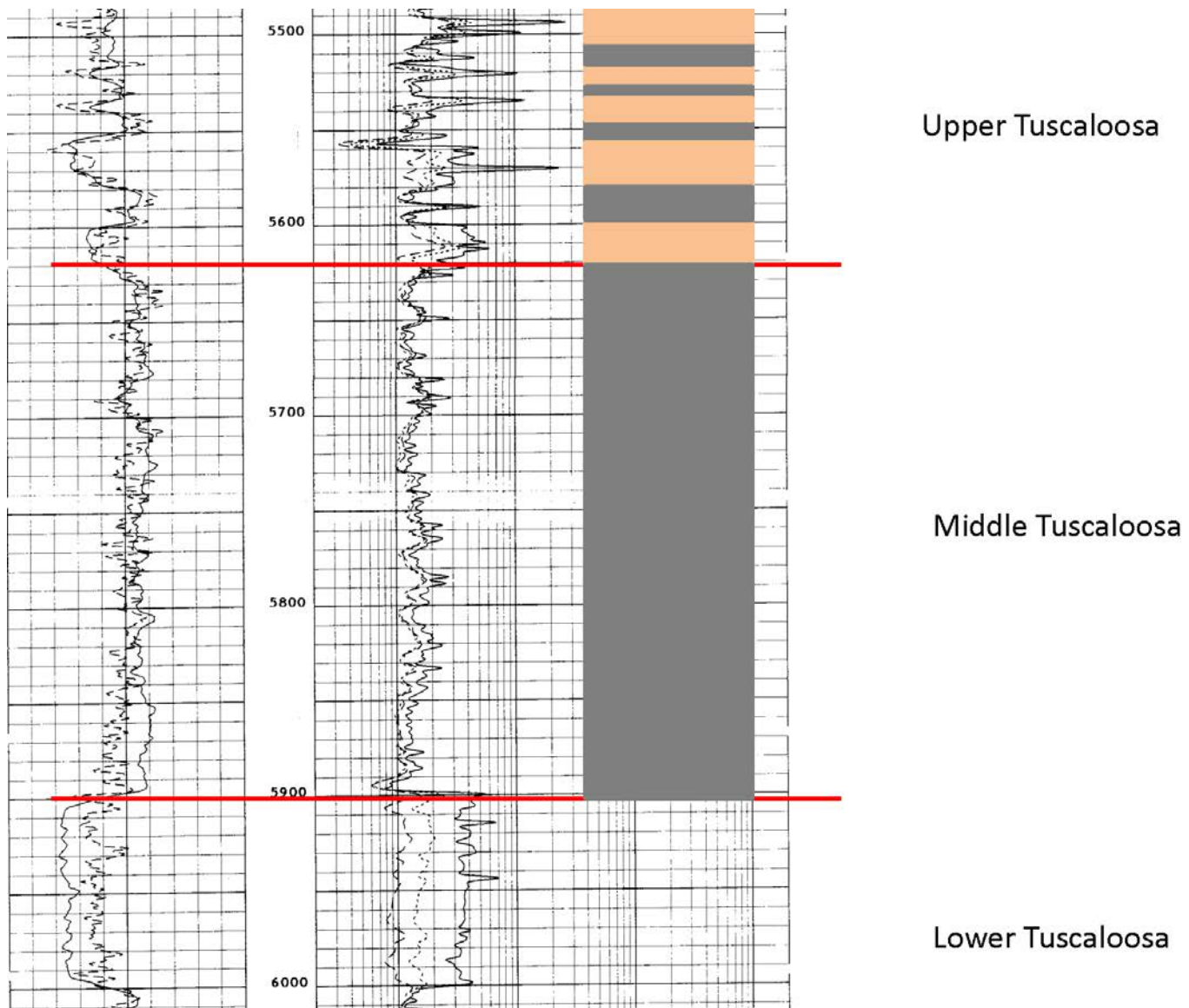


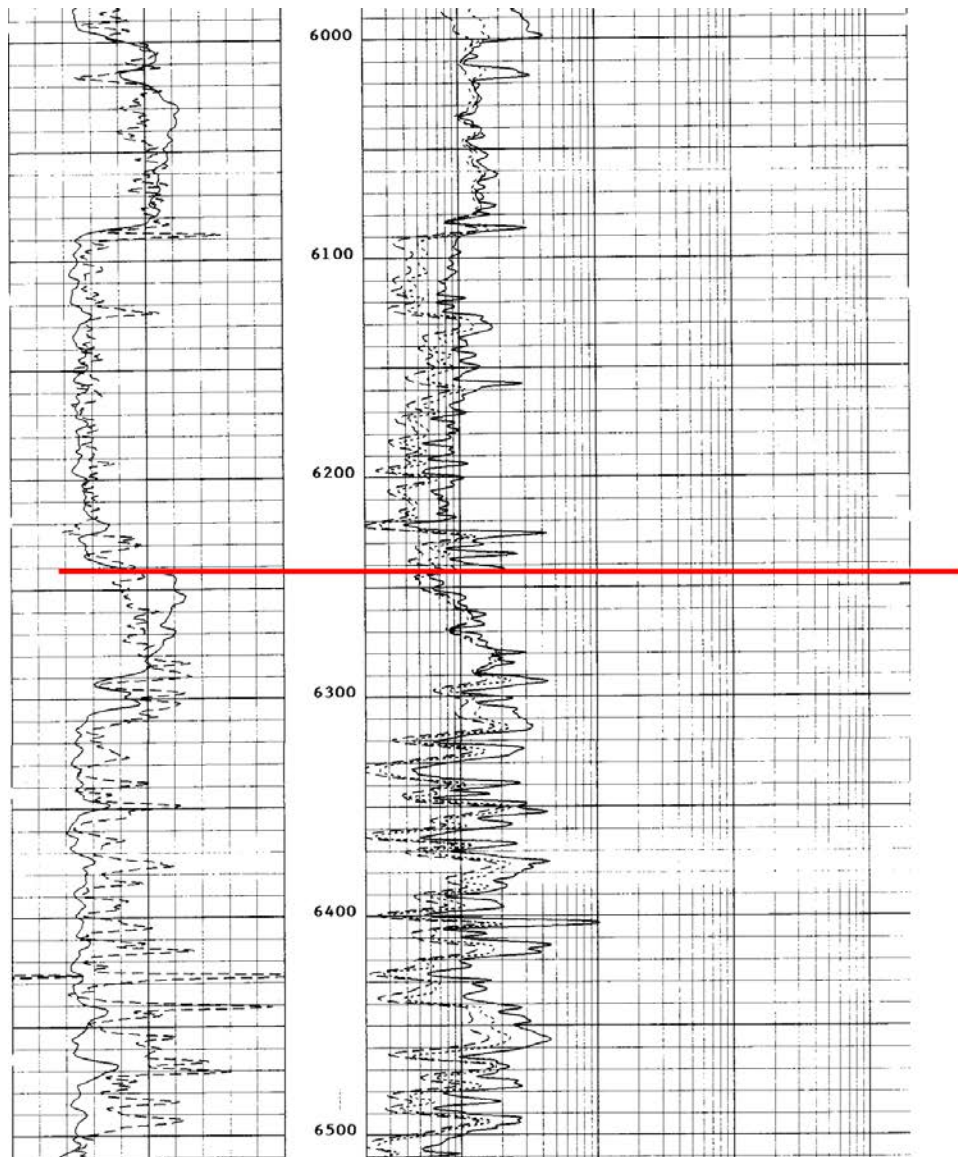
Sandstone

Selma





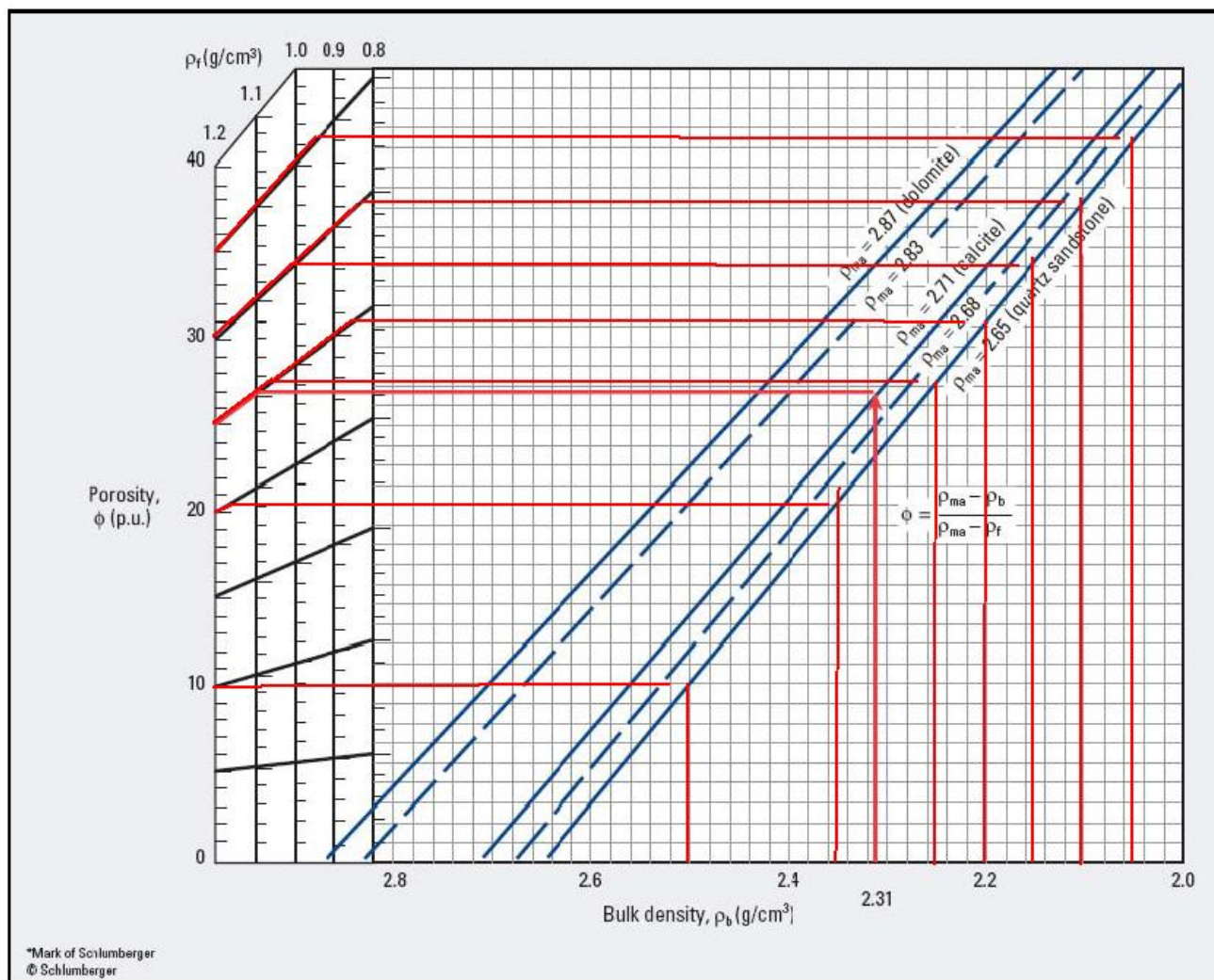




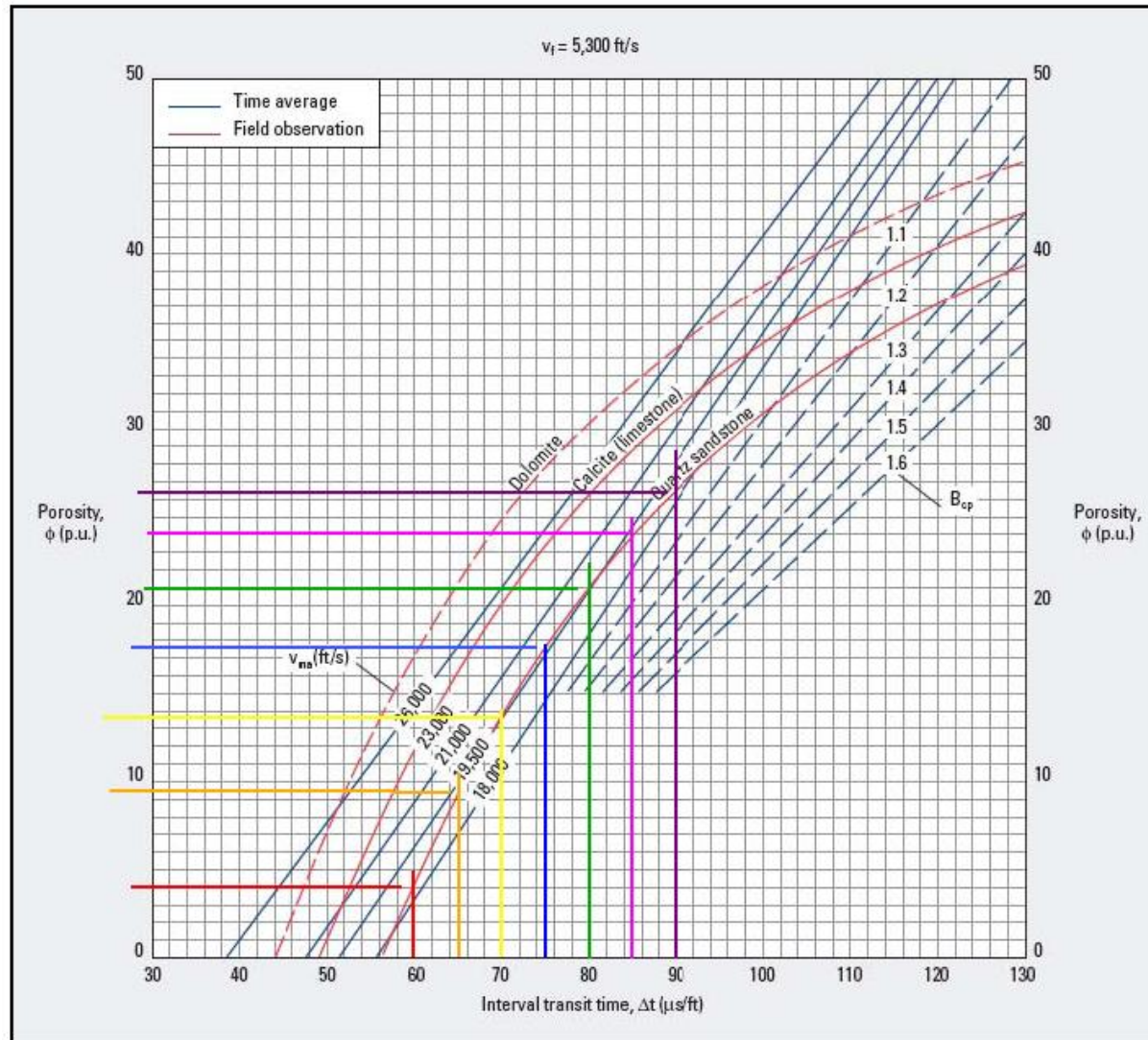
Lower Tuscaloosa

Lower Cretaceous

Appendix C
Schlumberger Porosity Graphs



Determination of porosity from true bulk density (from: Schlumberger, 2009).



Determination of porosity using interval transit time (from: Schlumberger, 2009).

Porous Zones																					
Permit #	County	Ground Elevation (ft)	Total Depth (ft)	Soil Group	Top (ft)	Bottom (ft)	Total Thickness (ft)	Interval Transit Time (μs/ft)	Neutron porosity	True Bulk Density (grams/cc)	Density Porosity	Lithlog	Estimated Porosity Value (%)								
													Sandstone								
													Figure AII-2	Figure AII-7	Figure AII-8	Figure AII-3	Figure AII-4	Figure AII-5	Figure AII-6	Figure AII-9	
370	Santa Rosa	NA	14480	Eutaw	5050	5085	35	75	-	-	-	-	-	-	-	17.5	-	-	-	-	
					5155	5180	25	75	-	-	-	-	-	-	-	17.5	-	-	-	-	
					5230	5255	25	65	-	-	-	-	-	-	-	9.5	-	-	-	-	
					5305	5325	20	70	-	-	-	-	-	-	-	13.5	-	-	-	-	
				Upper Tuscaloosa	5400	5530	130	60	-	-	-	-	-	-	-	4	-	-	-	-	
					5570	5640	70	60	-	-	-	-	-	-	-	4	-	-	-	-	
					5690	5710	20	70	-	-	-	-	-	-	-	13.5	-	-	-	-	
					5735	5780	45	70	-	-	-	-	-	-	-	13.5	-	-	-	-	
612	Walton	113.5	11533	Eutaw	3820	3895	75	90	-	-	-	-	-	-	-	26.5	-	-	-	-	
					3920	3945	25	90	-	-	-	-	-	-	-	26.5	-	-	-	-	
					3975	4000	25	85	-	-	-	-	-	-	-	24	-	-	-	-	
					4030	4050	20	85	-	-	-	-	-	-	-	24	-	-	-	-	
					4110	4120	10	80	-	-	-	-	-	-	-	21	-	-	-	-	
					4180	4210	30	75	-	-	-	-	-	-	-	17.5	-	-	-	-	
					4230	4255	25	75	-	-	-	-	-	-	-	17.5	-	-	-	-	
					4265	4280	15	70	-	-	-	-	-	-	-	13.5	-	-	-	-	
					4305	4320	15	65	-	-	-	-	-	-	-	9.5	-	-	-	-	
				Upper Tuscaloosa	4350	4375	25	65	-	-	-	-	-	-	-	9.5	-	-	-	-	
					4410	4530	120	80	-	-	-	-	-	-	-	21	-	-	-	-	
					657	Santa Rosa	202.1	16758	Eutaw	5550	5755	205	-	-	2.35	-	-	20	-	-	-
5820	5860	40	-	-						2.25	-	-	25	-	-	-	-	-	-	-	
Upper Tuscaloosa	5870	5910	40	-					-	2.25	-	-	25	-	-	-	-	-	-	-	
	5920	6000	80	-					-	2.3	-	-	25	-	-	-	-	-	-	-	
	6025	6035	10	-					-	2.5	-	-	10	-	-	-	-	-	-	-	
	6060	6070	10	-					-	2.5	-	-	10	-	-	-	-	-	-	-	
1027	Escambia	223	17957	Eutaw	6120	6140	20	-	-	2.3	-	-	25	-	-	-	-	-	-		
					5910	5950	40	-	15	2.5	-	-	10	21	-	-	-	-	-	-	
					6070	6125	55	-	30	2.2	-	-	25	37	-	-	-	-	-	-	
					6160	6180	20	-	30	2.15	-	-	30	37	-	-	-	-	-	-	
					6230	6260	30	-	30	2.1	-	-	30	37	-	-	-	-	-	-	
					6280	6290	10	-	30	2.25	-	-	25	37	-	-	-	-	-	-	
					6305	6315	10	-	33	2.2	-	-	25	40	-	-	-	-	-	-	
				Upper Tuscaloosa	6330	6340	10	-	28	2.2	-	-	25	35	-	-	-	-	-	-	
					6360	6380	20	-	39	2.05	-	-	35	na	-	-	-	-	-	-	
					6405	6420	15	-	30	2.25	-	-	25	37	-	-	-	-	-	-	
					6460	6480	20	-	21	2.35	-	-	20	38	-	-	-	-	-	-	
					6500	6535	35	-	24	2.35	-	-	20	31	-	-	-	-	-	-	
					6590	6605	15	-	39	2.15	-	-	30	na	-	-	-	-	-	-	
					6620	6630	10	-	39	2.05	-	-	35	na	-	-	-	-	-	-	

Appendix D
Storage Efficiency Calculations

Calculating Gamma (Okwen et al., 2009)

Estimated Flow Rate = 53,050,000 tonne/year 53.05 Mt/yr <<< Annual flow rate from Florida Pan-Handle Network
 145,342 tonne/day 5 MGD <<< Assumed max flow for one pump (Brown, 2011)
 145,342,466 kg/day 45561901.49 gpd 45.56 MGD
 168.2204 kg/s 52.7337 gps 4.56 MGD <<< Flow used for thesis

Thickness of formation = 104 m

Density of Brine in formation = 1019.12 kg/m³ Brown, 2011 0.4418 lb/in²/foot
 Density of CO₂ in formation = 842.75 kg/m³ MIT Calculator 100°F @ 2750psi 0.3654 lb/in²/foot
 $\Delta\rho$ = 176.37 kg/m³

Viscosity of Brine in formation = 0.000734268 kg/m s Brown, 2011
 λ_b = 1361.90

Intrinsic Permeability = 1.00E-09 m² typical value for sandstone (Fetter, 1988) 1.00E-05 cm²

Γ = 0.95193410 BOUYANCY AFFECTS PLUME (Okwen et al., 2009)

Viscosity of CO₂ in formation = 0.00008002 kg/m s (Pa- MIT Calculator 100°F @ 2750psi
 λ_c = 12496.88
 λ = 9.1761

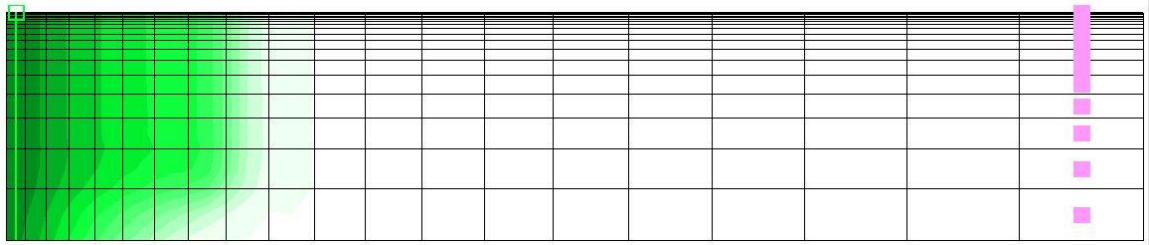
No Bouyancy Effects

Sr	0	0.15	0.3	0.45
ϵ	0.11	0.09	0.08	0.06

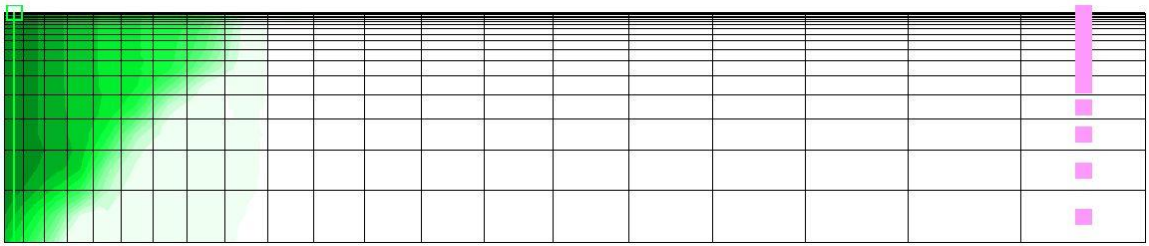
Bouyancy Effects

Sr	0	0.15	0.3	0.45
ϵ	0.10	0.08	0.07	0.05

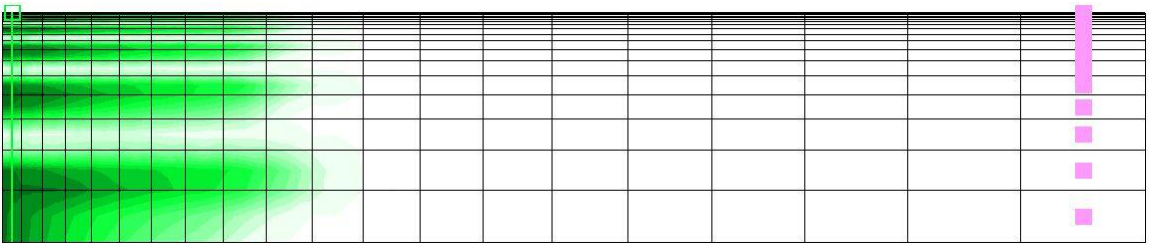
Appendix E
UTCHEM-9.0 Florida Pan-Handle Model



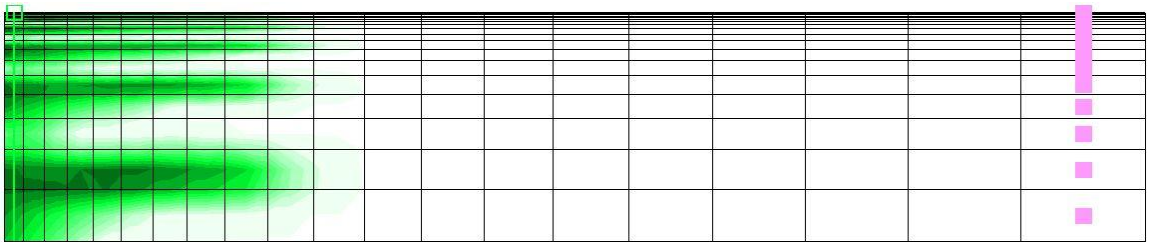
Model Run #1: 5mD Sandstone with No Shale



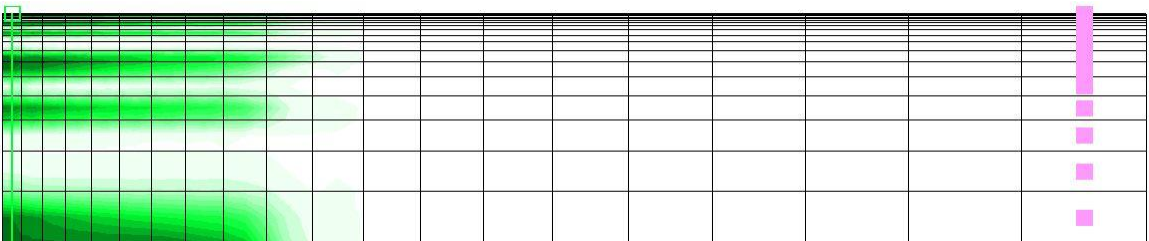
Model Run #2: 50mD Sandstone with No Shale



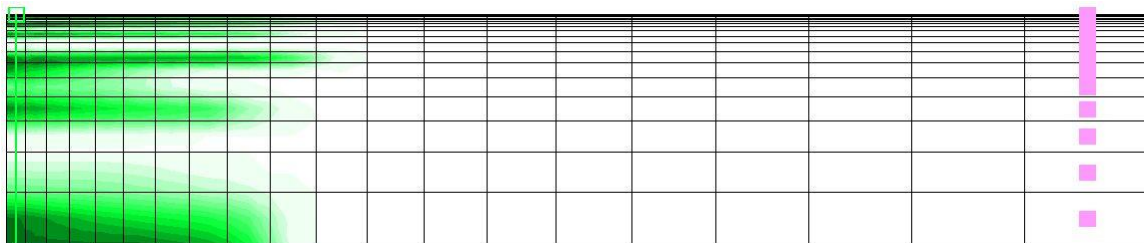
Model Run #3: 5mD Sandstone with 25% Shale



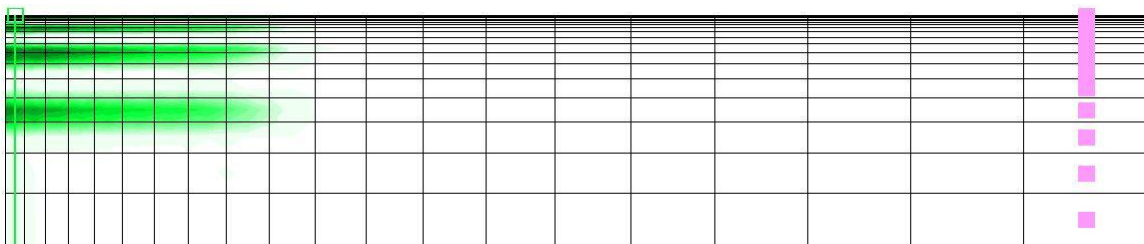
Model Run #4: 50mD Sandstone with 25% Shale



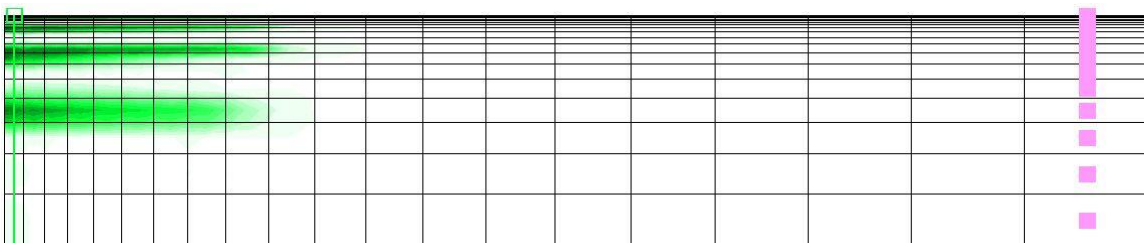
Model Run #5: 5mD Sandstone with 50% Shale



Model Run #6: 50mD Sandstone with 50% Shale



Model Run #7: 5mD Sandstone with 75% Shale



Model Run #8: 50mD Sandstone with 75% Shale

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Vita

Brandon Keith Poiencot was born _____ to parents Kyle and Glenda Reagan. Glenda made a career in the food service industry and Kyle continues his career in the United States Navy where he will retire in 2013. The U.S. Navy moved the family from Summerville _____, for four years, where Brandon's sister, Kaitlynn Rhea Reagan, was born. Two years later the family moved to Jacksonville, Fla., where they have remained.

Brandon graduated high school _____ and started college at the University of Central Florida in August 2000. Brandon would eventually earn a Bachelor of Science in Civil Engineering from the University of North Florida (UNF) in May 2007. Jones Edmunds & Associates, Inc. hired Brandon full-time as a civil engineer where he mostly performed work related to the design and permitting of water and wastewater treatment facilities and stormwater collection systems. In August 2010, he began pursuing a Master of Science degree at UNF.

Brandon continued his studies in civil engineering with a focus on water resources and environmental engineering. Graduate research work led to the topic of this thesis. Along the way to the completion of this thesis, Brandon has either been primary author or co-author for four published articles and two conference presentations. In December 2011, Brandon began working as a student intern with Golder Associates, Inc. and will start working full-time in May 2012.

