# LITHOLOGY AND PORE FLUID PREDICTION OF A RESERVOIR USING DENSITY, COMPRESSIONAL AND SHEAR WAVE LOGS: A CASE STUDY OF THE TANO BASIN

**By**

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## DECLARATION

I hereby declare that this submission is my own work towards the award of M.Phil. degree and that, to the best of my knowledge, it contains no material previously published by another person or material which has been accepted for the award of any degree of the university, except where due acknowledgment has been made in the text.

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**ABSTRACT**

Due to the higher uncertainties associated with the traditional method of determining lithology and pore fluid using well logs, quantitative rock physics analysis was carried out to determine the lithology and pore fluid of a reservoir in the Tano Basin. Inaccurate prediction of lithology and pore fluid, results in the inaccurate determination of other petrophysical properties such as porosity, permeability, net pay, etc. Rock physics analysis reduces the uncertainties related to the traditional method of predicting lithology and pore fluid. The primary objective of this thesis is to predict lithology and pore fluid using rock physics analysis, however, the oil-water-contact (O.W.C) and reservoir zone were also predicted. In this thesis, density, compressional wave velocity and shear wave velocity logs were used as input to calculate elastic parameters such as velocity ratio, Poisson's ratio, and Lamé parameters. The calculated velocity ratio log was used to differentiate between sand and shale. Rock physics analysis of the calculated Lamé parameters was used for comprehensive lithology prediction. A crossplot of Lamé's ratio ($\lambda/\mu$) and difference ($\lambda*\rho$ - $\mu*\rho$) using Goodway (2001) interpretation template was carried out. The gas sand, wet sand, and carbonate formations were delineated according to the crossplot analysis. Poisson's ratio and velocity ratio crossplot was also used to determine the pore fluid content. Oil sand, gas sand, and brine sand were predicted from the crossplot analysis. Oil-water-contact and reservoir zone were identified due to the rapid variations observed in the velocity ratio log. This thesis demonstrates how rock physics analysis can be used to improve lithology and pore fluid prediction of the Tano Basin.

# TABLE OF CONTENTS

## LIST OF TABLES

**LIST OF FIGURES**

**LIST OF SYMBOLS AND ACRONYMS**

| | | | |
|---|---|---|---|
| A | Atomic mass | $\lambda$ | Incompressibility |
| $\mu$ | Rigidity | $\theta$ | Porosity |
| E | Young modulus | G | Shear modulus |
| K | Bulk modulus | $\rho$ | Density |
| $\rho_e$ | Electron density | $\rho_b$ | Bulk density |
| $\rho_{matrix}$ | Matrix (rock) density | $\rho_{fluid}$ | Fluid density |
| $S_w$ | Water saturation | $K_g$ | Absolute permeability of gas |
| Rt | True formation resistivity | Rw | Resistivity of formation water |
| $K_o$ | Absolute permeability of oil | $\Phi$ | Poisson's ratio |
| Z | Molecular weight of a compound | | |

| | |
|---|---|
| Vp | Compressional wave |
| Vs | Shear wave |
| DHI | Direct hydrocarbon indicator |
| DLL | Dual lateral log |
| O.W.C | Oil water contact |

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# CHAPTER ONE

# INTRODUCTION

## 1.1 General Introduction

Lithology basically refers to the type of rock in the Earth crust. Different kinds of rocks exist in the subsurface but not all are conducive for hydrocarbon accumulation. For a subsurface rock to be a good hydrocarbon storage, the rock should be sedimentary with pore spaces. These pore spaces can be filled with hydrocarbons (Schlumberger, 1989a). Knowledge obtained about the lithology of a well can be used to determine a range of parameters including the much needed pore fluid content. Lithology and pore fluid prediction are vital for reservoir characterization. Lithology and pore fluid prediction are very important aspects of exploration and production such as geological studies, reservoir modeling, formation evaluation, enhanced oil recovery processes, and well planning including drilling and well completion management.

Accurate determination and understanding of lithology, pore fluid, pore shapes, and sizes are fundamental to other petrophysical analysis. Determining lithology and pore fluid are key for effective exploration and production of hydrocarbon. However, accurate prediction of lithology and pore fluid is, and will continue to be, a key challenge for hydrocarbon exploration and development (Kupecz et al., 1997). The accurate determination of lithology and pore fluid aids in the accurate determination of porosity, saturation, and permeability. The economic viability of a hydrocarbon field is also reliant on the quality and accuracy of lithology and pore fluid (Hami-Eddine et al., 2015). The growing difficulty in convention (reservoir that uses the natural pressure gradient for hydrocarbon extraction) and unconventional (reservoir that requires special recovery operations outside the conventional operating practices) reservoir has made precise lithology and pore fluid prediction very essential (Hami-Eddine et al., 2015). The accurate determination of lithology and pore fluid also aid petroleum engineering decisions making.

Lithology and pore fluid can be unambiguously determined using core samples obtained from underground formation. Core sample analysis for lithology and pore fluid prediction is expensive and usually involves vast amount of time and effort to obtain reliable information (Chang et al., 2002). Hence, this method cannot be applied to all drilled wells in a field. Also, different geoscientists may obtain inconsistent results based on their own observation and analysis (Akinyokun et al., 2009; Serra and Abbott, 1982). Cuttings obtained from drilling operations can also be used to determine lithology and pore fluid. The main disadvantage of using cuttings from drilling operation to determine lithology and pore fluid is that the retrieval depth of the cuttings are usually unknown and the samples are generally not large enough for precise and reliable determination of lithology and pore fluid (Serra and Abbott, 1982). Considering the limitations mentioned for other methodologies, there has been a growing interest in determining lithology and pore fluid using well log data which is cheaper, more reliable, and economical compared to the other methods stated above. Well logging also offers the benefit of covering the entire geological formation of interest coupled with providing general and excellent details of the underground formation (Serra and Abbott, 1982). Brigaud et al. (1990) observed that well logs offers a better representation of in-situ conditions in a lithological unit than laboratory measurements mainly because well logs sample finite volume of rock around the well and delivers uninterrupted record with depth instead of sampling of discrete point.

Well logging is a technique used to obtain continuous detailed recording of physical parameters of a geological formation as a function of time or depth, by measuring various physical, chemical and lithological properties of the formations (Alger, 1980). Marcel and Conrad Schlumberger were the first to implement logging in the hydrocarbon industry

(Schlumberger, 2000). For over a century, well logging has played a pivotal role in the detection and development of hydrocarbon resources. Well logs provide knowledge of the subsurface which can be used to predict the nature of the geological formation infiltrated during drilling. Information obtained from well logs when appended with additional information obtained from the analysis core data, can be used to determine the depth and the nature of the formation, fluid type and extent of fluid contact, porosity and permeability, flexibility of the hydrocarbon flow rate, formation pressure, net pay, hydrocarbon in place, recoverable hydrocarbon, and other relevant information at a higher precision. Well logging is one of the essential techniques used in the hydrocarbon industry for reservoir characterization. Well logs aid geoscientists to gain much needed knowledge about subsurface conditions. Well log analysis can be used to identify hydrocarbon bearing zone, calculate hydrocarbon volume, determine porosity and permeability, identify lithology, etc. Well logs interpretation can be used in obtaining essential information and properties of a reservoir since the complete coring and core analysis of the whole pay zone is impractical (Eshimokhai and Akhirevbuku, 2012). Well log analysis and interpretation are carried out in many steps but not randomly to avoid errors.

Well logs have been used to successfully predict lithology and pore fluid content of hydrocarbon reservoir. Ogungbemi (2014) used the ratio of compressional and shear wave velocities and their travel times to predict lithology of the “Benin River Field” located in the Niger Delta Basin in Nigeria. Due to the absence of gamma ray and spontaneous potential logs, velocity ratio was used to differentiate between sand and shale. However, velocity ratio cannot be used to effectively differentiate between carbonate and shale. Hence, the need for a comprehensive lithology prediction using well logs.

Inichinbia et al., (2014) also successfully determined lithology and pore fluid content in the Niger Delta basin using Lamé parameters calculated from density, compressional, and sonic wave velocity logs. The analysis of these Lamé parameters was used to identify gas sand of the reservoir. Despite the successful identification of gas sand, brine sand, and shale, rock physics analysis using Lamé parameters cannot be used to identify oil sand.

Kuffour (2008) used well log analysis and interpretation to determine petrophysical properties of six exploratory wells in the Tano Basin. Kuffour (2008) in determining petrophysical properties made a couple of assumptions including "reservoir formation considered is lithologically clean (no clay minerals)". It is mostly possible not to encounter a clean formation and in such cases, this assumption can be applied but the petrophysical properties determined would not be accurate. For instance, porosity, permeability, and water saturation which are very important petrophysical parameters, are calculated using the formulae below:

$$\theta = \frac{\rho_{matrix} - \rho_b}{\rho_{matrix} - \rho_{fluid}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1.1)}$$

$$S_w = \frac{a * R_w}{\theta^m * R_t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{( 1.2)}$$

$$K_g = \left(79 * \frac{\theta^3}{S_W}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1.3a)}$$

$$K_o = \left(250 * \frac{\theta^3}{S_W}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1.3b)}$$

where

$\theta$ = porosity,

$\rho_{matrix}$ = density of the matrix (rock formation)

$\rho_b$ = measured bulk density

$\rho_{fluid}$ = fluid density

$S_W$ = water saturation

$R_w$ = formation water resistivity

$R_t$ = true resistivity formation

a, m = empirical constants

$K_g$ = absolute permeability of gas

$K_o$ = absolute permeability of oil

From the equations above, it can be observed that the accuracy of porosity, permeability, and water saturation are influenced by the accuracy of the predicted lithology and pore fluid (Lithology and rock type determination, 2015). An effective means of determining lithology and pore fluid should therefore be used to avoid the inaccurate determination of petrophysical parameters.

Despite well log being the best form of lithology and pore fluid prediction, uncertainties in measurements, complexities of geological formation, and many others factors result in the unforeseen complication in lithology and pore fluid prediction. Some traditional well log interpretation techniques such as combining and cross plotting of log data have been established using well logs by combining and cross plotting of log data. These methods are recently used for quick evaluations (Ellis and Singer, 2008). The efficiency of these traditional methods is minimal when considering large heterogeneous reservoir data. To make lithology prediction of a heterogeneous reservoir with large dataset possible, several approaches have been presented. This approach includes petrophysics and rock physics analysis for lithology and pore fluid prediction.

Ultimately, lithology and pore fluid prediction can be achieved using petrophysics and rock physics analysis. Petrophysics, which refers to the study of both chemical and physical properties of rocks and their communication with pore fluid, is used to determine the hydrocarbon bearing reservoir of a well. In the hydrocarbon industry, petrophysics is primarily used for the study of reservoir. Petrophysical analysis employ methods that emphasize on the estimation of a single property at a time. Rock matrix and interconnected pore spaces are the main component of hydrocarbon bearing rocks. The pores can have dimensions varying from sub-microns for tight sandstones to centimeter for vuggy carbonate rock (Levorsen, 1967). The basic petrophysical properties are:

- Porosity: the measure of the ability of a rock to hold fluids and consists of the tiny spaces in the rock that hold the oil or gas. It regulates the storage capacity for hydrocarbon
- Permeability: the measure of the ability of a porous rock to allow fluids to pass through it. Permeability is affected by pressure and can controls the flow capacity of fluid in a rock.
- Capillary: the differential pressure between two unmixable fluid phases inhabiting the same pores. The differential pressure, caused by interfacial tension between the two phases, should be overcome to allow the flow of fluids. Capillary defines the quantity of producible hydrocarbon.
- Saturation: portion of porosity occupied by hydrocarbon or water. It is a direct measure of the quantity of fluid of a porous rock. Saturation basically influences the capacity of hydrocarbon or water storage of a reservoir.

All the above petrophysical properties are linked by the distribution of pore size. The accurate determination of these petrophysical properties is very essential in determining whether to develop a reservoir.

Rock physics establishes a bond between elastic properties (Vp/Vs, bulk and shear modulus, etc.), reservoir properties (permeability, porosity, lithology, etc.), and architecture properties (fractures) (Saberi, 2013). Rock physics improves understanding of physical properties which is the foundation for seismic interpretation. It provides the link between geology, geophysics, petrophysics, and reservoir engineering as shown in Figure 1.1 below.

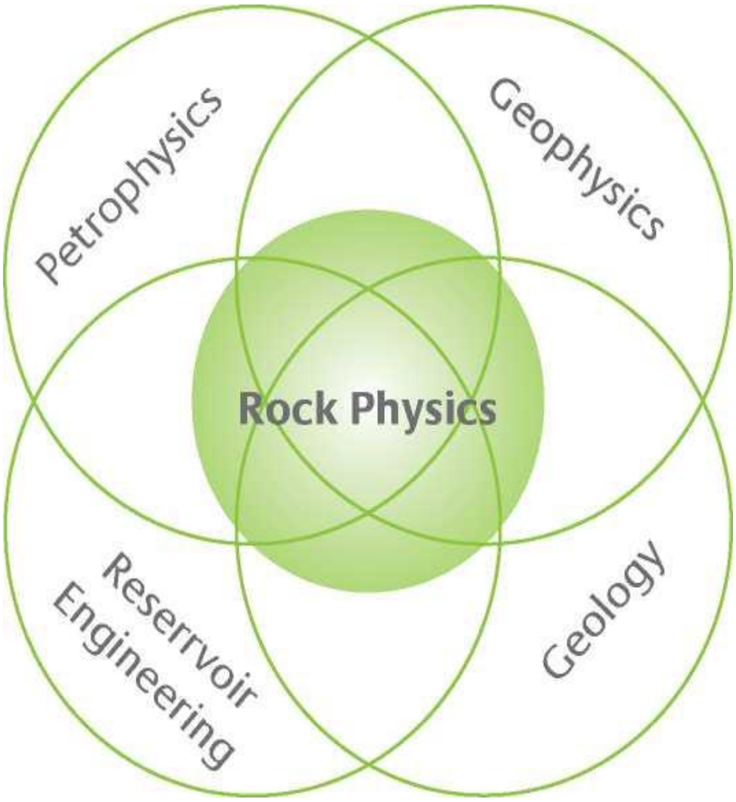


**Figure 1.1:** A diagram of how rock physics links petrophysics, geophysics, geology, and reservoir engineering.

### 1.2 Problem statement

The Tano Basin is one of the biggest and most producing hydrocarbon Basin in Ghana. About 62 wells have been drilled and the associated log data has been used for comprehensive analysis to determine various petrophysical properties including lithology and pore fluid content. In determining lithology, gamma ray log are used to differentiate sand from shale and calculating the volume of shale (Fens, 2000; Shankar, 2014). The presence of carbonates and other rock layers are difficult to be detected using gamma ray and spontaneous potential logs. Pore fluid are also usually predicted traditionally either using resistivity logs or a crossplot of porosity logs (density and neutron porosity). In the absence of resistivity logs, the porosity log can only be used to determine wet formation. Determining which fluid made the formation wet using porosity logs is impossible. It is therefore paramount to analyze log data using petrophysics and rock physics analysis to predict lithology and pore fluid content with less uncertainties.

Also, lithology and pore fluid prediction using petrophysics and rock physics analysis is unknown to have been carried out in the Tano. It is therefore paramount to determine the lithology and pore fluid using petrophysics and rock physics analysis to understand the effectiveness of this method in the Tano Basin.

## 1.3 Research objectives

The main aim of the research is to use density, compressional and shear wave velocity logs as input to predict the lithology and pore fluid of a reservoir in the Tano Basin. This research seeks to use petrophysics and rock physics analysis of log data to predict lithology and pore fluid content; however, the research was undertaken with the following specific objectives:

- Develop a MATLAB program to calculate elastic parameters such as velocity ratio, Poisson's ratio, Lamé parameters, etc.
- Identify the oil-water-contact
- Define the reservoir zone

## 1.4 Significance of the study

Lithology and pore fluid determination are very essential for the exploration and production process and are also fundamental to reservoir characterization. Understanding the lithology and pore fluid of a reservoir is the foundation from which other petrophysical parameters are determined. Porosity, permeability, and water saturation are physical properties that make it possible to evaluate a hydrocarbon reservoir. However, these physical parameters can be determined accurately only when lithology and pore fluid are determined accurately.

## 1.5 Scope of the study

Several wells have been drilled in the Tano Basin. Log data from three (3) wells have been provided for the study. After well grouping, one well was chosen for the detailed well log analysis. This study involved desk study, quantitative petrophysics and rock physics analysis of the well log data. The desk study involved assessing all information on the geology of the study area. A program, ELASP, was developed using MATLAB scientific programming environment to calculate elastic parameters. The calculated logs were then analyzed using RokDoc software. Petrophysics and rock physics analysis were performed on the log data to predict the lithology, pore fluid content, reservoir zone, and oil-water-contact of the well. The porosity of the reservoir was also calculated.

## 1.6 Thesis outline

The thesis consists of five (5) chapters. The first chapter introduces the project and includes the general introduction, problem statement, research objectives, significance of the project, and scope of the study as well as outline of the thesis. The second chapter is devoted to literature review and geology (regional and local) of the study area. The third chapter describes the data acquisition process and research methodology. The fourth chapter involves quantitative data analysis and discussion of the results obtained. Chapter five makes conclusions from the analysis and recommends possible future works.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Location and geological setting of the study area

The area under investigation is the Tano Basin, which is the eastern extension of the Cote d'Ivoire Basin located in the Gulf of Guinea, West Africa. It is roughly 35 km offshore of Ghana and in a water depth of about 75 m. It is East-West onshore-offshore structural basin (Davies, 1986). It covers an area of approximately 3000 square kilometers. It comprises the narrow Mesozoic coastal strip of southwestern Ghana, the continental shelf, and steep submarine Ivory Coast-Ghana ridge which form the continental slope (Mah, 1987).

The Tano Basin is a Cretaceous wrench altered pull-apart basin confined by the Romanche and the St. Paul transform fault as shown in Figure 2.1 below.

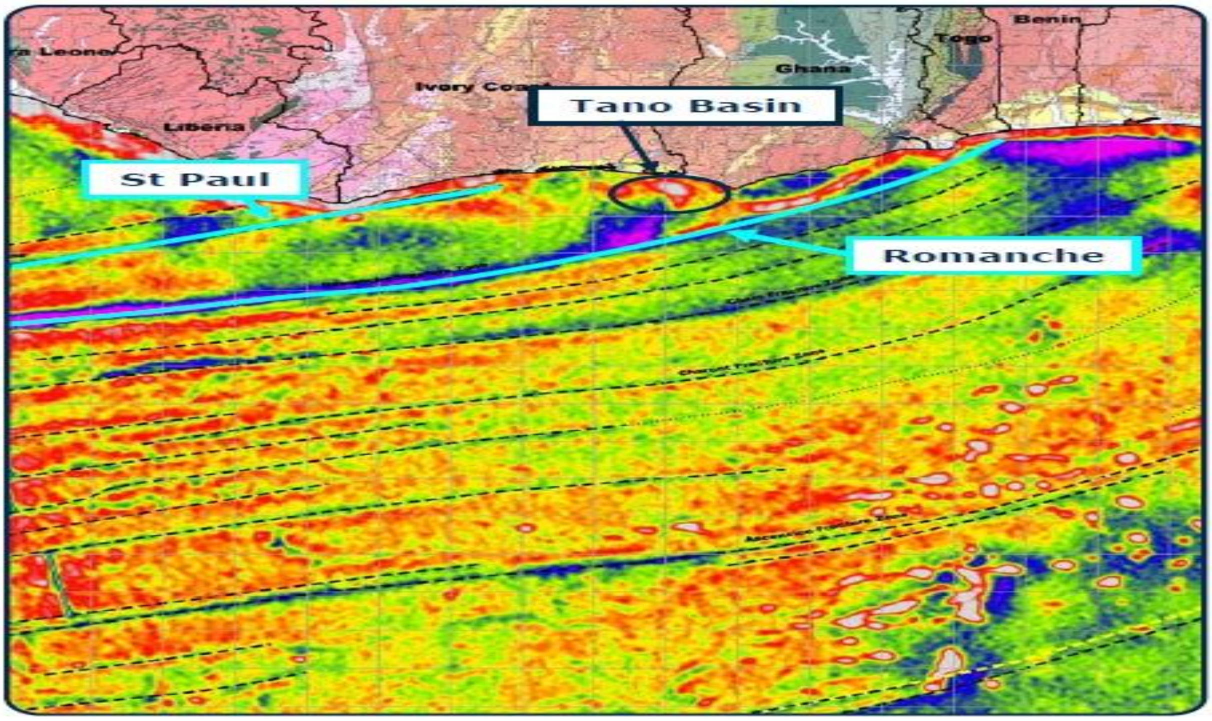


**Figure 2.1:** Tano Basin confined by Romanche and St Paul transform fault (Tullow report, 2008).

The Tano Basin is part of an extensional rift basin system which received substantial clastic sediment input from the African continent (Tullow report, 2008). The basin is divided into the SHALLOW WATER and DEEPWATER TANO as shown in Figure 2.2.

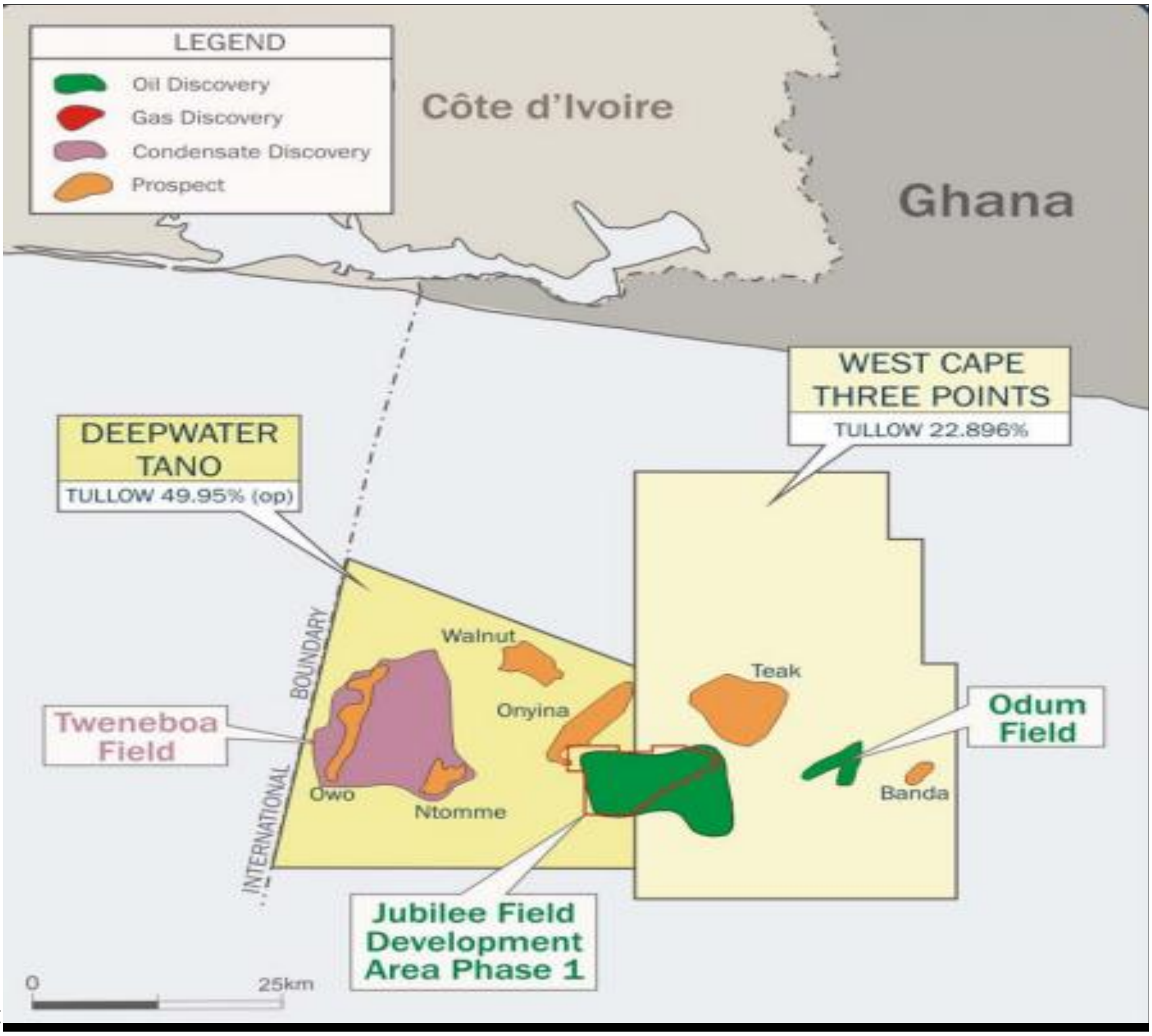


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**Figure 2.2:** A map of the Tano basin (Tullow Ghana Ltd, 2009).

The basin was formed due to the transitional movement, i.e. dynamic rifting and sinking, during the parting of Africa and South America, and opening of the Atlantic in the Albian. The rapid drowning of the West Africa transform margin created an ideal condition for the deposition of thick rich Cenomanian source rock. Numerous river systems donated substantial clastics into the deep basin which led to the deposition of huge turbidites. The burial depth of source rock and anoxic conditions which preserve organic material made it possible for oil generation. The presence of effective seal reserves the oil and gas for detection and development (Tullow report, 2008).

The basin has a thick upper Cretaceous drift section which is dominated by basin floor fans. The basin floor fan generates paths for migration and productive reservoir. The rift segment consists of shallow marine to continental deposits. The basin has a Cretaceous working play which comprises of Cenomanian-Turonian and Albian shale with Turonian slope fan, turbidite sandstones and Albian sandstones in tilted fault blocks as reservoirs. The hydrocarbon trap present is both structural and stratigraphic. Turbidite fans forms stratigraphic trap for oil, migration route and productive reservoir. Traps are usually formed at zones with thinner flank and where sand is absent (Tullow report, 2008).

## 2.2 Evolution and outcome of the Tano Basin

### 2.2.1 Evolution of the basin

The Tano Basin is a classic transform margin (differential movement due to the oceanic crust spreading is formed by slip on transform faults) basin, which was created during the Early Cretaceous as Africa was detached from South America (IHS report, 2011). Transform margin is the point of contact for transform faults at the continents and are usually associated with limited oceanic movement. Organic materials preserved at anoxic conditions can generate hydrocarbon provided they are buried under favorable conditions (Tullow report, 2008). The opening of the South Atlantic Ocean is the reason why the Basin exist. The strike-slip plate tectonics movement initiated the basin. The Gulf of Guinea margin shows two important tectonic differences to the “passive” South Atlantic margin of Nigeria: the influence of transform tectonics and the absence of salt and, therefore, of halokinesis (IHS Report, 2011).

### 2.2.1.1 Aptian - Albian (122 Ma – 108 Ma)

The South America and Africa plate where initially not separated as shown in Figure 2.3 below.

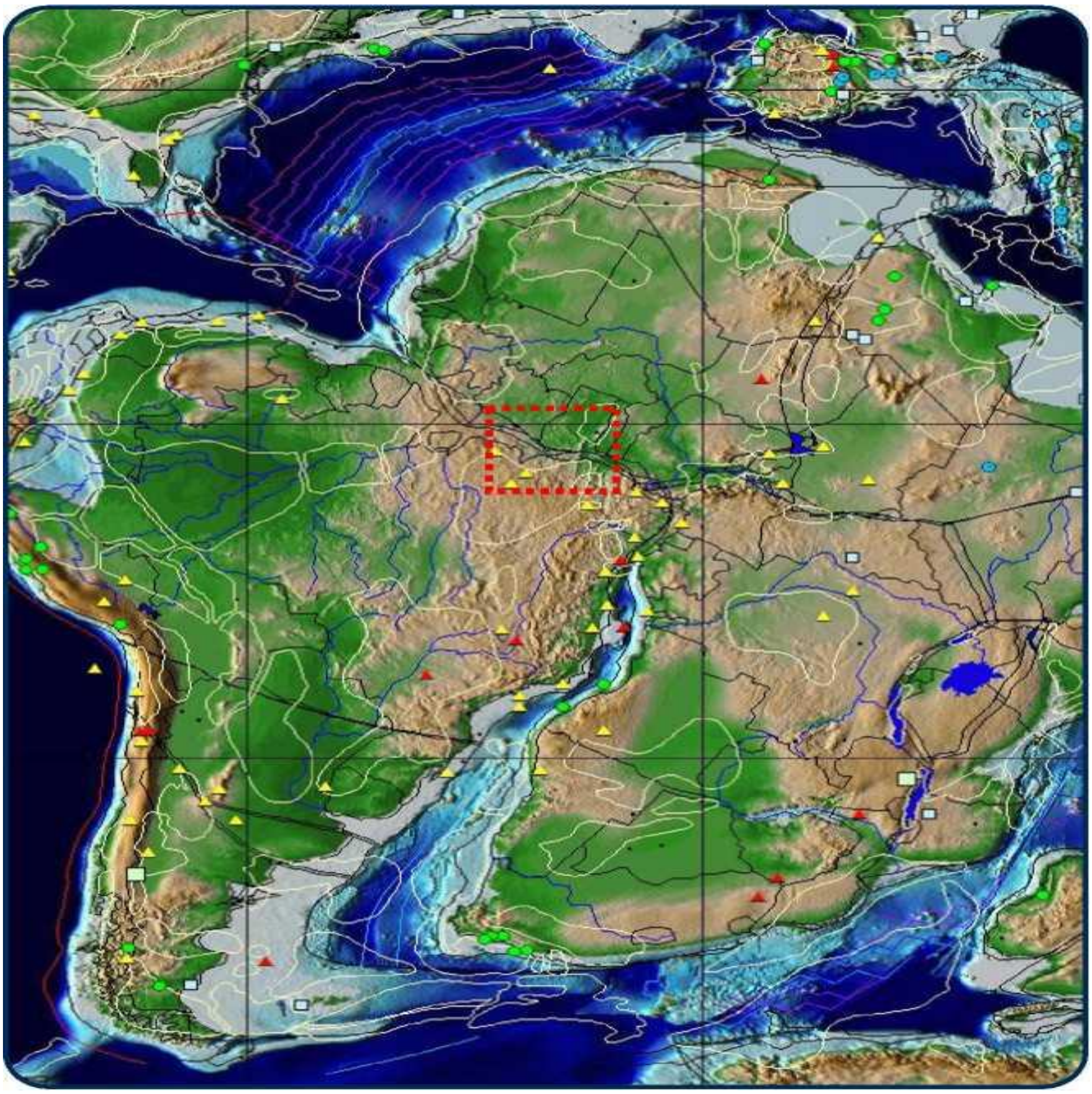

**Figure 2.3:** South America and Africa plate before the separation (Tullow report, 2008).

The Aptain marks the beginning of the departure of the North and South Atlantic as shown in Figure 2.4 below.

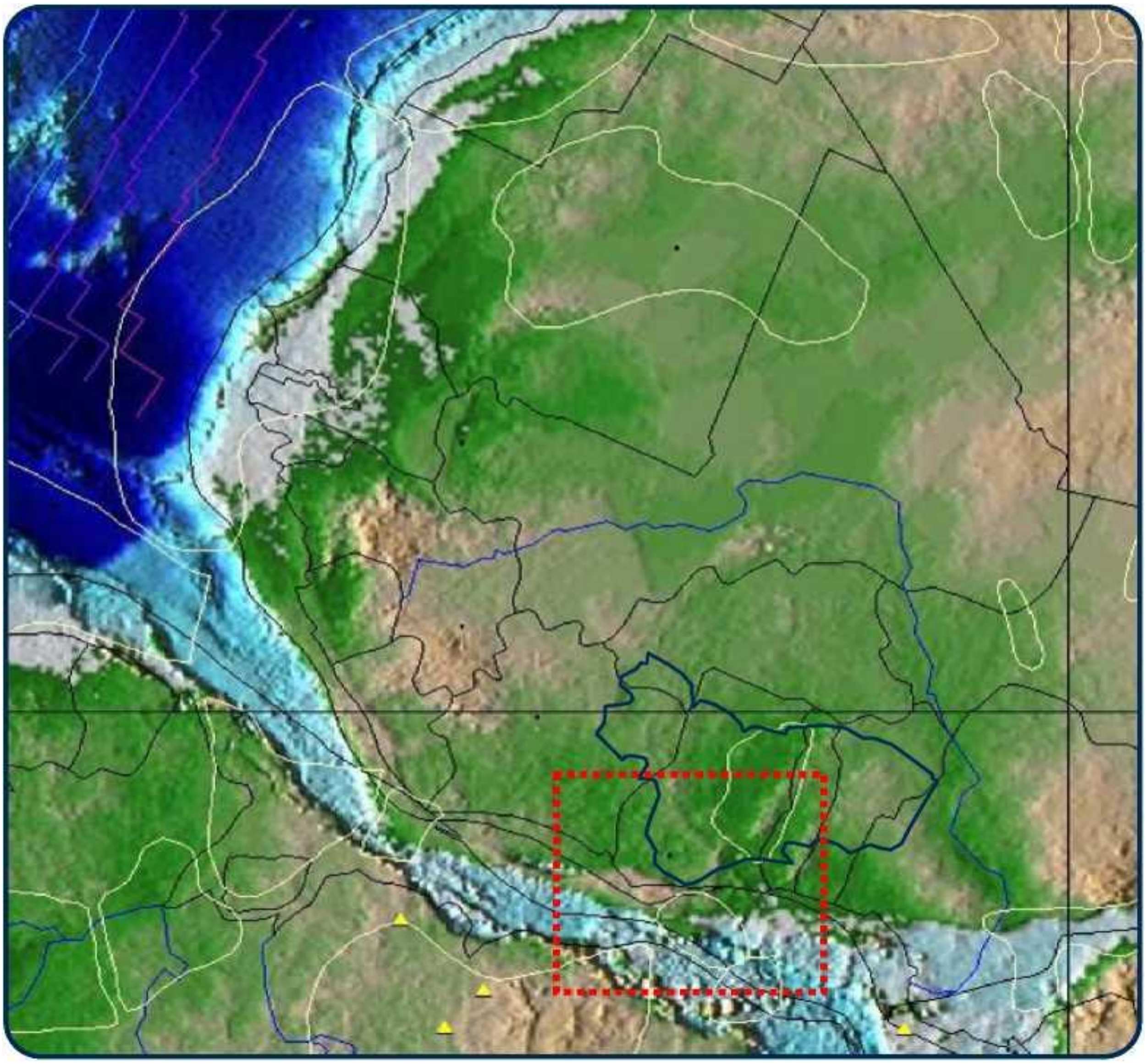

**Figure 2.4:** Gradual separation of South America and Africa plate (Tullow report, 2008).

Substantial topography was emerging in the West Africa Transform Margin which was initially not within the open ocean, started emerging due to the movement of the plates. Lakes provided an essential platform for the deposition of rich organic matter (Tullow report, 2008).

A dense syn-rift segment is recognized, starting with continental lacustrine to marine deposits in Aptian to Early Albians time. Tilted fault blocks which occurred in the Aptian-Albian were created due to marine incursion (localized uplift and erosion occurrence). Majority of the syn-rift sequence was the clastic depositional system which developed to the south of the east-west trending Lagune Fault Zone (Tullow report, 2008). The clastic deposition was mainly influenced by topology. The last contact among the plates of the continental crust, manifest by the Albian-Cenimanian unconformity, was in the Late Albian.

#### 2.2.1.2 Cenomanian – Turonian (93 Ma)

Cenomanian marks the complete separation of the African and South American plates as shown in Figure 2.4 below.

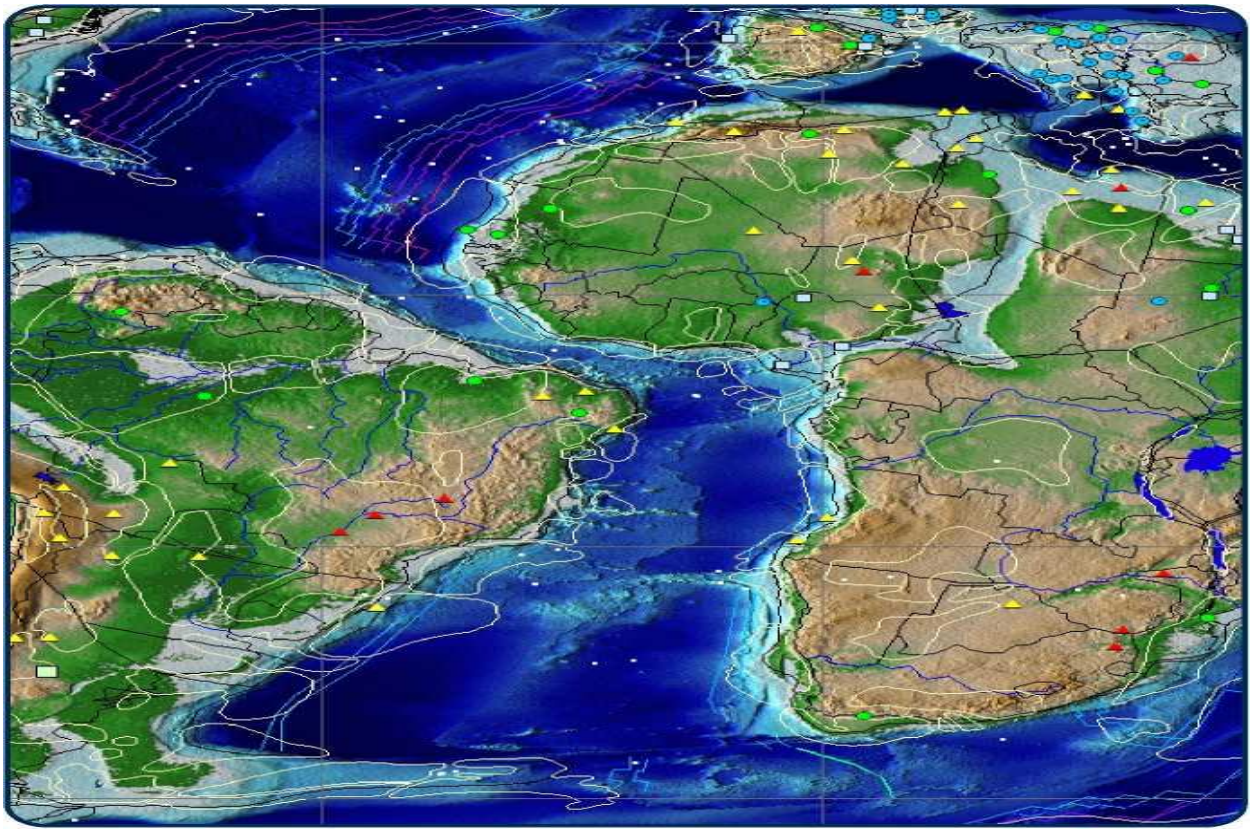

**Figure 2.5:** Complete separation of South America and Africa plate (Tullow report, 2008).

The swift sinking of the West African Transform Margins in the Cenomanian provides favorable environment for deposition of dense rich source rock. Creation of a deep basin, with significant river systems onshore, led to deposition of large turbidite fan/channel complexes in deep water (Tullow report, 2008).

In the late Cenomanian, oceanic spreading center was established between the Romanche and St. Paul Fracture Zones. The Albian age fault blocks are obscured by post transform sedimentation and marine deposit. The sediments are largely clastic with tiny carbonates present at the initial stages of drifting.

Following the oceanic opening and sea floor spreading, the continental margin was subsiding as oceanic crust cooled and foundered in the Gulf of Guinea area, and as the ocean-continent transition zone was readjusting structurally (IHS Report, 2011). The Ghanaian ridge spreading beside structural closure was as a result of local and irregular fault, manifest by regional unconformity occurring.

### 2.2.2 Outcome of Tano Basin evolution

#### 2.2.2.1 Source rock

The main source rock of the Tano basin are contained in the Albian and Cenimanian – Turonian series. The source rocks were then covered up upon the establishment of maturation peaks in later Cretaceous and Tertiary times (IHS report, 2011). Probable source rocks are also evident in Upper cretaceous, lower Senonian, and Maastrichtian.

#### 2.2.2.2 Reservoirs

Clastic reservoir of the lower and upper cretaceous exist in the Tano Basin. The Albian sandstone are the most important reservoirs and bulk of reserves have been discovered in deep water Ghana in upper cretaceous sandstones, which exhibit good to excellent reservoir properties (IHS Report, 2011)

#### 2.2.2.3 Seal

Seals are present in both the lower and upper cretaceous sequence. Regional, local, and intraformational shale made up the seal. Hydrocarbon that are migrated into the sandstone reservoir from the cretaceous and tertiary times are sealed by the shales in the lower and upper cretaceous sequences. Unconformities and local fault patterns present in the basin also enhances the integrity of sealing.

## 2.3 Well logging

Logging basically means “to create a record” of something. After Marcel and Conrad Schlumberger introduced well logging to the hydrocarbon industry, geoscientists have made enormous effort to improve the logging process. The logging method was improved mainly by improving the instruments used for data collection and software for data processing. Due to advance in technology, electronics, and instrumentation, the well logging technique has evolved swiftly. The well legging technology is applied in all the stages of exploration and production i.e. from first wild cat well drilling in a field to the desertion of the last productive level in the same field. Well logging can now be used to measure great number of physical properties of the geological formation (and the surrounding environment) intersected by a well and both in open and cased hole conditions (Che, 2011). Well logging has numerous applications which includes:

- Petrophysical analysis
- Formation Evaluation
- Reservoir characterization

- Reservoir management
- Production optimization
- Geomechanics
- Geosteering

The logs significant to this research are density logs, compressional wave velocity logs, and shear wave velocity logs.

## 2.4 Petrophysics and rock physics

### 2.4.1 Petrophysics

Well log analysis and modeling is a central component of the exploration and production process. Petrophysical behavior and reservoir rock properties are assessed using geophysical well log data, core data, and if available, seismic data in collaboration with geology. The precision of petrophysical properties to be extracted during petrophysical analysis depends on the type and number of log data available.

During well logging, as the logging tools are being pulled up in the well, their sensors are measuring certain physical properties of formations (Welex, 1978). After logging, it is the task of the well log analyst to determine the existence and quantity of hydrocarbon in the well. Petrophysical analysis is employed to determine petrophysical properties of a reservoir which includes:

- Lithology: the type of rock matrix present in the formation. The physical and chemical properties of a rock formation is detected by tools which are used to measure formation properties (Oil India Department, 2011). A petrophysicist can use well log data such as gamma ray, neutron density, bulk density, and their combination with local geology and core data as aid, to determine lithology.

- Porosity: the volumetric void space existing between grains, cracks, or cavities of a material capable of storing fluids (Smithson, 2012). It is usually expressed as a fraction and ranges between 0 and 1. Two types of porosity, namely primary and secondary porosity, can exist in rocks. Primary porosity describes the porosity that exists at the time the rocks are formed whilst secondary porosity is developed after rock deposition. Porosity can also be described as effective or total. The ratio of the total pore space of a rock to the bulk volume describes total porosity whilst effective porosity describes the total porosity minus porosity of shale.
- Permeability: an intrinsic property of a rock describing the ease of flow of fluids through a formation (Desbrandes, 1985). The unit of permeability is darcy. Permeability can be grouped into absolute and effective permeability. Absolute permeability is the permeability existing in a rock occupied by a single fluid while effective permeability is the permeability existing in a rock occupied by more than one fluid. Permeability is not sensitive to the fluid type (oil, gas, or water) but affected by different flow rates per unit pressure due to differences in viscosity and saturation.
- Saturation: the amount of pore space occupied with fluid. Water saturation, then, is the amount of pore space occupied with water. Hydrocarbon saturation also refers to the amount of hydrocarbon in the pore space of a formation. If only water exist in the pores of a rock, then the formation is said to have a 100% water saturation. Water saturation less than 100% basically implies the presence of hydrocarbon and is calculated using the relation $(1 - Sw)$ (Pirson, 1963).
- Net pay: the thickness of a rock that contributes to economically viable production with current technology, prices, and cost (Crain, 1986). Net pay is a varying parameter since technology, prices, and cost keeps varying. Determination of net pay

is accomplished by placing cut offs on permeability, porosity, water saturation, and shale volume.

### 2.4.2 Rock physics

Rock physics is an indispensable tool for an efficient interpretation, providing the basic relationship between the lithology, fluid, and geological deposition environment of the reservoir (Chi and Han, 2009). Rock physics can also be applied to build a template to enhance reservoir characterization (Ødegaard and Avseth, 2004; Avseth et al., 2005).

Rock physics provides information that is valuable to provide the link between petrophysics, geomechanics, and seismic data and the internal rock properties such a porosity, mineralogy, pore space, pore fluid, etc. Various rock physics templates are available but suitable rock physics model must be consistent with available well log data, core samples, reservoir engineering figures, and seismic data. Rock physics is integrated into the general techniques, strategies, algorithms, and the complete process of exploration, and simultaneously is an integrating part of this process, because rock physics couples and connects the different disciplines (Schön, 1996). Rock physics models were first created from petrophysical study of well log and core data. The models were then updated and enhanced by geological information and acquired seismic data. The rock physics model when compared to available reservoir properties are consistent and can be used for numerous applications.

### 2.4.3 Rock physics and petrophysics

While petrophysics evaluates reservoir formation and properties, rock physics emphasizes on understanding the relationships between the measured geophysical records and the in-situ rock properties. Petrophysics and rock physics analysis are usually carried out independently but when integrated, enormous understanding of the relation between reservoir formation and in-situ rock properties can be obtained (Saberi, 2013). To integrate the petrophysics and rock physics processes, a strong relation between the two disciplines is required. Outcome of petrophysical analysis provides primary input (porosity, volume of shale, etc.) used to construct and condition an effective rock physics model. These input parameters are often updated and used to calibrate the rock physics model. Such a model embodies a valid relationship at the well location. However, to use such a model on a larger scale, the model should be calibrated with available information including seismics. To make the model global, geological knowledge, geochemistry, and other data should be incorporated in the model.

### 2.4.4 Challenges of rock physics

Rock physics has made significant advancement which has increased its application. However, rock physics has many challenges and unanswered questions. The challenges encountered make the science of rock physics tough in some circumstances to create a valid model. These problems encountered require more research on the science and application of rock physics. Rock physics challenges described by Saberi (2013) include but are not limited to:

- Velocity variation: velocity estimation is a very herculean task due to the complexity of the subsurface. Many factors affect velocity but some of these factors are unaccounted for by combining the available information. This accounts for failures in rock physics models which cannot be explained scientifically but the same models may work at a different locations.

- Assumptions: rock physics models are based on assumptions which validate them under certain conditions. The assumption made restrict the application of rock physics to specific conditions.

## 2.5 Software Used

RokDoc software by Ikon Science is the primarily software used for the project analysis. RokDoc is a powerful, easy to use, comprehensive quantitative interpretation software. The academic license was used to operate the software. RokDoc software is made available largely because of the on-going partnerships between Ikon Science and major oil companies in addition to the over 170 companies directly feeding into its development.

RokDoc software was used for this project mainly because it provides interpreters access to rock physics, forward modelling, seismic inversion, geopressure, advanced quantitative reservoir analysis and geomechanics. Also, it allows researcher to maximize the value of available data and regional knowledge.

# CHAPTER THREE

# METHODOLOGY

## 3.1 Data Acquisition

The logging process can be done during or after the well is drilled. Below is a description of the data collection procedure.

### 3.2.1 Density logging

Density logging is a type of well logging which can offer continuous record of information regarding bulk density of formation along the borehole length. In geological terms, bulk density is related to the mineral forming the rock. Density log can be used to:

- calculate porosity
- determine lithology and mineralogy
- determine permeability
- determine fluid type

The density logging tool placed in a sonde, has a detector and a source filled with artificial gamma ray (Cobalt or Cesium), and slowly dropped down the drilled hole. The plough-shaped edge of the sonde can penetrate the mudcake. The spring also enables the sonde to press against the wallrock of the well. These artificial gamma rays in the source emits 0.66 MeV gamma rays into the surrounding formation resulting in the elastic collision between the emitted gamma rays and electrons of the surrounding formations. This elastic collision known as Compton scattering results in the reduction of energy. The quantity of Compton scattering collisions is directly related to the number of electrons in the formation (Schlumberger, 1989b). The number of collisions over any particular interval of time depends upon the abundance of electrons present (the electron density index), which in turn is a function of the density of the formation (Keary et al., 2002). The quantity of gamma rays that are sensed by the detector are related to the electronic density of the formation. By measuring the quantity of returned gamma rays detected, density can be estimated.

Electronic density relates the bulk density mathematically as

$$\rho_e = 2\rho_{bulk} * \frac{Z}{A} \quad (3.1)$$

where

$\rho_e$ = electronic density,

$\rho_{bulk}$ = formation bulk density,

A = atomic number,

Z = molecular weight of the compound.

The response of the density tool is controlled by the electronic density in g/cm³. The low penetrative ability of the gamma ray limits the area of investigation. When the density log has been correctly calibrated, it provides consistent information about the bulk density of the matrix. Table 1 below are some rock matrix with the associated empirically derived density.

**Table 1**: Rock matrix with the associated density. (Peng and Zhang, 2007)

| ROCK MATRIX | DENSITY (g/cm³) |
|---|---|
| Sandstone | 2.0 – 2.6 |
| Limestone | 2.5 – 2.8 |
| Dolomite | 2.5 – 2.6 |
| Shale | 2.0 – 2.7 |

Figure 3.1 below is a sample density logging tool.

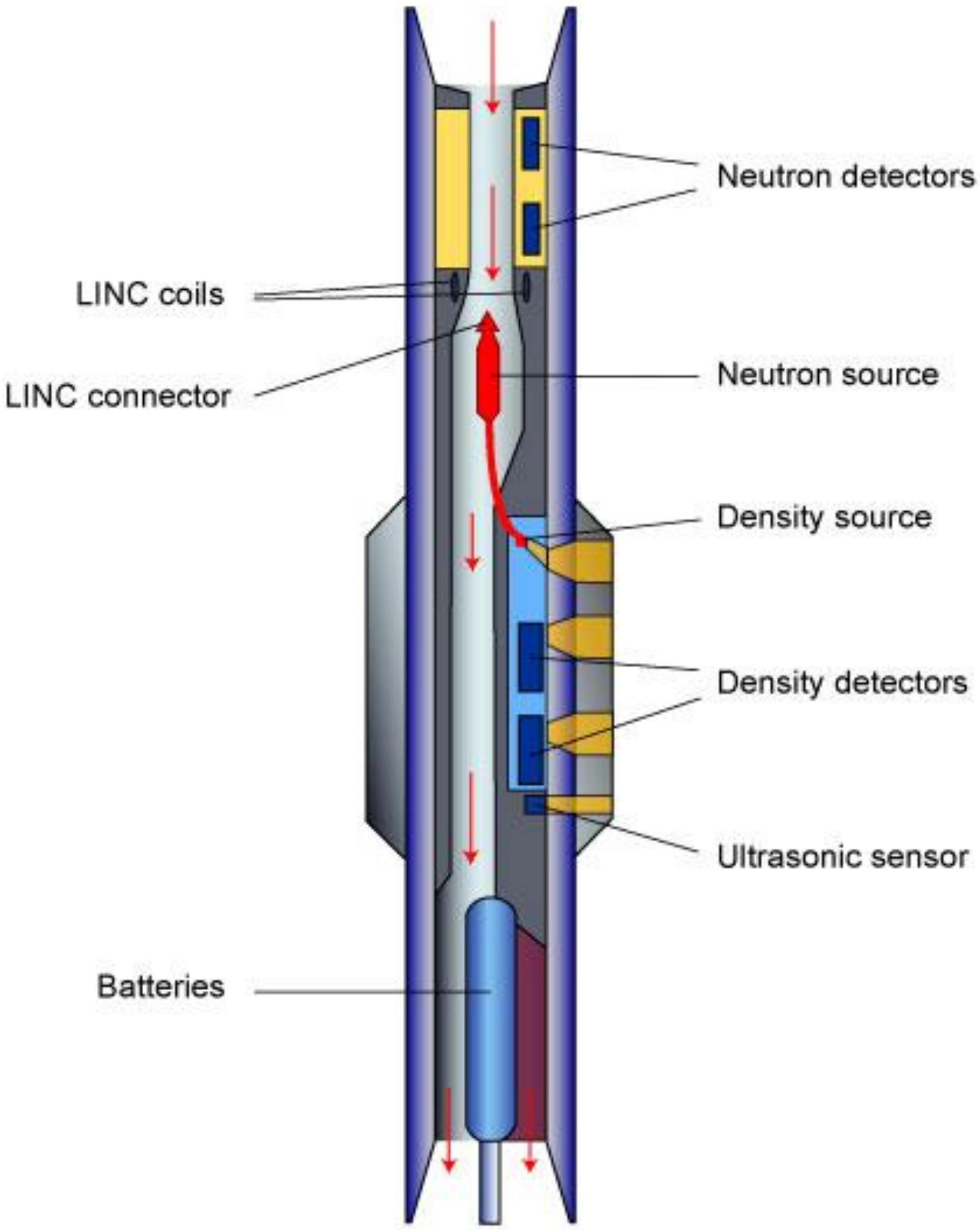


**Figure 3.1:** A sample density logging tool (Courtesy: International Ocean Discovery Program)

### 3.2.2 Acoustic logging

Data acquisition using acoustic logging covers an extensive range. Acoustic logs are reliant on Snell's Law inherent properties to transmit sound from the logging through the rocks to the receiver. Acoustic logs require a borehole filled with fluid to enhance their operational capabilities. Acoustic logs can be used to:

- Estimate porosity
- Identify lithology
- Determine the mechanical properties of rocks.

Acoustic logging is based on the wave propagation theory in an elastic medium. The propagation of sound through a source (transducer) in an elastic medium results in oscillating motion called acoustic wave (Paillet and Cheng, 1991; Mavko et. al., 1998; Hearst et. al., 2000). Acoustic logging tools are specifically designed to measure one or more of velocity, amplitude, amplitude attenuation, and/or frequency. Acoustic logging tools are used to record the travel time of a compressional wave as it propagates through a formation, and can also record shear velocity which can be used to enhance understanding of rock mechanical properties.

The sonde used for acoustic logging has either one source and two receivers or two sources and four receivers as shown in Figure 3.2. The source which generally consists of piezoelectric transducer is about 1.5 m from the closest receiver and the receivers about 0.3 m apart. An ultrasonic frequency of 20 – 40 kHz is generated and transmitted by the source through the medium. The particles of the medium only vibrate around the central point. Since the wallrock invariably has a greater velocity than the drilling fluid, part of the sonic pulse is critically refracted in the wallrock and part of its energy returns to the sonde as a head wave (Keary et al., 2002). The measurement of the differential travel time between the receivers can be made because a timer is activated for each of the sonic pulses. The direction of propagation of particles with direction of wave propagation as reference are used to classify acoustic waves. Longitudinal and transverse waves are the two types of acoustic waves. Longitudinal (compressional) waves propagate parallel to the direction of propagation of the wave while transverse (shear) waves propagate perpendicular to the direction of travel of the wave. Figure 3.2 is a schematic diagram of an acoustic logging tool.

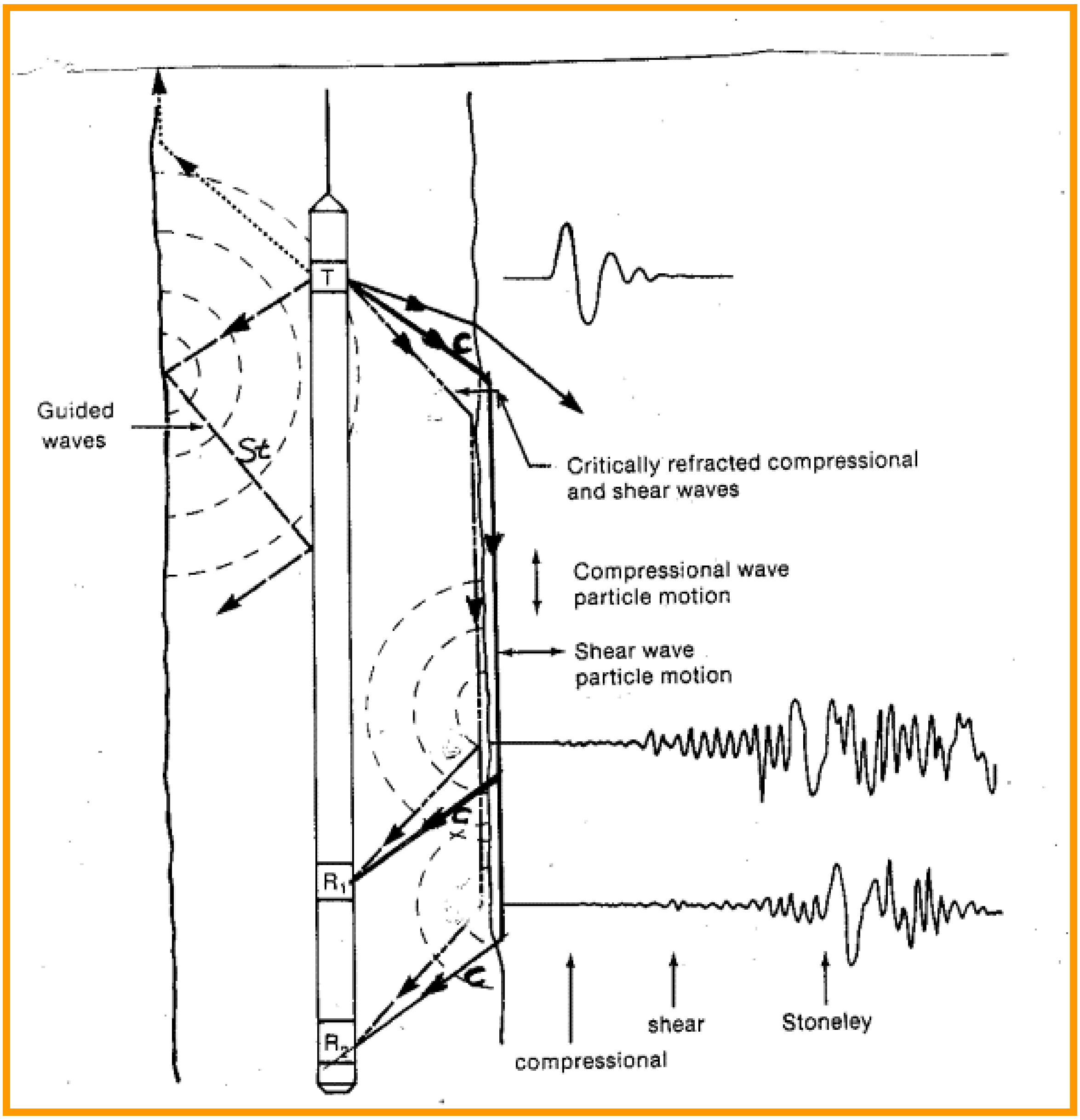


**Figure 3.2:** A sample acoustic logging tool (Courtesy: Crain's Petrophysics Handbook).

Acoustic logs can offer valuable information about physical rock structure when calibrated correctly. The physical structure of the rock defines the ability of sound to travel through rocks. The amplitude, speed and phase relationships of a transmitted sound wave that returns to an acoustic receiver is a function of all of the combined matrix densities, interconnections, cementation, fracturing, and porosities within the matrix (Thomas, 1977). Because the total transit time from the transmitter to the receiver includes the path through the borehole fluid, borehole compensated (two or four receivers) logging tools are used (Kuffour, 2008). Porosity can be determined from acoustic log using the relationship established between porosity and transit time as shown in equation 3.2 below.

$\theta = (\Delta t - \Delta t_{ma}) / ((\Delta t - \Delta t_{f})$ …………………………………………………………… (3.2)

where

$\Delta t$ = acoustic transit time (**µ**sec/ft)

$\Delta t_{ma}$ = acoustic transit time of interstitial fluids (**µ**sec/ft)

$\Delta t_{f}$ = acoustic transit time of rock matrix (**µ**sec/ft)

**3.3 Research methodology**

Well log data can be a source of essential information capable of defining and describing reservoir and other important parameters. Three wells have been considered for this thesis but only one well, WELL Z, was chosen for the detailed analysis. This well was chosen because compressional wave velocity log, shear wave velocity log, and density log present were in good condition.

The methodology employed for this research are listed below:

- Loading of the input logs (density, compressional, and shear wave logs)
- Conditioning, editing, and reconstruction of input logs.
- Developing a program to compute velocity ratio, Poisson’s ratio, and Lamé parameters.
- Petrophysics and rock physics analysis of data.

These steps were carefully carried out to avoid or reduce errors. The research methodology in chronological order is presented above.

A display of the flow chart for the methodology and analysis is presented in Figure 3.3.

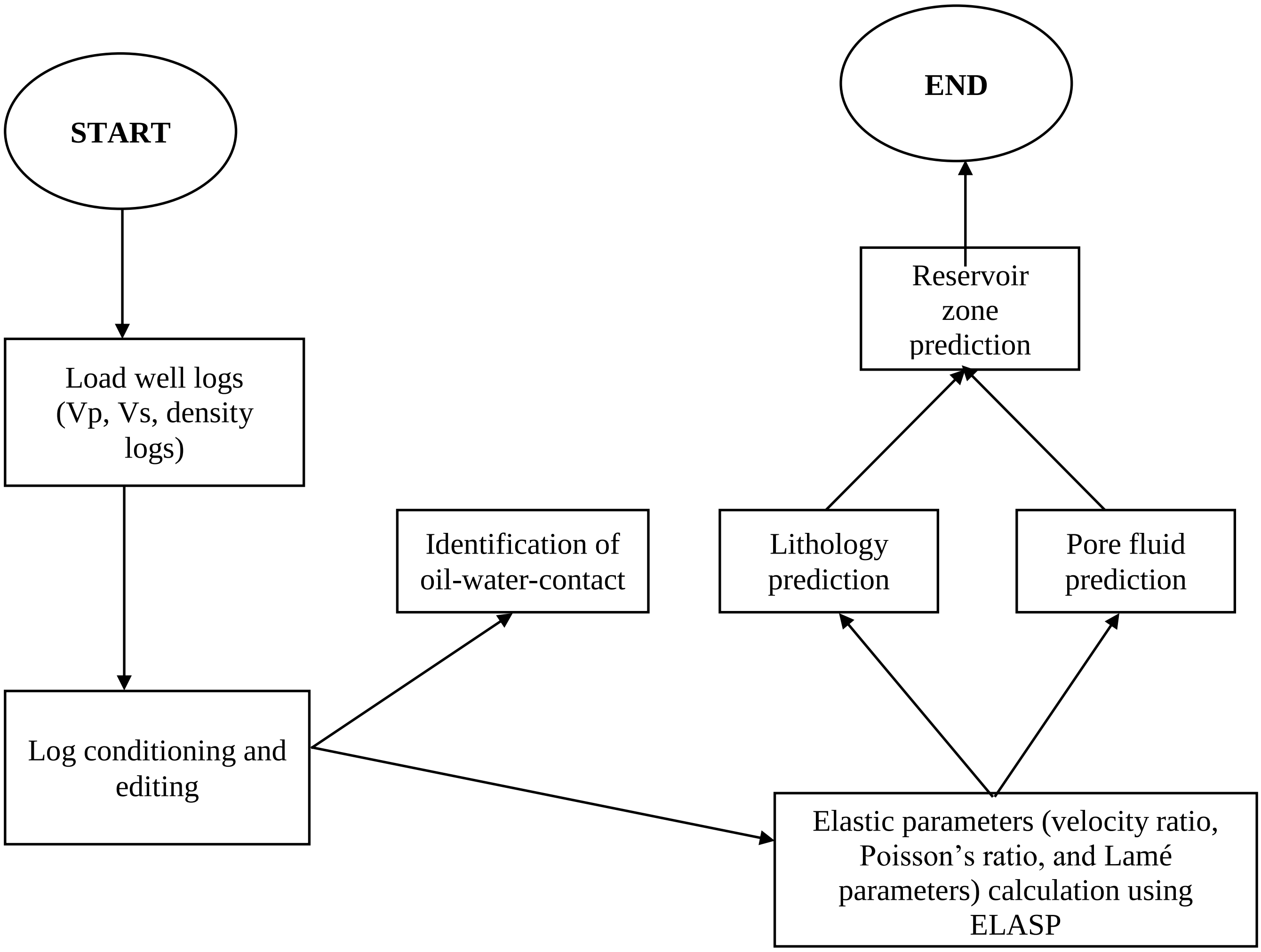


**Figure 3.3:** Research flow chart

### 3.3.1 Loading well log data

The density, compressional wave velocity, and shear wave velocity logs of WELL Z were imported and displayed using the RokDoc Software. The Kelly bushing elevation, log type, and unit were specified prior to the display of the log data. Figure 3.4 below shows the log data before conditioning and editing.

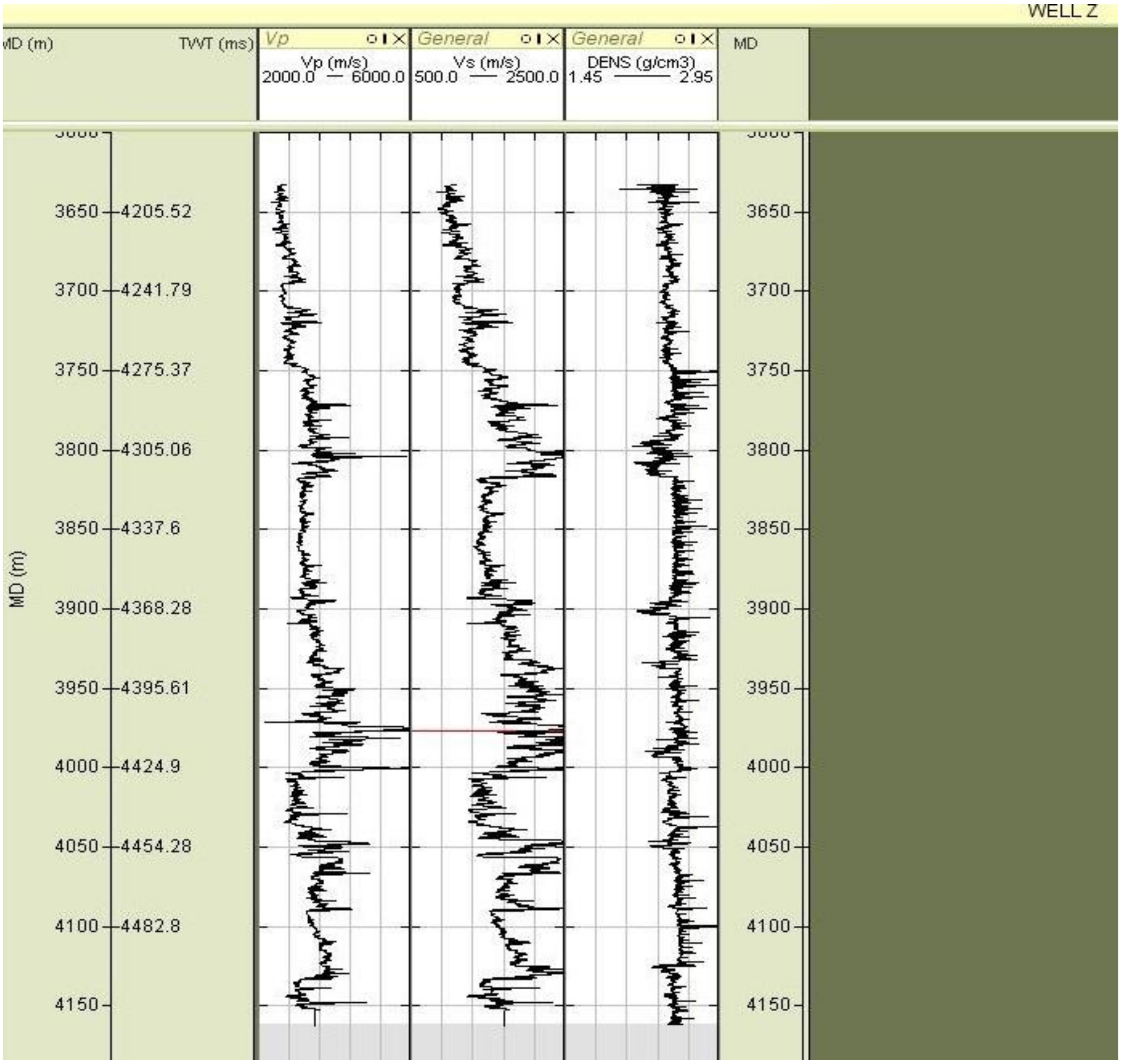


**Figure 3.4:** A display of WELL Z

### 3.3.2 Log conditioning and editing

Well logs data are often regarded by geophysicists as “hard data” because the probing instruments take the measurements from a very close range to the rocks under in-situ conditions (Bediako, 2011). Hence, well logs are not exposed to rigorous editing and conditioning as seismic data. This can be a source of error because log data are exposed due to geological complexities, uncertainties in measurement, etc.

Almost all well log data need to be edited and corrected before interpretation of the log. This corrections are applied to eliminate or reduce errors such as: mud filtrate invasion, gaps, deficient log data, etc. Editing and conditioning of well log is usually generalized if not ignored prior to rock physics application and geophysical modeling. Frequent editing of well log data would require depth shifting, estimation of pseudo-data to replace bad log data, and invasion corrections (if necessary) (Smith, 2011). The editing process are often oversimplified by geophysicist because these edits are below seismic resolution (Walter, 2012). However, prior to any log-based seismic models, log editing should be executed carefully to avoid inaccurate assumptions and seismic amplitude response.

The density and compressional wave velocity logs used for the study was of good quality, however, the shear wave velocity log had a gaps. The error due to the gap (red line in the Vs log) was corrected using the spline interpolation technique. One gap was identified, however, the quantity of unrecorded data can be estimated. The new log, labelled as Vs_1, was plotted and displayed. The logs with the gaps and interpolated new log are shown on the next page as Figures 3.5 and 3.6 respectively.

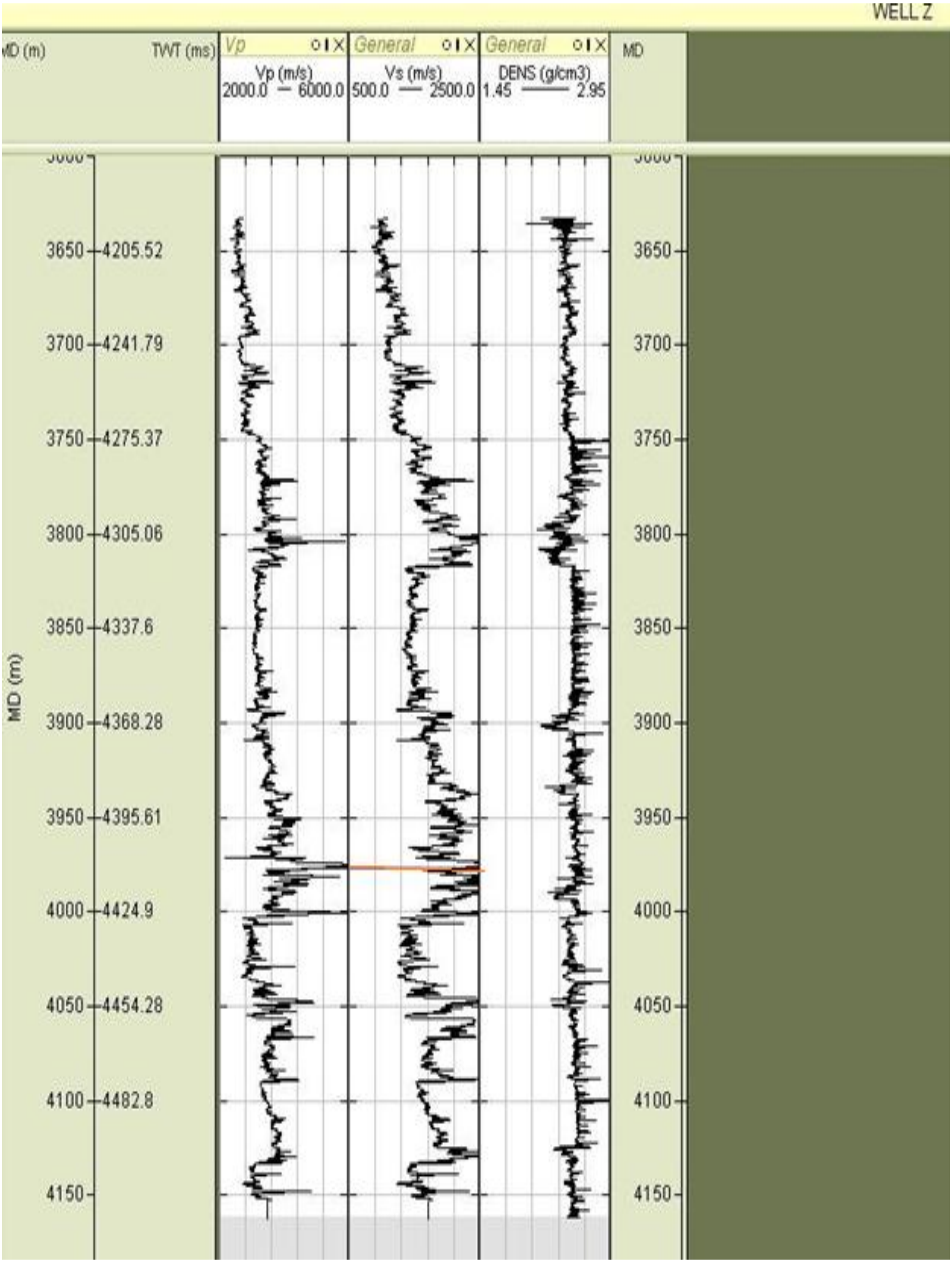


**Figure 3.5:** Gap present in shear wave velocity logs shown in red.

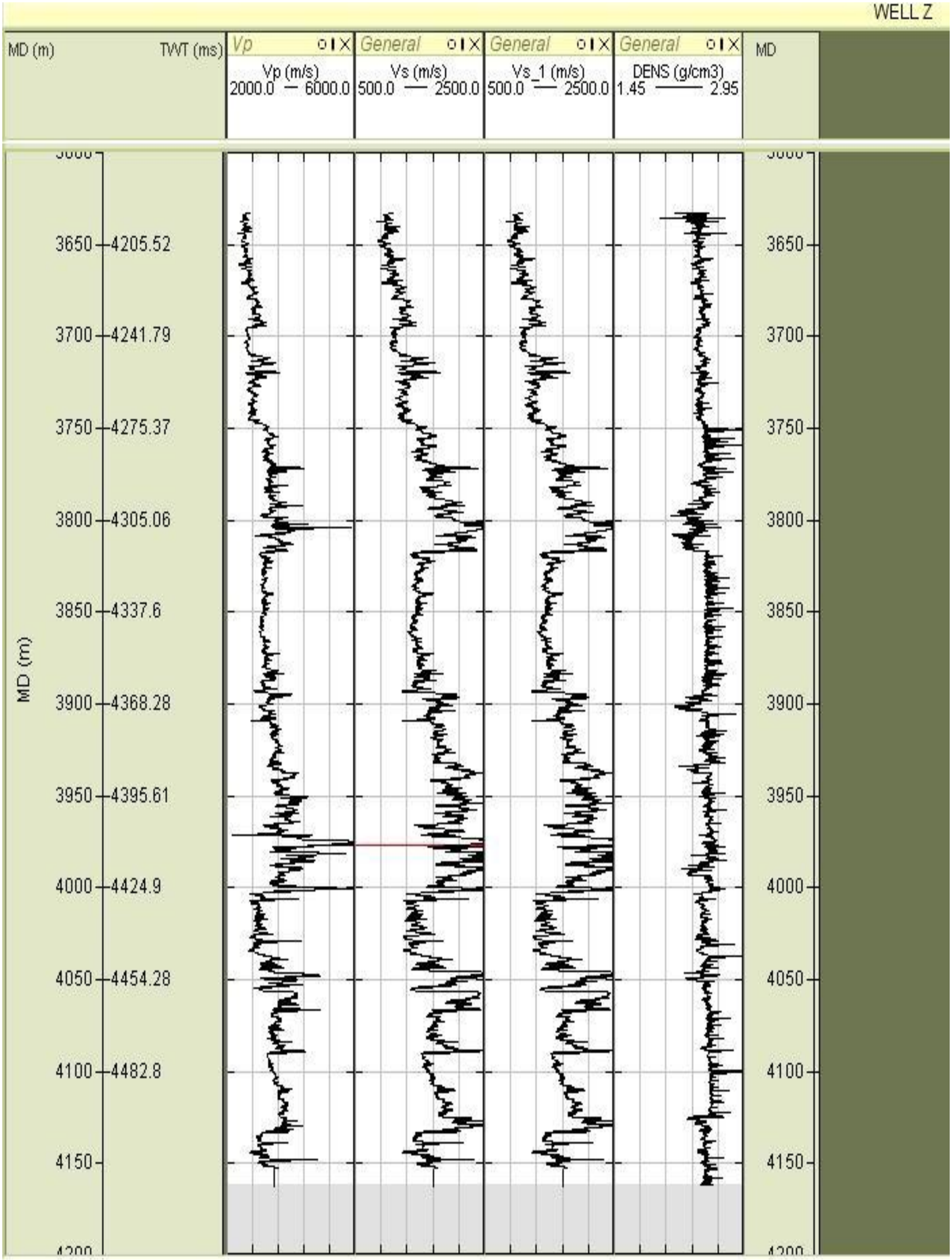


**Figure 3.6:** Well Z with interpolated Vs log

### 3.3.3 Calculating elastic parameters using ELASP

Lamé parameters ($\lambda$, $\mu$), velocity ratio, and Poisson's ratio are important elastic parameters for quantitative analysis of well logs. Lamé parameters ($\lambda$, $\mu$) are used by interpreters to gain insight into rock physics (Perez and Ton, 2010). Lamé parameters also aid in lithology and fluid determination, which is the main objectives of this research, hence the need to calculate these parameters. Poisson's and velocity ratios aid in fluid and lithology discrimination. Poisson's and velocity ratios can also be used to identify the different pore fluid content of a formation.

To calculate these useful elastic parameters, a computer program, ELASP, was develop using MATLAB scientific programming software.  was used to compute velocity ratio, Poisson's ration, and Lamé parameters using density and velocity logs as input. Velocity ratio, Lamé parameters, and Poisson's ratio were calculated using equations (3.2), (3.3b), (3.4b), and (3.5) respectively.

$$v = {}^{V_p}\!/_{V_s} \quad \text{……………………………………………………} (3.2)$$

$$Vs = \sqrt{(\mu/\rho)} \quad \text{……………………………………………………} (3.3a)$$

making $\mu$ the subject of equation (3.3a),

$$\mu = \rho * V_s^{\,2} \quad \text{……………………………………………………} (3.3b)$$

$$\text{But } Vp = \sqrt{\frac{\lambda+2\mu}{\rho}} \quad \text{……………………………………………………} (3.4a)$$

making λ the subject of equation (3.4a),

$$\lambda = \rho * V_p^{\,2} - 2 * \rho * V_s^{\,2} \quad \text{……………………………………………………} (3.4b)$$

$$\Phi = \frac{\lambda}{2 * (\lambda + \mu)} \quad \text{……………………………………………………} (3.5)$$

where

v = velocity ratio,

Vp = compressional wave velocity log

Vs = shear wave velocity logs

$\lambda$ = incompressibility

$\mu$ = rigidity modulus

ρ = density

$\Phi$ = Poisson's ratio

To ensure that the unit of the calculated Lamé parameters is Pascal, the unit of the input parameters were converted to g/cc$^3$ for density, and m/s for the velocity log.

The ELASP program uses the density, compressional, and shear wave velocity logs as input to calculate the elastic parameters. The following conditions must be satisfied to ensure accurate calculation of the elastic parameters:

- the exported log data must be in excel with the extension "xls", "xlsx", "xlsm", or "xlsb".
- the excel data must be on sheet 1
- Measured depth, Vp, Vs, and density logs must be on rows A, B, C, and D respectively.

After calculating the elastic parameters, the results are exported and displayed on an excel sheet. The calculated parameters are then loaded and plotted using RokDoc. Below is a log some calculated elastic parameters.

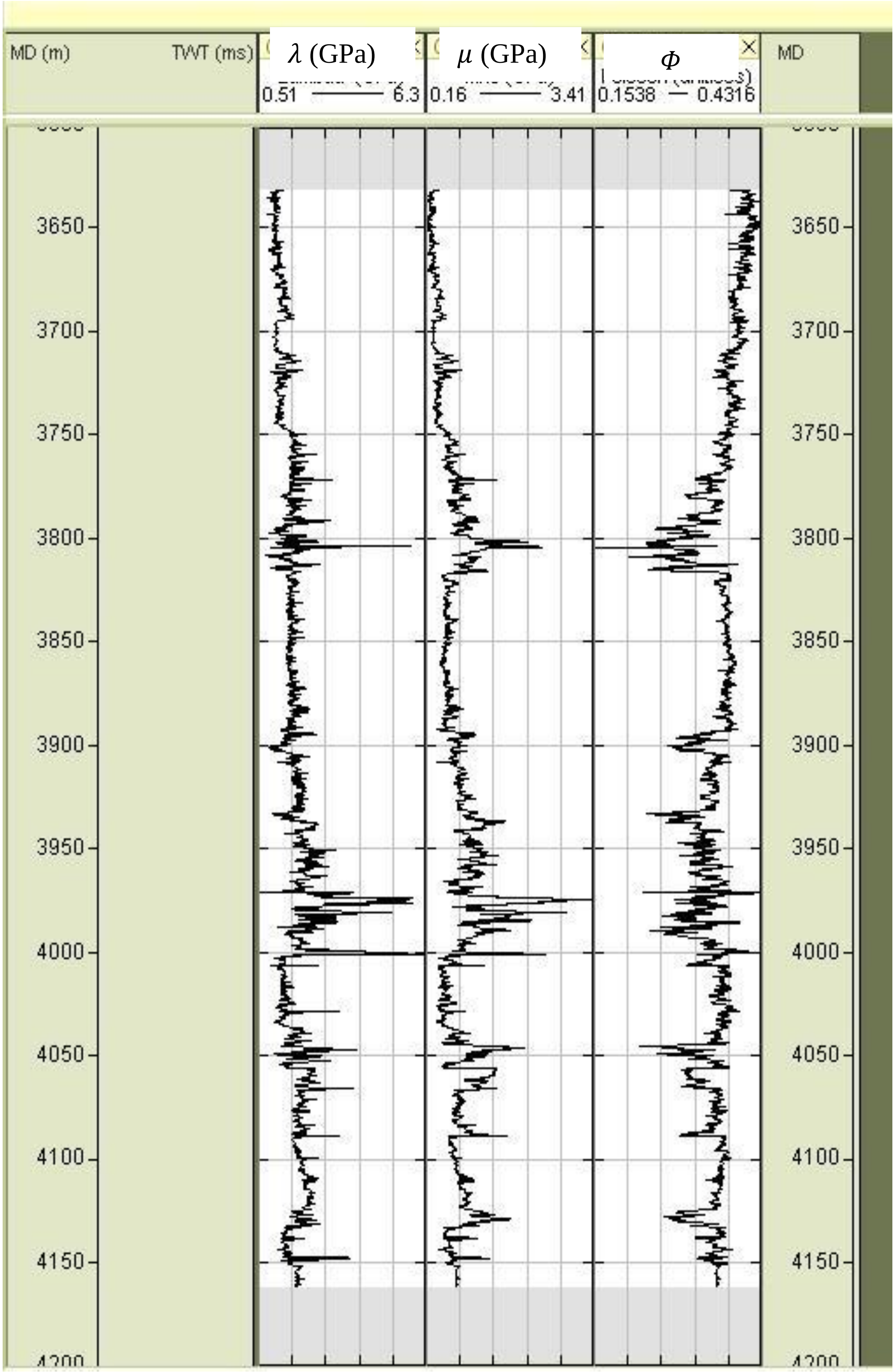


**Figure 3.7:** A display of some calculated elastic log parameters

# CHAPTER FOUR

# RESULTS AND DISCUSSIONS

## 4.1 Sand and shale discrimination using velocity ratio

The principal step of well log analysis is to differentiate clean sand from shale using baseline on the log data and to delineate zones of interest, i.e. hydrocarbon filled clean sand. Due to the absence of gamma ray logs which are generally used to infer lithology, velocity ratio log was used to determine the lithology. Vp logs can be used to determine lithology, porosity, and pore fluid. Despite Vp logs been valuable, they are influenced by three separate properties of rocks, i.e. density, bulk and shear moduli, which make Vp ambiguous for lithology prediction. The Vp/Vs ratio, however, is independent of density and can be used to derive Poisson's ratio, which is a much more diagnostic lithological indicator (Kearey et al., 2002). The velocity ratio of different lithologies proposed by Castagna et al. (1985) using velocity ratio are found in Table 2 below.

**Table 1**: Velocity ratio for different rock types (Castagna et al., 1985).

| Range of $V_p/V_s$ | Rock type |
|---|---|
| 0.1 – 1.2 | Fine grained sand |
| 1.2 – 1.45 | Medium grained sand |
| 1.46 – 1.6 | Coarse grained sand |
| 1.6 – 1.8 | Sandstone |
| Above 2.0 | Shale or Clay |

Using a shale baseline of 1.80, an imaginary line was established to differentiate sand from shale. Deflection to the right of the baseline represents shale whilst deflection to the left of baseline represents sand. Shale and carbonate discrimination using velocity ratio is difficult because they both have velocity ratio above 1.80. Figure 4.1 shows sand and shale layers using velocity ratio log.

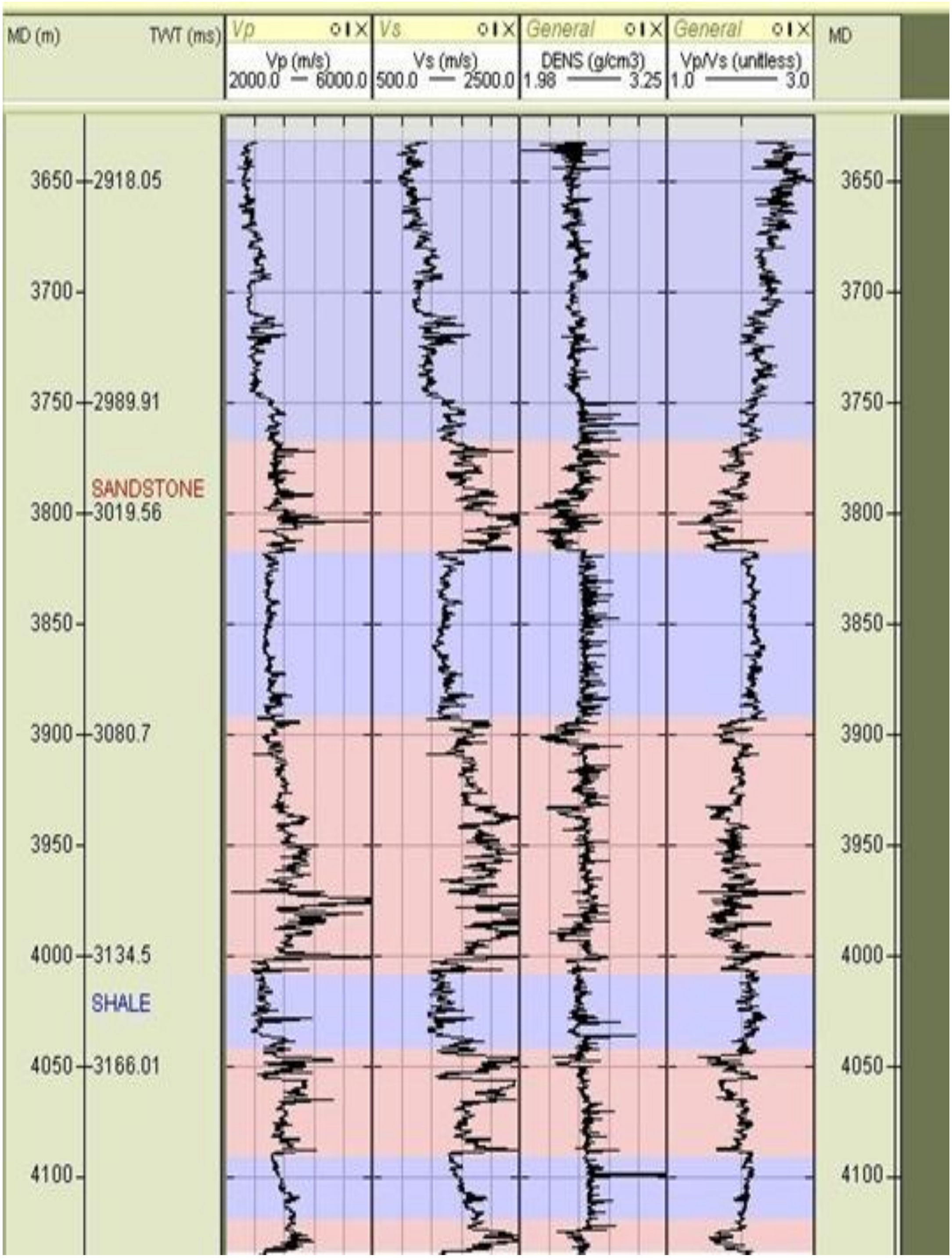


**Figure 4.1:** Sand and shale discrimination using Vp/Vs log

### 4.2 Lithology prediction using Lamé parameters

Velocity ratio is effective for distinguishing sand from shale. However, velocity ratio cannot be used to predict other lithologies such as carbonate. Lithology prediction using Lamé parameter accounts for the pitfall of lithology discrimination using velocity. The Lamé parameter which is sensitive to fluid and lithology was used for the comprehensive lithology prediction of the well. Determining reservoir properties using Lamé parameter was recognized by Goodway (2001) and Dewar and Downton (2002). Goodway (2001) encouraged the use of relationship between Lamé parameters $\lambda$ (incompressibility) and $\mu$ (rigidity), and $\rho$ (density) and how they can be used to differentiate lithology and identify gas sand. Lambda ($\lambda$) and mu ($\mu$) are very sensitive to pore fluid and rock matrix respectively. Lamé parameters help interpreters to better understand rock physics. $\mu * \rho$ referred to as rigidity is the "resistance to strain resulting in shape change with no volume change" (Goodway et al., 1999). $\mu * \rho$ is very useful for discriminating lithology. The unique result from this methodology is the fact that sand has a higher mu – rho than overlying shale. $\lambda * \rho$, usually referred to as incompressibility, is useful for fluid detection and discrimination. Research has shown that hydrocarbon filled sandstone is less dense than water filled sandstone (Klein and Philpotts, 2012). Hence, hydrocarbon filled sandstone has low $\lambda * \rho$ values.

Pore fluid and mineral property affect the lithology of a formation. From the Lamé parameters calculated, a cross plot of the difference ($\lambda *\rho$ - $\mu *\rho$) and the ratio ($\lambda / \mu$) was carried out and analyzed.

Figure 4.2 below is a log of λ * ρ (lambda-rho), μ * ρ (mu-rho), and Lamé constant (λ / μ).

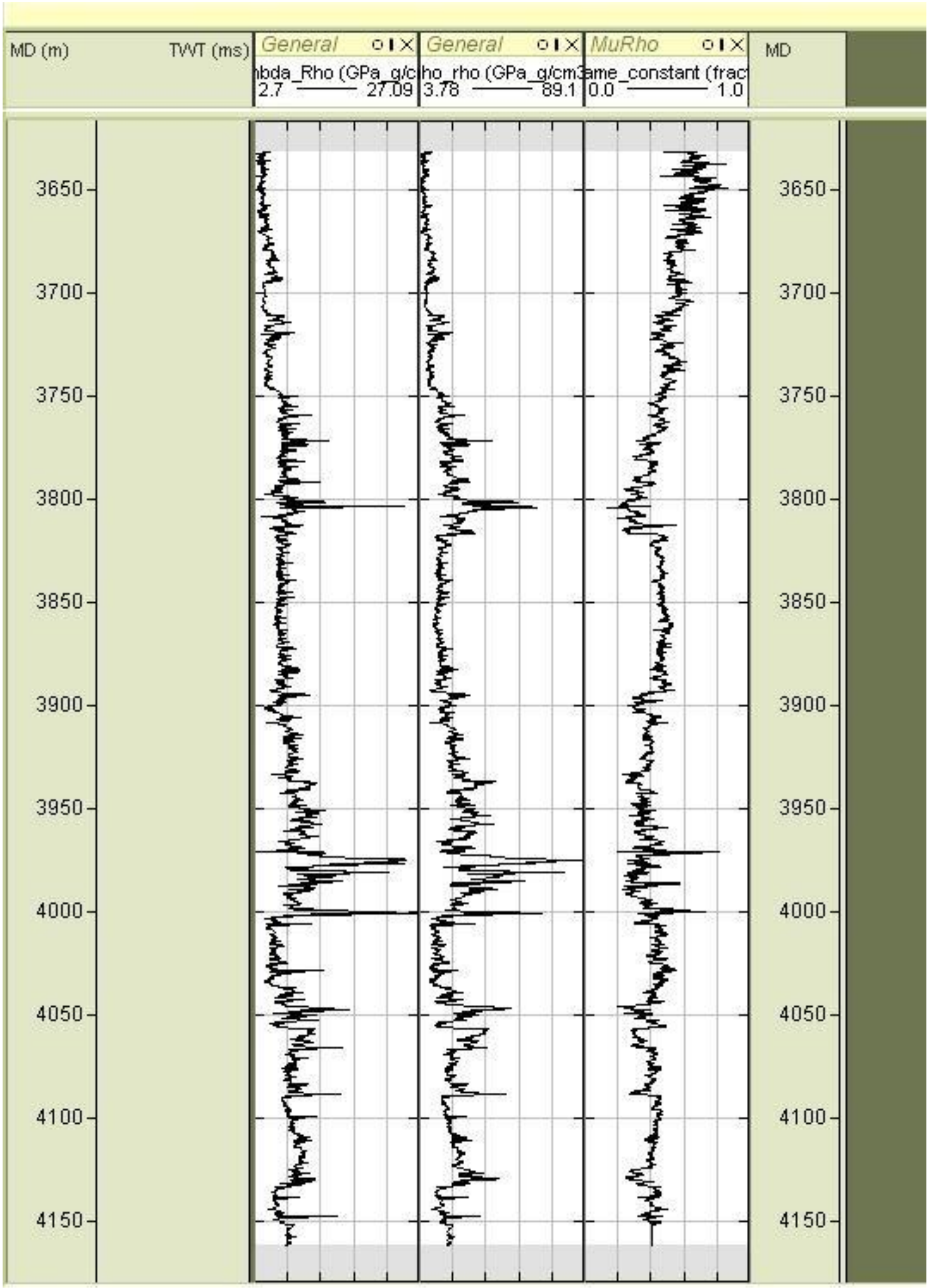


**Figure 4.2:** Display of λ *ρ, μ *ρ, and λ / μ from left to right

Figure 4.3 below also shows the crossplot of the difference and ratio. From the crossplot analysis, the various lithology and fluid detected and map as gas sand, wet sand, shale, and carbonate. Figure 4.3 below shows the outcome of the analysis. As shown in Figure 4.3, some section of the log was not categorized. This section represent the log data which did not pass the constrain imposed on the rock physics analysis.

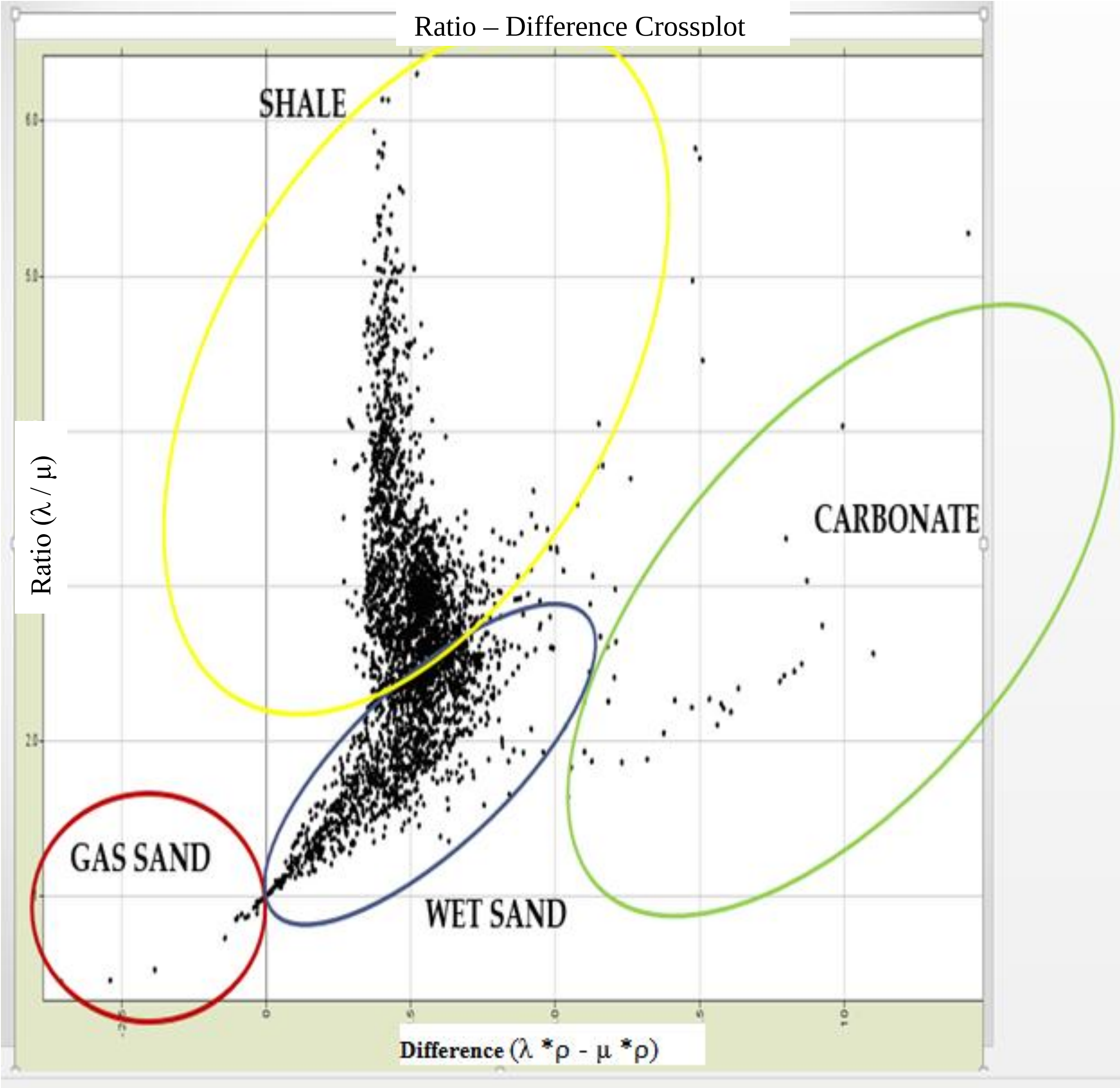


**Figure 4.3:** Ratio (λ / μ) and difference (λ * ρ - μ *ρ) cross plot

The selected area in the crossplot was displayed on the ratio and difference logs. The yellow layer represents shale content in the formation, the tiny red section represents the gas sand, the green and blue layers represent carbonate and wet sand respectively. Figure 4.4 below shows the various lithology and some pore fluid content.

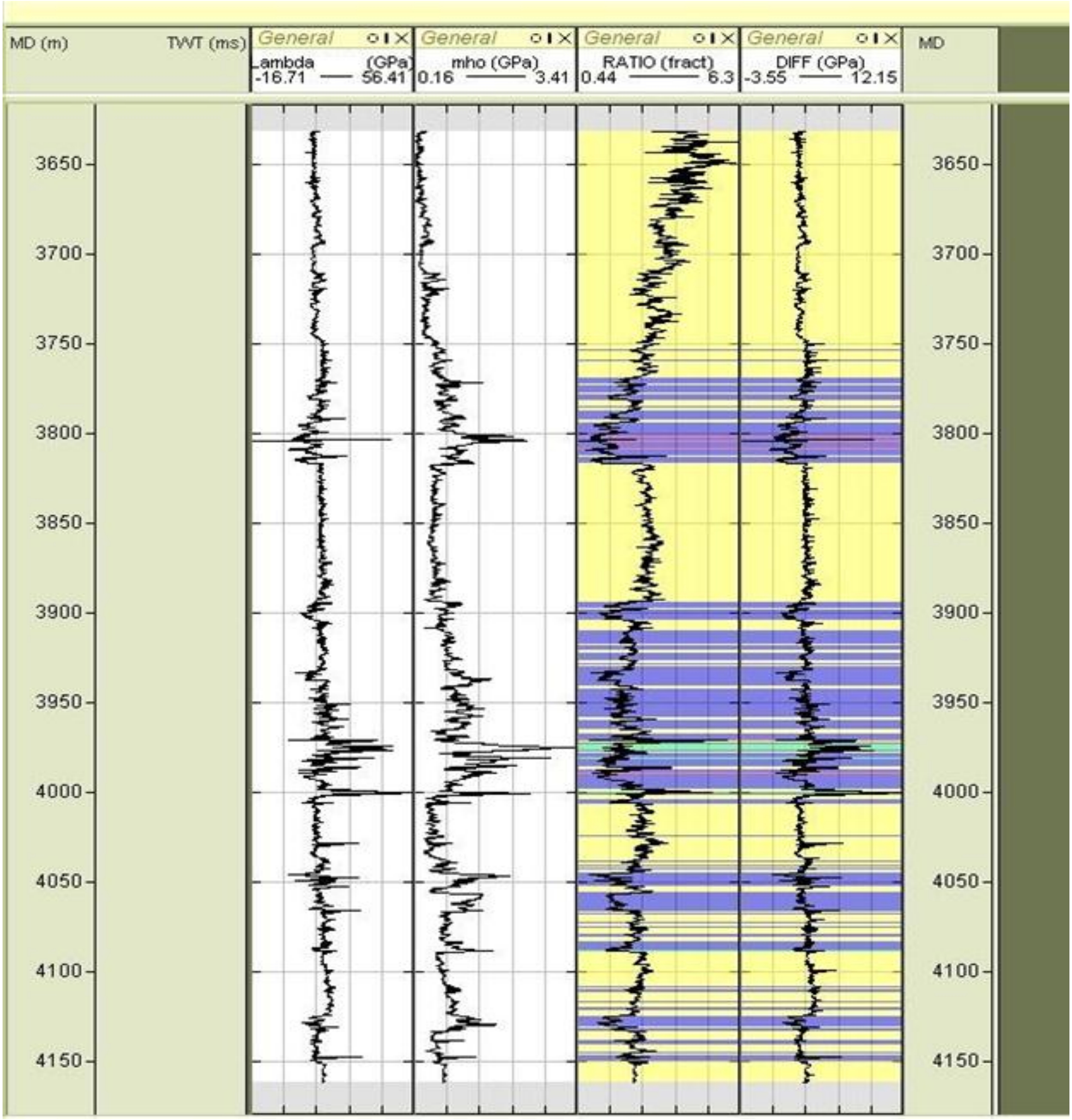


**Figure 4.4:** Comprehensive lithology prediction

The sandstone reservoir in WELL Z corresponds to a low incompressibility (lambda) but high rigidity (mu). This affirms the fact that λ, μ, and ρ are good for detecting gas filled sand, wet sand, and shale.

### 4.3 Pore fluid prediction using Vp/Vs and Poisson's ratio

A crossplot of velocity ratio and Poisson's ratio was carried out and analyzed. From the pore fluid prediction guideline shown in Figure 4.5 below, the various pore fluid content was predicted.

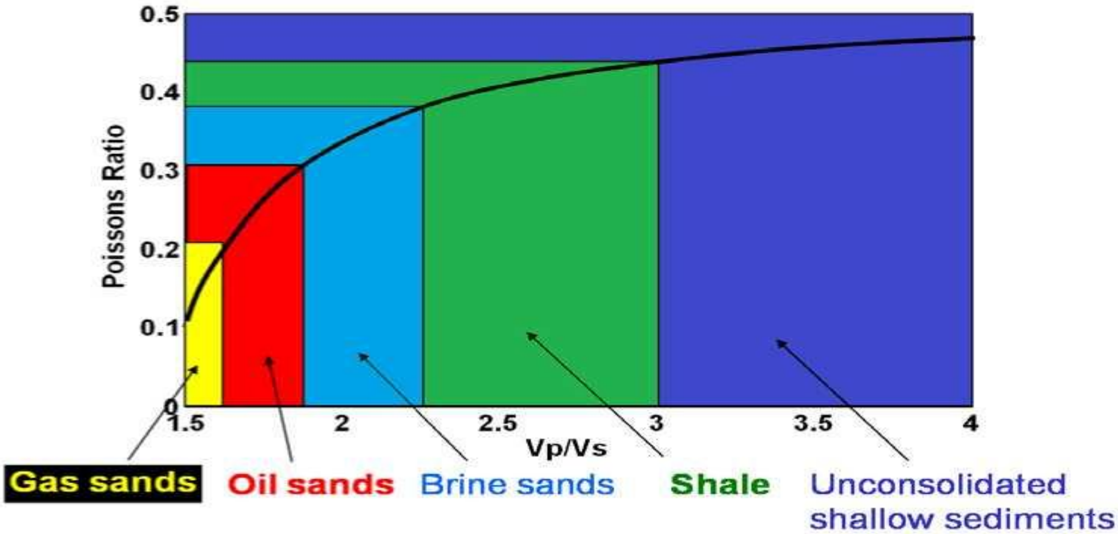


**Figure 4.5:** Guideline for pore fluid prediction using Poisson's ratio and velocity ratio

Pore fluid prediction is possible by analyzing the relationship existing between Poisson's ratio and velocity ratio. The crossplot of Poisson's ratio and velocity ratio is shown in Figure 4.6 below. From the interpretation guide, it can be observed that gas and oil sand have lower Poisson's and velocity ratio compared to brine sand and shale. The gas sand, oil sand, brine sand, and shale was selected on the crossplot.

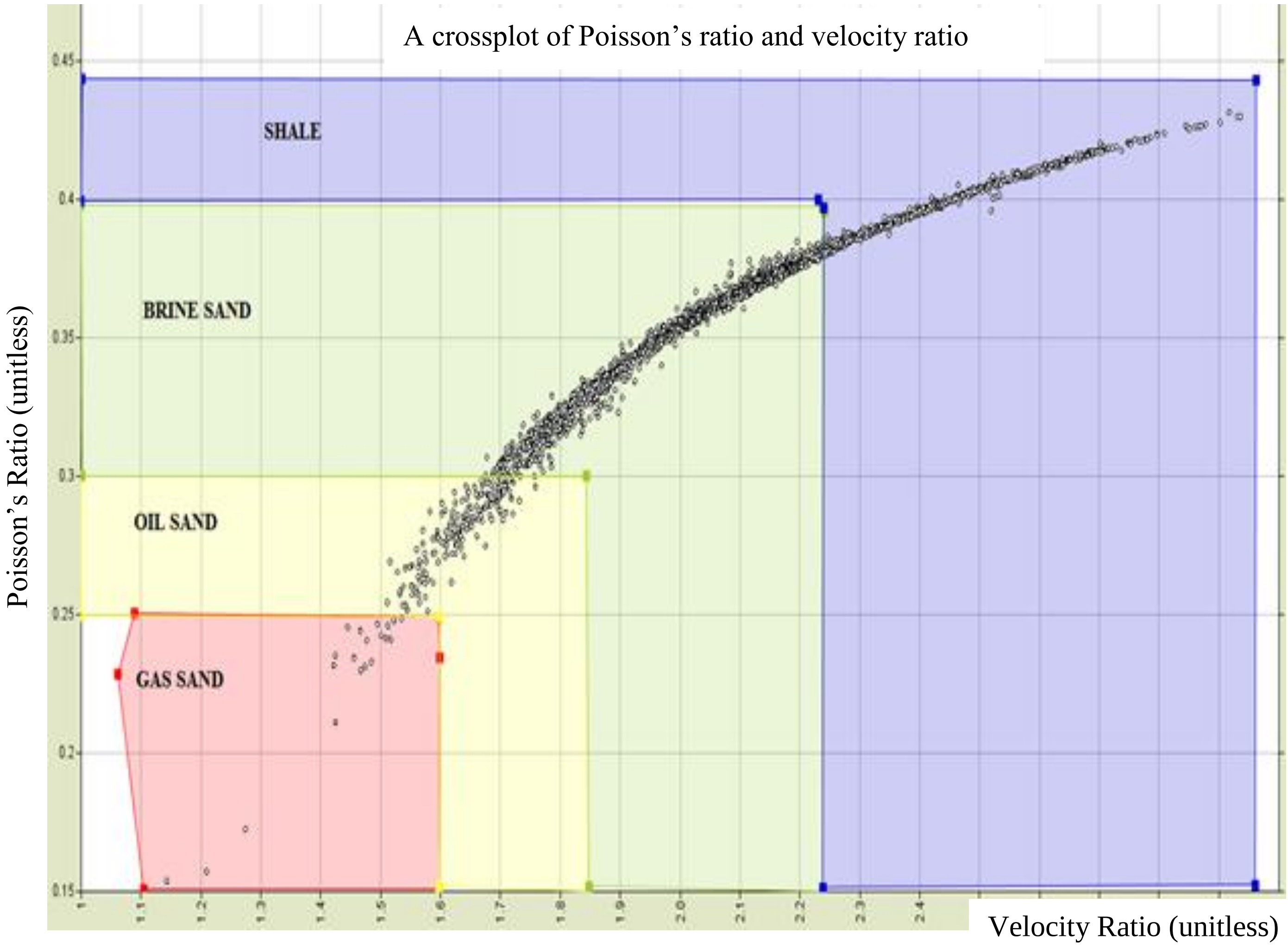


**Figure 4.6:** A crossplot and interpretation of Poisson's ratio and velocity ratio

The selected area in red represents gas sand present in WELL Z. The yellow and green selected area represents the oil sand and brine sand. The selected blue area represents shale. The selected area in Figure 4.6 above are displayed on the log below as shown in Figure 4.7 below.

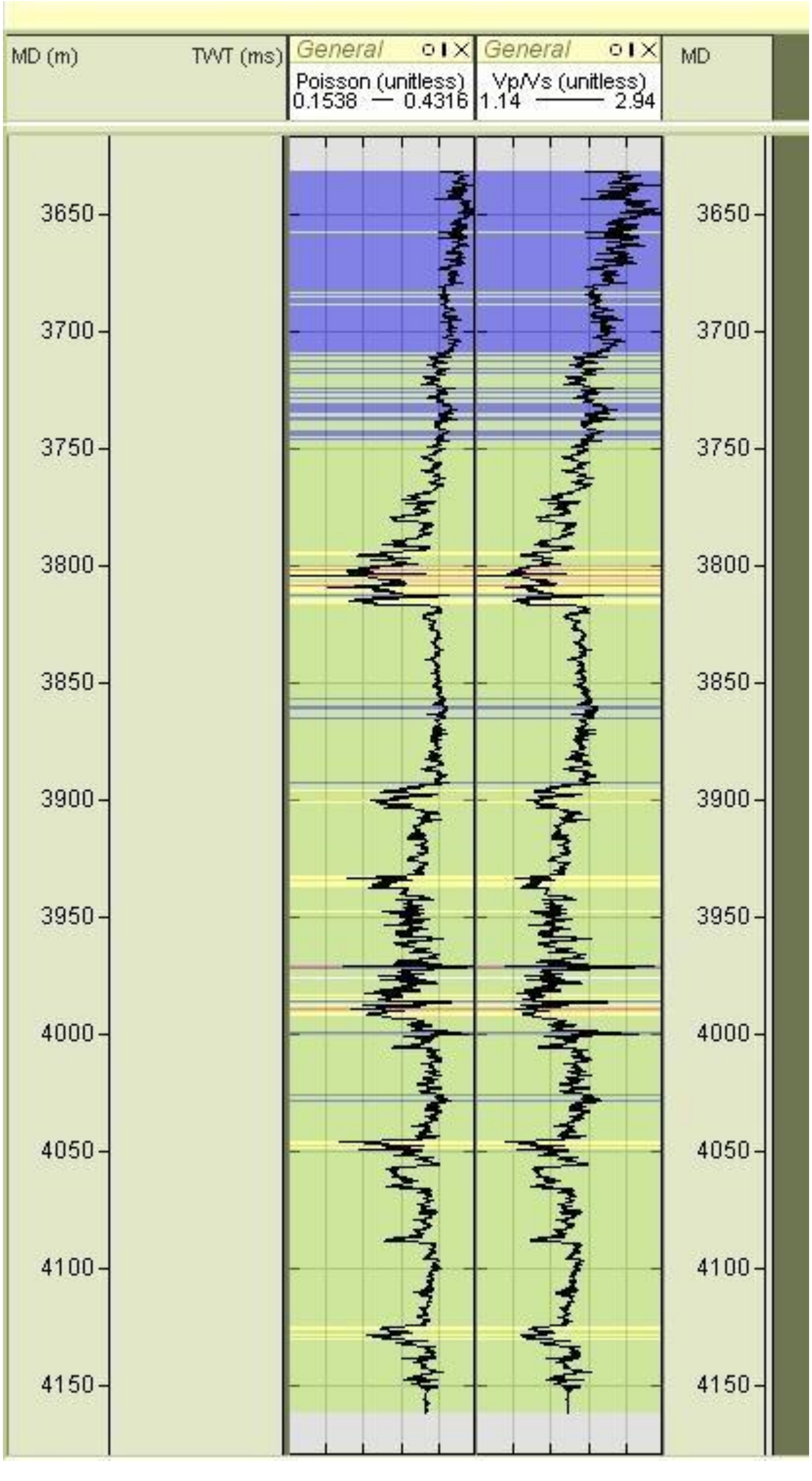


**Figure 4.7:** Predicted pore fluid displayed on log. Red represents gas sand, yellow represents oil sand, and green represents brine sand.

## 4.4 Reservoir zone and oil water contact (O.W.C)

The velocity ratio was not only used to deduce lithology but also to detect the presence of hydrocarbons in pores. Velocity ratio is very sensitive to pore fluid of sedimentary rocks. In an oil layer, compressional wave velocity decreases as shear wave velocity increases (Bahremandi et al., 2012). Tathan (1982) realized that the velocity ratio is much lower in hydrocarbon saturated environment than the liquid saturated environment. The reduction and increase in compressional and shear wave velocity respectively with an increase of hydrocarbon, make velocity ratio more sensitive to fluid change than Vp and Vs individually. Velocity ratio decreases in hydrocarbon layers because density decreases in the shear wave velocity while bulk modulus decreases in compressional wave velocity. This is very crucial in determining fluid and oil water contact. Figure 4.8 shows the oil-water-contact.

At the depth of 3804.04 m, a rapid reduction in velocity ratio is observed. This corresponds to a decrease of Vp from 5876.26 m/s to 3444.86 m/s corresponding to an increase in Vs from 2940.26 m/s to 3014.04 m/s. This anomaly is due to the fact that the compressional and shear wave velocities are propagated from an oil layer into a water layer. The boundary where the rapid velocity contrast is observed is the oil-water-contact (O.W.C) which occurs in medium to coarse grained sandstone. Figure 4.8 shows oil-water-contact of the reservoir.

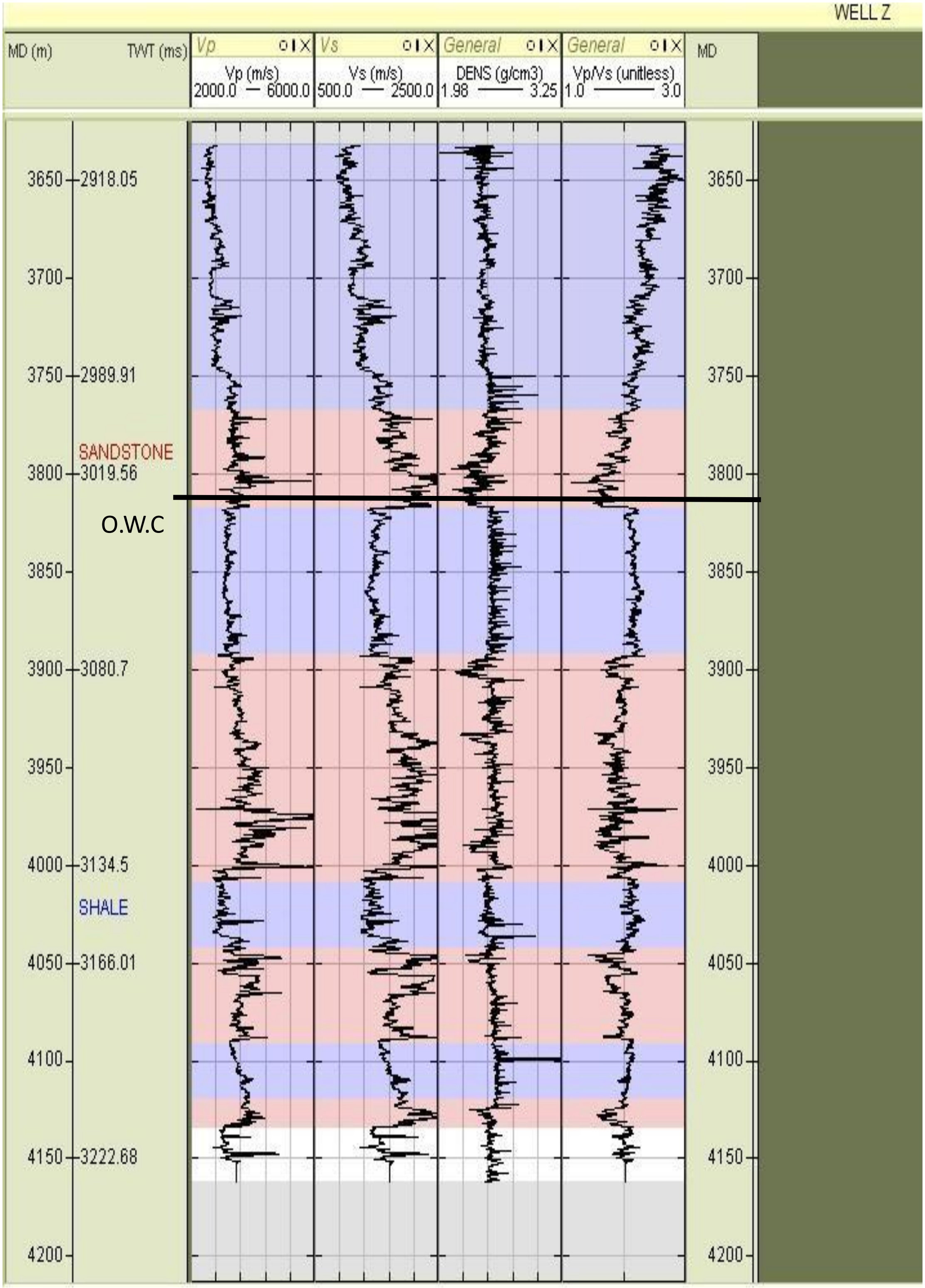


**Figure 4.8**: Oil-water-contact of the reservoir in WELL Z.

From Figure 4.8 above, it can be observed from the velocity ratio log that the shale content decreases from the beginning of the log to a depth of 3705.6 m. At the depth of 3705.6 m, the velocity ratio increases resulting in the increase of shale content. Hence, the top of the reservoir (cap rock) was estimated at a depth of 3705.6 m due to the increase in the shale content observed by the increase in velocity ratio.

At the depth of 4000.15 m, the compressional wave velocity log decreases whiles the shear wave velocity logs increases resulting in the increase in velocity ratio increases from 1.42 to 2.84. This anomaly, visibly by the change in the velocity ratio was associated to the base of the reservoir.

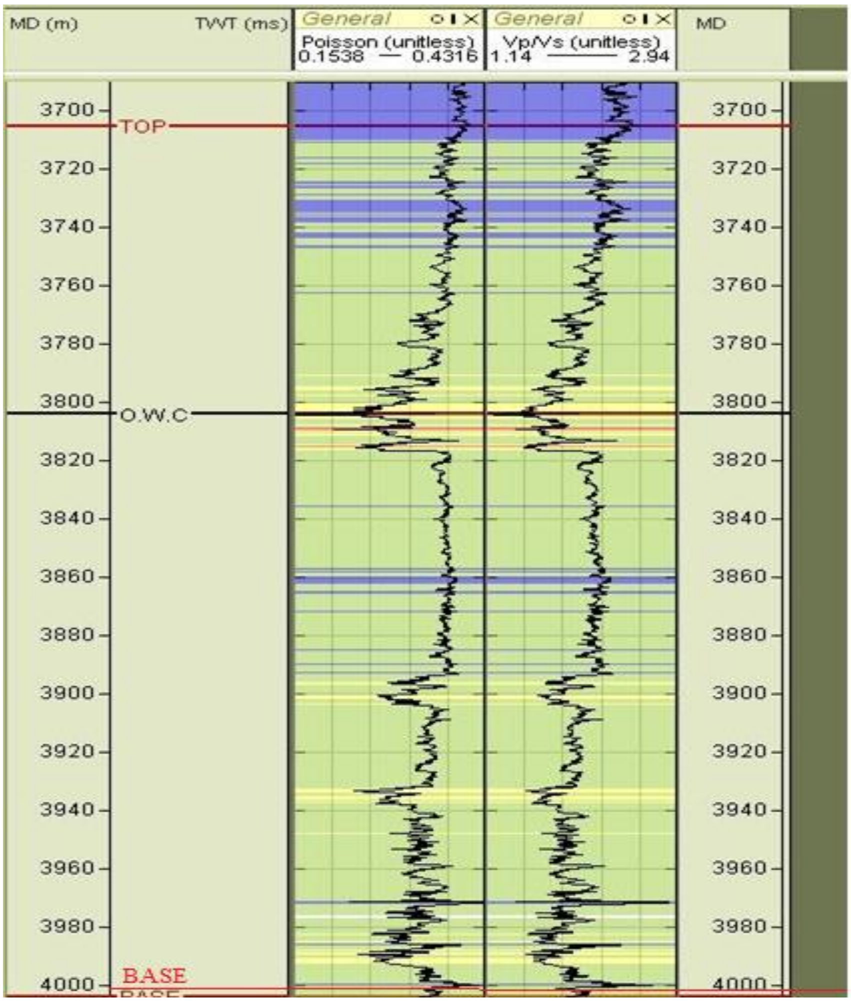


**Figure 4.9:** Base and Top of the reservoir

# CHAPTER FIVE

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusion

Identification and estimation of lithology and pore fluid of a reservoir is largely based on the interpreter's capability to use available data. Well log data provide useful parameters to determine lithology and pore fluid. Petrophysics and rock physics analysis of log data were successfully applied to well log data in the Tano Basin.

Density, compressional, and shear wave velocity logs were used as input for this research. A MATLAB program, ELASP, was developed to calculate elastic parameters such as velocity ratio, Poisson's ratio, and Lamé parameters. These elastic parameters were plotted using RokDoc software. Velocity ratio log was used to differentiate sand from shale to understand the general overview of the distribution of sandstone in the well. Castagna et al. (1985) empirical values of velocity ratio for rock types was used. After the sand and shale differentiation using velocity ratio, rock physics analysis using Lamé parameters was carried out to determine the presence of other lithology besides sand and shale. From the calculated Lamé parameters, a crossplot Lamé difference ($\lambda * \rho - \mu * \rho$) and ratio ($\lambda / \mu$) was analyzed. Using Goodway (2001) interpretation technique, gas sand, wet sand, carbonate, and shale were predicted from the crossplot.

Pore fluid content was determined using the calculated velocity ratio and Poisson's ratio. From the analysis of velocity ratio and Poisson's ratio, the gas sand, oil sand, and brine sand was mapped out. The gas sand predicted from the rock physics analysis using Lamé parameter was confirmed by the analysis of velocity ratio and Poisson's ratio. The analysis of velocity ratio and Poisson's ratio was used to further describe the wet sand predicted by the rock physics analysis of Lamé parameter. The wet sand from the rock physics analysis of Lamé parameter was predicted to comprise of oil sand and brine sand.

## 5.2 Recommendations

A review of the literature suggests that analysis of this type of work has not been carried out in the Tano and other Basin’s in Ghana. This may be due to the numerous methods of log interpretations. It is therefore recommended that rock physics and petrophysical analysis of log data be carried out in the Tano Basin to reduce the risk of wrong prediction of reservoir parameters. Also, other logs such as gamma ray log should be used to improve rock physics constrain used for the rock physics analysis. Moreover, since rock physics is a link between reservoir engineering, geophysics, petrophysics, and geology, core and reservoir data should be used to enhance the interpretation.

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**APPENDIX**

**A. MATLAB CODES TO LOAD LOG AND CALCULATE ELASTIC (VELOCITY RATIO, POISSON'S RATIO, AND LAMÉ PARAMETERS) PARAMETERS**

A1. CONSTRAINING THE INTERFACE

```
Choose default command line output for ELASP
handles.output = hObject;
% Update handles structure
guidata(hObject, handles);
% UIWAIT makes ELASP wait for user response (see UIRESUME)
% uiwait(handles.figure1);
% constraining the interface
set(handles.pushbutton2,'enable','off')
set(handles.pushbutton4,'enable','off')
set(handles.pushbutton5,'enable','off')
```

A2. IMPORTING INPUT (DENSITY, COMPRESSIONAL WAVE VELOCITY, AND SHEAR WAVE VELOCITY) LOG DATA

```
function pushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% loading excel file
[pathname,filename]=uigetfile({'*.xls;*.xlsx;*.xlsm;*.xlsb'},'Select Input File');
if isequal (pathname,0) || isequal (filename,0)
```

```
    beep
    msgbox('File loading cancelled','File loader','modal')
else
    h=waitbar(0,'File loading in progress');
    steps=1000;
    for step=1:steps
        waitbar(step/steps)
    end
    close(h)
    msgbox('File loaded Successfully')
    set(handles.edit1,'string',fullfile(filename,pathname));
end
set(hObject,'enable','off')
set(handles.pushbutton2,'enable','on')
set(handles.pushbutton4,'enable','on')
set(handles.pushbutton5,'enable','on')
```

A3. RESET THE PARAMETER

```
function pushbutton4_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton4 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% reser the parameters
set(handles.edit1,'string','Please select file to load','ForegroundColor','k')
set(handles.edit1,'enable','inactive')
```

```
set(handles.pushbutton1,'enable','on')
set(handles.pushbutton2,'enable','off')
set(handles.pushbutton4,'enable','off')
set(handles.pushbutton5,'enable','off')
set(hObject,'enable','off')
```

A4. CLOSE ELASP

```
function pushbutton4_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton4 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% reser the parameters
set(handles.edit1,'string','Please select file to load','ForegroundColor','k')
set(handles.edit1,'enable','inactive')
set(handles.pushbutton1,'enable','on')
set(handles.pushbutton2,'enable','off')
set(handles.pushbutton4,'enable','off')
set(handles.pushbutton5,'enable','off')
set(hObject,'enable','off')
```

A5. CALCULATE VELCITY RATIO

```
function pushbutton5_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton5 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
%calculation velocity ratio
```

```
fn=get(handles.edit1,'string');

[A]=xlsread(fn,1);

M=A(:,1);

Vp=A(:,2);

Vs=A(:,3);

den=A(:,4);

V=Vp./Vs.;   %where V is velocity ratio

xlswrite('COMPUTED LOGS.xls',all,'COMPUTED LOGS','A1')

xlswrite('COMPUTED LOGS.xls',v ,'Normal Gravity','E2')
```

A6. CALCULATE LAMÉ PARAMETERS

```
function Calculate_Lame_Callback(hObject, eventdata, handles)

% hObject    handle to Calculate_Lame (see GCBO)

% eventdata  reserved - to be defined in a future version of MATLAB

% handles    structure with handles and user data (see GUIDATA)

% calculating Lamr parameters

fn=get(handles.edit1,'string');

[A]=xlsread(fn,1);

M=A(:,1);

Vp=A(:,2);

Vs=A(:,3);

den=A(:,4);

mu = den.*Vs.*Vs;

lambda = den.*Vp.*Vp-2.*mu;

xlswrite('COMPUTED LOGS.xls',all,'COMPUTED LOGS','A1')
```

```
xlswrite('COMPUTED LOGS.xls',mu ,'Normal Gravity','F2')

xlswrite('COMPUTED LOGS.xls',lambda ,'Normal Gravity','G2')
```

A7. CALCULATE POISSON’S RATIO

```
function Calculate_Poisson’s_Callback(hObject, eventdata, handles)

% hObject    handle to Calculate_Poisson’s (see GCBO)

% eventdata  reserved - to be defined in a future version of MATLAB

% handles    structure with handles and user data (see GUIDATA)

%calculating Poisson’s ratio

fn=get(handles.edit1,'string');

[A]=xlsread(fn,1);

M=A(:,1);

Vp=A(:,2);

Vs=A(:,3);

den=A(:,4);

mu = den.*Vs.*Vs;

lambda = den.*Vp.*Vp-2.*mu;

Poisson’s = lambda./(2*(lambda+mu));

xlswrite('COMPUTED LOGS.xls',all,'COMPUTED LOGS','A1')

xlswrite('COMPUTED LOGS.xls',Poisson’s ,'Normal Gravity','H2')
```

B. MATLAB CODE TO CALCULATE OTHER ELASTIC PARAMETERS (BULK MODULUS, YOUNG MODULUS, ACOUSTIC IMPEDANCE, SHEAR IMPEDANCE).

B1. CALCULATE BULK MODULUS

```
function Calculate_Bulk_Callback(hObject, eventdata, handles)
% hObject    handle to Calculate_Poisson’s (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
%calculating Poisson’s ratio
fn=get(handles.edit1,'string');
[A]=xlsread(fn,1);
M=A(:,1);
Vp=A(:,2);
Vs=A(:,3);
den=A(:,4);
mu = den.*Vs.*Vs;
lambda = den.*Vp.*Vp-2.*mu;
bulk = lambda+((2*lambda)/mu);
xlswrite('COMPUTED LOGS.xls',all,'COMPUTED LOGS','A1')
xlswrite('COMPUTED LOGS.xls',bulk ,'Normal Gravity','I2')
```

B2. CALCULATE SHEAR AND YOUNG MODULUS

```
function Calculate_Shear.Young_Callback(hObject, eventdata, handles)
% hObject    handle to Calculate_Poisson’s (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
```

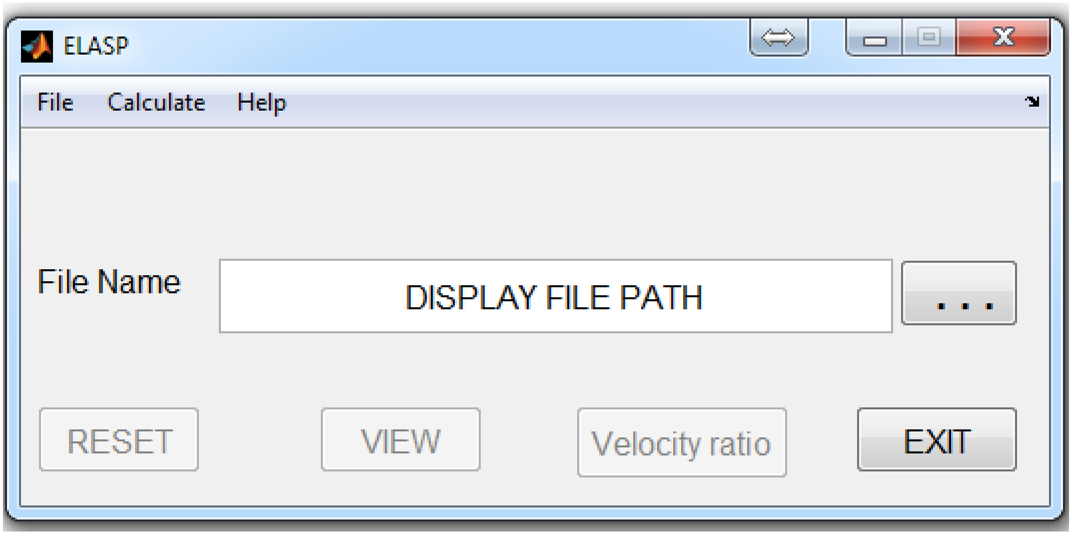
```
%calculating Poisson’s ratio
fn=get(handles.edit1,'string');
[A]=xlsread(fn,1);
M=A(:,1);
Vp=A(:,2);
Vs=A(:,3);
den=A(:,4);
mu = den.*Vs.*Vs;
lambda = den.*Vp.*Vp-2.*mu;
bulk = lambda+((2*lambda)/mu);
Poisson’s = lambda./(2*(lambda+mu));
young = bulk*(1-2*Poisson’s);
shear = young./(2*(1+Poisson’s))
xlswrite('COMPUTED LOGS.xls',all,'COMPUTED LOGS','A1')
xlswrite('COMPUTED LOGS.xls',young ,'Normal Gravity','J2')
xlswrite('COMPUTED LOGS.xls',shear ,'Normal Gravity','K2')
```

B3. CALCULATE ACOUSTIC AND SHEAR IMPEDANCE

```
function Calculate_Impedance_Callback(hObject, eventdata, handles)
% hObject    handle to Calculate_Poisson’s (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
%calculating Poisson’s ratio
fn=get(handles.edit1,'string');
[A]=xlsread(fn,1);
```

```
M=A(:,1);

Vp=A(:,2);

Vs=A(:,3);

den=A(:,4);


AI = den.*Vp;

SI = den.*Vs;


xlswrite('COMPUTED LOGS.xls',all,'COMPUTED LOGS','A1')

xlswrite('COMPUTED LOGS.xls',AI ,'Normal Gravity','M2')

xlswrite('COMPUTED LOGS.xls',SI ,'Normal Gravity','N2')
```

C. Interface and main function of ELASP




| **File** | **Calculate** | **Help** |
|---|---|---|
| New | Lamé parameters | ELASP Help |
| Open | Poisson's ratio | About ELASP |
| Save | Bulk/ Young/ Shear Modulus | |
| Exit | Acoustic/ Shear impedance | |