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INTEGRATING PETROPHYSICAL AND ELASTIC ROCK PROPERTIES (VP / VS RATIOS) FOR LOG-FACIES CLASSIFICATION IN STATIC RESERVOIR MODELLING IN THE KK FIELD, NIGER DELTA

A THESIS

PRESENTED TO THE DEPARTMENT OF PETROLEUM ENGINEERING

AFRICAN UNIVERSITY OF SCIENCE AND TECHNOLOGY ABUJA, NIGERIA

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD

OF A DEGREE OF MASTER OF SCIENCE IN PETROLEUM ENGINEERING

BY

CHE ELVIS SHU

DECEMBER, 2011

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INTEGRATING PETROPHYSICAL AND ELASTIC ROCK PROPERTIES (VP / VS RATIOS) FOR LOG-FACIES CLASSIFICATION IN STATIC RESERVOIR MODELLING IN THE KK FIELD, NIGER DELTA

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KEY WORDS

- Petrophysical properties
- Elastic (Vp/Vs)
- Rock Physics
- Integration of petrophysical and elastic properties
- Log-facies Classification
- Petroleum Reservoirs
- Conventional
- Optimization
- Better classification
- Well 1 (TMB_4)
- Well 2 (TMB_1)

SCIENTIFIC ENVIRONMENT

This research has been performed both at the Department of Petroleum Engineering at the African University of Science and Technology, Abuja-Nigeria and at the University of Nigeria, Nsukka, during the period from June – November 2011 under the supervision of Professors, Mosto Onuoha (University of Nigeria, Nsukka), Godwin Chukwu (Chair Petroleum Engineering Department, AUST and Professor Emeritus, University of Alaska Fairbanks, USA) and Associate Prof. Debasmita Misra (University of Alaska Fairbanks, USA).

PREFACE

This thesis is submitted to the Department of Petroleum Engineering, African University of Science and Technology (AUST), Abuja-Nigeria in candidacy of the M.Sc. in Petroleum Engineering.

The work entails integrating petrophysical properties derived from formation evaluation analysis and elastic properties computed through a rock physics model for log-facies classification of the wells studied in KK field, Niger Delta. As a result, facies classification in static reservoir modelling would be optimised for seismic reservoir characterisation. A change of scale and domain of a log-facies classification will also be used to tackle the problem related to reconciling seismic and log data scales.

DEDICATION

This work is dedicated first of all to the Almighty God for inspiration and wisdom.

Secondly to my lovely parents Mrs. Muma Florence and Mr. Ayonghe Joseph, the entire Muma's and Ayonghe's families and to my Fiancé, in appreciation of their genuine support for whatever and wherever I am today.

ACKNOWLEDGEMENT

I would like to first and foremost give thanks to the Almighty God for seeing me through this work successfully.

Secondly, I want to express my sincere gratitude to my supervisor Professor Mosto Onuoha and committee members Professor Emeritus Godwin Chukwu and Associate Professor Debasmita Misra whose help, guidance, encouragement, and dedication from preliminary to concluding levels, enabled me acquire writing skills and new learning techniques. Without them, it would have been almost impossible to write this thesis. I appreciate their tireless efforts towards the realization of this thesis.

I am grateful to all my lecturers in the Department of Petroleum engineering, most especially, Professors Wumi Iledare, D. Tiab, Dulu Appah, Dr. Ossisanya, Dr. A. Igbokoyi, Dr. Nnaemeka E., and Mr. Frack E., for their support, constructive feedback and recommendations. I would always be indebted to you all.

Many thanks go to my course mates in the Petroleum Engineering Department who make up a significant diversity from different countries, and enabled me develop alternative models of thinking and an open minded culture. In addition, I convey thanks to my mates from other Departments, whose friendship, hospitality and love, enlightened and helped me stay focused. The good memories and times well spent will always be remembered.

My sincere gratitude goes to the African University of Science and Technology for awarding this scholarship to me, which many students are not opportuned to have.

Finally I want to thank all my friends, espacially Akum Polycarp, Kunle O., Bezezu Atem, Suh Celestine, Neba Philip, Fai Honore, Bafon Godlove and Nkem Sixtus and other relations: Dr. Amobi E., Mr. Okeugo C. G, Mr. Okey Nebedum., Mrs. Grace A., Mr. Titus O., Mr. N. Abraham, Mrs. Hadja and Mr. and Mrs. Ben Arnold. Your moral, emotional, and spiritual support throughout my studies will forever be cherished.

ABUJA, DECEMBER 2011

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ABSTRACT

As reservoirs become more complex and drilling operations more expensive, the need to reduce both inefficiencies and costs for constructing and analyzing high quality static models is essential. The effective and efficient production of petroleum from a reservoir lies on the proper characterization of the reservoir. Once the static model resulting from reservoir characterization is satisfactory and heterogeneities taken care of, it is but evident that the uncertainties will be minimized, hence proper optimization of production.

The problem to be solved is that of appropriately classifying log-facies for static reservoir modelling using an integrated approach (combining both petrophysical and elastic rock properties) which arises from the need to better characterise a reservoir as a function of its log-facies.

The aim of this work is to integrate petrophysical properties (porosity, water saturation and density) derived from formation evaluation analysis and elastic properties (velocities-Vp, Vs and Vp/Vs ratio) computed through a rock physics model for log-facies classification in static reservoir modelling. Hence, optimizing facies classification for seismic reservoir characterization.

The methodology used for this work consists of five steps: acquisition and log data gathering; loading, importing and quality check of data; petrophysical property computations and interpretation; rock physics model computations and log-facies classification. This approach is applied to real log data from two wells in the KK field operated by the Shell Petroleum Development Corporation in the Niger Delta.

The results demonstrated an improvement in the classification obtained by integrating both petrophysical and elastic data. Good log-facies analysis leads to the construction of a better static model and without this, including characterisation input, geological models will not be very accurate.

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DISCLAIMER

This work is done under the supervision of eminent professors and guidance from other collaborators. Neither of them, makes any warrant, express or implied, or assumes any liability or responsibility for the accuracy, completeness, or usefulness of any information, or process disclosed, or represents that its use would not infringe (violate or breach) privately owned rights.

CHAPTER ONE

INTRODUCTION

1.1 PROBLEM DESCRIPTION

The main objective of this work is to present a strategy for including log-facies classification in static reservoir modelling by combining rock physics and formation evaluation analysis. Well logs are measured in depth and provide high resolution vertical data, but no insight into property variation in the inter-well spacing. Seismic data are measured in time and provide great lateral detail but is quite limited in its vertical resolution. When correlated, well logs and seismic data derived from rock physics can be used to create a fine-scale 3D model of the subsurface.

Insight into the rock properties (petrophysics) comes from a combination of basic geologic understanding and well bore measurements. Based on an understanding of how the area was formed over time, geologists can predict the types of rock likely to be present and how rapidly they vary spatially. Well log and core measurements provide samples to verify and fine-tune that understanding. Seismic surveys measure acoustic impedance contrasts between rock layers. As different geologic structures are encountered, the sound wave reflects and refracts as a function of the impedance contrast between the layers. Velocity varies by rock type and can therefore be correlated to rock properties using rock physics relationships between the inversion attributes and petrophysical properties such as porosity, lithology, water saturation, and permeability. Once well logs are properly conditioned and edited, a petrophysical rock model is generated that can be used to derive the effective elastic rock properties (rock physics model) from fluid and mineral parameters as well as rock structure information. The model parameters are calibrated by comparison of the synthetic to the available elastic sonic logs or seismic data. The vertical resolution of log interpretation is representative of the well-log scale and the lateral resolution of the elastic properties from rock physics model interpretation is representative of the seismic scale. So, the need to proper characterise a reservoir using log-facies gotten through a combination of the two types of rock properties (petrophysical and elastic properties).

In summary, the problem to be solved within the scope of this work is that of appropriately classifying log-facies using an integrated approach of petrophysical properties and elastic rock properties. This is different from the normal or conventional way of log-facies classification in which some of the facies cannot be clearly identified and if done, they cannot be clearly differentiated from each other. Proper log-facies classification leads to the construction of a better static reservoir model and without log-facies analysis and characterization input a geological model is not very accurate.

1.2 OBJECTIVES OF THE STUDY

Just like any other study, this work is accomplished under some objectives outlined as follows:

- Obtain petrophysical rock properties from formation evaluation analysis.
- Obtain elastic properties computed through a rock physics model.
- Integrating these properties for log-facies classification.
- Optimizing facies classification in static reservoir modelling for seismic reservoir characterization.

1.3 SCOPE OF THE STUDY

From the KK field in the Niger Delta operated by the Shell Petroleum Development Corporation, well logs were collected from two wells. These logs were quality checked using Hampson Russell software. Petrophysical properties were obtained after a careful and detailed interpretation of the well logs, from which elastic rock properties were derived using a series of rock physics transformations. This was proceeded by cross plots of the petrophysical and elastic properties and those of petrophysical properties only. After proper zoning, results showed different log-facies for both wells reflecting an improvement in such a classification.

1.4 MOTIVATION FOR THE STUDY

- The need to properly characterise a reservoir using log-facies obtained through a combination of two types of rock properties (petrophysical and elastic properties).
- To prepare data for building up an excellent static reservoir model with both high vertical and lateral details and resolution since a log-data inclined model has limited lateral details (though high vertical resolution) and seismic-data inclined model with high lateral details (limited vertical resolution).
- Improvement of reservoir characterization using multiple data input.

CHAPTER TWO

LITERATURE REVIEW

2.1 LOCATION OF STUDY AREA

The study area is the KK field which is located in the Niger Delta region of Nigeria. A map view of the Niger Delta Region is thus presented.

Figure 1a: Map showing location of study area (courtesy: geography.about.com)

A review of literature is presented to provide the background information for the work. The scope of the review includes the following:

- Formation evaluation (wherein petrophysical properties are obtained).
- Rock physics studies for elastic properties determination.
- Seismic reservoir characterization.
- Log-facies classification.
- Clues on geological model building.

2.2 FORMATION EVALUATION

As reservoirs become more complex and drilling operations more expensive, the need to reduce both inefficiencies and costs for acquiring and analyzing high quality formation evaluation information is essential. In formation evaluation, there are basic questions we need to answer such as:

- What does my reservoir contains: water or hydrocarbons?
- If hydrocarbons, is it oil or gas?
- How much is there?
- Where is it? And can I get it out?
- What kind of rock is there and what are its properties?

The answers to the above questions helps in reservoir characterization, drilling program, and to a lesser extent in completion plan design, perforation and stimulation strategies, and facilities design. The parameters usually evaluated include lithology, porosity, permeability, water, oil and gas saturations, clay content, etc. Several tools exist for formation evaluation which includes cores, logging, borehole imaging, borehole seismic, etc. For example, using sonic logs, the interval transit time is transformed to velocities which are used to estimate effective porosity, elastic moduli, and fracture detection, lithology determination and well-to-well correlation.

Formation evaluation also incorporates tying log derived data to core data or using core data to calibrate logs obtained from a well (Steve Cuddy et al., 2004) when the authors were evaluating a tight gas field with large hydrocarbon accumulation in the UK, Coring of the reservoir highlighted the presence of thinly bedded heterolithic sequences consisting of thin sand and silt layers. Due to the thinness of the beds, conventional wire line logs were unable to resolve the sands and the proportion of sand in the sequence was generally underestimated. However, after a careful evaluation, it was found out that high-resolution logs (sample interval of 2” compared with the conventional 6”) could also identify this thin layering but adding elastic properties to the well logs will give better information than the high-resolution logs.

WELL LOGS

Logging is a general term which means to “make a record” of something. Geoscientists use many types of “logging” including core-logging, cuttings-logging, radioactive logging and geophysical well logging. Geophysical well logging was first developed for the petroleum industry by Marcel and Conrad Schlumberger in 1927 (Papp, E., 2002). Since the first log was run in the 1920s, the technology has evolved very rapidly and revolutionized the hydrocarbon E & P industry. Well logging technology is now used in all the phases of the E&P process from the drilling of the first wild cat well in a field up to the abandonment of the last productive level in the same field. Well logs can now measure a large number of physical properties of the geological formation (and the surrounding environment) intersected by a well and both in open and cased hole conditions. Well logging technology plays a pivotal role in the exploration and production process of hydrocarbon resources. Some of the well logging applications include:

- Petrophysics and Formation Evaluation;
- Reservoir Characterization;

- Reservoir Management and Production Optimization;
- Geology and Geomechanics (the geologic study of the behavior of soil and rock); and
- Geosteering (in the process of drilling a borehole, geosteering is the act of adjusting the borehole position i.e inclination and azimuth angles to reach one or more geological targets), etc.

The logs relevant to this work are Neutron porosity logs, Gamma Ray logs, Density logs, Resistivity logs and Sonic logs.

2.2.1 NEUTRON POROSITY LOG

According to Papp E. (2002) neutron porosity logging uses an active neutron source to emit neutrons into the rocks around a borehole. Because free neutrons are almost unknown in the Earth, the flux of neutrons subsequently recorded at the detector in the tool can be used as an indicator of the condition in the surrounding rocks.

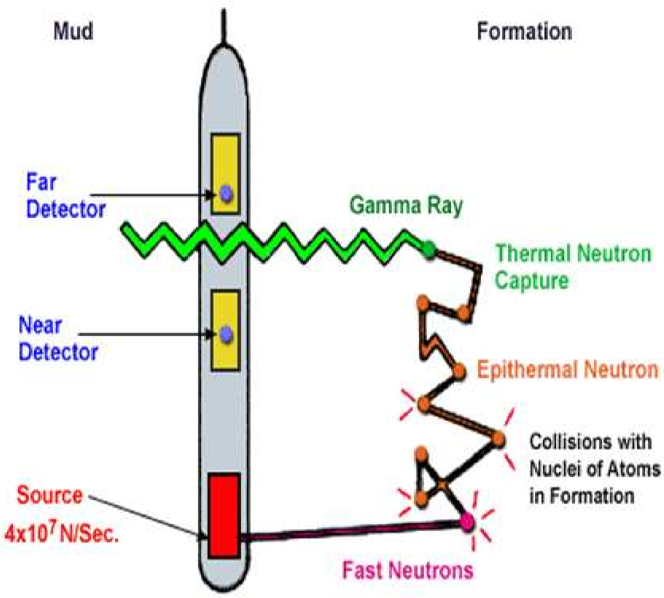


Figure 1b: The Neutron logging tool and how it works (courtesy: Schlumberger well services)

The neutrons entering the rocks of the borehole wall from the tool are at high energy and generally have great penetrating power. The exception is when significant concentrations of hydrogen exist. In this case, the neutrons rapidly loose energy due to collisions with the hydrogen nuclei and become what are known as "thermal neutrons". These thermal neutrons behave in many respects like a diffusing gas and form a spherical shell around the source in the probe. The radius of this sphere will depend primarily on the concentration of hydrogen in the environment around the probe. Because the technique is sensitive to lithological differences, neutron porosity logs can be very useful in cross plots with other log data to help

determine lithology. The parameter of interest obtained from the Neutron Log is Porosity.

2.2.2 Gamma- Ray Log

The simplest radioactive method in geophysical well logging is the natural gamma log (Papp E., 2002). These logging tools record the level of naturally occurring gamma ray emissions from the rocks around a borehole.

The simplest of these types of tools records only the total gamma ray signal. This signal is comprised essentially of gamma ray emissions at different energy levels from the radioactive isotopes of the elements potassium (40K), Thorium (232Th) and Uranium (238U) and the daughter products in the decay series of each (Papp E., 2002). Logging of the gamma ray signal emanating from the rocks around a borehole can provide considerable information about the geology and the processes that have operated.

David Gibson et al as referenced by Papp E., 2002 elucidated in their work that in sedimentary rock sequences, relatively high natural gamma counts are recorded in shales and other clay-rich sediments and relatively low counts are recorded in clean quartz sandstones and limestones. The high signals observed in clay-rich sediments are largely due to the affinity of clay minerals for potassium. However, many regolith clays are leached and do not contain substantial amount of potassium.

Therefore, this interpretation is not always applicable for regolith units. Gamma Ray log can be run in both open and cased hole and it gives a reflection of shale or clay content or better still lithology indicator within a formation, correlation between wells, determination of bed boundaries, mineral analysis, etc. Figure 2a below presents an example of a GR Log.

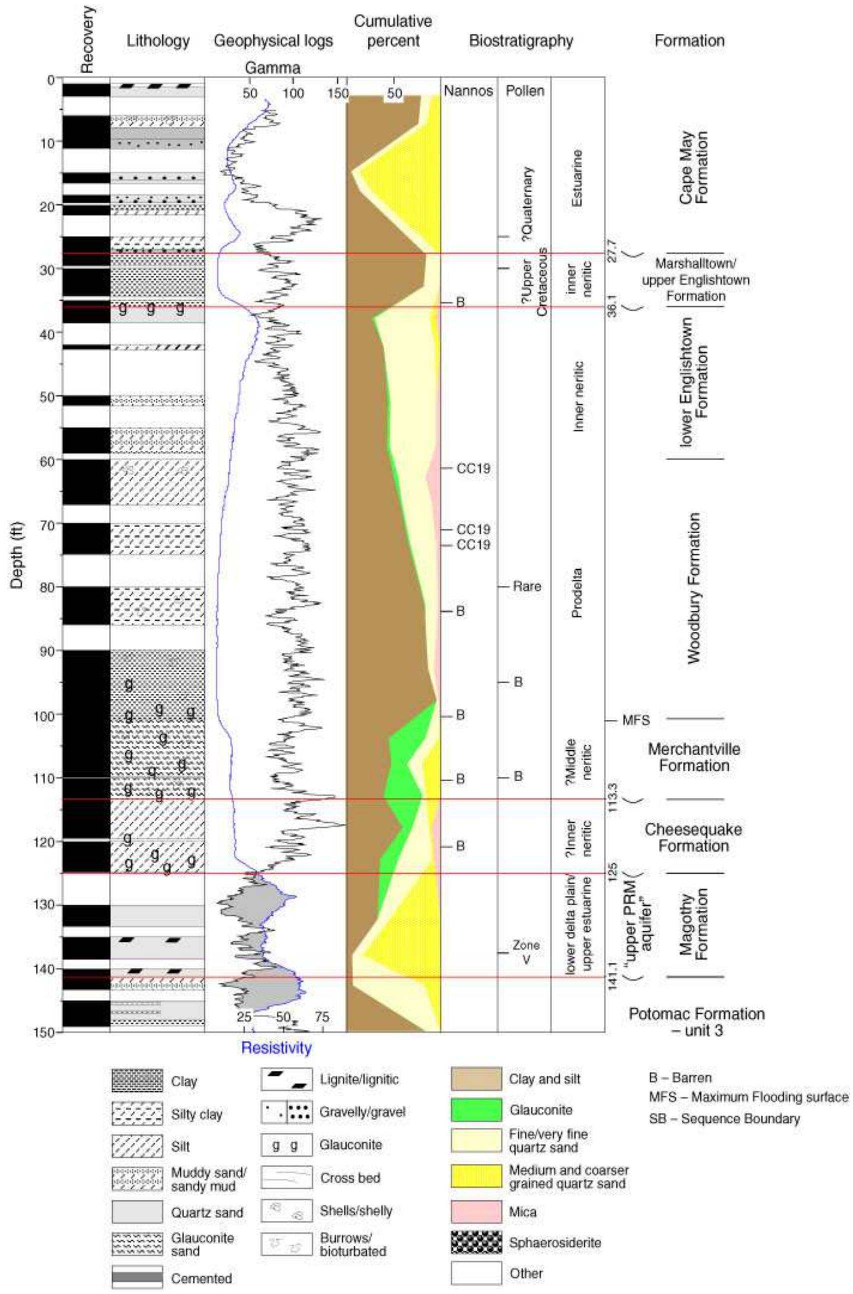


Figure 2a: Representing Gamma-Ray Log (GR Log)

2.2.3 DENSITY LOG

The formation density log is a porosity log that measures electron density of a formation (Schlumberger, 2000). Dense formations absorb many gamma rays, while low-density formations absorb fewer. Thus, high-count rates at the detectors indicate low-density formations, whereas low count rates at the detectors indicate high-density formations. Therefore, scattered gamma rays reaching the detector are an indication of formation density, which in turn is related to the porosity and grain density.

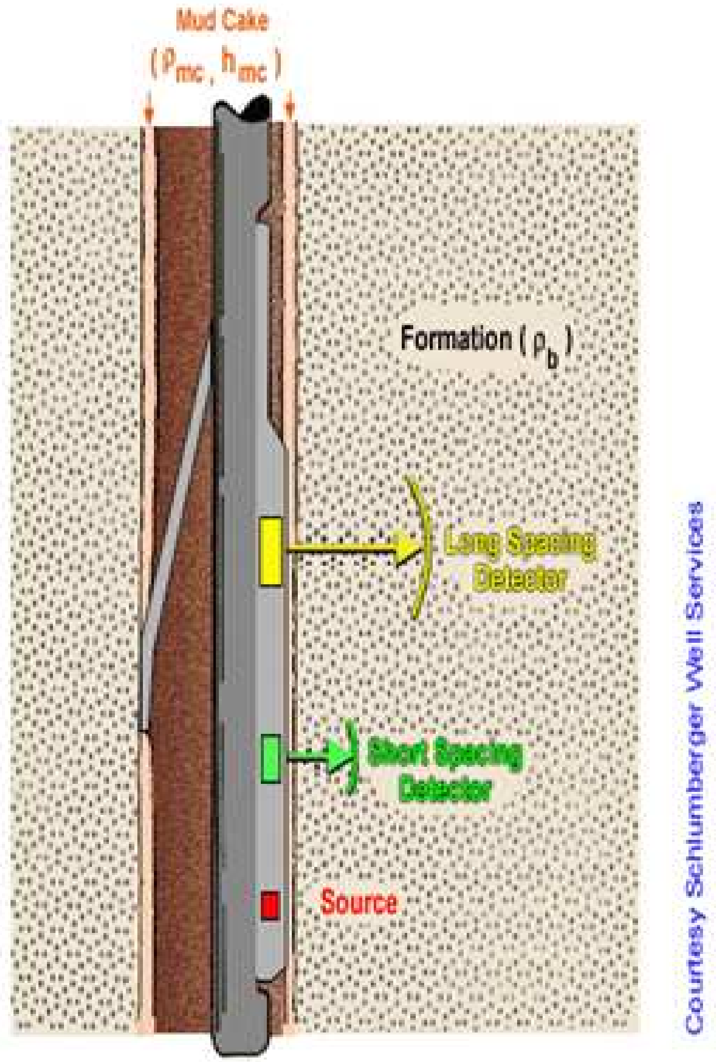


Figure 2b: Density logging tool within a formation (courtesy: Schlumberger well services)

2.2.4 RESISTIVITY LOG

If a material containing unbound charged particles is subjected to a voltage difference then an electrical current will flow. The impedance to this flow is called the electrical resistance and it is a function of the geometry of the current flow and the intrinsic resistivity of the material (Papp E. in 2002). In other words, resistivity measures the electrical properties of the formation and it is the inverse of conductivity. The ability to conduct electric current depends on the volume of water, temperature and salinity of the formation.

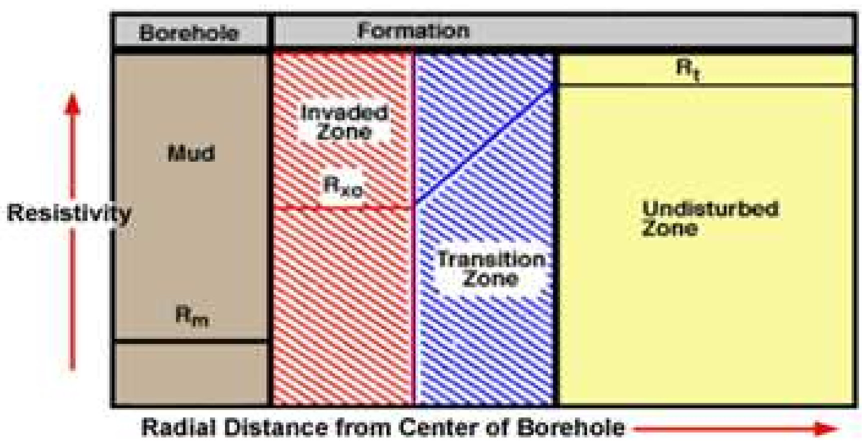


Figure 2c: Resistivity of different zones in the formation from Center of borehole (Alger et al., 1971)

Some materials such as quartz and muscovite have high resistivity, while others have more moderate values (eg. sand) and for some the resistivity is low eg. clay, saline groundwater (Keys, 1988). The resistivity and conductivity rating of some earth materials is as follows.

Increasing Resistivity ↑		Increasing Conductivity ↓
	Rocks	
	Gas	
	Oil	
	Fresh water	
	Salt water	

The factors that affect the resistivity of a formation include resistivity of water, porosity of the formation, pore geometry (tortuosity), lithology of the formation, degree of cementation, and type and amount of clay in the rock. This resistivity log is used to determine the hydrocarbon versus water-bearing zones, indicate permeable zones and determine resistivity porosity.

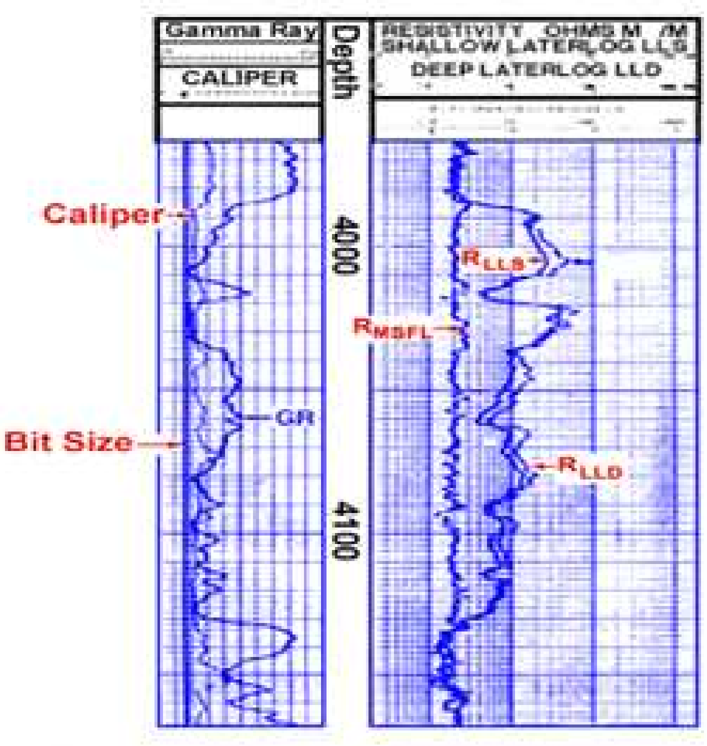


Figure 2d: Different extends of Resistivity log with Gamma-ray log (Alger et al., 1971)

From the resistivity log, values for formation resistivity are obtained and in turn are related to the water saturation.

2.2.5 SONIC LOG

As explicitly explained and illustrated by Chopra and Papp (2002), sonic tools work by transmitting a sound (i.e waves) through the rocks of the borehole wall. A basic sonic tool generally consists of two modules, one with the transmitter and the other contains two or more receivers (fig.3). The two parts are separated by a rubber connector to reduce the amount of direct transmission of acoustic energy along the tool from the transmitter to the receiver.

The transmitter injects a sinusoidal wave-train of acoustic energy into the formation. The detectors subsequently receive a complex signal, because of the multiplicity of ray paths that the wave-train can take through the formation. The fastest arrival (in uncased holes) will generally be through the rocks near the borehole wall. Detection of this signal uses a signal processing algorithm involving cross-correlation between the original wave train generated by the transmitter and the coda (closing section) received by the detectors. In practice, sonic logging actually measures the "time of flight" along the fastest signal path (fig. 2e). Because this time of flight is dependent on the density of the medium, it can be used to calculate the average density of the rocks through which the signal passed.

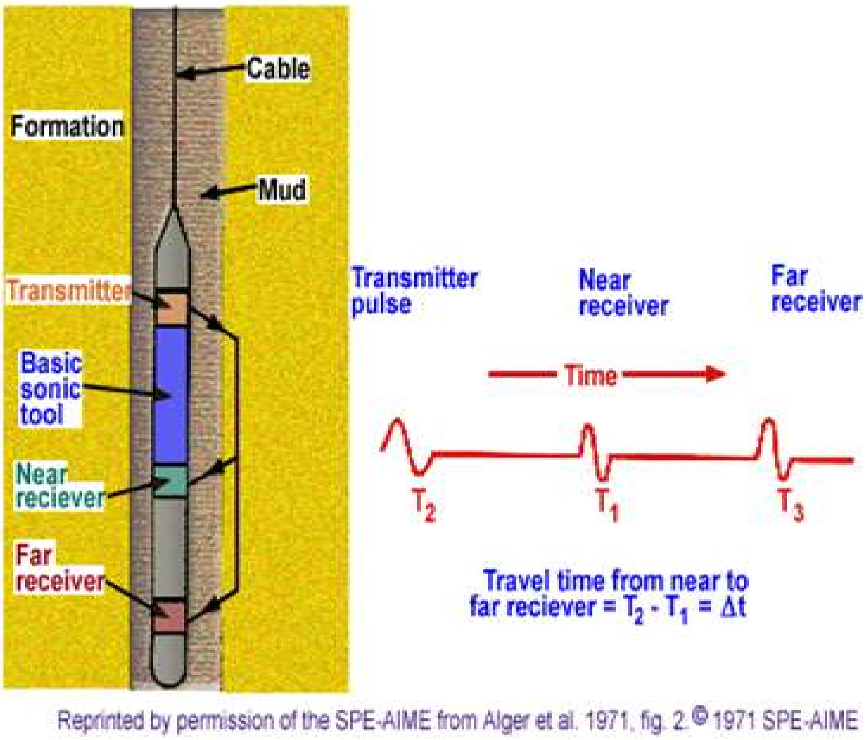


Figure 2e: Acoustic logging tool (Alger et al., 1971)

Acoustic tools measure the speed of sound waves in subsurface formations. While the acoustic log can be used to determine porosity in consolidated formations, it is also valuable in other applications, such as:

indicating lithology (using the ratio of compressional velocity over shear velocity), determining integrated travel time (an important tool for seismic/wellbore correlation), correlation with other wells, detecting fractures and evaluating secondary porosity, evaluating cement bonds between casing, and formation, detecting over-pressure, determining mechanical properties (in combination with the density log), and determining acoustic impedance (in combination with the density log).

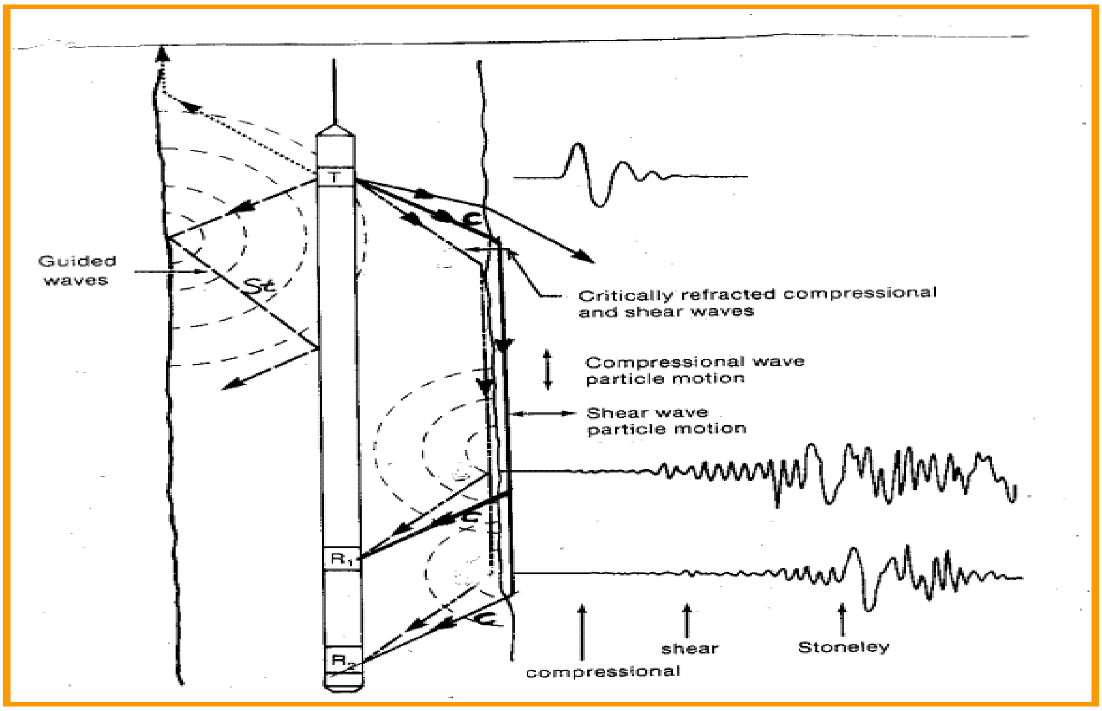


Figure 3: Schematic diagram of a simple sonic log showing sound paths, following Snell's Law (courtesy of Crains Petrophysical Handbook, 2000)

Sonic logging tools were initially developed for the petroleum industry as porosity measuring devices, and they have a similar use in regolith (layer of loose rock resting on bedrock and covers most of the earth's land surface). In hard rock environments, where porosities are generally low, sonic logs can be very useful lithological probes. A very important use of sonic logs is for correction of interval velocities used in seismic processing and interpretation. This leads to better velocity models for seismic processing and analysis.

2.3 ELASTIC WAVES (VP AND VS)

Elastic waves are generated using many equipment depending on whether the acquisition is onshore or offshore. These equipments include Sledge hammer, Dynamite and Vibroseis for onshore waves generation and an Air gun for offshore waves generation. Vp and Vs are elastic waves that propagates through a medium rather than along an interface. They are also called body waves and travels faster than Surface waves.

a) **P-wave:**

It is an elastic body wave in which particles motions are parallel to the direction of wave propagation. It`s velocity is faster than S-wave. P-waves incident on an interface at other than normal incidence can produce reflected and transmitted S-waves, in that case known as converted waves. They travel through rocks and liquids media (Sroor M., 2010).

b) **S-wave:**

An elastic body wave in which particle motion is perpendicular to the direction of wave propagation. S-waves are generated by most land seismic sources, but not by air guns. They do not travel through liquid medium (Sroor M., 2010).

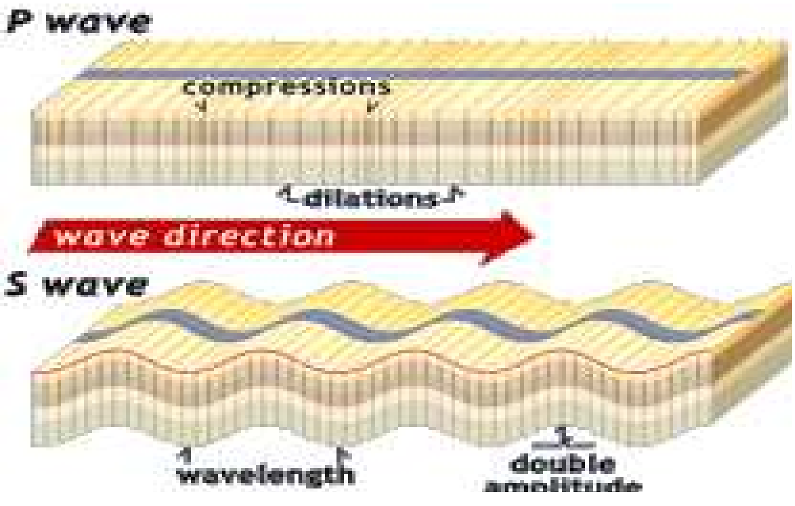


Figure 4: Compressional and Shear Wave propagation mode (Courtesy: Mahmoud Sroor, 2010)

Other seismic wave types are the surface waves that propagate at the interface between two media (Sroor M., 2010) and include the following:

Rayleigh waves whose particles move in an elliptical path.

Love wave in which particles oscillate horizontally and perpendicularly to the direction of wave propagation.

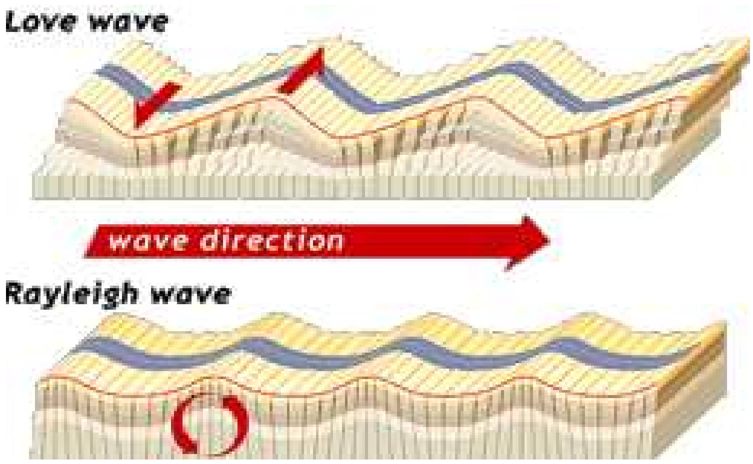


Figure 5: Rayleigh and Love Wave propagation mode (Courtesy: Mahmoud Sroor, 2010)

The Stoneley wave is another surface wave generated by a sonic tool in a borehole. Last but not the least are Tube waves which occurs in cased wellbores when Rayleigh waves encounters a wellbore and perturbs the fluid in wellbore but suffers little energy loss & very high amplitude

But note that all these surface waves are not included in this particular work scheme.

2.4 Rock Physics Analysis

According to Maffioletti et al., 2010, a rock physics model is established in order to accurately link acoustic and elastic variables with petrophysical properties (porosity, clay content and saturations as derived from the quantitative log interpretation). A rock physics model is required to understand how rock properties are related with respect to velocities, impedances or other seismic attributes and to integrate geologic information that can be obtained from seismic data into the reservoir. The vertical resolution of log interpretation and rock physics modelling is representative of the well-log scale. The type of rock physics model we use depends on the geological scenario we deal with. A well known family of rock physics model is "granular media models", which is based on Hertz-Mindlin contact theory. The input data for the model are the petrophysical curves obtained from formation evaluation analysis: effective porosity, volumetric fractions (e.g. quartz, smectite, kaolinite and muscovite) and water saturation. This model allows computation of saturated- rock elastic properties (Vp and Vs) for the scenarios described by well log data and even for fluid and lithology substitution sensitivity analysis.

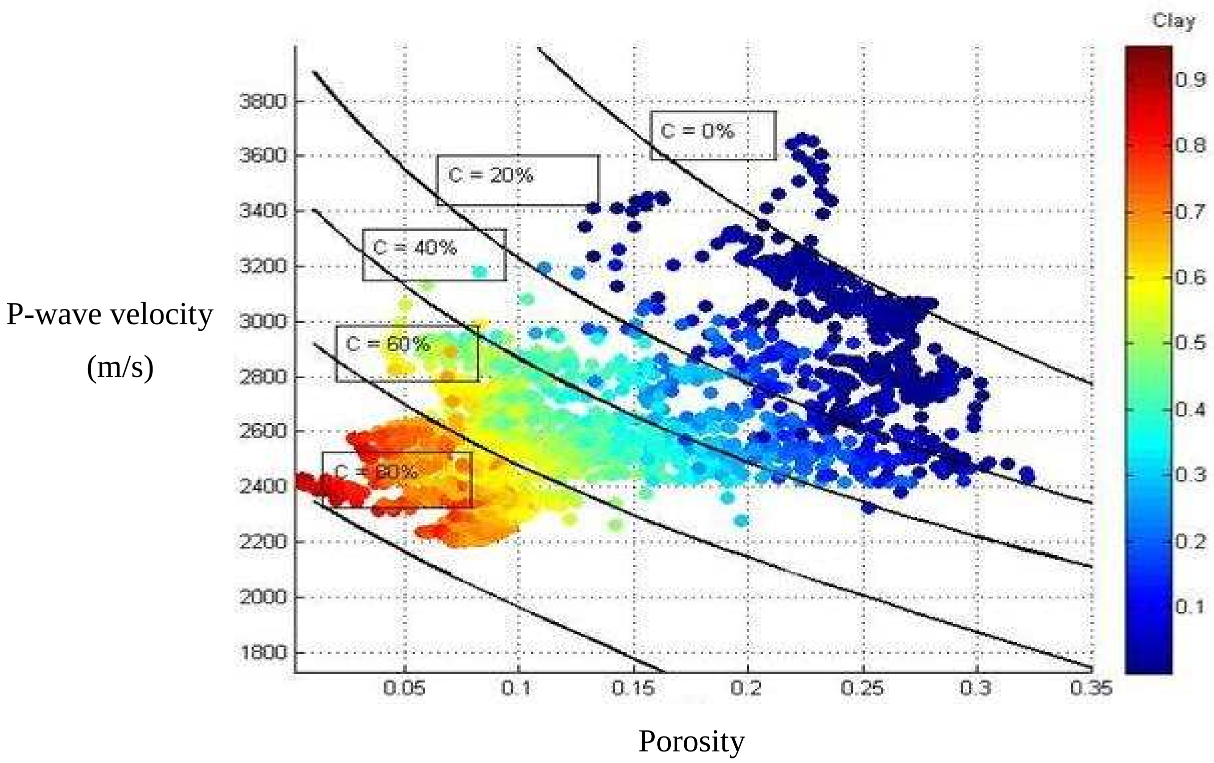
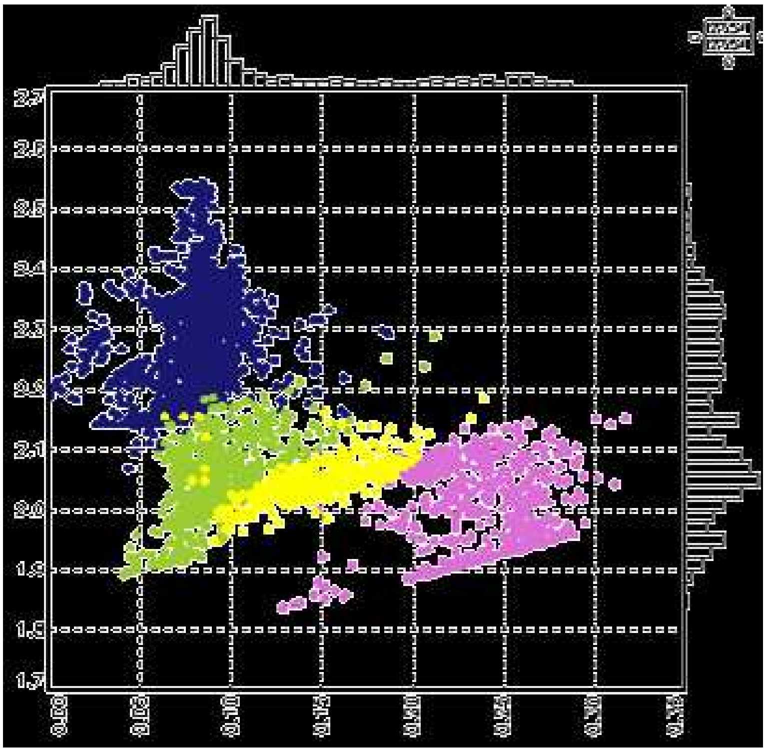


Figure 6: Rock physics model. P-wave velocity obtained by rock physics model versus effective porosity, color coded by volume of clay (Courtesy: Maffioletti et al., 2010)

The estimated velocities are integrated in log facies classification in order to improve the discrimination of facies and to guarantee the link between log facies and seismic facies classification. Log facies characterization is achieved via a multivariate statistics technique carried out using volumetric logs (sand, silt, clay fractions and effective porosity) and Vp/Vs ratio as input.

Different fluid saturation scenarios are taken into account in order to value their effect on Vp/Vs: in particular log from the “brine” scenarios is used to consider rock petrophysical features regardless of any influence by hydrocarbon (Maffioletti et al., 2010,) . A Vp/Vs ratio plot versus porosity was plotted (Fig.7)

Vp/Vs ratio



Porosity

Figure 7: Vp/Vs ratio from rock physics model versus effective porosity, colour coded for the 4 facies- Brine scenario (Courtesy: Maffioletti et al., 2010)

Colors: Blue = Hemipelagic shale, Green = Very low concentration turbidite, Yellow = Low concentration turbidite, Purple = High concentration turbidite.

From their studies, a new log-facies classification was finally proposed and four classes where coded and defined as follows:

Log-Facies 1. Hemipelagic shales (HEMI).

Log-Facies 2. Very low concentration turbidite or heterolithics (VLCT)

Log-Facies 3. Low concentration turbidite (LCT)

Log-Facies 4. High concentration turbidite (HCT)

One of the most serious and common mistakes observed in industry practice is the use of inappropriate velocity–porosity relations for seismic mapping of porosity and litho-facies (Avseth et al, 2001). Rock physics diagnostic analysis of well logs and cores, coupled to the geologic model, usually leads to more rational velocity–porosity relations.

The sensitivity of seismic velocities to critical reservoir parameters, such as porosity, litho-facies, pore fluid type, saturation, and pore pressure, has been recognized for many years. However, the practical need to quantify seismic-to-rock-property transforms and their uncertainties has become most critical over the past decade, with the enormous improvement in seismic acquisition and processing and the need to interpret amplitudes for hydrocarbon detection, reservoir characterization, and reservoir monitoring. Rock physics modelling can help us understand the behaviour of the reservoir and non-reservoir zones and correct for some of the problems encountered in well log data (Avseth et al., 2001). One purpose of rock physics modelling is to allow reliable prediction and perturbation of seismic response with changes in reservoir conditions and to make predictions of seismic properties away from the wellbore. The need for inclusion of rock physics in log-facies classification cannot be over emphasized as good classsification is gotten from it, e.g sands may have essentially the same porosity and composition, yet they have very different seismic signatures (Avseth et al., 2001).

2.5 SEISMIC RESERVOIR CHARACTERIZATION

Seismic Reservoir Characterization, also known as reservoir geophysics, has evolved over the past several years into a multi-disciplinary, business-critical function in most Exploration, Development and Production organizations. Sheriff (2000) defines reservoir geophysics as "The use of geophysical methods to assist in delineating or describing a reservoir or monitoring the changes in a reservoir as it is produced."

Seismic reservoir characterization is applied across a wide spectrum of the oilfield life cycle from discovery and early development to tertiary recovery. One critical part of this process is careful analysis and understanding of petrophysical properties from well logs and core data (Joel Walls et al, 2001). The basic steps in seismic reservoir characterization analysis are to:

- Collect and organize input log and seismic data.
- Perform geophysical log interpretation for volume minerals, porosity, and fluids.
- Determine fluid properties (oil API, brine salinity, etc.) and reservoir pressure-temperature.
- Perturb reservoir properties using rock physics effective medium models (pseudo-well modeling).
- Compute synthetic seismic traces.
- Generate trend curves and cross plots.
- Create graphics and digital output files.

The primary benefits of seismic petrophysics (seismic characterization) are improved well-to-seismic ties, improved calibration of seismic attributes to reservoir properties, and more reliable models of seismic response due to reservoir changes (vertically laterally, and temporally). These models can improve interpretation of 3D seismic data, especially acoustic and elastic impedance inversion. This improved interpretation can reduce drilling risk, enhance field productivity, and ultimately increase asset value.

2.6 LOG-FACIES CLASSIFICATION

Log-facies are referred to as sedimentary units which are defined on the basis of comparable log characteristics and characterized from wire line logs (Tavakoli et al, 2006). Log-facies are applied for a set of log responses which characterizes bed stratum and allows it to be distinguished from others

(Serra, 1986). In a broad spectrum, rock facies are a body of rocks with specified characteristics that

reflect the conditions under which it was formed (Reading and Levell 1996).

Sedimentary facies are important in reservoir characterization because flow properties are commonly assigned using facies-specific correlations. In uncored wells, sedimentary facies cannot be observed directly, and facies are inferred from petrophysical data. Multivariate statistical methods (beta-Bayesian, multinomial logistic regression, and discriminant analysis) provide a powerful vehicle to extract facies responses from different well logs, to predict facies in uncored wells and evaluate uncertainty.

Classification of litho-facies is a reflection of the non-linearity between the porosity and permeability and

even between other petrophysical parameters (Heon, et al., 1999). According to Lake et al (2005), mapped probabilities of the individual facies show the spatial continuity and geologic character of the underlying depositional environment. The identification and mapping of rock facies is important for reliable reservoir characterization. Traditionally, facies identification and mapping is based on inspection of core data and/or well-log signatures, a procedure that has subjective aspects as it relies on samples from only a very small portion of the reservoir. Such identification is also difficult to perform at the onset of the exploration stage due to lack of sufficient well data. To overcome this limitation, a simple, practical approach is used to identify and classify facies from seismic amplitude data using basic statistical concepts. This gives the importance of integrating petrophysical and seismic derived data in characterizing a reservoir.

Maffioletti (2010) and his group applied multivariate statistical technique using volumetric logs (sand, silt, clay fractions and effective porosity) and Vp/Vs ratio as input and cluster analysis to classify or characterize log-facies. In her work, different fluid saturation scenarios are taken into account in order to value their effect on Vp/Vs: in particular log from the “brine” scenarios is used to consider rock petrophysical features regardless of any influence by hydrocarbon.

In addition, log-facies classification is usually integrated in seismic reservoir characterization studies,

where different scales and different resolutions data are combined in the inversion workflow. It is worth noting that log-facies are defined at a vertical resolution scale higher than seismic resolution (for seismic resolution dies down with depth because of the reduced signal to noise ratio); logs usually are analysed in depth domain, whereas seismic data usually are in time domain. Problems of change of scale and domain occur and the statistically representativeness of log data in the two domains cannot be ignored (Maffioletti, 2010). However, we can use alternatively or together an acoustic layer definition (markers),

different filtering techniques (Backus, 1962), and/or blocking for continuous logs.

2.7 Clues in constructing a geologic or static model

It is but evident that the most important phase of a reservoir study is probably the construction of a static model of the reservoir rock, given both the large number of activities involved, and its impact on the end results. As we know, the production capacity of a reservoir depends on its geometrical/structural and

petrophysical characteristics. The availability of a representative static model is therefore an essential

condition for the subsequent dynamic modelling phase.

A static reservoir study typically involves four main stages, carried out by experts in the various disciplines (Cosentino, 2001).

2.7.1 STRUCTURAL MODELLING. Reconstructing the geometrical and structural properties of the reservoir, by defining a map of its structural top (i.e identifying the basic geometrical structure of the hydrocarbon traps and in which case, we are dealing with the external boundaries of the reservoir) and the set of faults running through it. This stage of the work is carried out by integrating interpretations of geophysical surveys (especially seismic surveys) with available well data against which the resulting map is calibrated. Furthermore, the interpretation of the set of faults running through a reservoir has considerable impact on its production characteristics, and in particular on the most appropriate plan for its development.

The interpretation of the set of faults within a reservoir is generally based on four types of data that are subsequently integrated and these include inconsistencies in correlation; well test data; geophysical tests (discontinuity in seismic signal indicates presence of faults) and dynamic well test data (where the faults have an impact on fluid flow, and thus on pressure patterns over time).

According to L. Cosentino, 2001, procedures for constructing a three-dimensional structural reservoir model vary according to the applications used, but generally include the following steps.

- **Modelling of major faults**. These are faults which bind the main blocks forming the reservoir. The fault planes are in this case explicitly modelled as surfaces, which in turn define the boundaries of the main blocks of the three-dimensional model.
- **Construction of geological surfaces**. This involves the generation of parametric surfaces within each main block, which represent the main geological horizons, typically the top and bottom of the main sequences. These surfaces must be consistent with the depths measured in all available wells.
- **Modelling of minor faults**. Whilst affecting fluid dynamics, these faults have only a slight impact

on the overall geometry of the reservoir, locally displacing the geological surfaces.

Figure 8 shows an example of a three-dimensional structural reservoir model: the major faults, surfaces and minor faults are clearly visible. It is obvious that structures of this complexity cannot be modelled using traditional two-dimensional mapping methods.

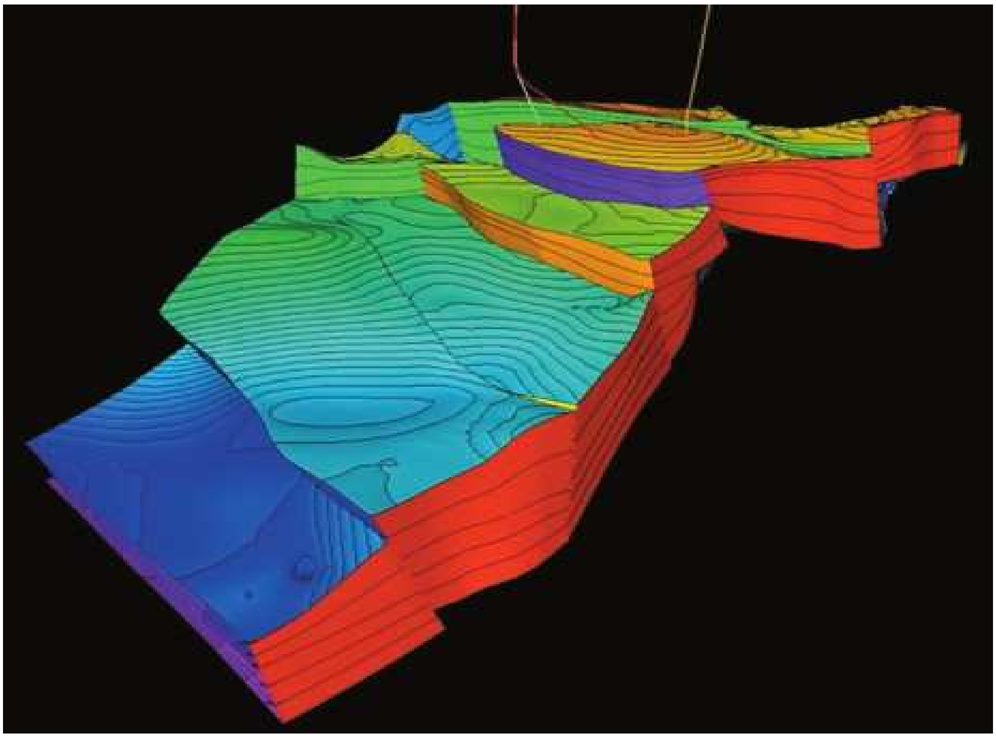


Figure 8: A 3-D structural reservoir model (courtesy: L. Cosentino, 2001)

2.7.2 STRATIGRAPHIC MODELLING. This involves defining a stratigraphic scheme using well data, which form the basis for well-to-well correlations. The data used in this case typically consist of electrical, acoustic and radioactive logs recorded in the wells, and available cores, integrated where possible with information from specialist studies and production data. Here, the Geologist must perform a well-to-well correlation (using logs recorded in open hole or cased hole, and cores) with the aim of defining the stratigraphic horizons bounding the main geological sequences within the hydrocarbon formation.

The challenge in this modelling is definition of the depositional environment of the reservoir. However, when the sedimentary sequences present a significant lateral extension, the correlations between wells may be relatively simple. This is true, for example, for shelf areas, with both terrigenous and carbonates sedimentation, dominated by tidal phenomena. Drilling data, biostratigraphy and palynology, pressure and production data are used for the validation of the stratigraphic scheme. This model consists of a series of thickness maps of the individual geological horizons located between the upper and lower boundary surfaces of the reservoir. In a three-dimensional stratigraphic model, we can see the different depositional geometries of the various sedimentary units.

2.7.3 LITHOLOGICAL MODELLING. Definition of a certain number of lithological types (basic facies) for the reservoir in question, which are characterized on the basis of proper lithology, sedimentology and petrophysics. This classification into facies is a convenient way of representing the geological characteristics of a reservoir, especially for the purposes of subsequent three-dimensional modelling. It involves defining the spatial distribution of the reservoir rock’s petrophysical characteristics.

2.7.4 PETROPHYSICAL MODELLING. Some of the main petrophysical characteristics of the reservoir rock, such as porosity, water saturation, and permeability are determined by quantitative interpretation of well logs. Core data represent the essential basis for the calibration of interpretative processes.

The results of these different stages are integrated in a two (2D) or three-dimensional (3D) context, to build what we might call an integrated geological model of the reservoir. On the one hand, this represents the reference frame for calculating the quantity of hydrocarbons in place, and on the other, it forms the basis for the initialization of the dynamic model.

CHAPTER THREE

METHODOLOGY

The methodology for this work is divided into five steps:

1) Acquisition and Log data gathering from the field;

2) Loading, Importing and Quality check of data;

3) Petrophysical Property Computations and Interpretation;

4) Rock Physics Model Computations (for elastic parameters or properties);

5) Log-facies classification;

All these steps were separately and carefully examined to evaluate their contribution to the make-up of this work. As a result, all the activities carried out in each step were analyzed and the rest followed suit. The analysis followed the chronology as presented above i.e. starting from the acquisition and log data gathering from the field to loading, importation and QC, through petrohysical and elastic properties computations and ending with the classification of the log-facies.

A display of the flow chart for the methodology is hereby presented.

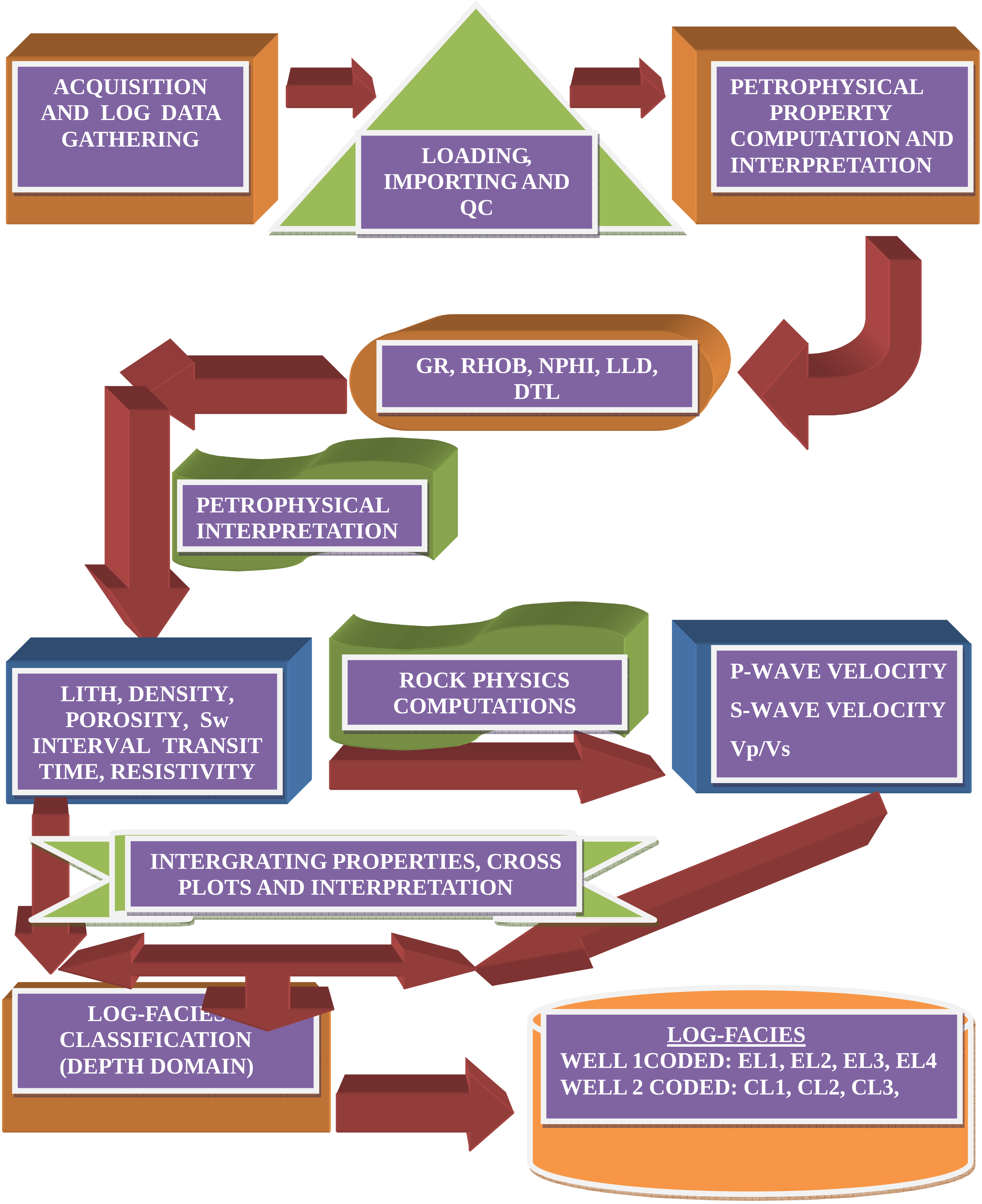


Figure 9: Flow Chart of Methodology

3.1 ACQUISITION AND LOG DATA GATHERING

As part of any research, data is required for complete and proper realization of its objectives or aims.

The data needed for this work were log data from the KK field in the tertiary Niger Delta. The field is operated by the Shell Petroleum Development Corporation. The well logs were of varying types. Some wells had a lot of logging information, while others had incomplete log suites.

However, two good wells (i.e wells with good log suites as shown by their tracts) were selected from amongst the many for this research. One of the wells was chosen to serve as a control (well 2). The logs obtained from these wells included Gamma-Ray (GR) log, Lateral log, Resistivity log, Neutron Porosity (NPHI) log, Effective Porosity (PHIE) log, Spontaneous Potential (SP) log, Caliper (CALI) log, Lithology (LITH) log, Sonic (DT) log, Lateral Deep Log (LLD), Lateral Short Log (LLS), Bulk Density (RHOB) and Spectral Gamma Ray (SGR).

The wells were coded as TMB_4 and TMB_1 which are represented as wells 1 and 2 respectively. Their different logs examined included:

a) For TMB_1(Depth = 7950-11300ft)

The logs considered for this well were carefully selected based on the aim of this work. As a result, the following logs were selected: GR, SP, CALI Log, Neutron Porosity Log, Lateral Log, and Density Log.

These logs are displayed in fig. 10.

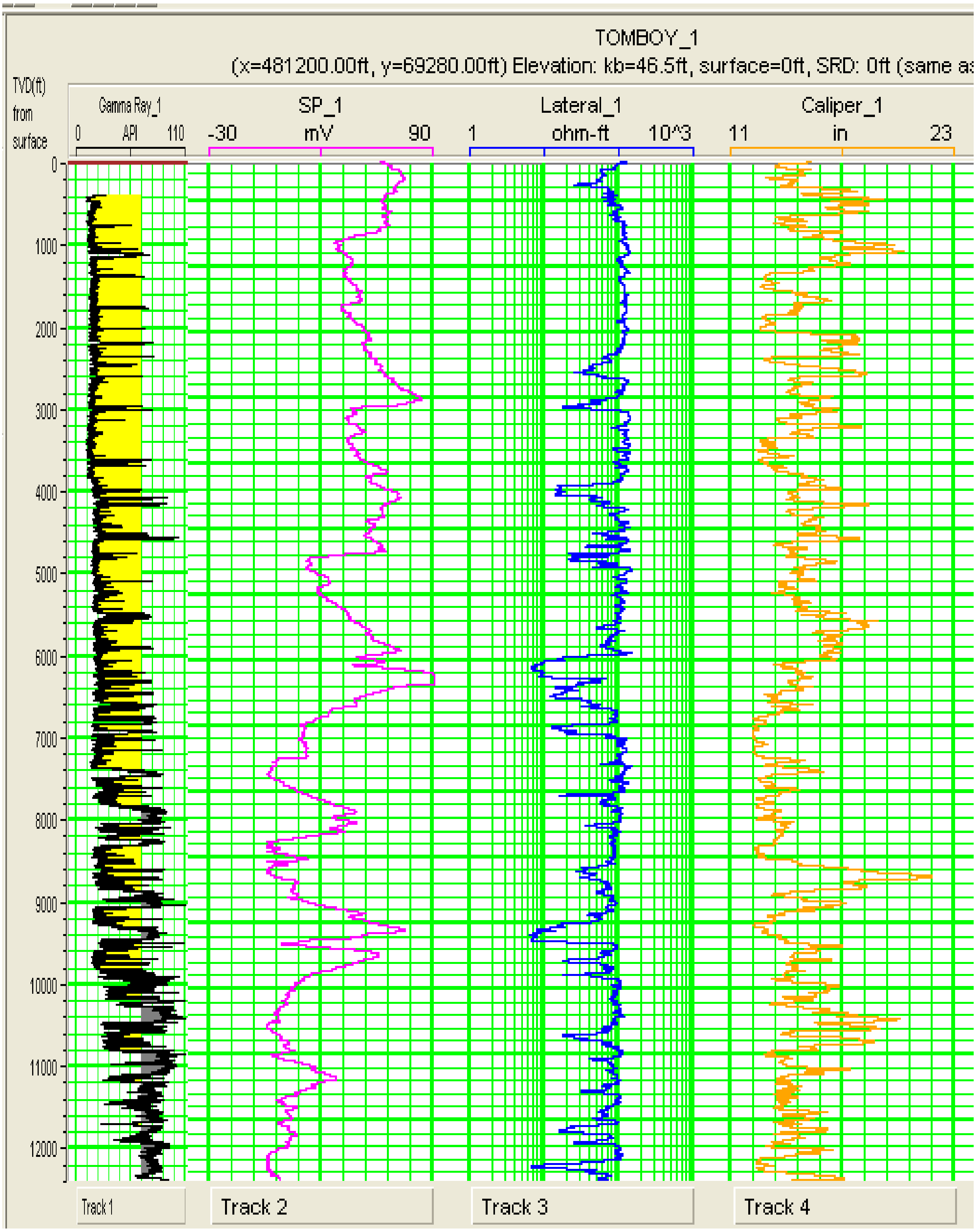


Figure 10: Display of well log tracts for TMB_1

b) For TMB_4 (Depth = 3900-7700ft)

GR, SP, CALI, CILD, DT, DTL, LITH, LLD, Sw, LLS, NPHI, PHIE, RHOB and SGR.

A view of some of the tracts display is presented in fig 11:

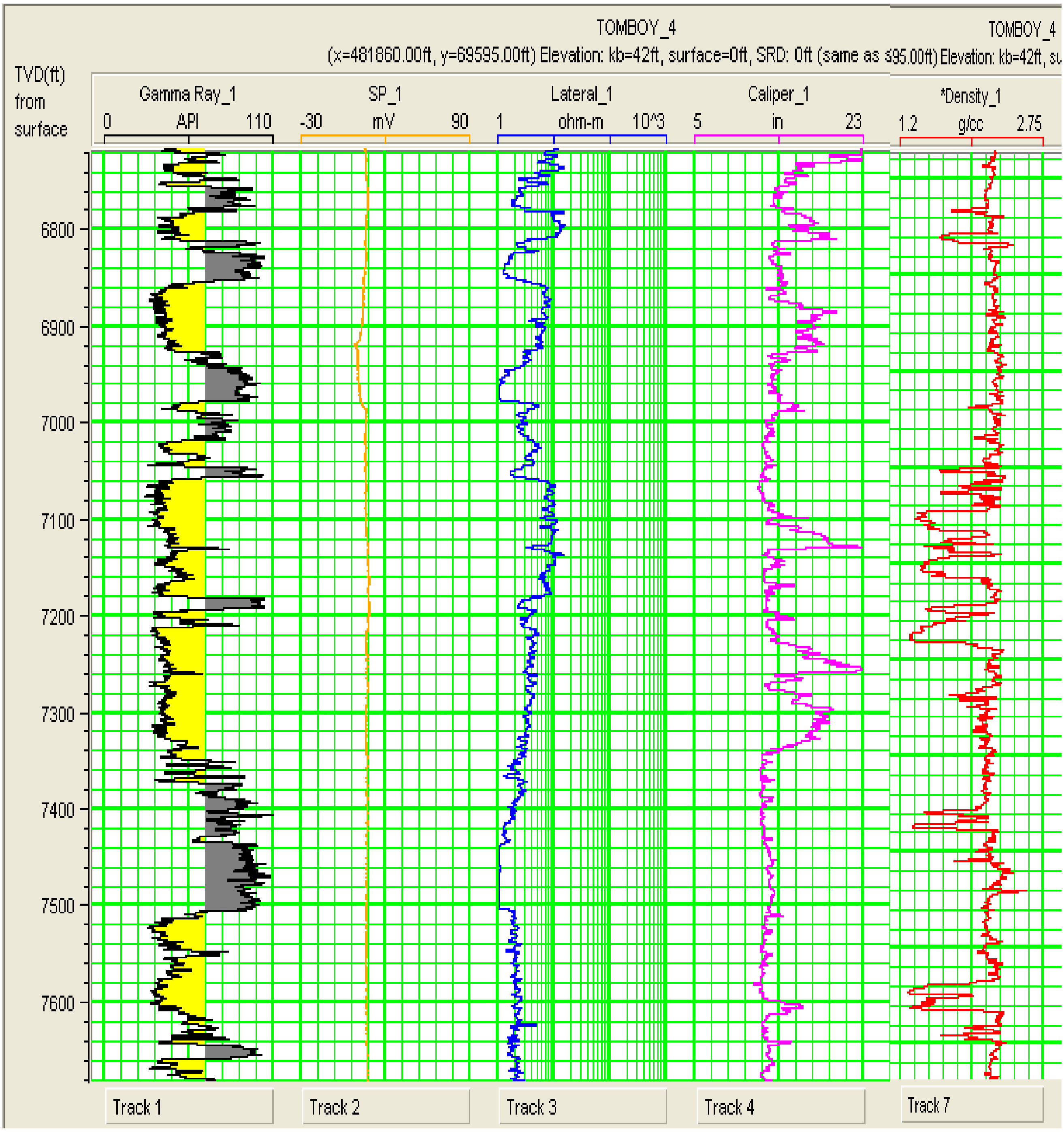


Figure 11: Display of well log tracts for TMB_4

3.2 LOADING, IMPORTING AND QUALITY CHECK OF DATA

3.2.1 LOADING OF LOG DATA

The logs were carefully and conveniently loaded into the work station and a file name created to ensure quick and easy access of the data for subsequent use.

Some of the log data was loaded into Opendtech for editing and this facilitated the work.

3.2.2 IMPORTING DATA

The raw data was imported into the software (HAMPSON-RUSSELL). A database was created to ensure that the work was appropriately stored in the work station. This setup took a few minutes to an hour for success to be achieved.

3.2.3 QUALITY CHECK OF DATA

QC as applied to logs simply involves a series of checks that were carried out on the log tracts. These include:

Removal of logs which were irrelevant to the work. For example the LLD, LLS, CILD, SGR, etc were screened out of the raw data set. This went a long way to reduce the data set and made it relatively easier and convenient to work with.

Quality check within this scope of work also embodies the adjustment of the Start Amplitude (SAV) and End Amplitude (EAV) Values. This enables the logs to show appreciable tracts from which they can be qualitatively and quantitatively interpreted. Some of the tracts after adjustment are shown in the figure 12. From the original or raw log data, the lateral log tract for TMB_4 (well 1) which depicts to an extent the resistivity of the formation did not at a higher percentage match with the lithology. This is because it is expected that low lateral log readings should be for shale bodies and high readings for sand. However, after the amplitude adjustments, the tracts could be seen matching the various lithology i.e higher readings for sand and lower readings for shale (Fig 12).

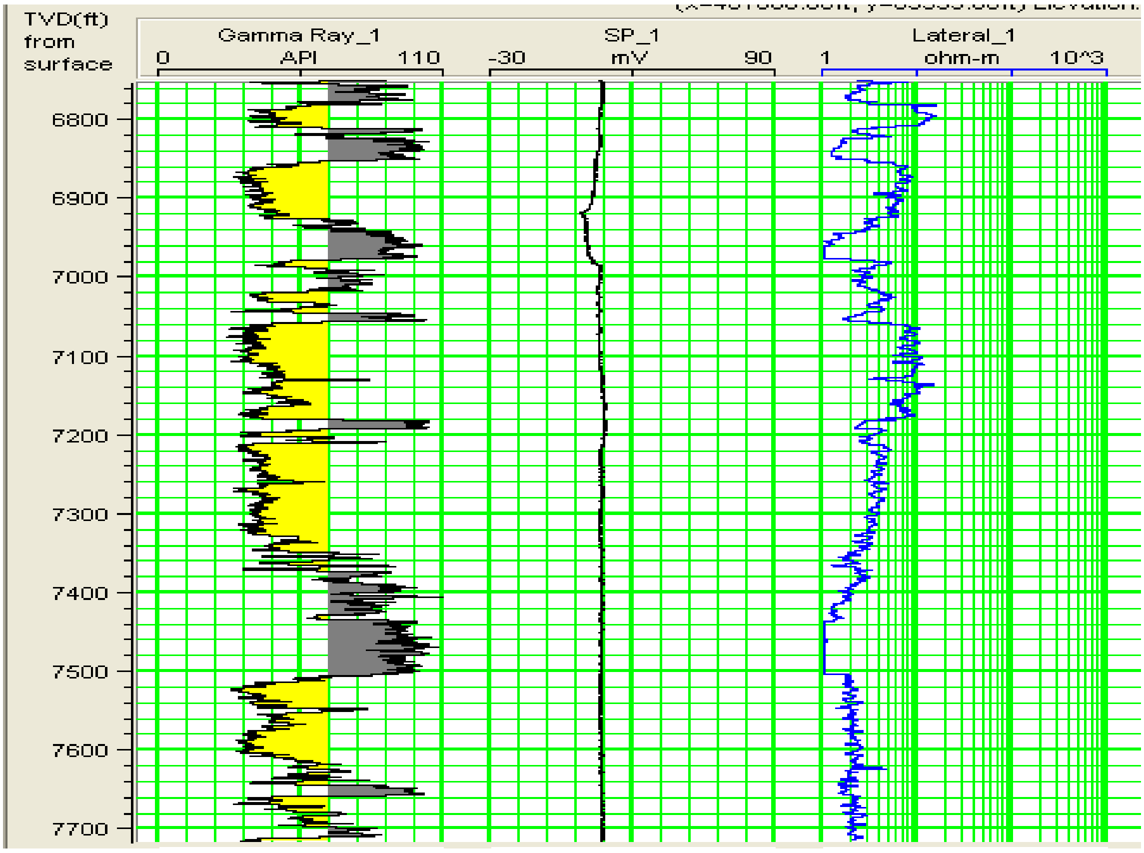


Figure 12: A Display of adjusted log tracts forTMB_4 showing lateral log matching with lithology

Furthermore, allocating the right units for the different log parameters was also incorporated within the quality check process e.g. Depth in feets (ft), GR in API, P-wave velocity in ft/s, density in g/cc, etc.

Attributing colors to or coloring the different log tracts was done for clear reading and visualization and infill of multiple colors to the GR log to differentiate between sand (yellow color) and shale (grey color) as shown in fig.12 above.

In addition, observation of tracking logs was interpreted as a result of QC. If tracking occurs between two logs, it means there was no inversion as it was the case for this work and vice versa. However, the Neutron and Density logs exhibited zones of inversion and no inversion.

The QC was carried out on both wells to render them suitable for picking correct intervals and subsequently for rock physics analysis and scenarios simulation.

3.3 PETROPHYSICAL PROPERTY COMPUTATIONS (PPC) AND INTERPRETATION

This refers to the calculation and subsequent interpretation of petrophysical parameters especially those that were missing in the raw or original data and those that did not have good enough information to give reliable results. The parameters of consideration computed were Porosity, Density and Sw. The equations used included: Gardner's equation and other mathematical relations.

For Density, the Gardner's (1974) relationship was used to create a density log by applying an exponential transform to an input P-wave log. This parameter was computed only for TMB_1

$$\ell = C_1\ [Vp]^{0.25}$$ ....Eqn. 1

where C1 = Constant = 0.23034, ℓ = Density (g/cc) and Vp = P-wave (ft/s)

This equation is used on the assumption that the rock is isotropic, all minerals making up the rock have the same velocities, and the rock is fluid-saturated and should be used only for consolidated cemented rocks.

For Porosity, the following equations were used: From Serra, 1984.

$$\Phi = \frac{0.9\sqrt{[Rw \times Rt]} \times (\ell m - \ell h) + (\ell ma - \ell obs)}{(\ell ma - \ell h)}$$ .... Eqn. 2a

$$\Phi = \frac{\ell ma - \ell obs}{\ell ma - \ell fl}$$ .... Eqn. 2b

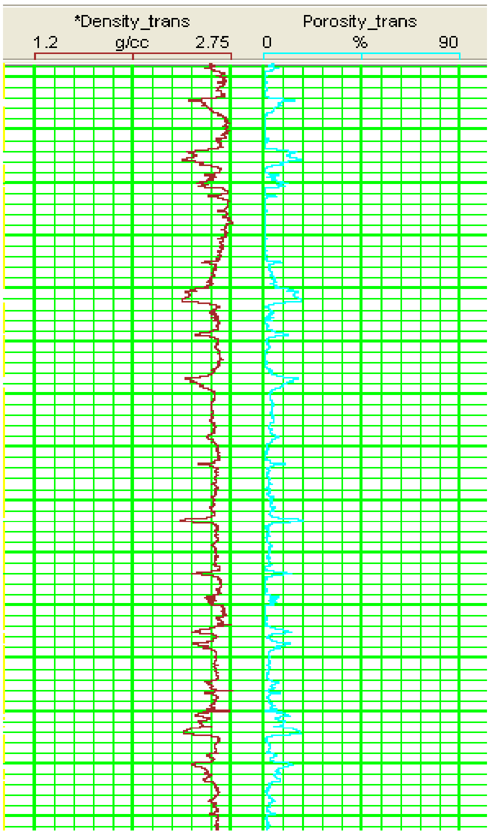
Where Φ = porosity, ℓma = rock matrix density, ℓfl = fluid density, Rw = true resistivity, Rw = water resistivity, ℓobs = observed density, ℓh = hydrocarbon density

For Sw, Archie's (1942) empirical formula was used.

$$Sw = \sqrt[n]{\frac{a\ R_W}{R_t\ \Phi^m}}$$ ....Eqn. 3

Where Sw = water saturation, a = tortuosity factor, n = saturation exponent, m = cementation exponent

These computed logs are displayed in figures 13a and 13b as follows:



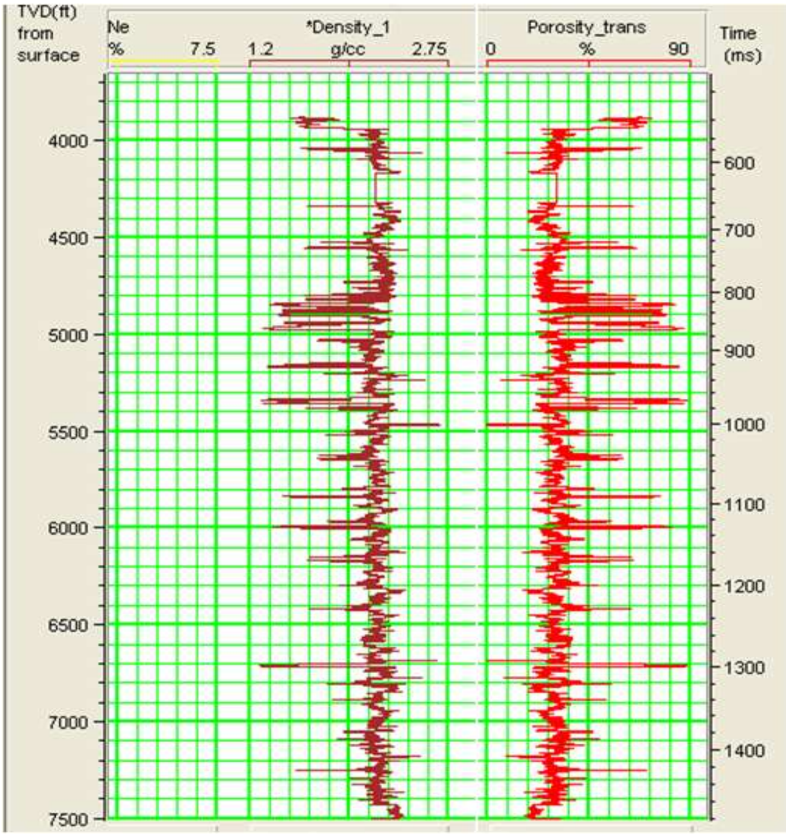


Figure 13a: Computed Density and Porosity Logs for TMB_1

Figure 13b: Computed Density and Porosity Logs for TMB_4

It is worth noting that after the transformation, the computed logs were displayed differently. The Density log as "Density_ trans" and Porosity as "Porosity trans" as shown in figures 13a and 13b except for the density for TMB_4 which was not computed. These computed logs were used subsequently for cross plots against elastic properties (Vp/Vs, Vp and Vs).

The parameters to be interpreted included: porosity and density, interval transit time, lithology, resistivity and water saturation, each interpreted from its corresponding log type i.e porosity from Neutron-Porosity log and computed Porosity log, density from RHOB log, interval transit time form Sonic log, lithology from GR log, resistivity from Resistivity (or lateral log) log and finally Sw from Sw log tracts. The lithology of the formation was seen from the GR log (which span from 0 – 110 API) to be solely sand and shale as illustrated in the fig.12 above. The separation was taken at a baseline of 65 API.

In this regard, any spread of the litho-type from 65 API and below was considered sand and from 65 API and above considered shale.

Interpreting the resistivity of the formation which had a range 1 – 10^3 ohm-m, areas of high resistivity values were seen to correspond to sand layers and vice versa for shale (fig.11 and 12). The density of the various rock layers in the formation range from 1.2 – 2.75 g/cc (figs.13a and 13b above) and this was studied to ensure that they match with the other log readings.

After computation of the porosity, its examined range was from 0 – 90 % for TMB_4 which is much greater than that for TMB_1 which range from 0 – 25%. This may be because TMB_1 is a more tight formation and TMB_4 might have fractures or more shale to increase the porosity. Moreover, during this examination, these log readings had a match with the density readings and as the Density readings were increasing, those of porosity were decreasing and vice versa. This is because high porosity means the pores are filled with air which is less dense hence, decrease density than when the pores are filled with matrix giving it a high density.

The sonic log which gave a measure of the interval transit time (ΔT) for wave velocity through the formation which was interpreted and used to compute the elastic wave velocity, Vp. This Vp, is simply the inverse of the interval transit time and expressed mathematically as:

$$V_P = \frac{1}{\text{Interval transit time}} \quad \text{...Eqn. 4a}$$

or

$$V_P = \frac{1}{\Delta \mathrm{T}} \quad \text{...Eqn. 4b}$$

Sw values were calculated using Archie's equation, and done using Microsoft Excel Spreadsheet, hence high and low water-bearing intervals could easily be mapped out with respect to depth of the formation e.g. the highest and lowest Sw values were 80% and 8.4% at depths of 7490ft and 3888.5ft respectively for TMB_4.

3.4 ROCK PHYSICS MODEL COMPUTATIONS (RPMC)

In the methodology, a rock physics model was first established in order to accurately link acoustic and elastic variables with petrophysical properties (porosity, saturations, Density, etc as derived from the quantitative log interpretation). In order to understand how rock properties are related with respect to velocities (seismic attributes), a rock physics model was required and to integrate geological information that can be obtained from seismic data into the reservoir.

The velocities examined were both the Vp and Vs velocities and were computed from a series of rock physics models or equations. Their ratios i.e Vp/Vs ratios were also calculated for both wells. It should be noted that some of the elastic properties like P-wave velocity were computed using petrophysical parameters as input e.g from resistivity and density.

The set of rock physics equations included: Faust's equation, Castagna's equation and Gardner's equation.

A) P-WAVE COMPUTATION

The Faust's (1951) equation was used to calculate Vp from resistivity log. Here a Sonic log is created by applying a transform to an input resistivity log.

$$\mathbf{P-wave = C_1[Depth \times Resistivity]^{\frac{1}{6}}} \quad \text{...Eqn. 5}$$

Where C1 = constant = 1948.00000

Resistivity (ohms/ft) and Depth (ft)

B) S-WAVE COMPUTATION

The Castagna's (1985) relationship was used to create a shear wave velocity log by applying a linear transform to an input P-wave log. The equation is as follows:

$$\mathbf{S-wave = C_1 \times P-wave + C_2} \quad \text{..Eqn. 6}$$

Where C1 = constant = 0.86190

C2 = constant = -3845.14439

S-wave and P-wave in ft/s

Some of the assumptions used during the application of the equations include:

- In order to value the effects of different fluid saturations, the ''brine'' scenarios was assumed during the rock physics analysis and used to consider rock petrophysical features regardless of any influence on hydrocarbon.
- The Gardner's equation was used on the assumptions that the rock is isotropic, all minerals making up the rock have the same velocities, the rock is fluid-saturated and should only be used only for consolidated cemented rocks.
- Furthermore, the equations assumes that the formation is made up of only sand and shale.

C) VP/VS RATIO

Vp/Vs ratios are calculated using (equation 7) both P-wave and S-wave or from Depth-Time curves. For this work, the former was used. The ratios were calculated for both wells and their log tracts and including those of Vp and Vs for TMB_4 are shown below. The ratios are then used to do the cross plots. Figure 14 shows the log tracts for the computed Vp, Vs and Vp/Vs ratios.

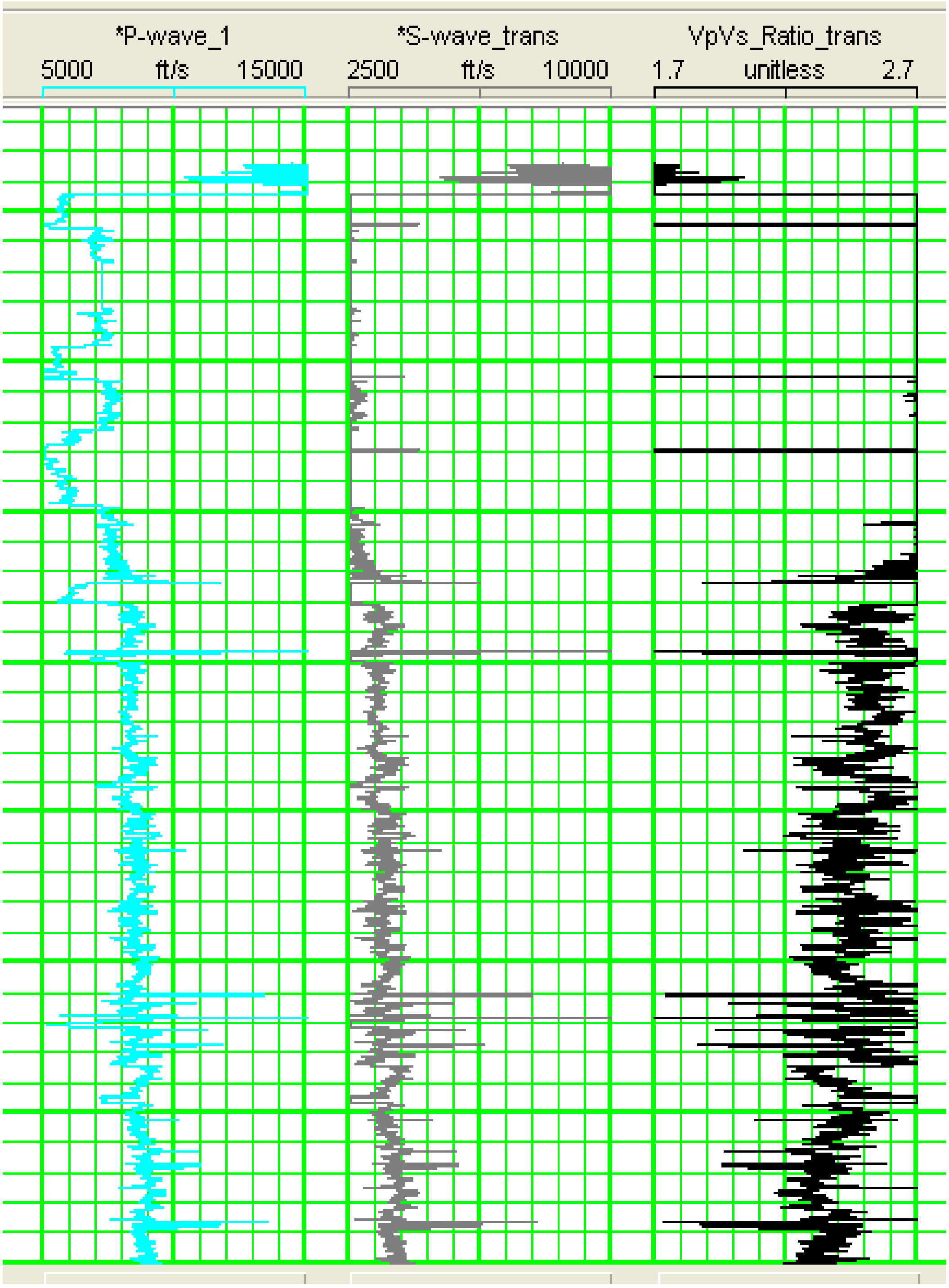


Figure 14: P-wave, S-wave and Vp/Vs ratio computed for TMB_4

The computed log tracts for TMB_1 were also established.

3.5 LOG-FACIES CLASSIFICATION

In this light, cross plots of petrophysical parameters versus the elastic attributes were used for the log-facies classification. A number of these curves (cross plots) were plotted using the data from all the wells. For the purpose of this research, the cross plots were done for three elastic attributes which included: Vp/Vs ratio, Vp and Vs while the petrophysical parameters considered were Porosity, Water Saturation, and Density. Each of these elastic properties was plotted against all the petrophysical parameters. Only TMB_4 had the complete plots of these parameters while for the well TMB_1, a few significant plots were used to validate those of TMB_4. This was purposely done to confirm the trend in the plots for different wells within the same field. The trend of the plotted parameters were obtained although some discrepancies were observed in the case where the well data was poor.

It should be noted that the number of plots done for each well was largely at my (i.e the writer) discretion and to a lesser extend the quality of data. Furthermore, each of the parameters plotted was colour coded with GR log in order to differentiate the various rock types. Colour coding means to shade or overwrite the colours of the original parameters when plotted, giving a colour of the GR demarcations which is then used to conveniently tell the lithology and describe them according to the plotted parameters e.g the porosity versus Vp/Vs ratio plot was colour coded by the GR log and as a result, the different rock units within the formation could be clearly interpreted using the integrated porosity and Vp/Vs information. The same procedure was adopted for all the plots.

Table 1 shows the two wells with their various cross plots.

Table 1: Different wells and their various cross plots.

WELLS	WELL 1 (TMB_4)	WELL 2 (TMB_1)
PARAMETERS	Porosity vs Vp/Vs	Sw vs Vp
PARAMETERS	Sw vs Vp/Vs	Sw vs Porosity
PARAMETERS	Density vs Vp/Vs	Sw vs Density
PARAMETERS	Porosity vs Vp	χ
PARAMETERS	Sw vs Vp	χ
PARAMETERS	Density vs Vp	χ
PARAMETERS	Porosity vs Vs	χ
PARAMETERS	Sw vs Porosity	χ
PARAMETERS	Sw vs Density	χ

From the above table, well 1 had many plots (specifically nine). This was because it happened to be the well with best data. On the other hand, well 2 had three cross plots. In order to bring out the various log-facies from the plots, zoning was done guided by the scattered data points on the plot and the colour code of the GR log. Data points of the same colour which cluster at the particular sections on the plot were zoned. This was preceded by generation of cross sections which showed how the various log-facies are distributed throughout the entire depth of the well with specific characteristics and was done for all the wells. One of the cross plots is displayed in figure 15a and 15b.

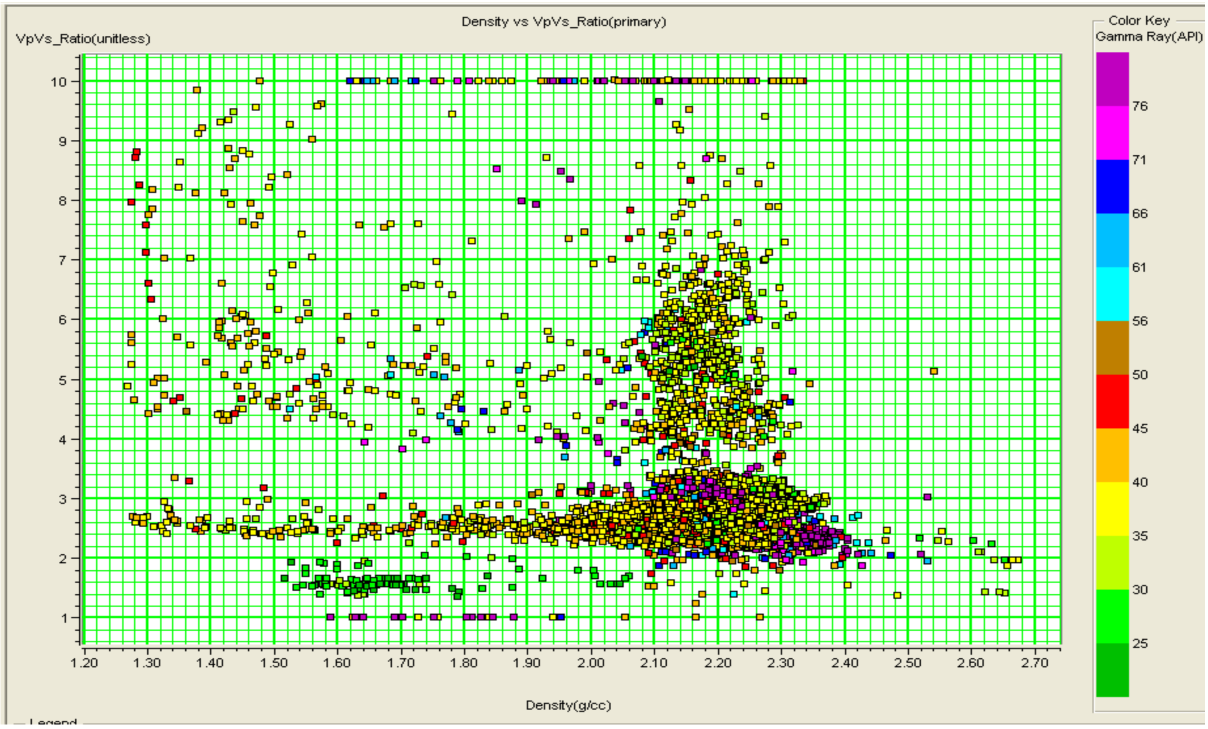


Figure 15a: Density versus Vp/Vs Ratio cross plot for TMB_4 colour coded by GR (Before zoning)

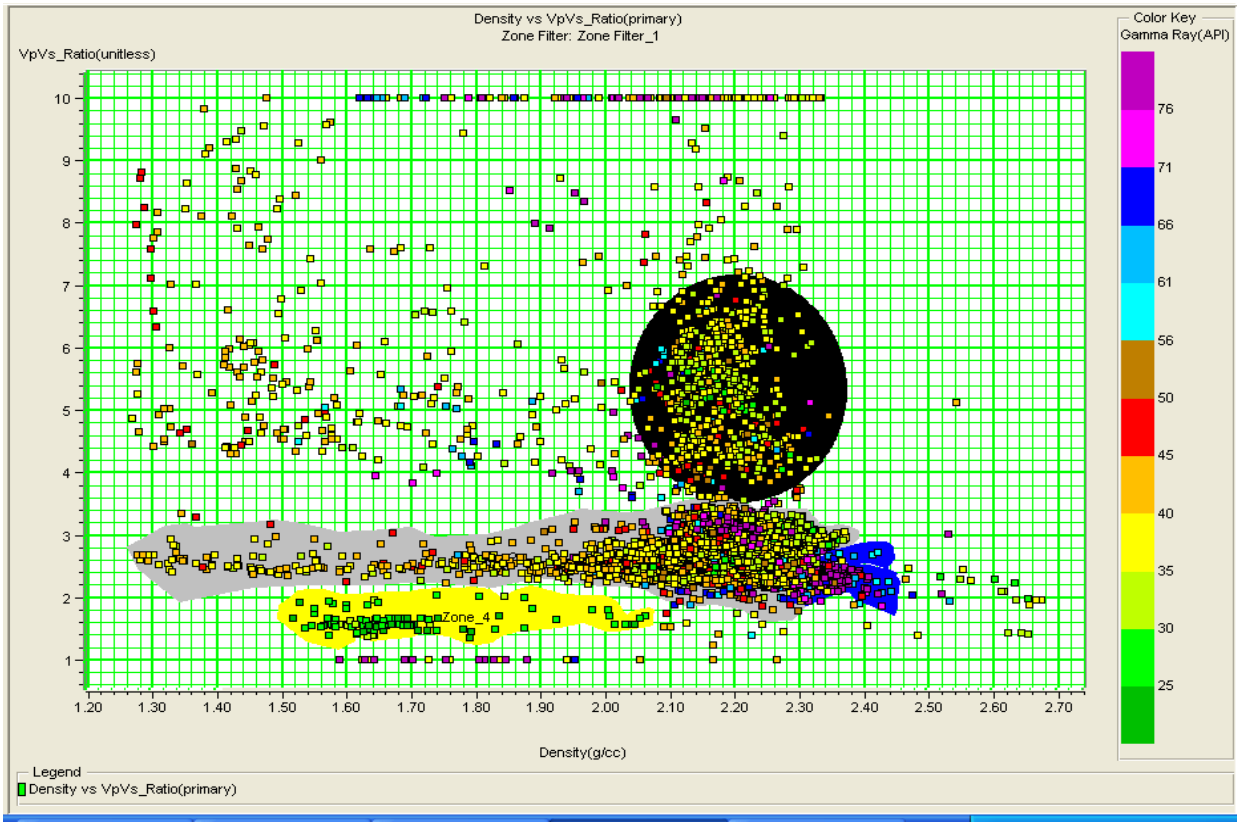
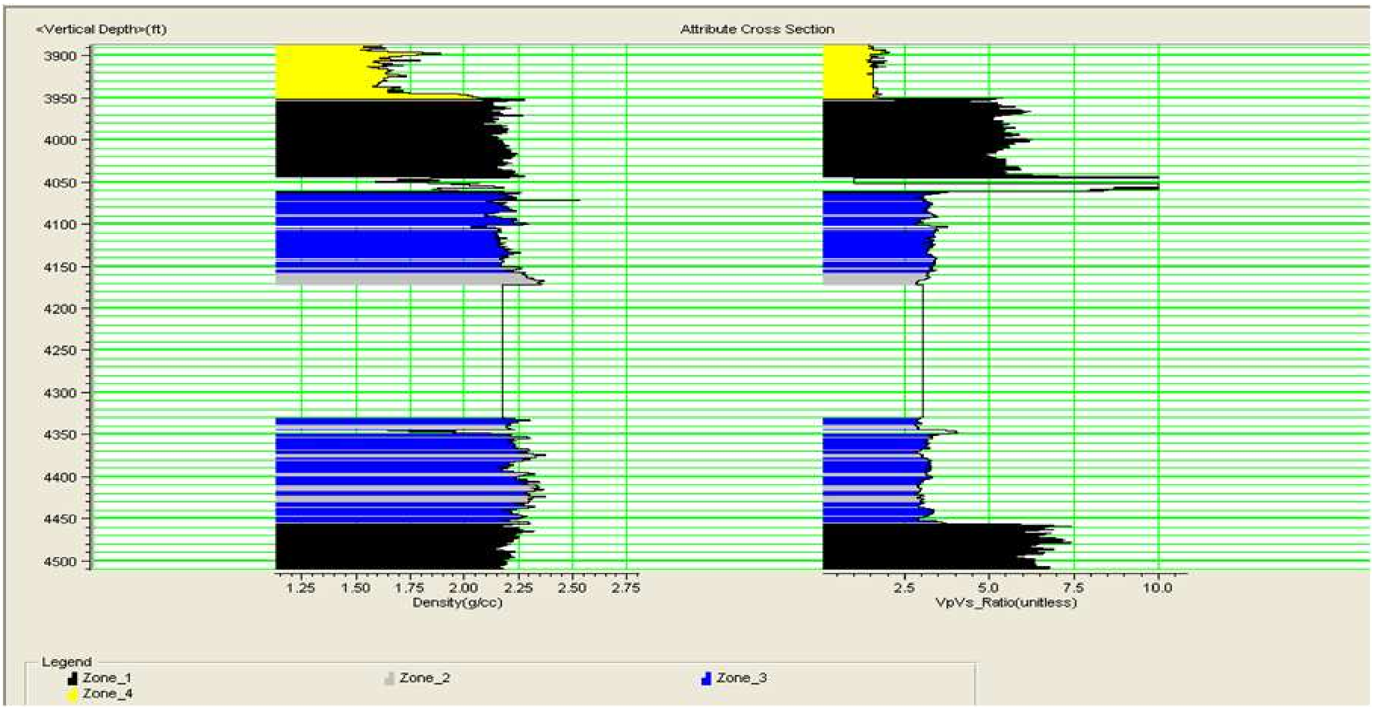
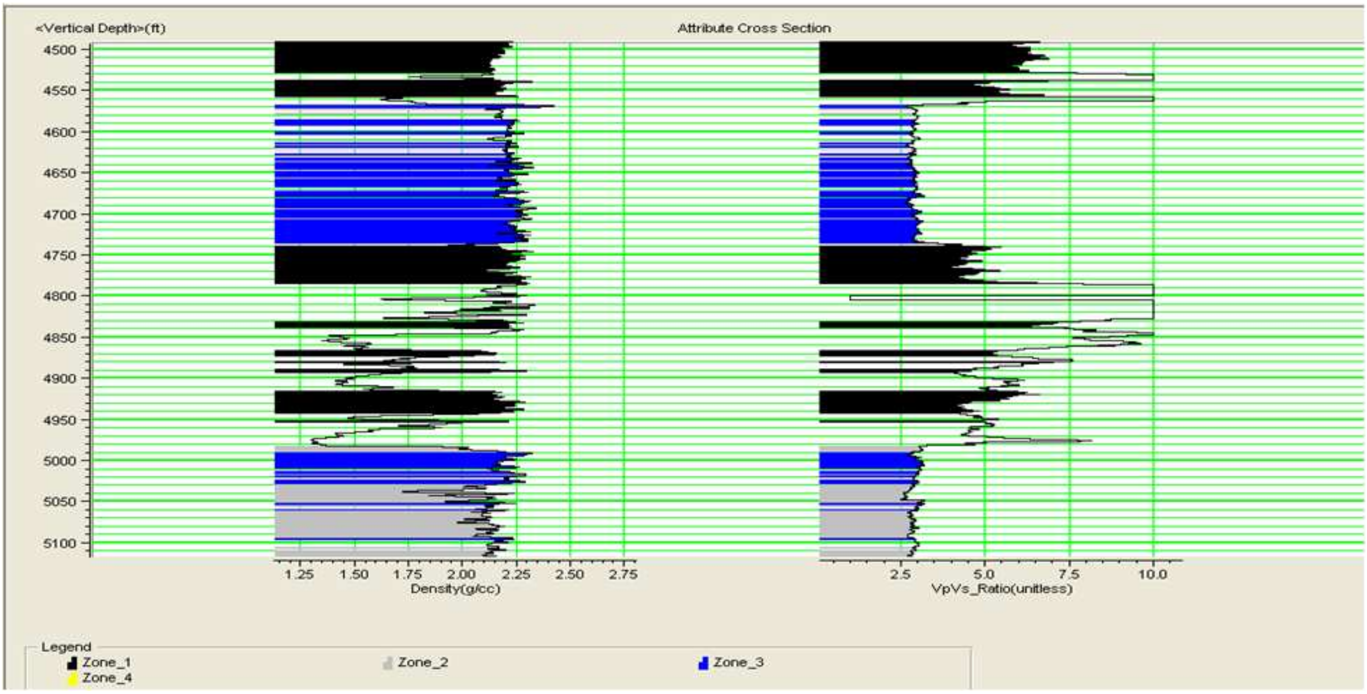


Figure 15b: Density versus Vp/Vs Ratio cross plot for TMB_4 colour coded by GR (After zoning)

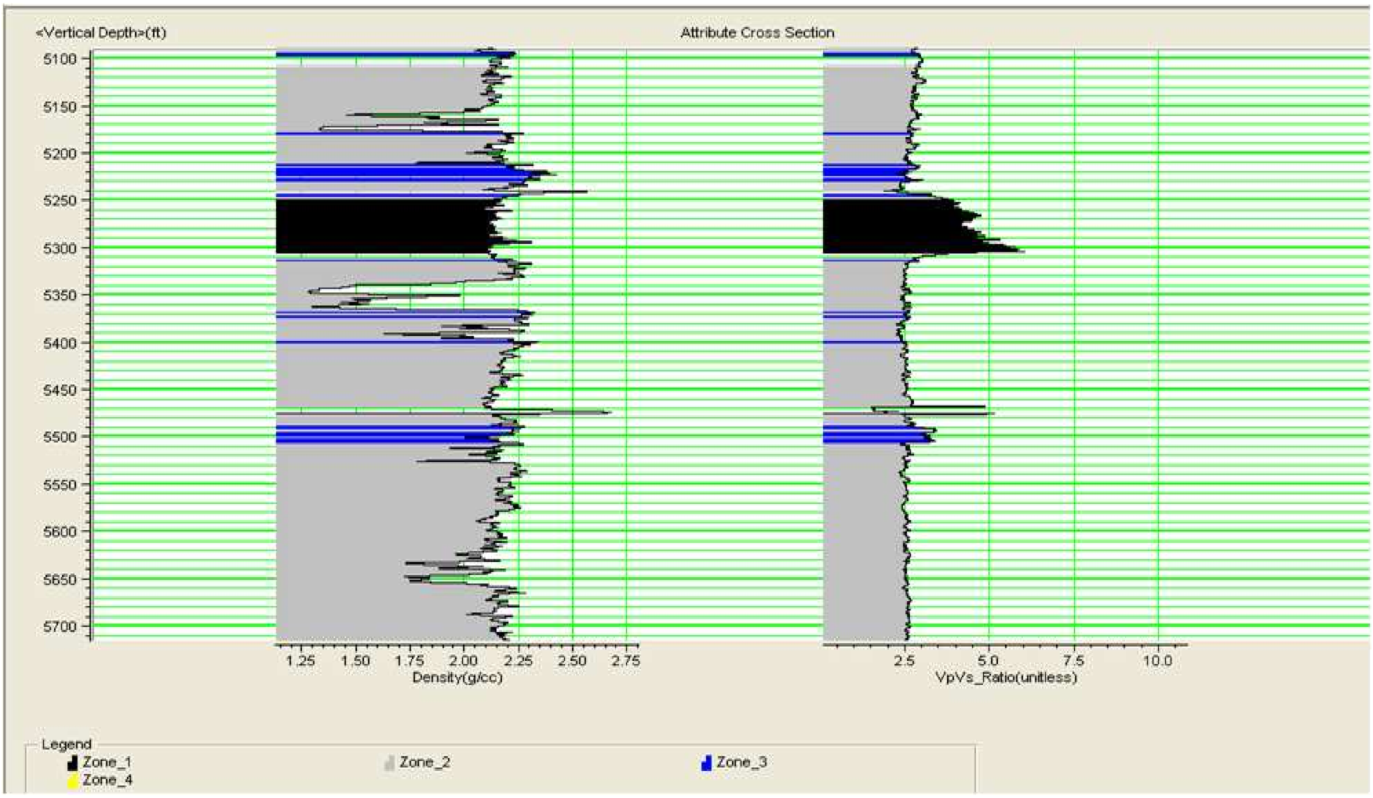
From the cross plots, the shaded zones designate the various log-facies (denoted EL1 to EL4 for TMB_4 and CL1 to CL3 for TMB_1) which show particular characteristics. An example of a cross section is that of Density versus Vp/Vs for TMB_4 (fig: 16a - g).



a)

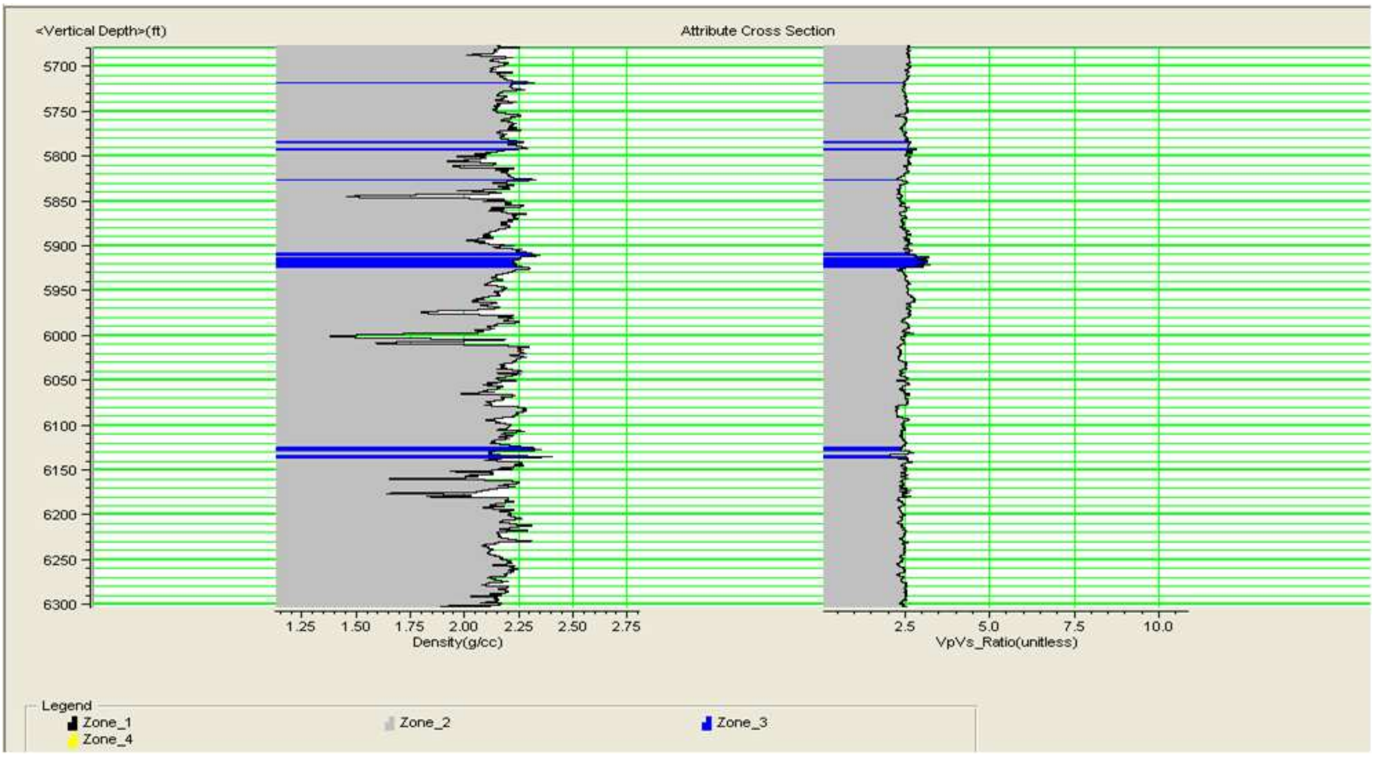


b)



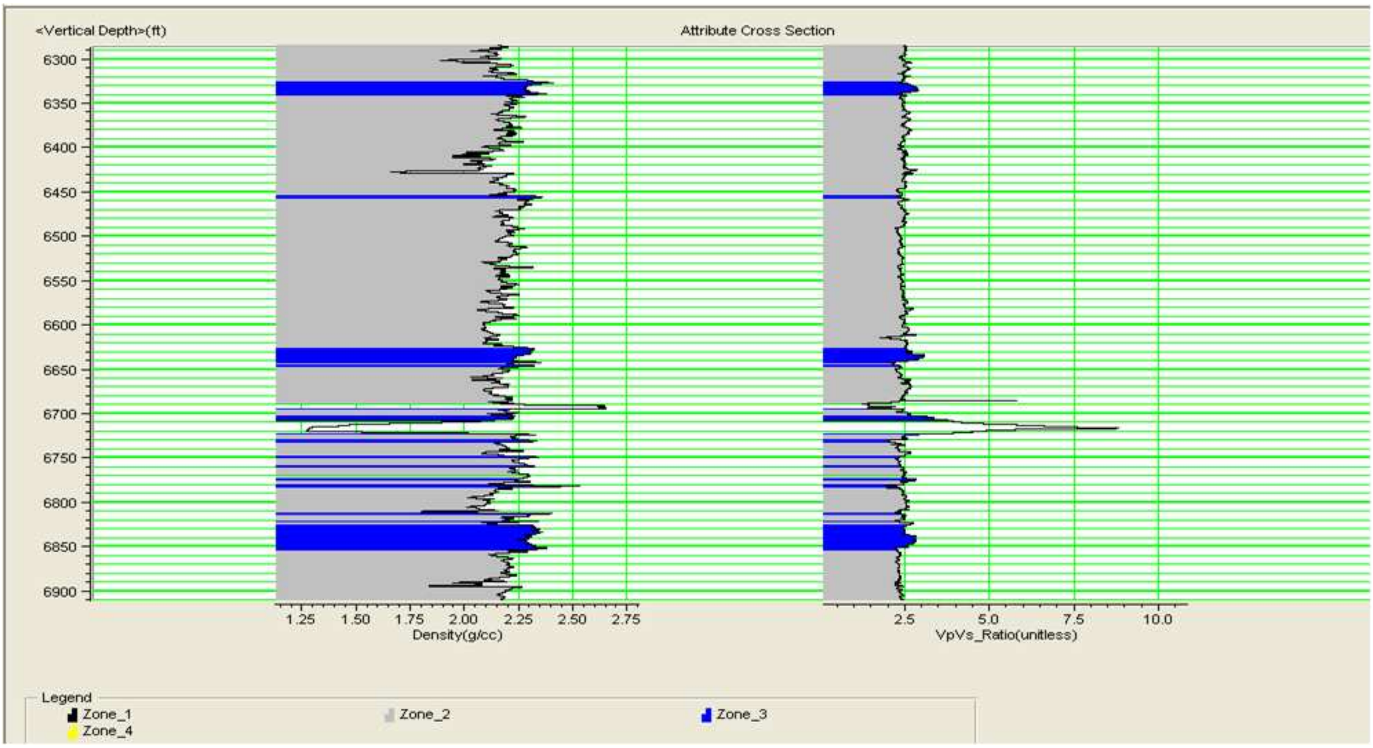
<Vertical Depth>(ft)
Attribute Cross Section
5100
5150
5200
5250
5300
5350
5400
5450
5500
5550
5600
5650
5700
1.25 1.50 1.75 2.00 2.25 2.50 2.75
Density(g/cc)
2.5 5.0 7.5 10.0
VpVs_Ratio(unitless)
Legend
Zone_1
Zone_2
Zone_3
Zone_4

c)



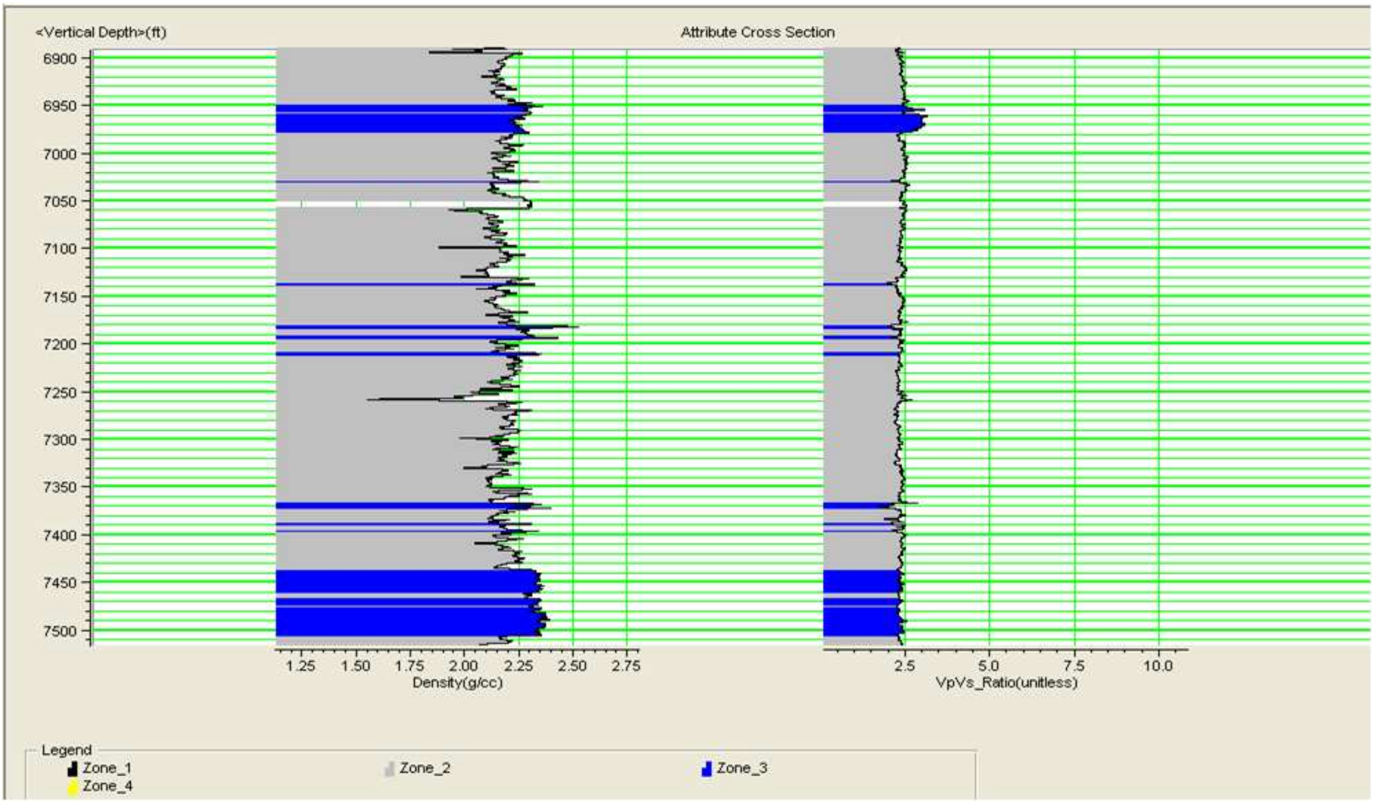
<Vertical Depth>(ft)
Attribute Cross Section
5700
5750
5800
5850
5900
5950
6000
6050
6100
6150
6200
6250
6300
1.25 1.50 1.75 2.00 2.25 2.50 2.75
Density(g/cc)
2.5 5.0 7.5 10.0
VpVs_Ratio(unitless)
Legend
Zone_1
Zone_2
Zone_3
Zone_4

d)



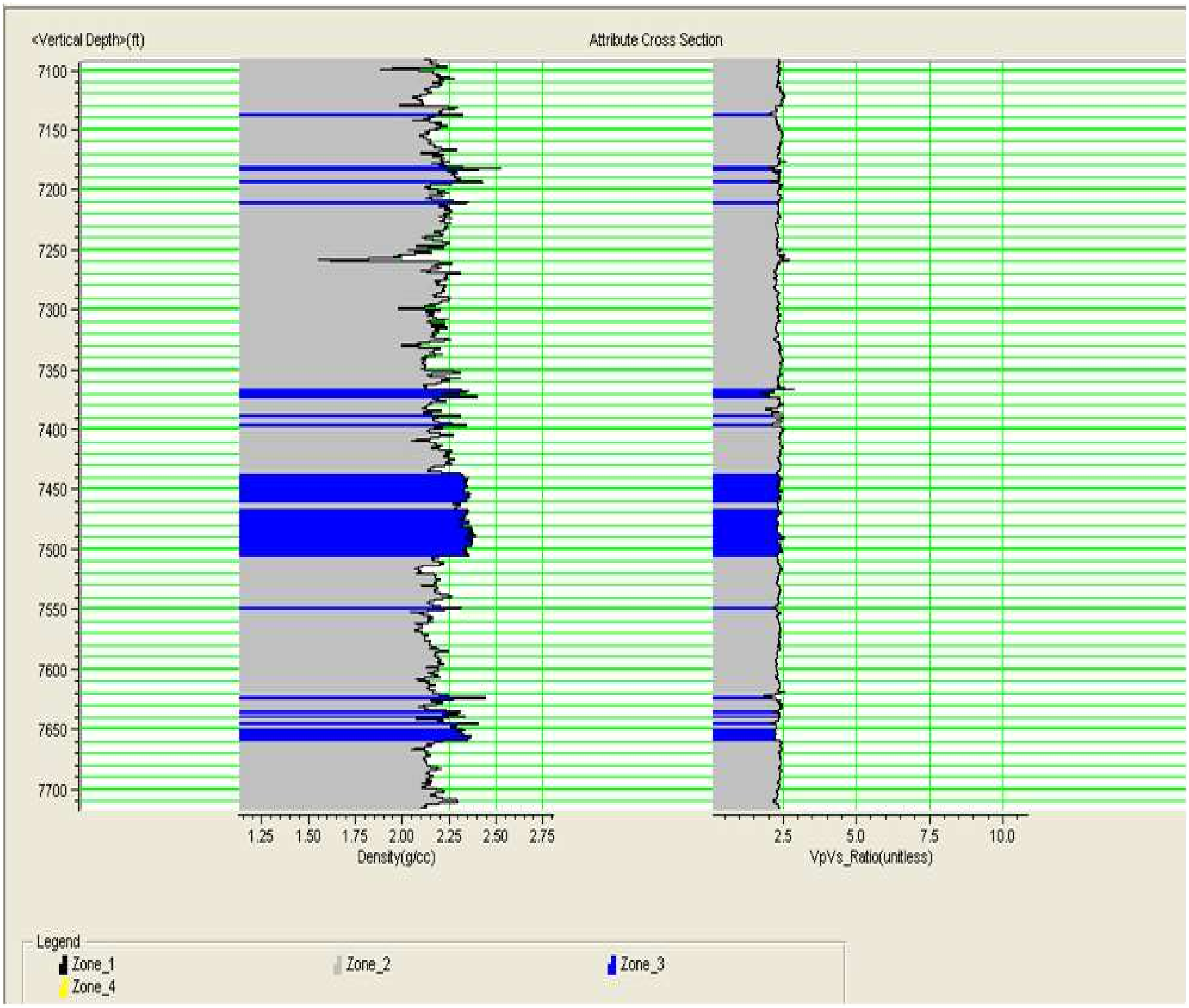
<Vertical Depth>(ft)
Attribute Cross Section
6300
6350
6400
6450
6500
6550
6600
6650
6700
6750
6800
6850
6900
1.25 1.50 1.75 2.00 2.25 2.50 2.75
Density(g/cc)
2.5 5.0 7.5 10.0
VpVs_Ratio(unitless)
Legend
Zone_1
Zone_2
Zone_3
Zone_4

e)



<Vertical Depth>(ft)
Attribute Cross Section
6900
6950
7000
7050
7100
7150
7200
7250
7300
7350
7400
7450
7500
1.25 1.50 1.75 2.00 2.25 2.50 2.75
Density(g/cc)
2.5 5.0 7.5 10.0
VpVs_Ratio(unitless)
Legend
Zone_1
Zone_2
Zone_3
Zone_4

f)



g)

Figure 16a - g: Cross section through TMB_4 for Density vs Vp/Vs ratio plot

In addition, to actually reveal or show the improvement in the log-facies classification for static reservoir modeling by the integration of both petrophysical and elastic properties, cross plots of petrophysical parameters only were produced (e.g Water Saturation vs Porosity). These were done for virtually all the wells and were treated the same as the other curves previously mentioned.

An example of such cross plots is that of Sw versus Porosity fromTMB_1 as seen in fig 17a and 17b.

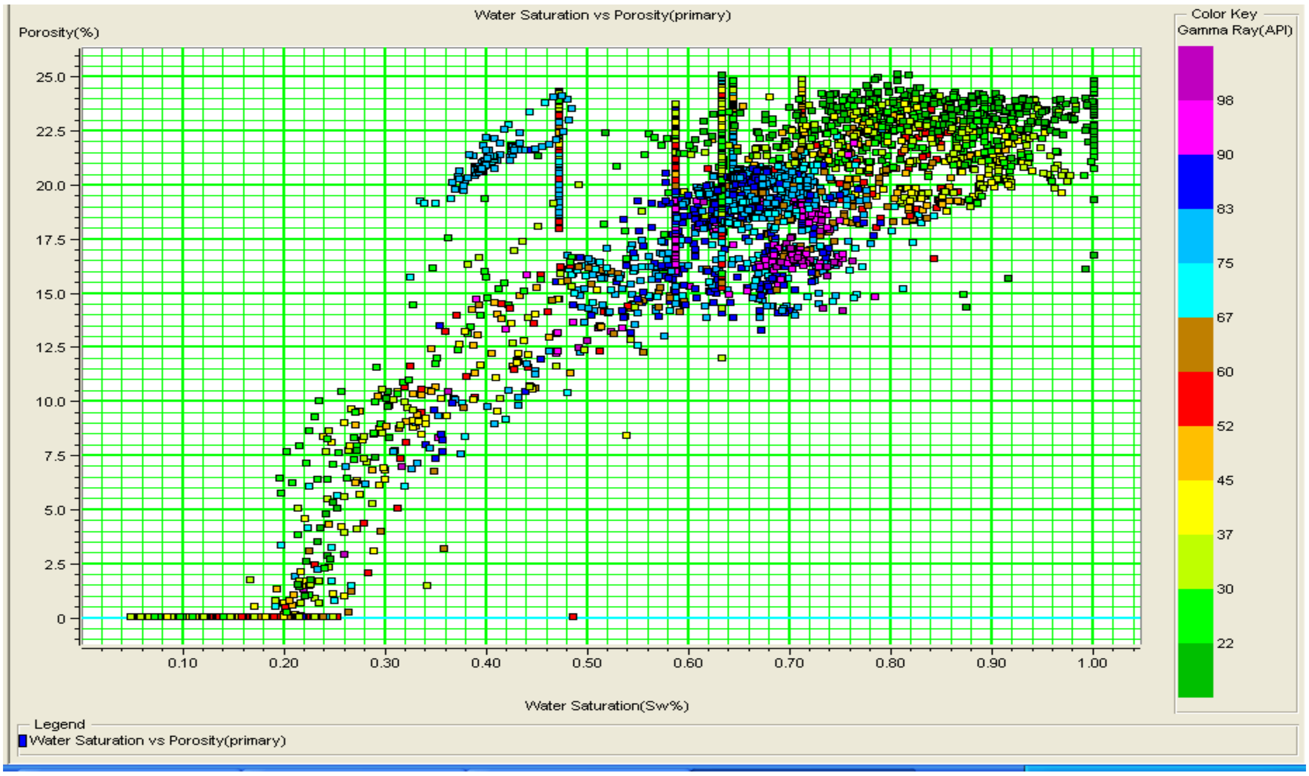


Figure 17a: Sw vs Porosity before Zoning

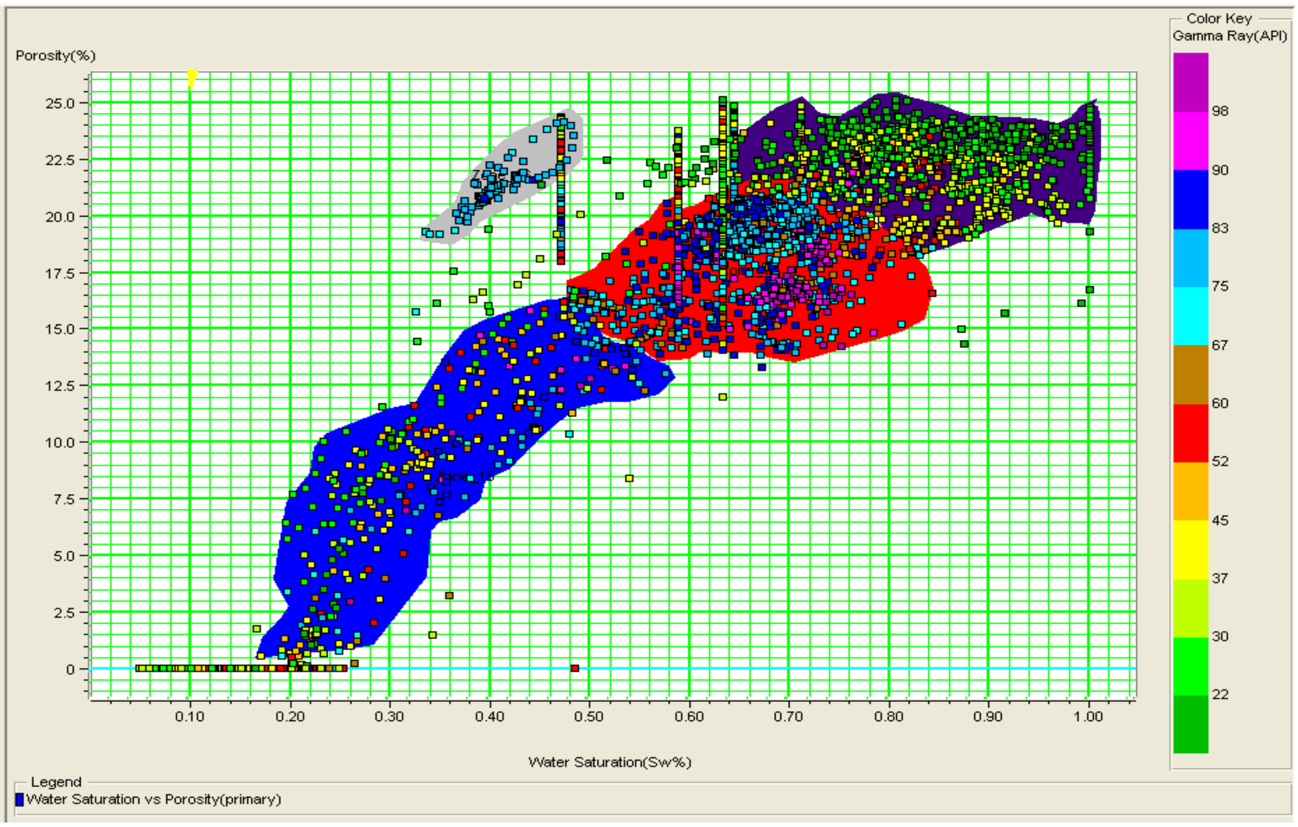


Figure 17b: Sw vs Porosity after Zoning

CHAPTER FOUR

RESULTS AND INTERPRETATION

4.1 RESULTS

The classification of the log-facies is done with the help of several cross plots. The plots before zoning, after zoning, the various cross sections with depth, and the identified log-facies for TMB_4 and TMB_1 are presented as follows:

4.1.1 RESULTS FOR TMB_4 (WELL 1)

Six cross plots will be presented in this case. All the log-facies obtained from the cross plots for this well are coded as EL1, EL2, EL3 and EL4. For the pertophysical versus elastic property cross plots (plots A-E), the facies range from EL1 to EL4, while for the petrophysical cross plot (plot F) only, the log-facies range from EL1 to EL3.

A) POROSITY versus Vp/Vs Ratio

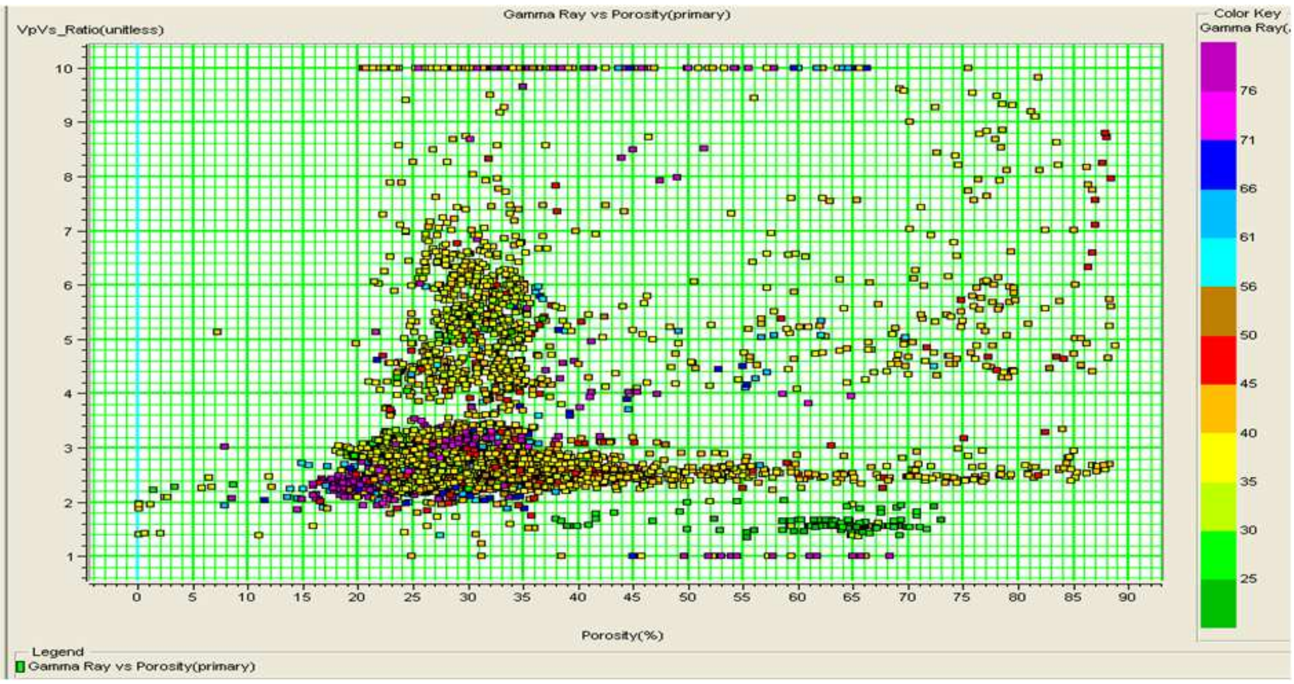


Figure 18a: Porosity versus Vp/Vs Ratio cross plot for TMB_4 colour coded by GR (before zoning)

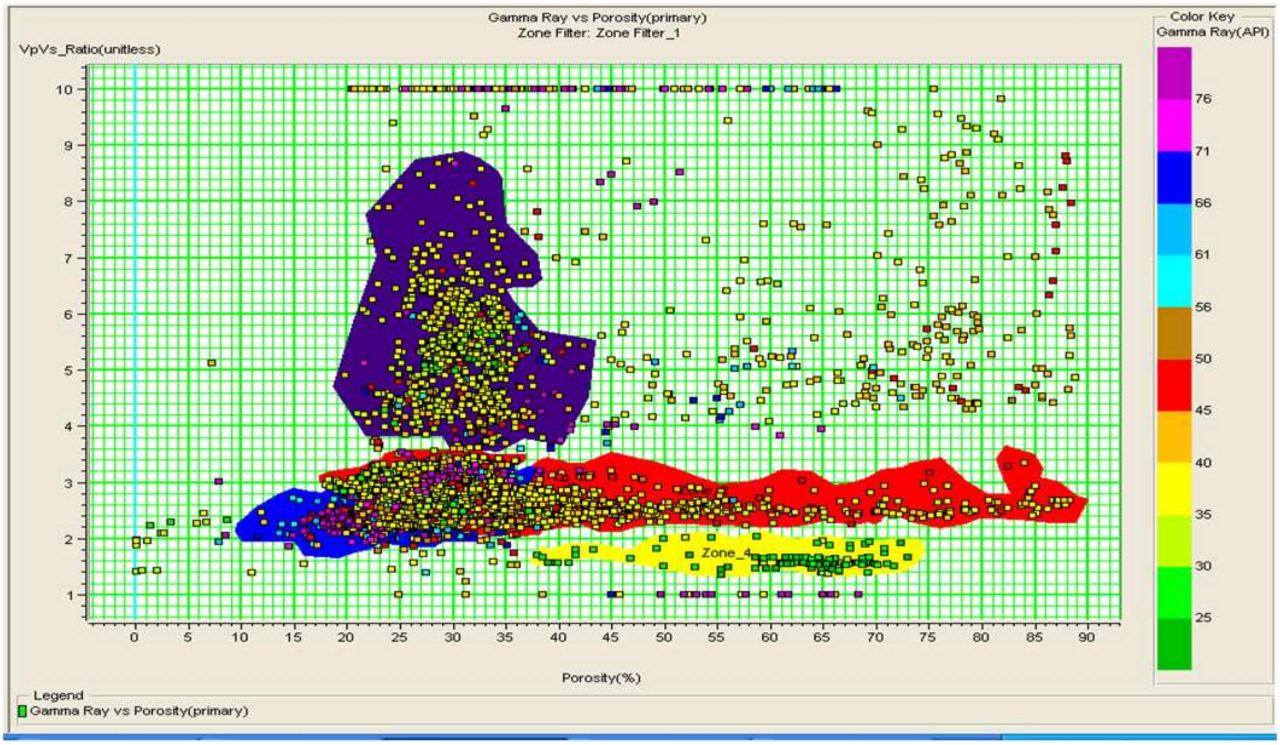
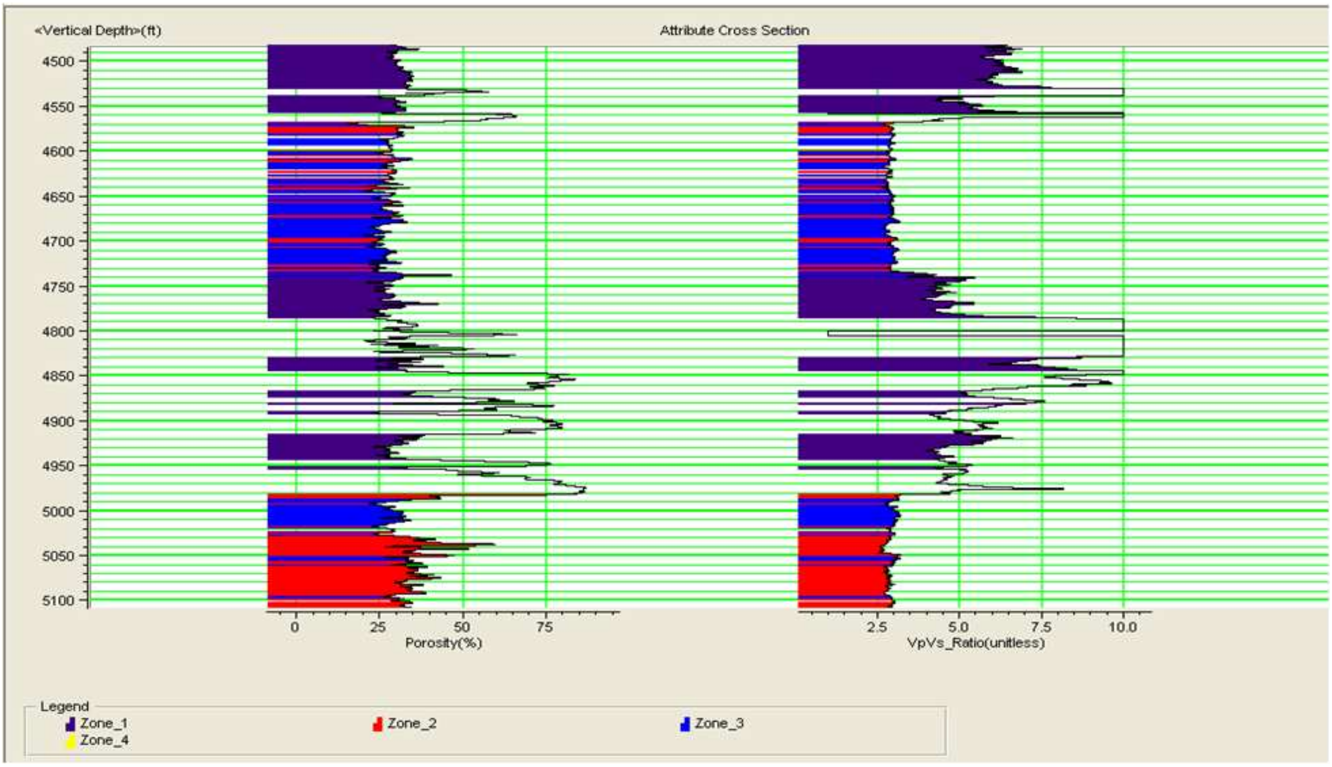


Figure 18b: Porosity versus Vp/Vs Ratio cross plot for TMB_4 colour coded by GR (after zoning)

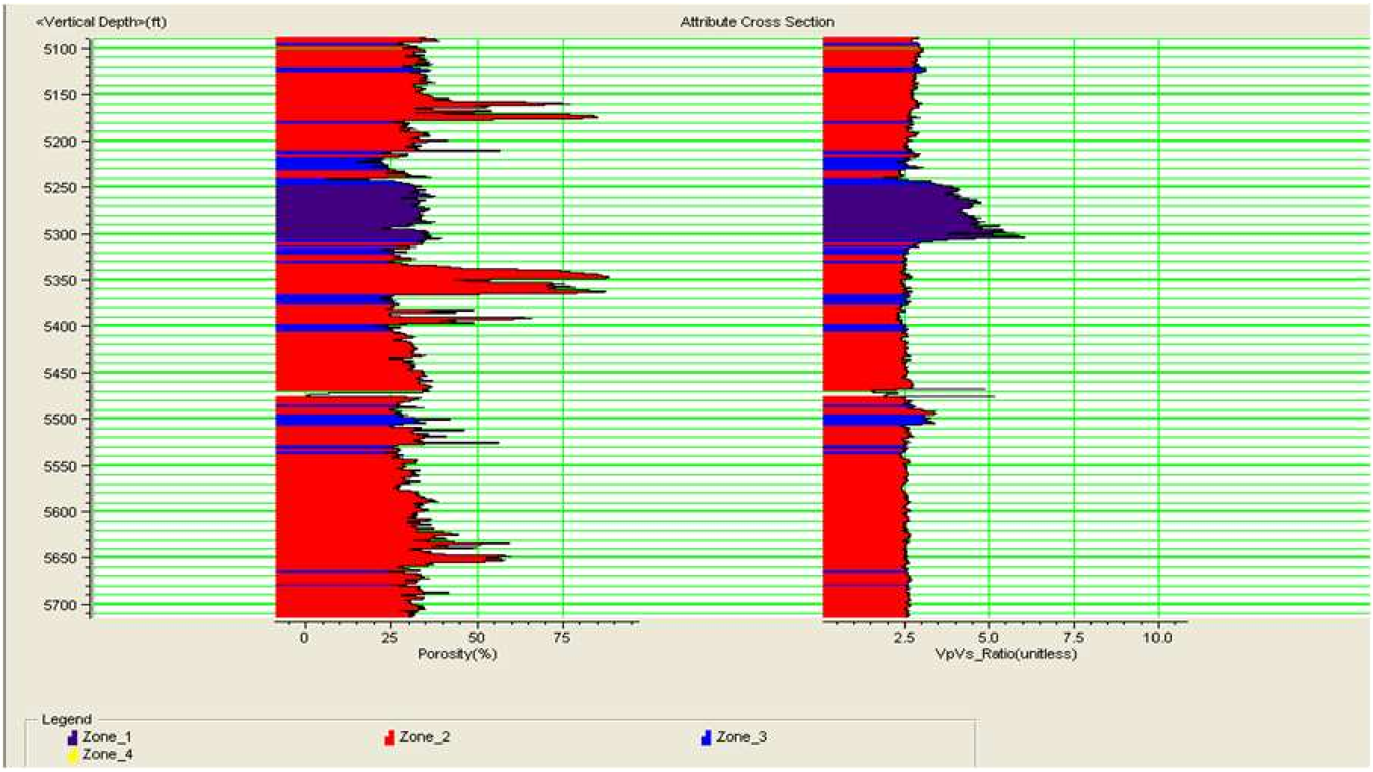
The first Porosity versus Vp/Vs plot (fig. 18a) is presented so as to show how the original plot looked before zoning and fig. 18b is the resultant plot after zoning from which the log- facies are classified.

CROSS SECTION

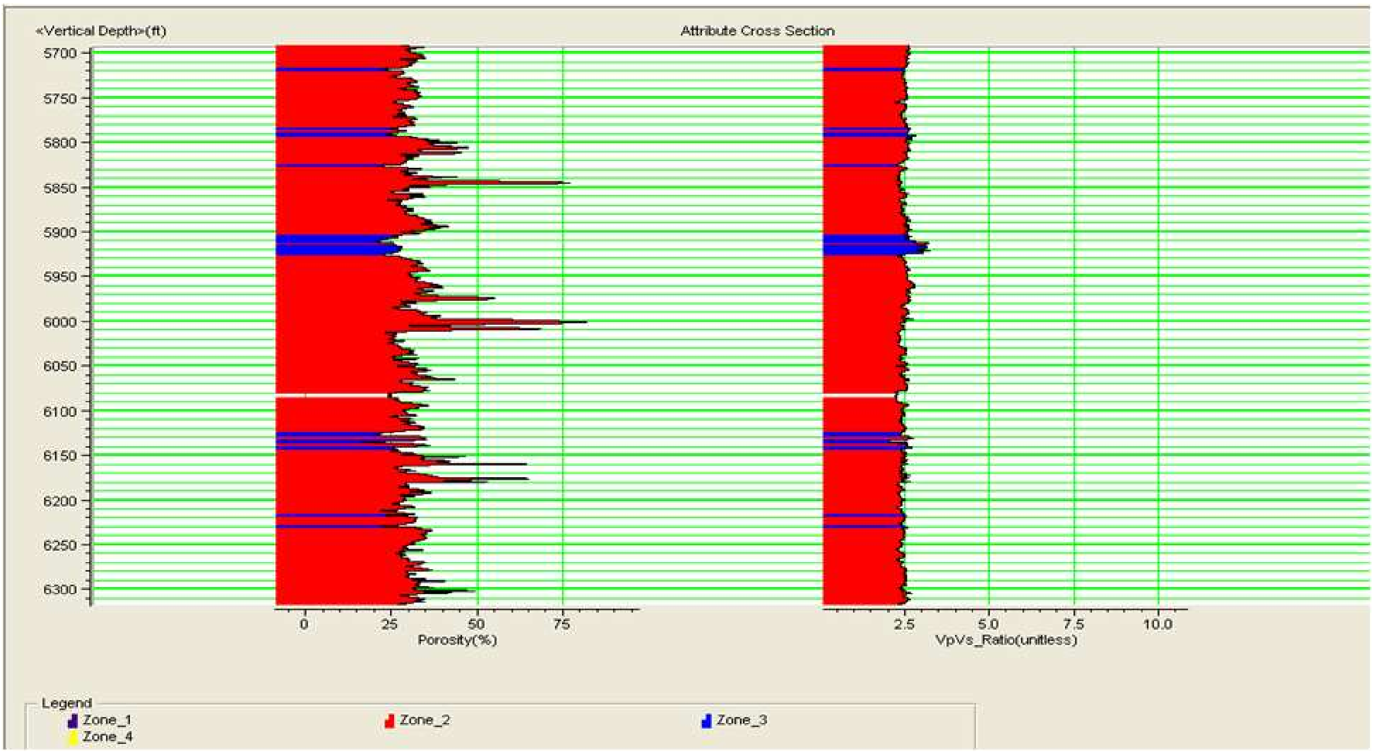
a)


<Vertical Depth>(ft)
Attribute Cross Section
4500
4550
4600
4650
4700
4750
4800
4850
4900
4950
5000
5050
5100
0 25 50 75
Porosity(%)
2.5 5.0 7.5 10.0
VpVs_Ratio(unitless)
Legend
Zone_1
Zone_2
Zone_3
Zone_4

b)

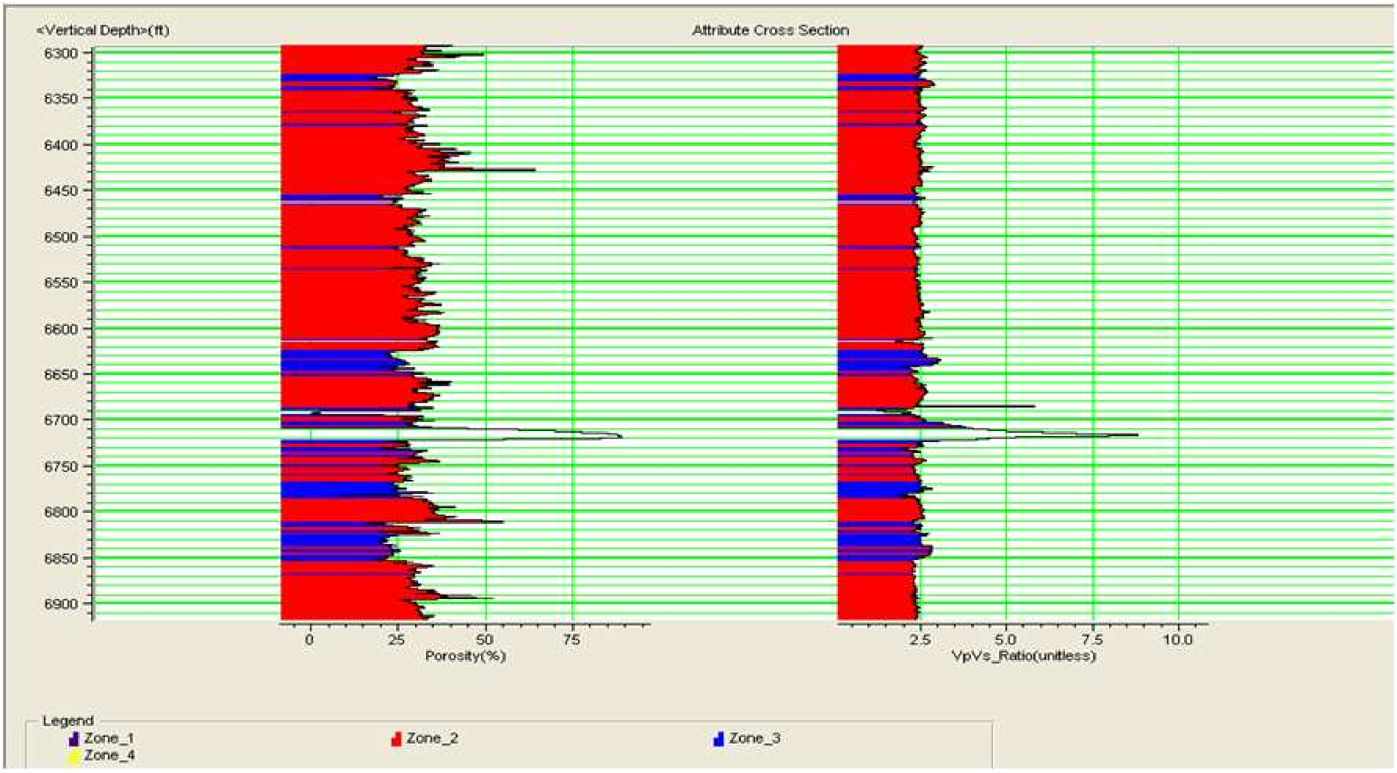

<Vertical Depth>(ft)
Attribute Cross Section
5100
5150
5200
5250
5300
5350
5400
5450
5500
5550
5600
5650
5700
0 25 50 75
Porosity(%)
2.5 5.0 7.5 10.0
VpVs_Ratio(unitless)
Legend
Zone_1
Zone_2
Zone_3
Zone_4

c)



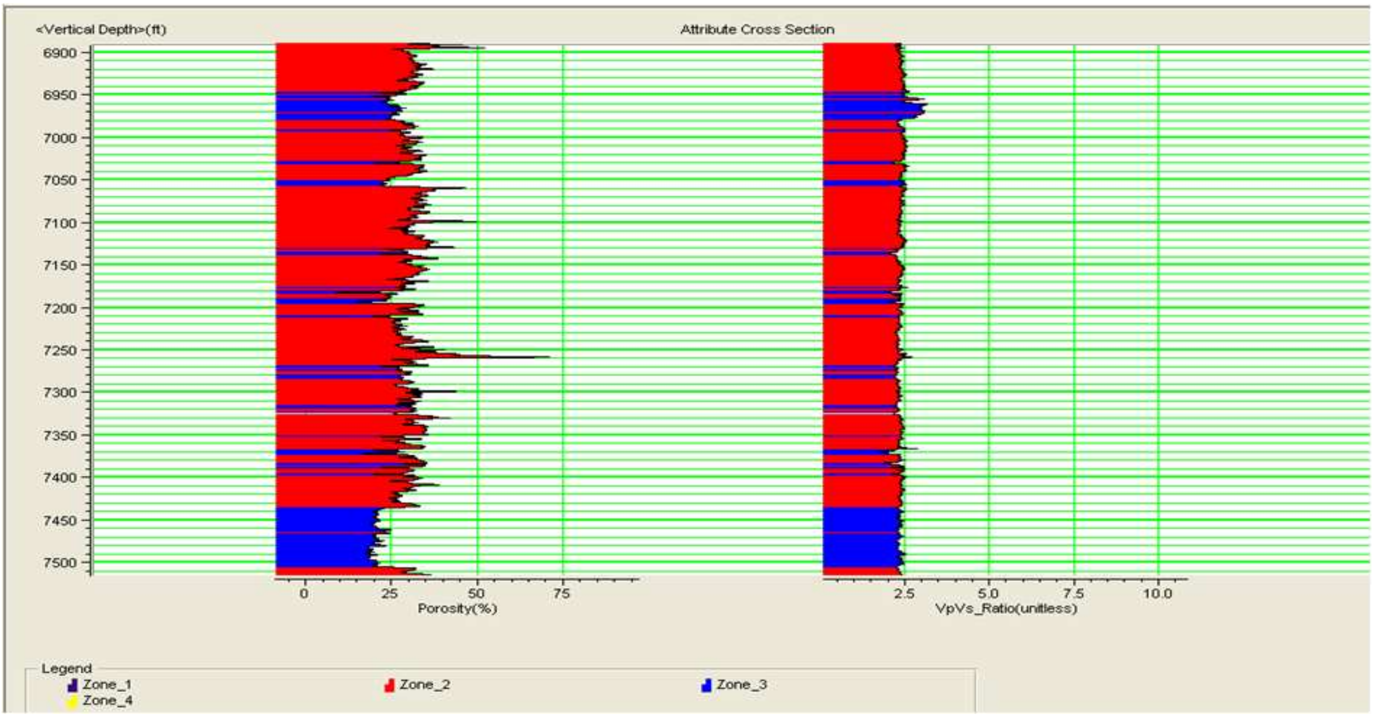
<Vertical Depth>(ft)
Attribute Cross Section
Porosity(%)
VpVs_Ratio(unitless)
Legend
Zone_1
Zone_2
Zone_3
Zone_4

d)

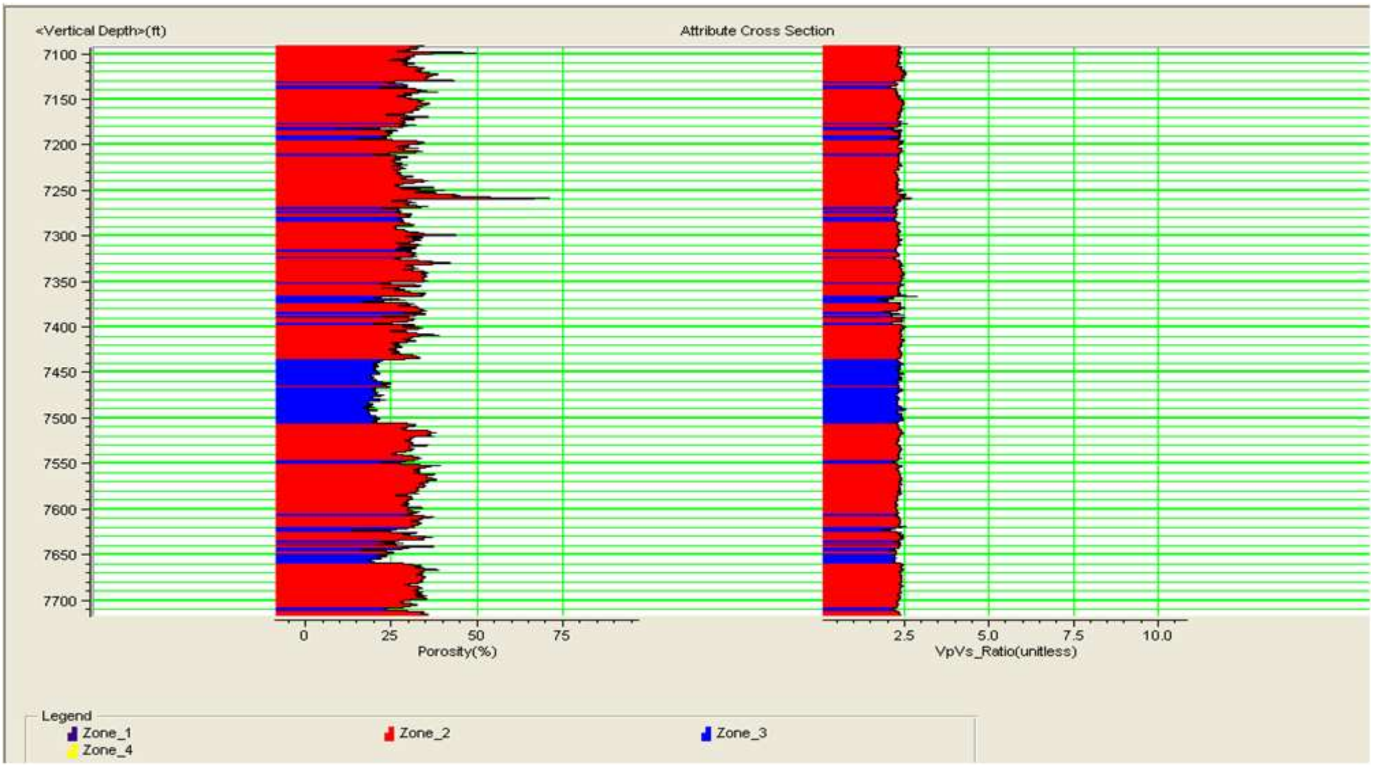


<Vertical Depth>(ft)
Attribute Cross Section
Porosity(%)
VpVs_Ratio(unitless)
Legend
Zone_1
Zone_2
Zone_3
Zone_4

e)



f)



g)

Figures 19a - g: Porosity vs Vp/Vs ratio plot for TMB_4 (Cross section)

The four log-facies that were obtained from the plot above were denoted EL1 to EL4 and presented in tabular format with their corresponding litho-names as follows:

Table 2: Representation of the various litho-facies, colour, Vp/Vs ratio and Porosity range

FACIES NUMBER	GIVEN ACRONYM	LITHO-NAME	COLOUR ON PLOT	VP/VS RANGE (UNITLESS)	POROSITY RANGE (%)
1	EL1	SAND	PURPLE	3.6 – 8.8	20 - 40
2	EL2	SHALY SAND	RED	2.0 – 3.6	17 – 88
3	EL3	SHALE	BLUE	1.6 – 3.2	10 - 39
4	EL4	CLEAN SAND	YELLOW	1.2 – 2.2	37 - 70

B) WATER SATURATION versus Vp/Vs

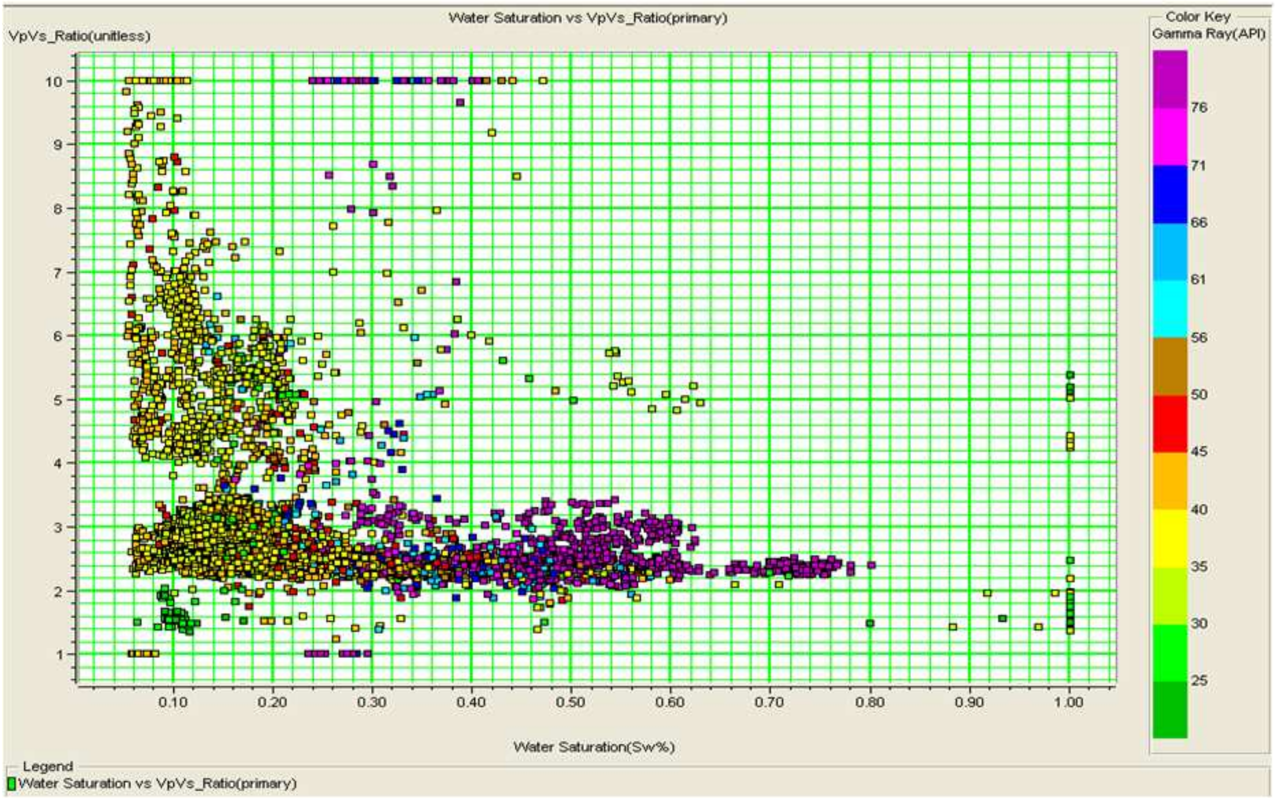


Figure 20a: Sw versus Vp/Vs Ratio cross plot for TMB_4 colour coded by GR (before zoning)

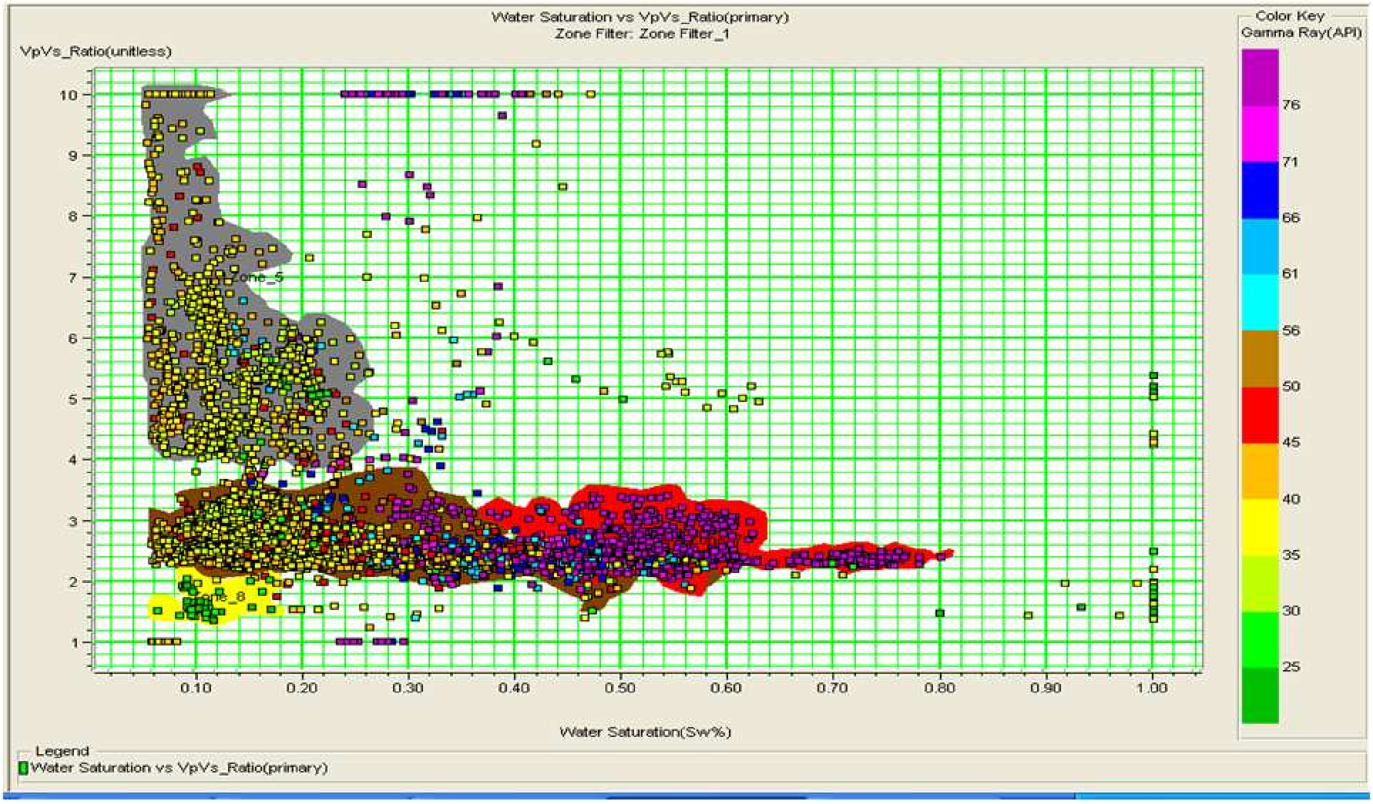
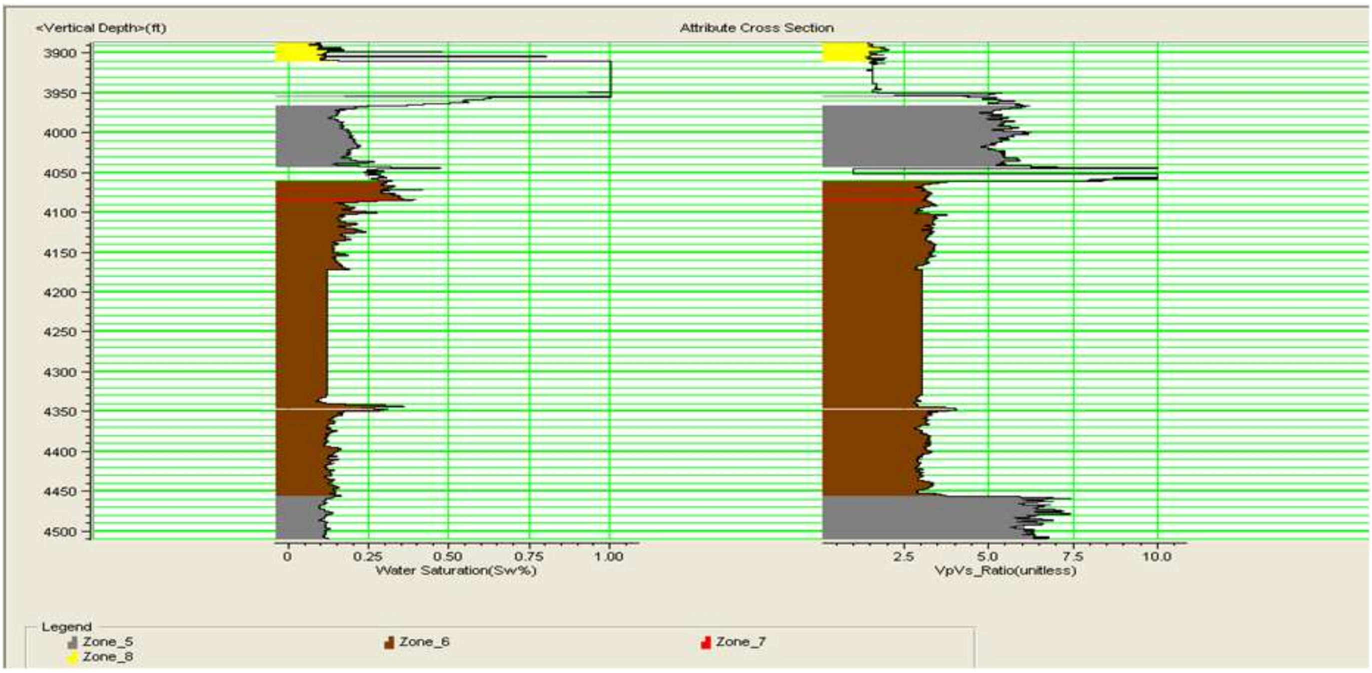
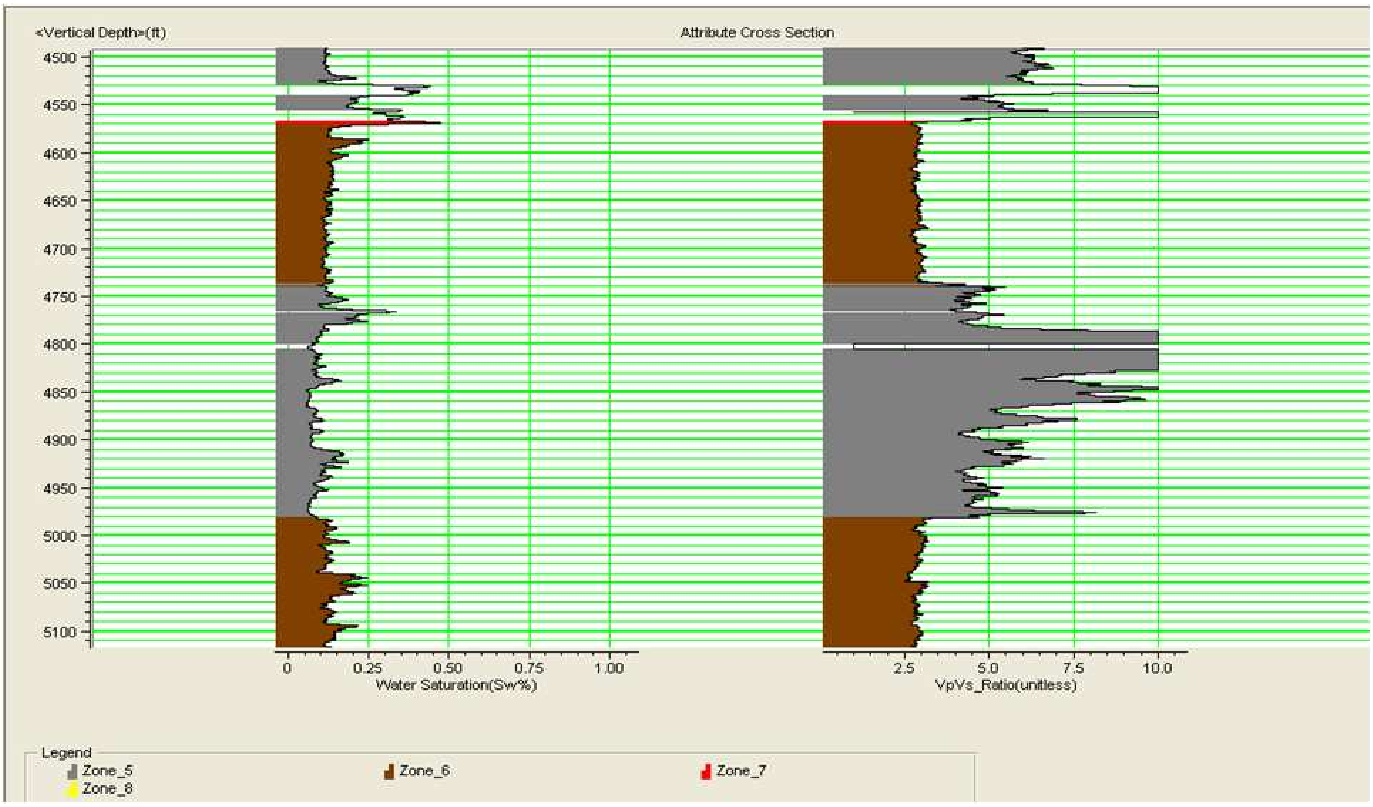


Figure 20b: Sw versus Vp/Vs Ratio cross plot for TMB_4 colour coded by GR (after zoning)

CROSS SECTION

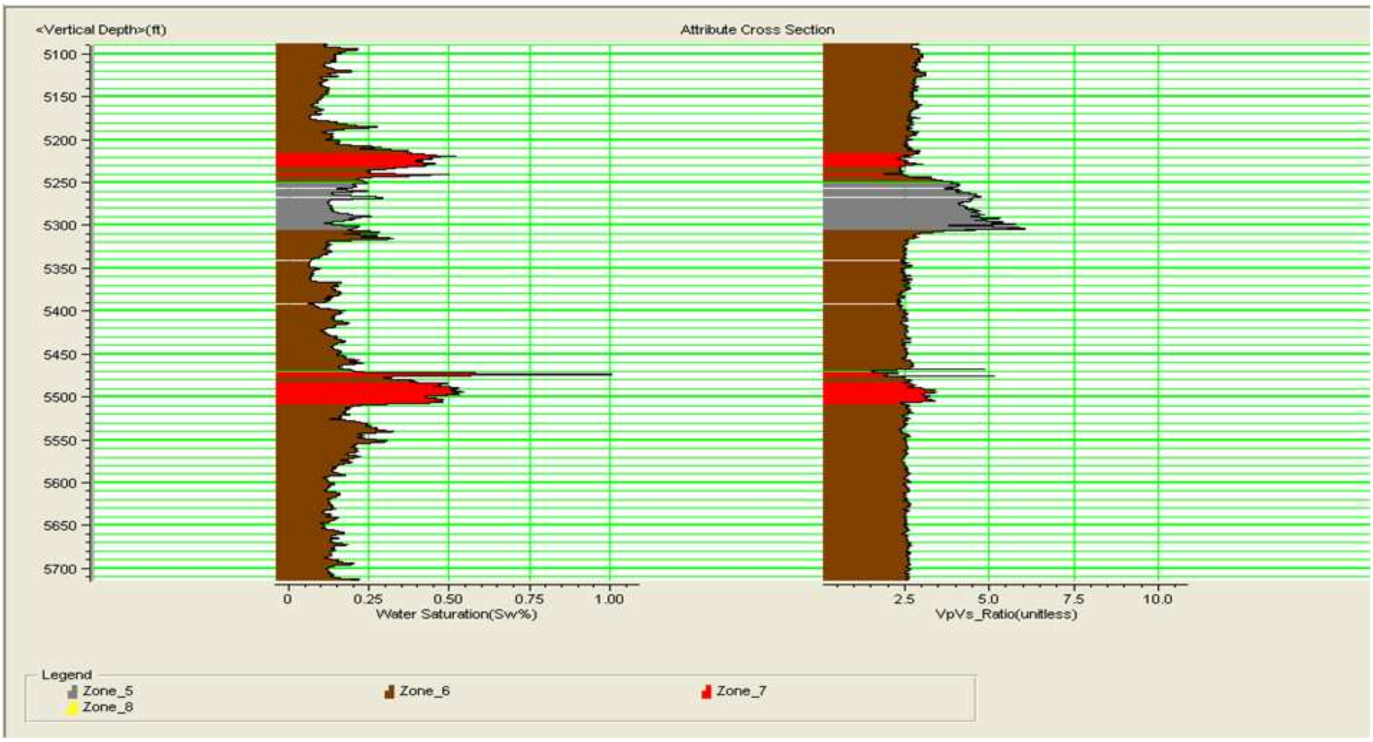


a)



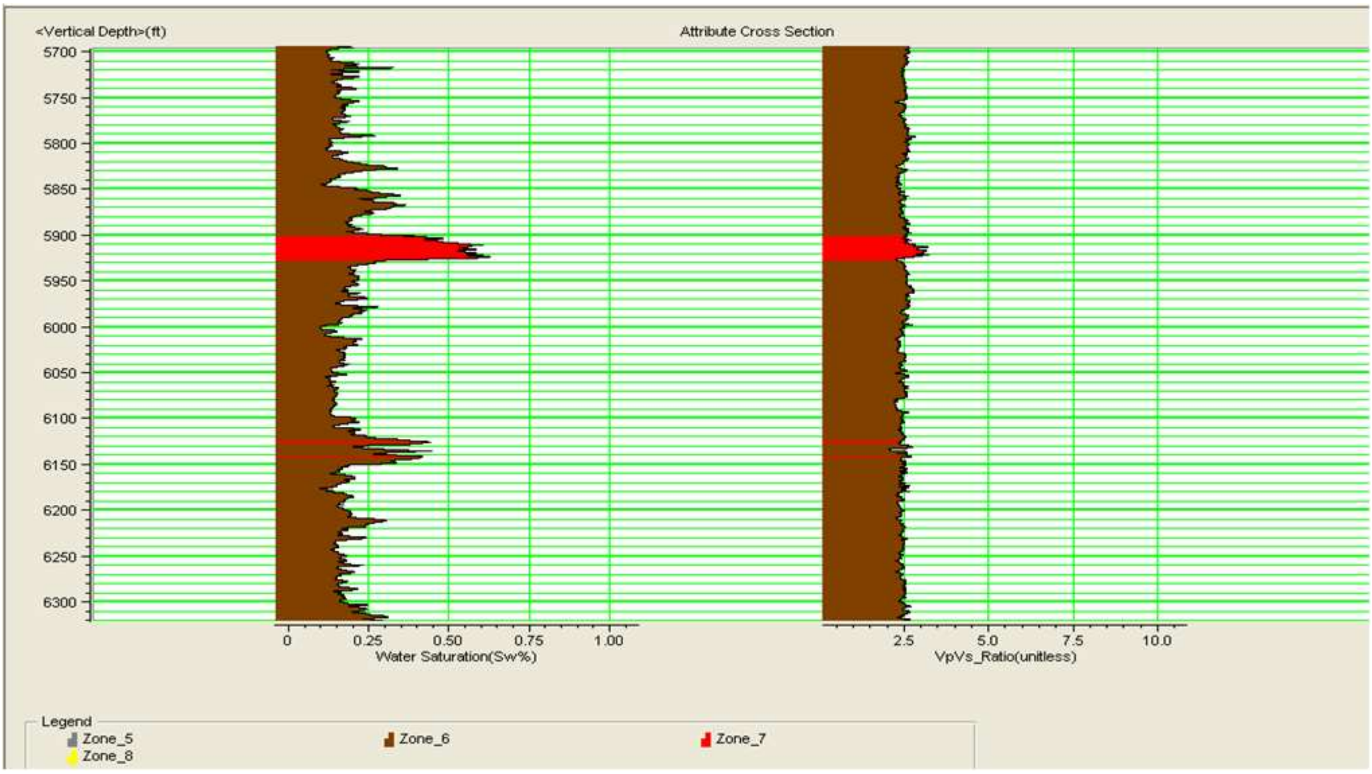
<Vertical Depth>(ft)
Attribute Cross Section
4500
4550
4600
4650
4700
4750
4800
4850
4900
4950
5000
5050
5100
0
0.25
0.50
0.75
1.00
Water Saturation(Sw%)
2.5
5.0
7.5
10.0
VpVs_Ratio(unitless)
Legend
Zone_5
Zone_6
Zone_7
Zone_8

b)



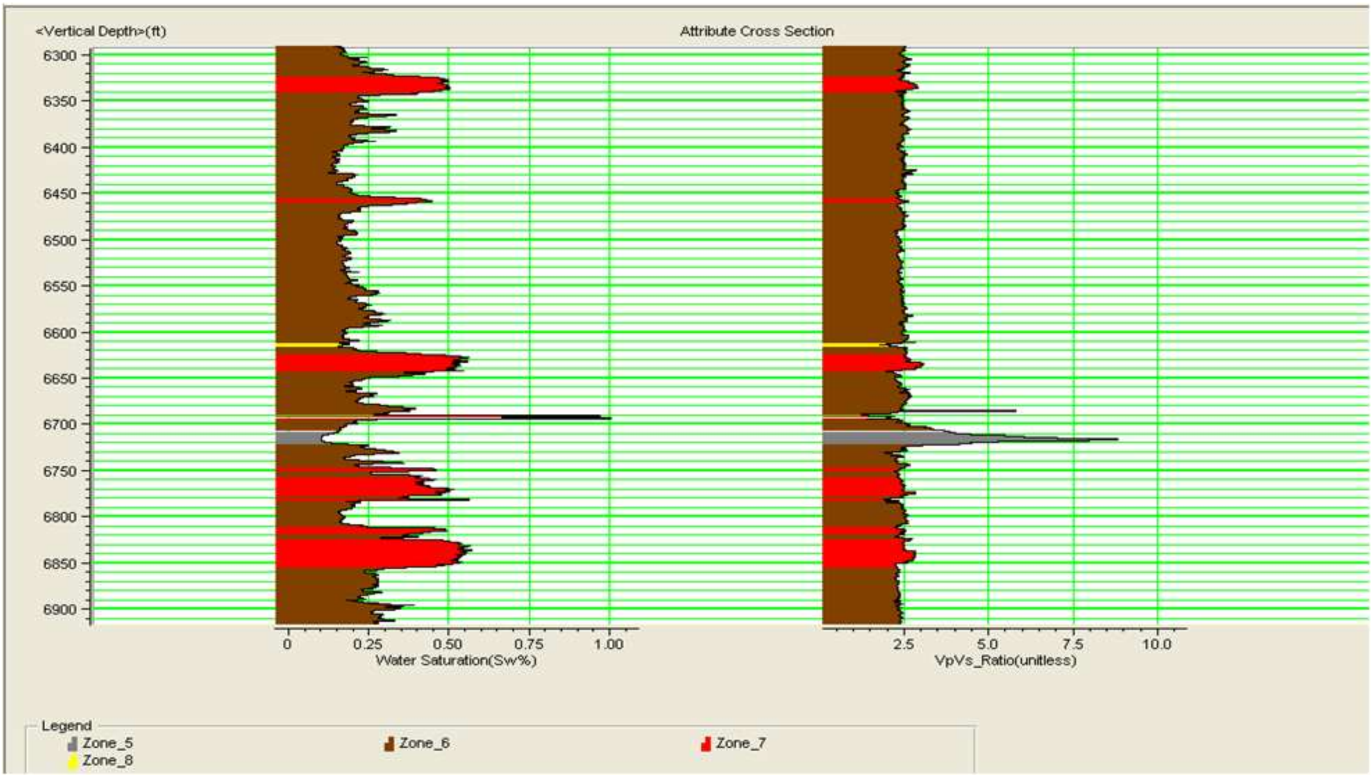
<Vertical Depth>(ft)
Attribute Cross Section
5100
5150
5200
5250
5300
5350
5400
5450
5500
5550
5600
5650
5700
0
0.25
0.50
0.75
1.00
Water Saturation(Sw%)
2.5
5.0
7.5
10.0
VpVs_Ratio(unitless)
Legend
Zone_5
Zone_6
Zone_7
Zone_8

c)



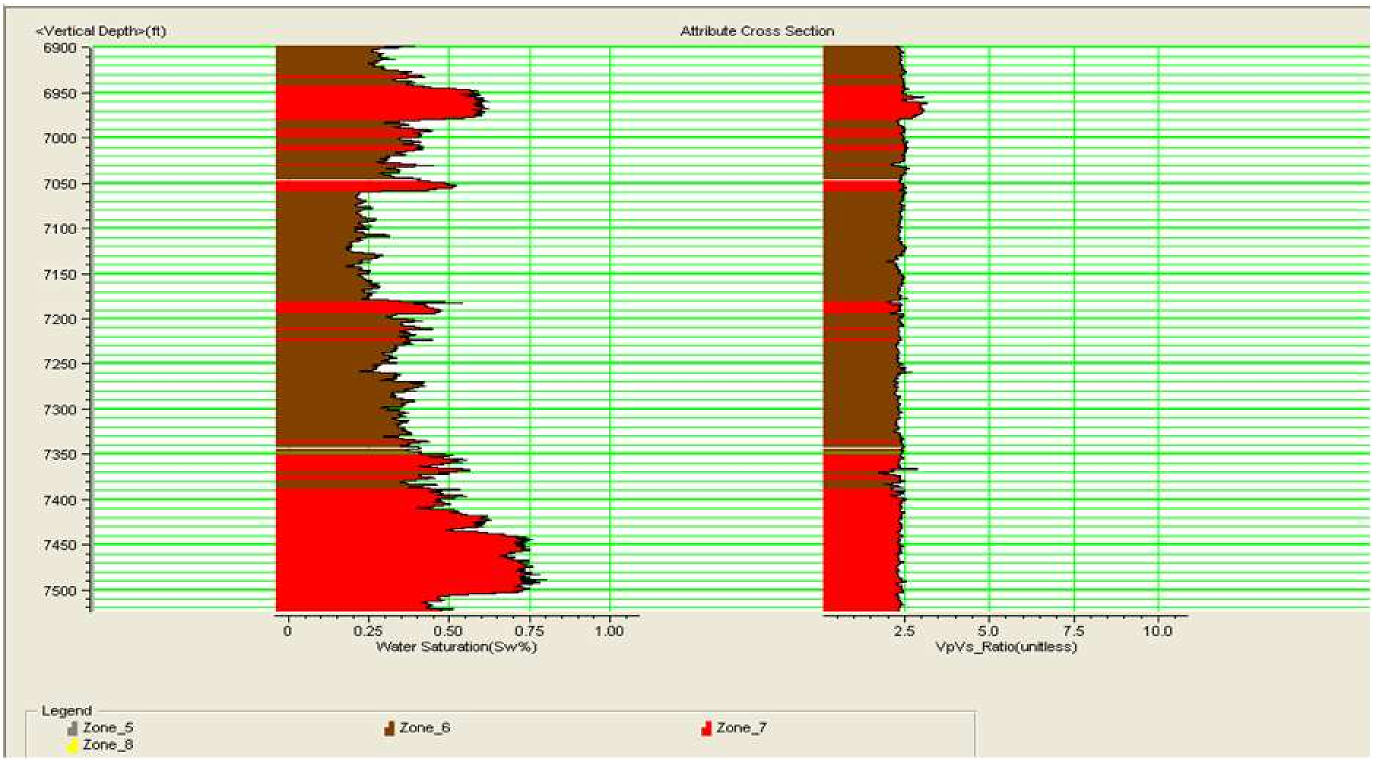
<Vertical Depth>(ft)
Attribute Cross Section
5700
5750
5800
5850
5900
5950
6000
6050
6100
6150
6200
6250
6300
0 0.25 0.50 0.75 1.00
Water Saturation(Sw%)
2.5 5.0 7.5 10.0
VpVs_Ratio(unitless)
Legend
Zone_5
Zone_6
Zone_7
Zone_8

d)

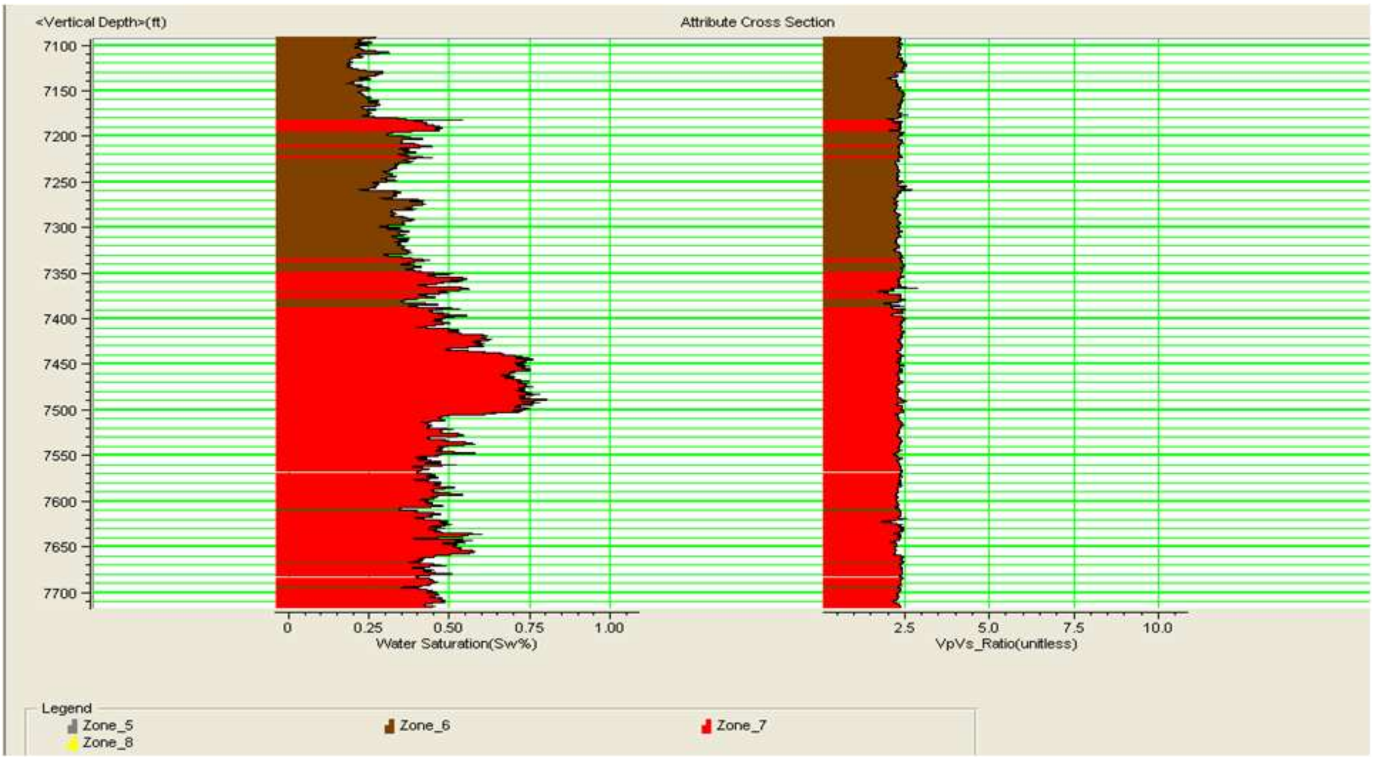


<Vertical Depth>(ft)
Attribute Cross Section
6300
6350
6400
6450
6500
6550
6600
6650
6700
6750
6800
6850
6900
0 0.25 0.50 0.75 1.00
Water Saturation(Sw%)
2.5 5.0 7.5 10.0
VpVs_Ratio(unitless)
Legend
Zone_5
Zone_6
Zone_7
Zone_8

e)



f)



g)

Figures 21a - g: Sw vs Vp/Vs ratio plot for TMB_4 (Cross section)

The log-facies are presented in the table 3.

Table 3: Representation of the various litho-facies, colour, Vp/Vs ratio and Sw ranges

FACIES NUMBER	GIVEN ACRONYM	LITHO-NAME	COLOUR ON PLOT	VP/VS RANGE (UNITLESS)	SW RANGE (%)
1	EL1	SAND	GREY	3.8 – 10.2	5.0 - 26
2	EL2	SHALY SAND	BROWN	1.6 – 3.8	6.0 – 60
3	EL3	SHALE	RED	1.8 – 3.6	37 – 81
4	EL4	CLEAN SAND	YELLOW	1.2 – 2.2	6.0 - 18

C) POROSITY versus P-WAVE

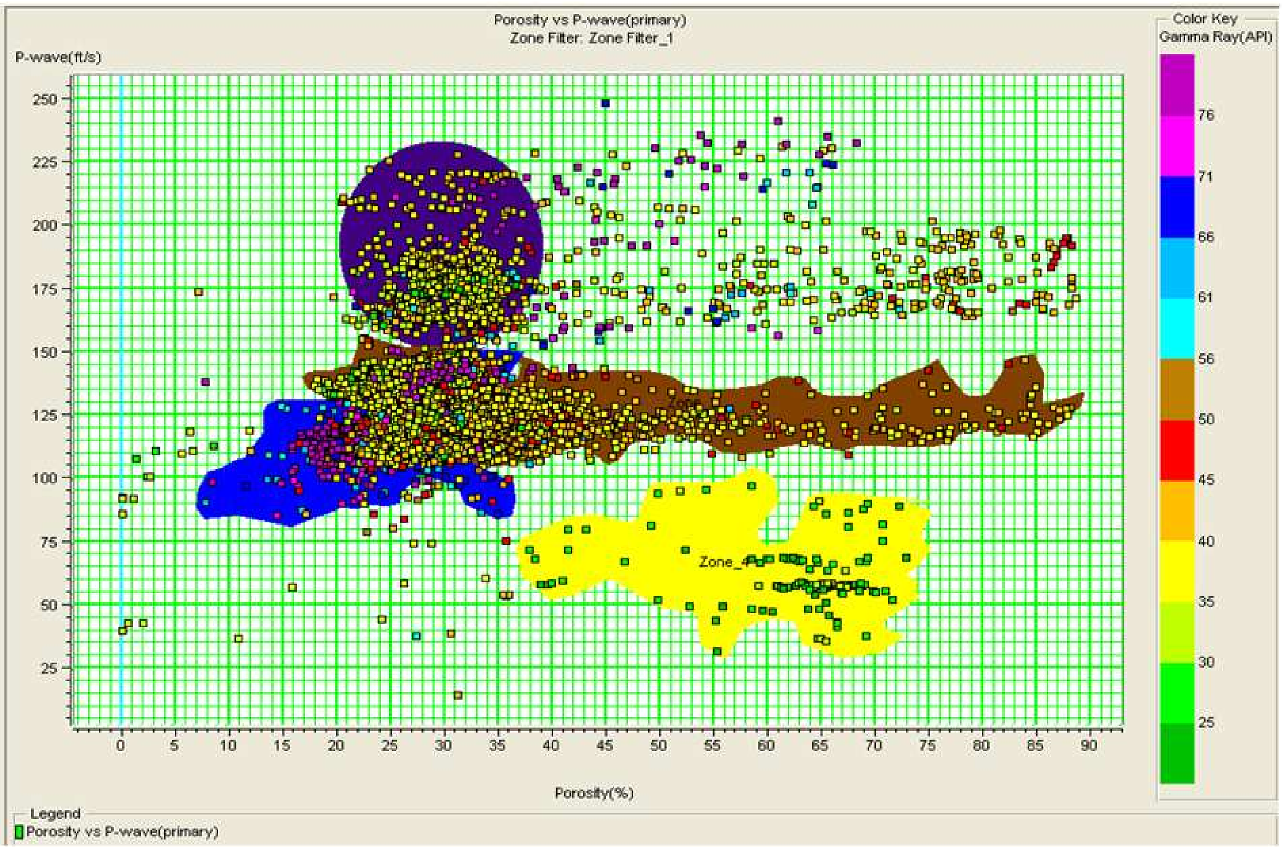
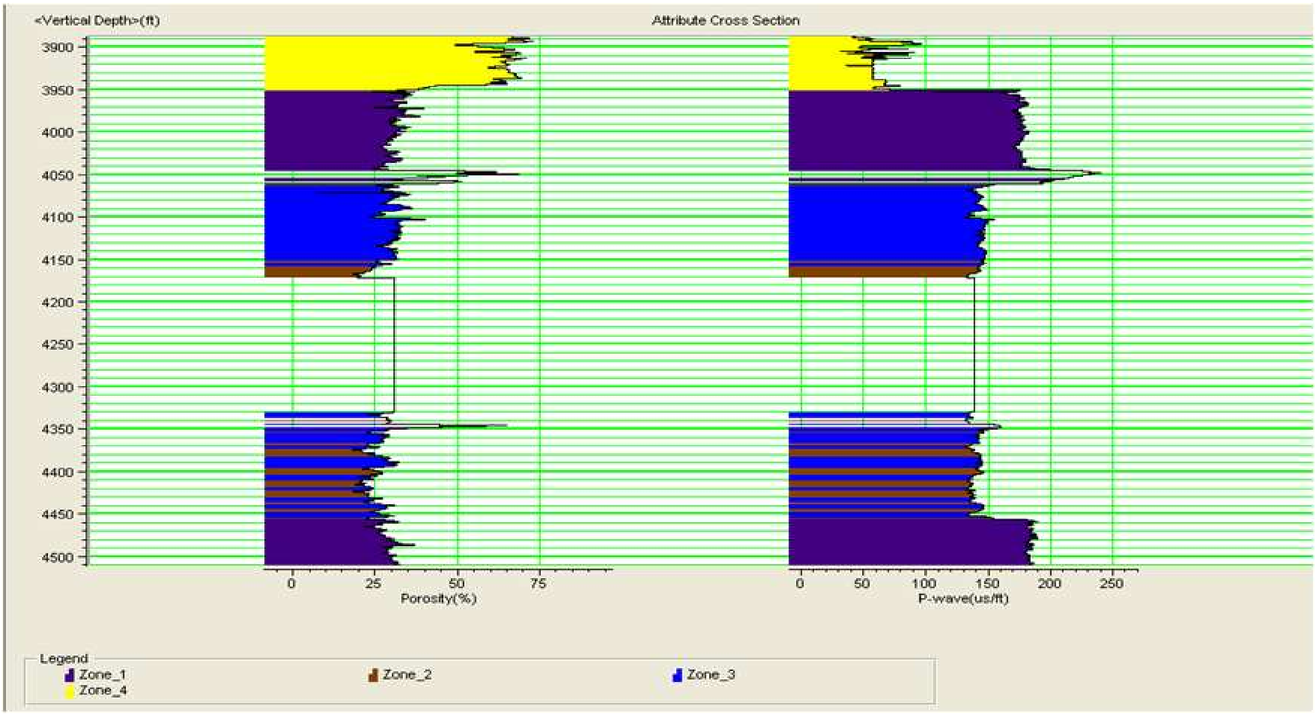
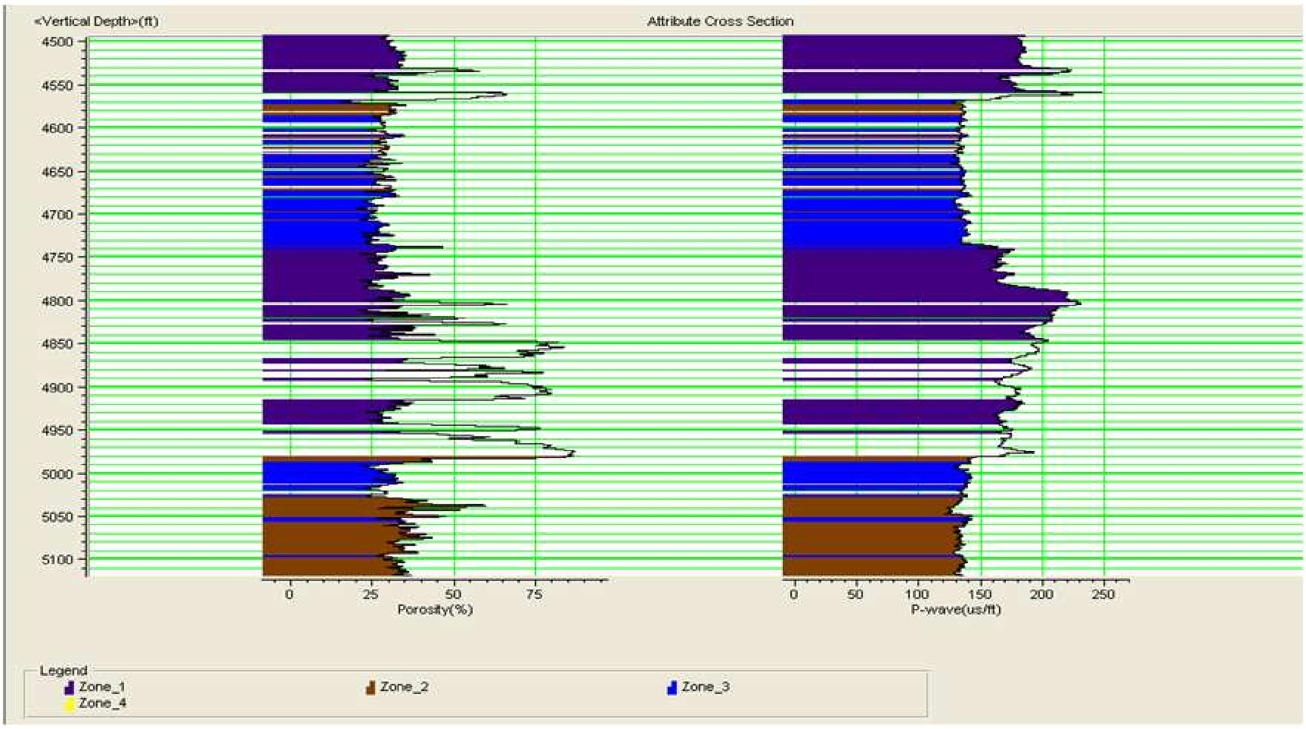


Figure 22: Porosity versus Vp cross plot for TMB_4 colour coded by GR (after zoning)

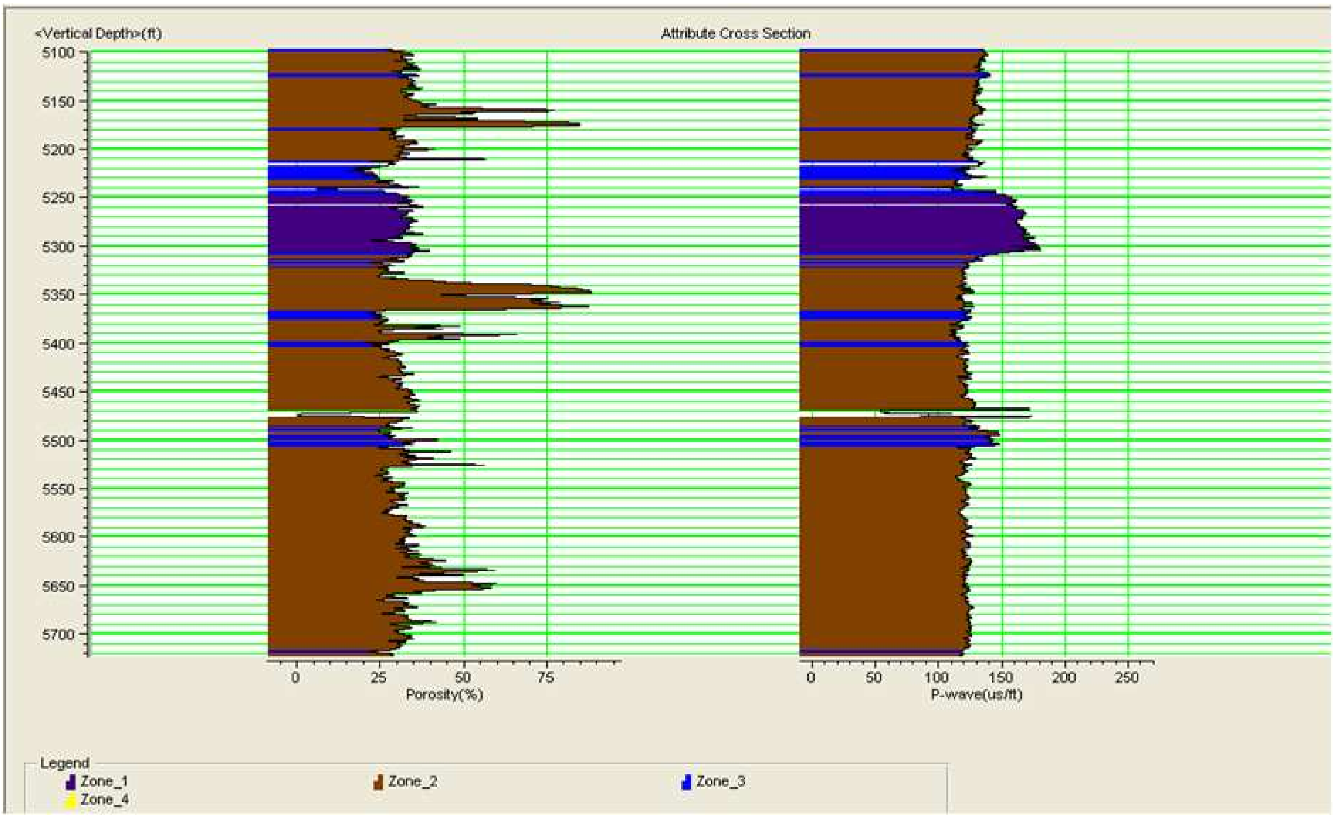
CROSS SECTION



a)



b)



<Vertical Depth>(ft)
Attribute Cross Section
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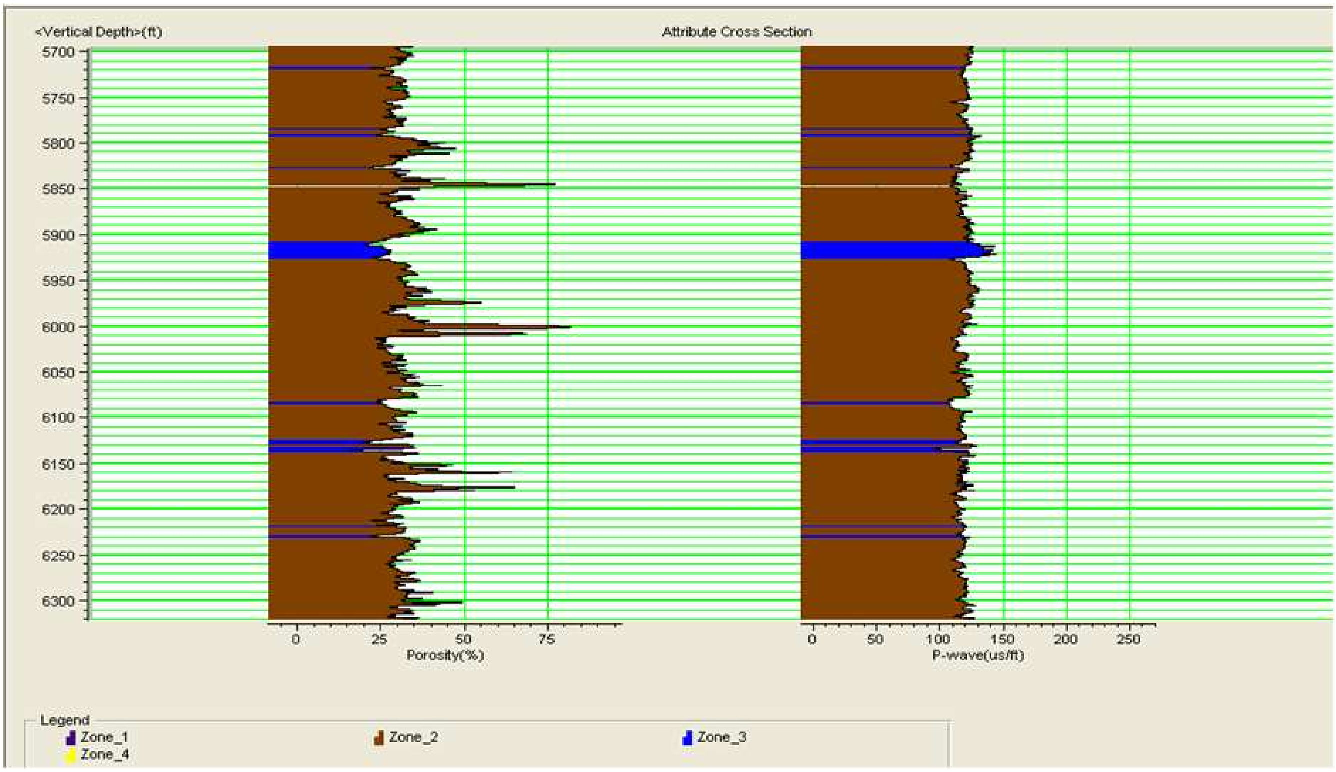
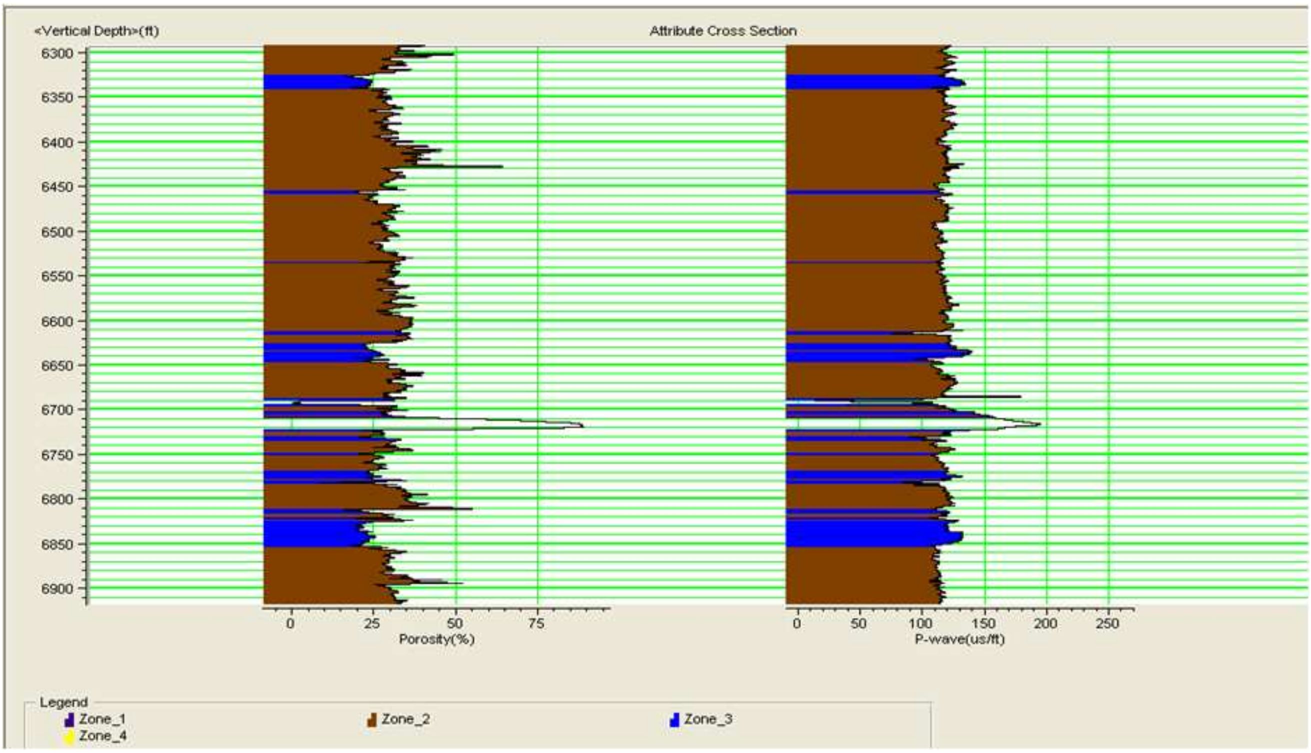
5150
5200
5250
5300
5350
5400
5450
5500
5550
5600
5650
5700
0
25
50
75
Porosity(%)
0
50
100
150
200
250
P-wave(us/ft)
Legend
Zone_1
Zone_2
Zone_3
Zone_4

c)



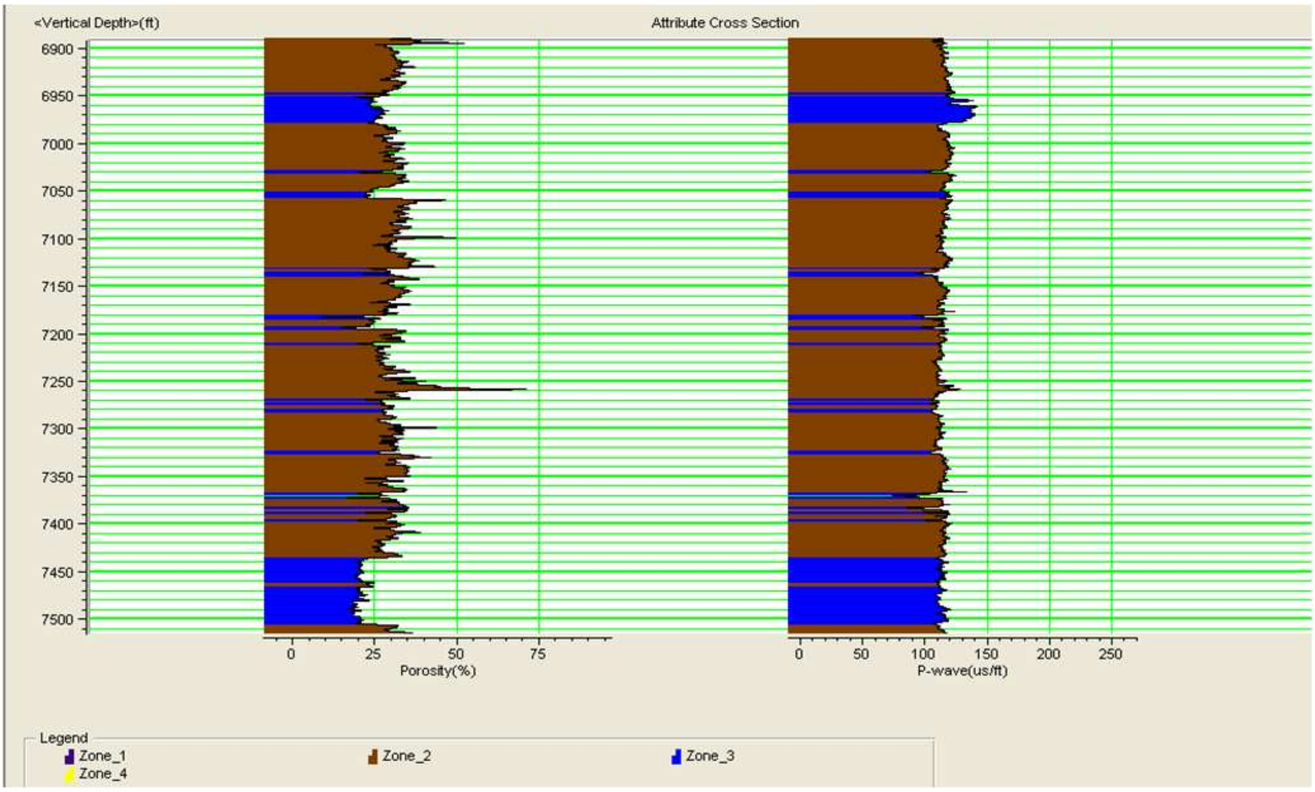
<Vertical Depth>(ft)
Attribute Cross Section
5700
5750
5800
5850
5900
5950
6000
6050
6100
6150
6200
6250
6300
0
25
50
75
Porosity(%)
0
50
100
150
200
250
P-wave(us/ft)
Legend
Zone_1
Zone_2
Zone_3
Zone_4

d)



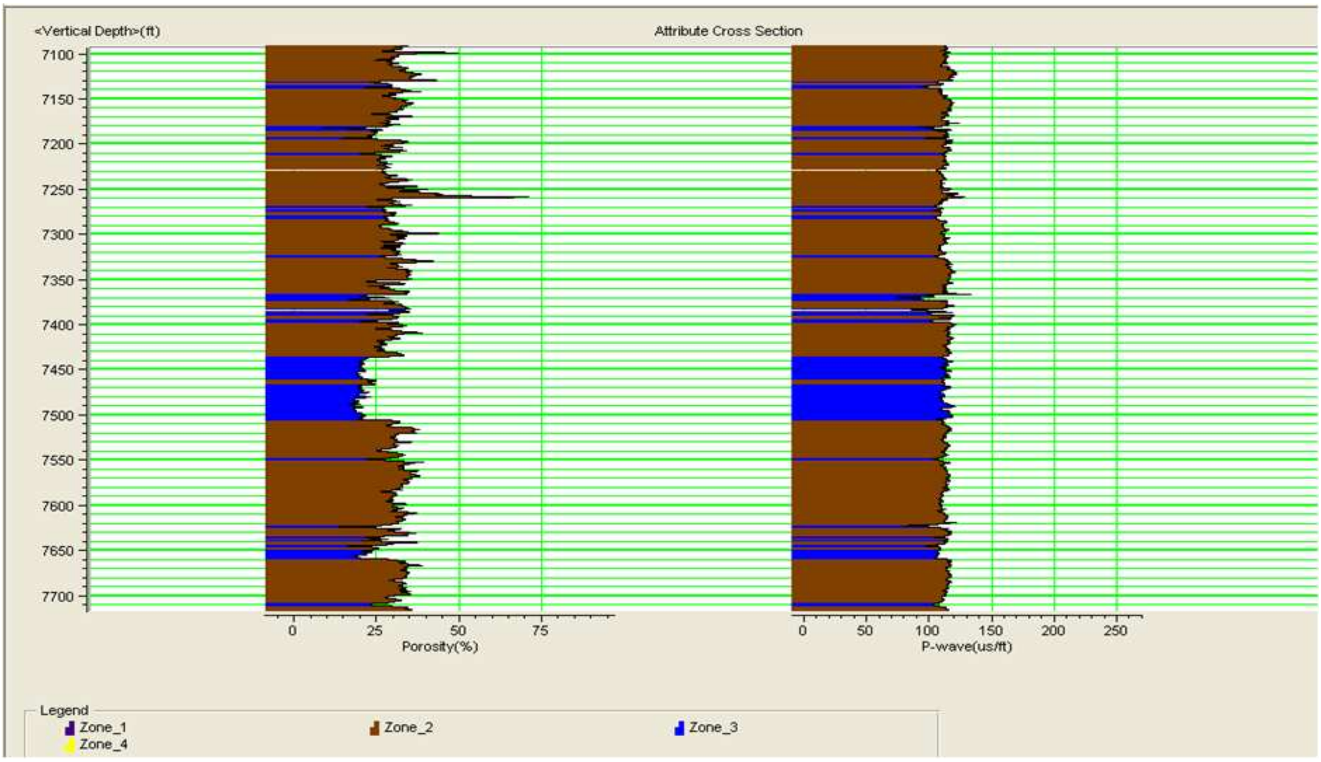
<Vertical Depth>(ft)
Attribute Cross Section
6300
6350
6400
6450
6500
6550
6600
6650
6700
6750
6800
6850
6900
0 25 50 75
Porosity(%)
0 50 100 150 200 250
P-wave(us/ft)
Legend
Zone_1
Zone_2
Zone_3
Zone_4

e)



<Vertical Depth>(ft)
Attribute Cross Section
6900
6950
7000
7050
7100
7150
7200
7250
7300
7350
7400
7450
7500
0 25 50 75
Porosity(%)
0 50 100 150 200 250
P-wave(us/ft)
Legend
Zone_1
Zone_2
Zone_3
Zone_4

f)



g)

Figures 23a - g: Porosity vs Vp plot for TMB-4 (Cross section)

The log-facies are presented in the table 4.

Table 4: Representation of the various litho-facies, colour, Vp and Porosity range

FACIES NUMBER	GIVEN ACRONYM	LITHO-NAME	COLOUR ON PLOT	VP RANGE (FT/S)	POROSITY RANGE (%)
1	EL1	SAND	PURPLE	150 – 235	20 - 40
2	EL2	SHALY SAND	BROWN	105 – 155	17 – 89
3	EL3	SHALE	BLUE	85 – 150	7.0 – 37
4	EL4	CLEAN SAND	YELLOW	30 – 105	37 - 75

D) WATER SATURATION versus P-WAVE

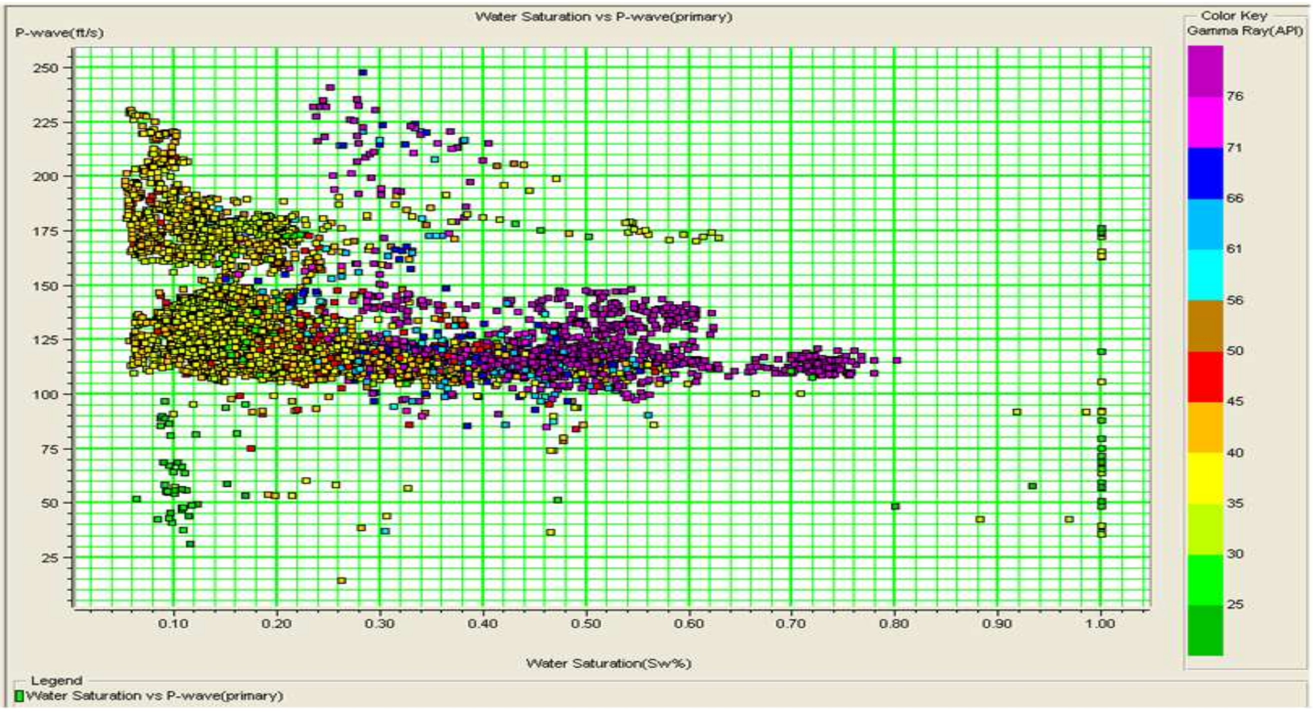


Figure 24a: Sw versus Vp cross plot for TMB_4 colour coded by GR (before zoning)

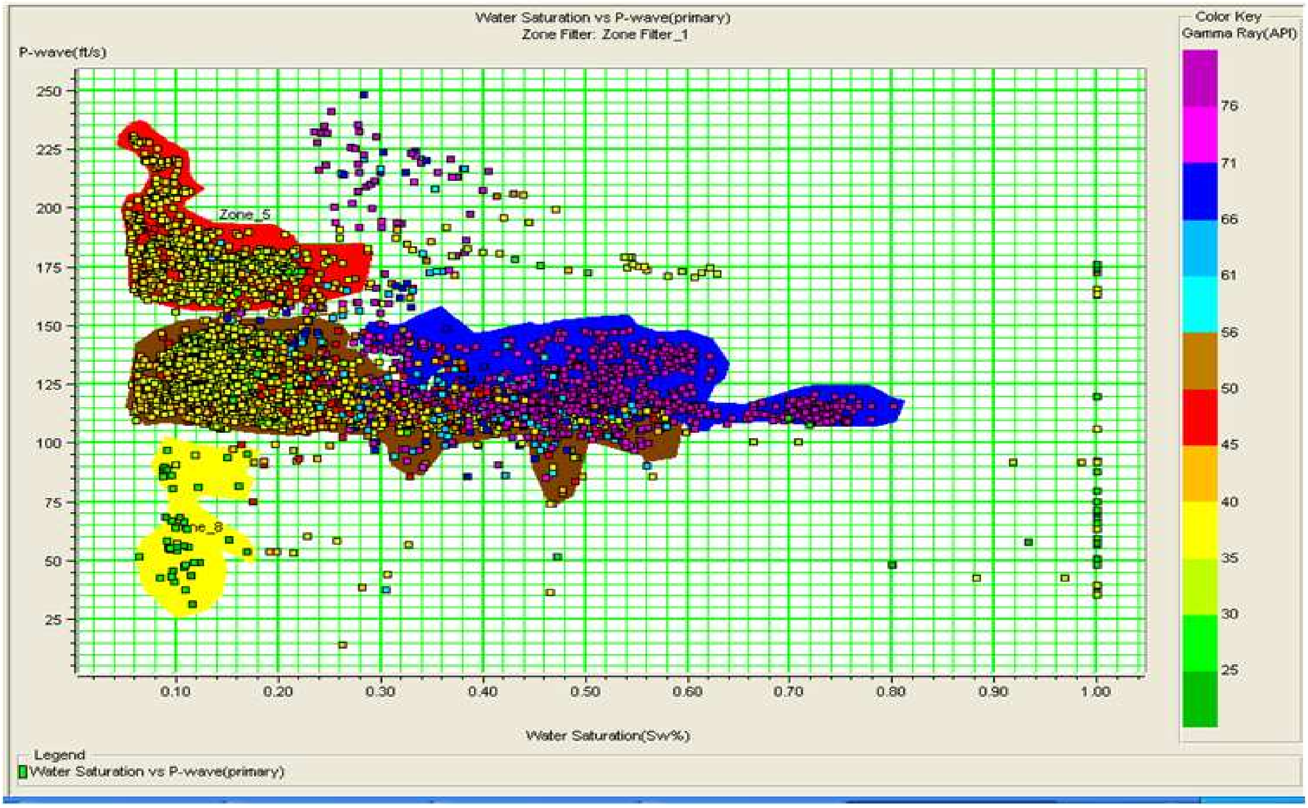
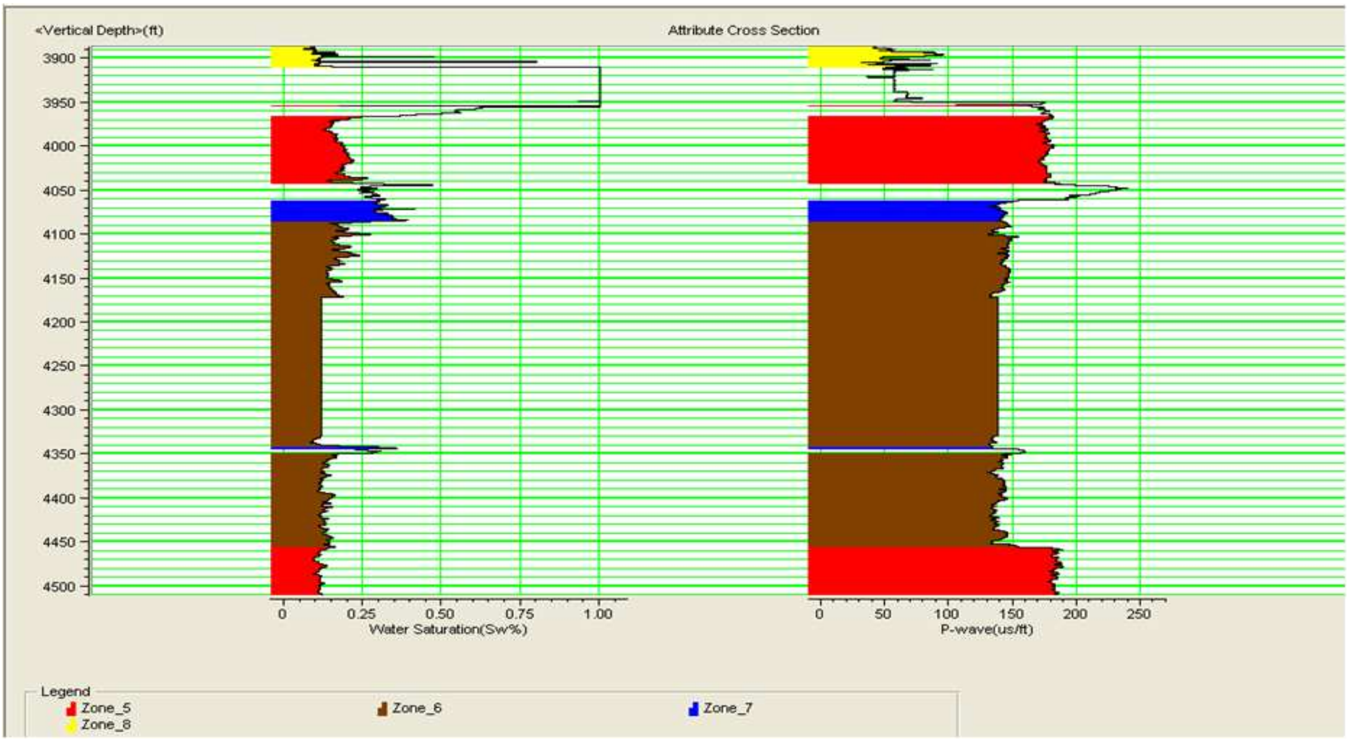
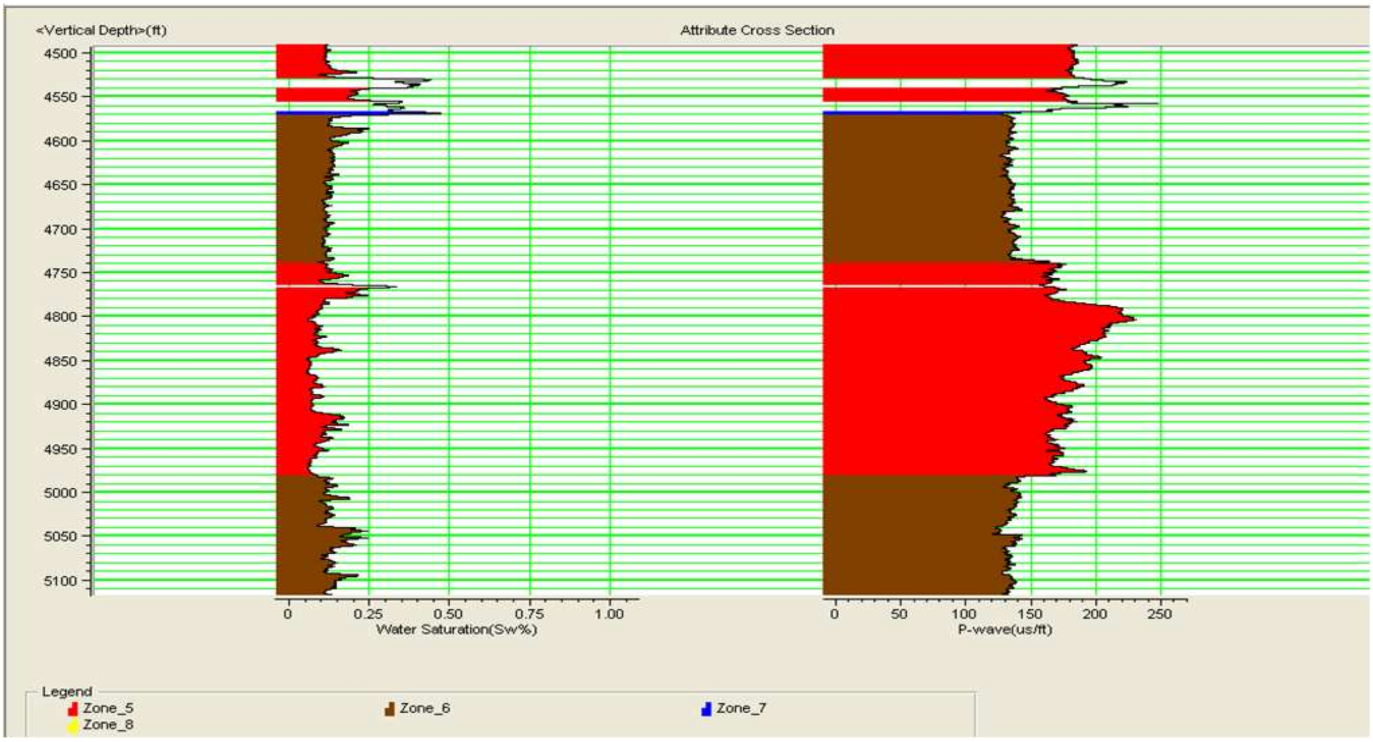


Figure 24b: Sw versus Vp cross plot for TMB_4 colour coded by GR (after zoning)

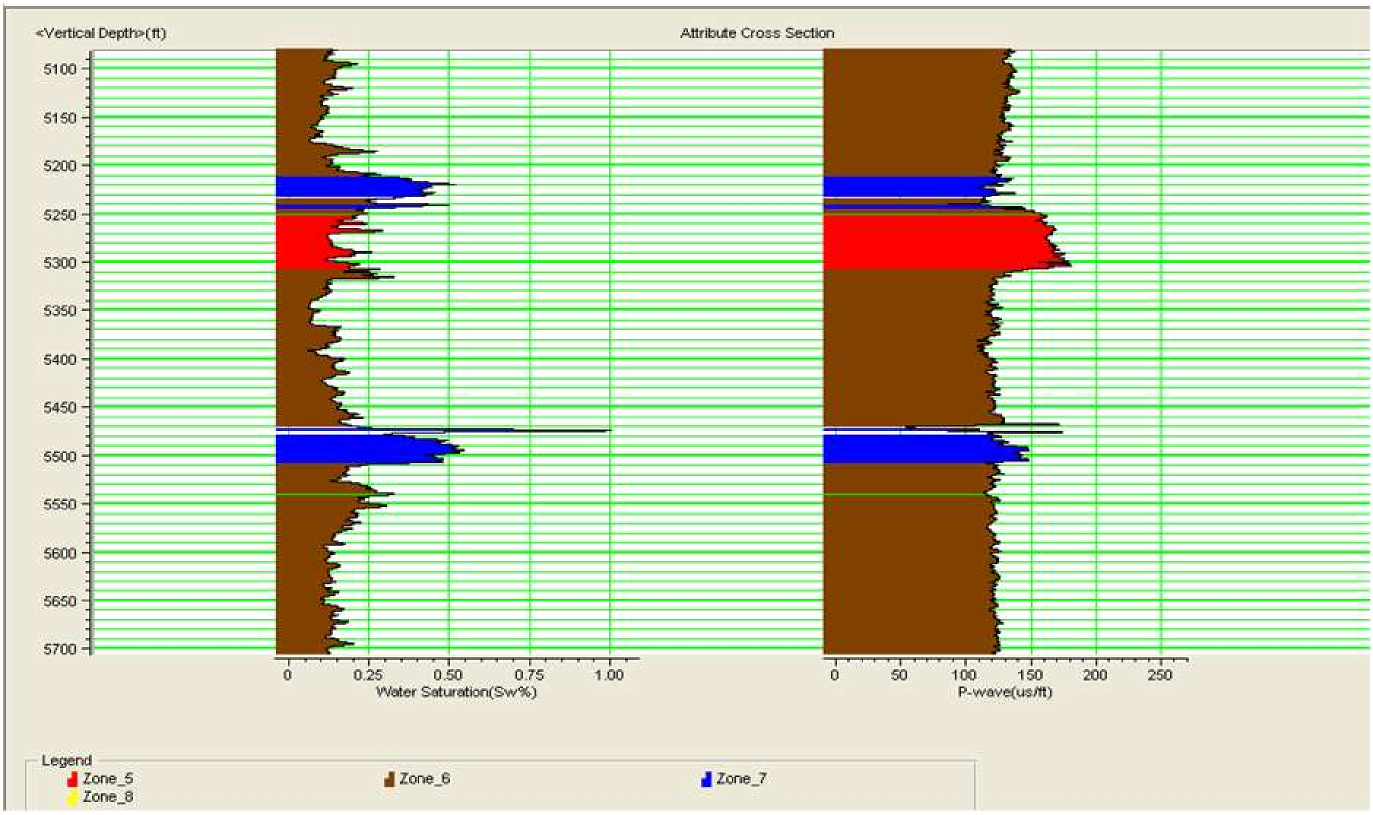
CROSS SECTION



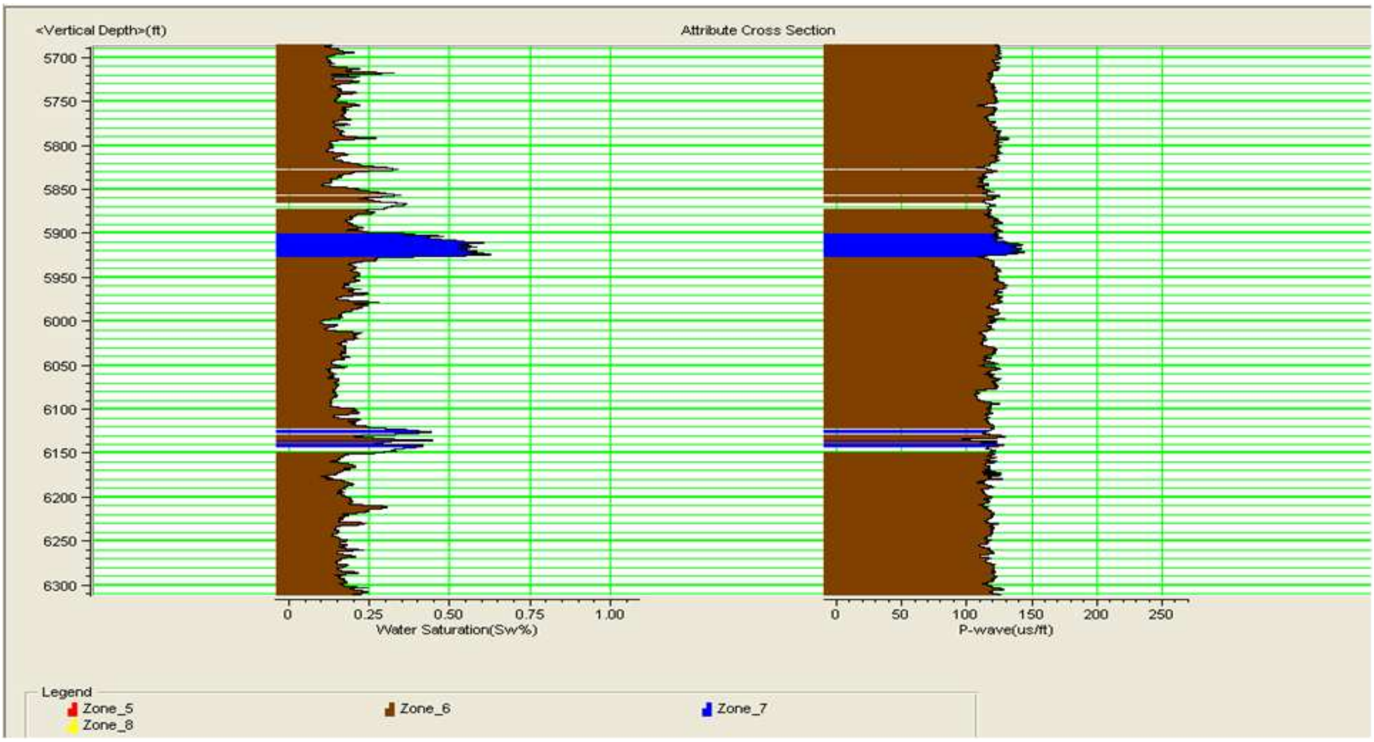
a)



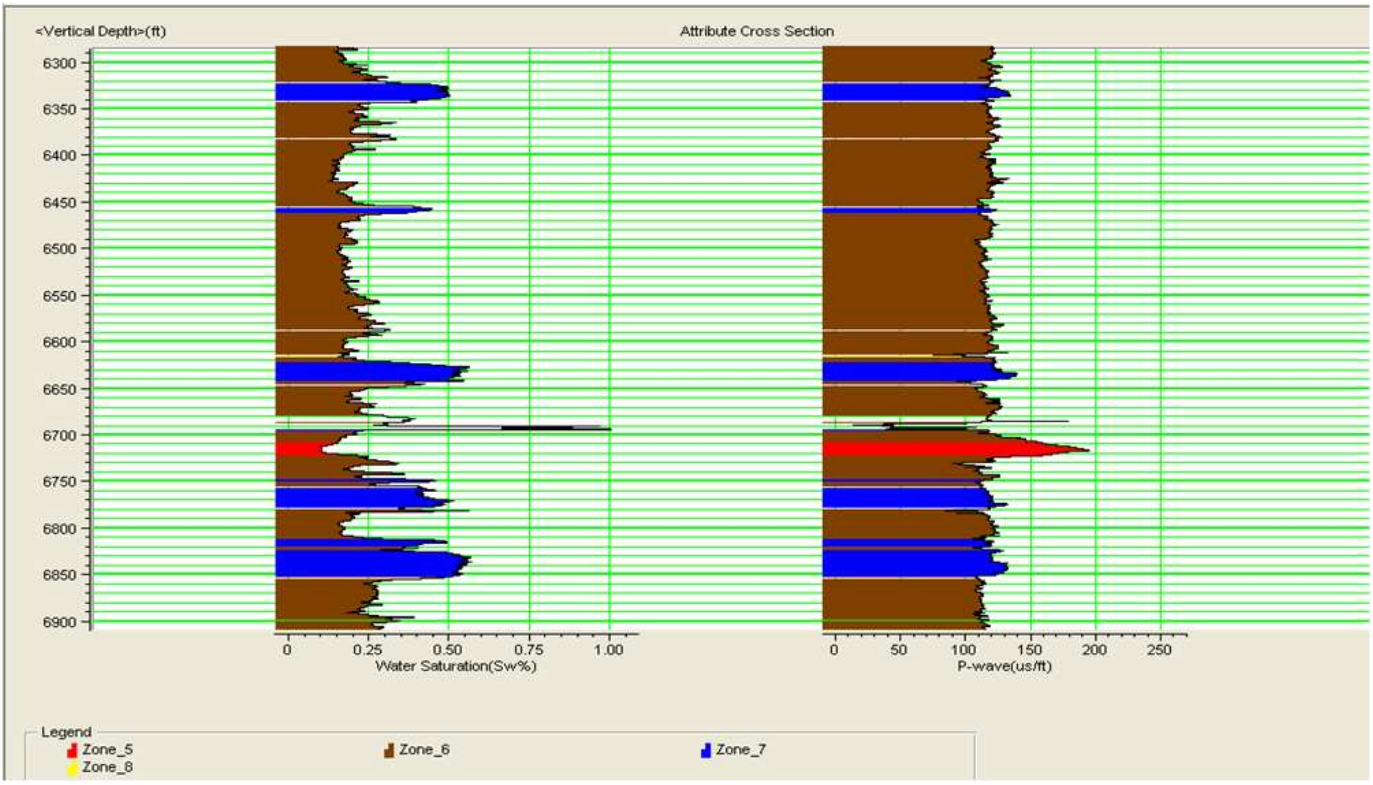
b)


<Vertical Depth>(ft)
Attribute Cross Section
5100
5150
5200
5250
5300
5350
5400
5450
5500
5550
5600
5650
5700
0
0.25
0.50
0.75
1.00
Water Saturation(Sw%)
0
50
100
150
200
250
P-wave(us/ft)
Legend
Zone_5
Zone_6
Zone_7
Zone_8

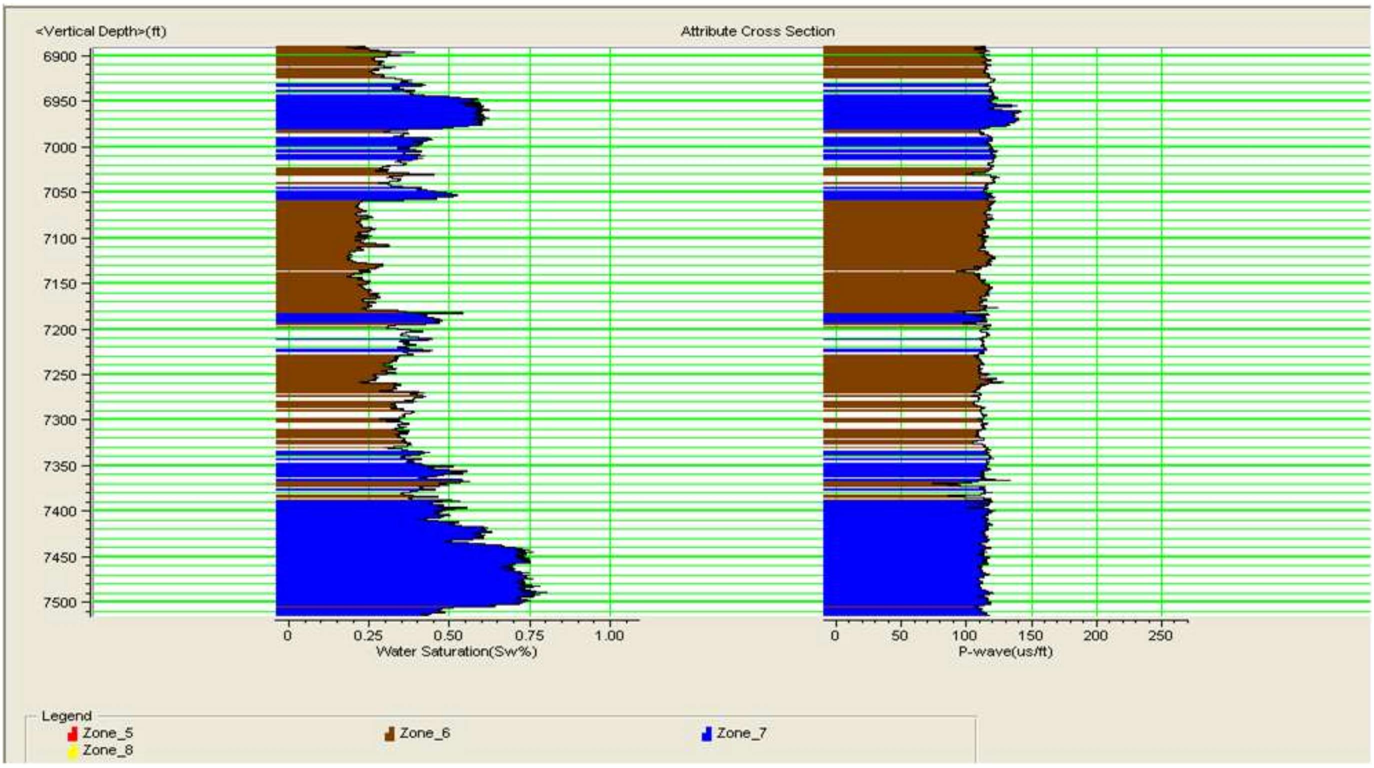
c)


<Vertical Depth>(ft)
Attribute Cross Section
5700
5750
5800
5850
5900
5950
6000
6050
6100
6150
6200
6250
6300
0
0.25
0.50
0.75
1.00
Water Saturation(Sw%)
0
50
100
150
200
250
P-wave(us/ft)
Legend
Zone_5
Zone_6
Zone_7
Zone_8

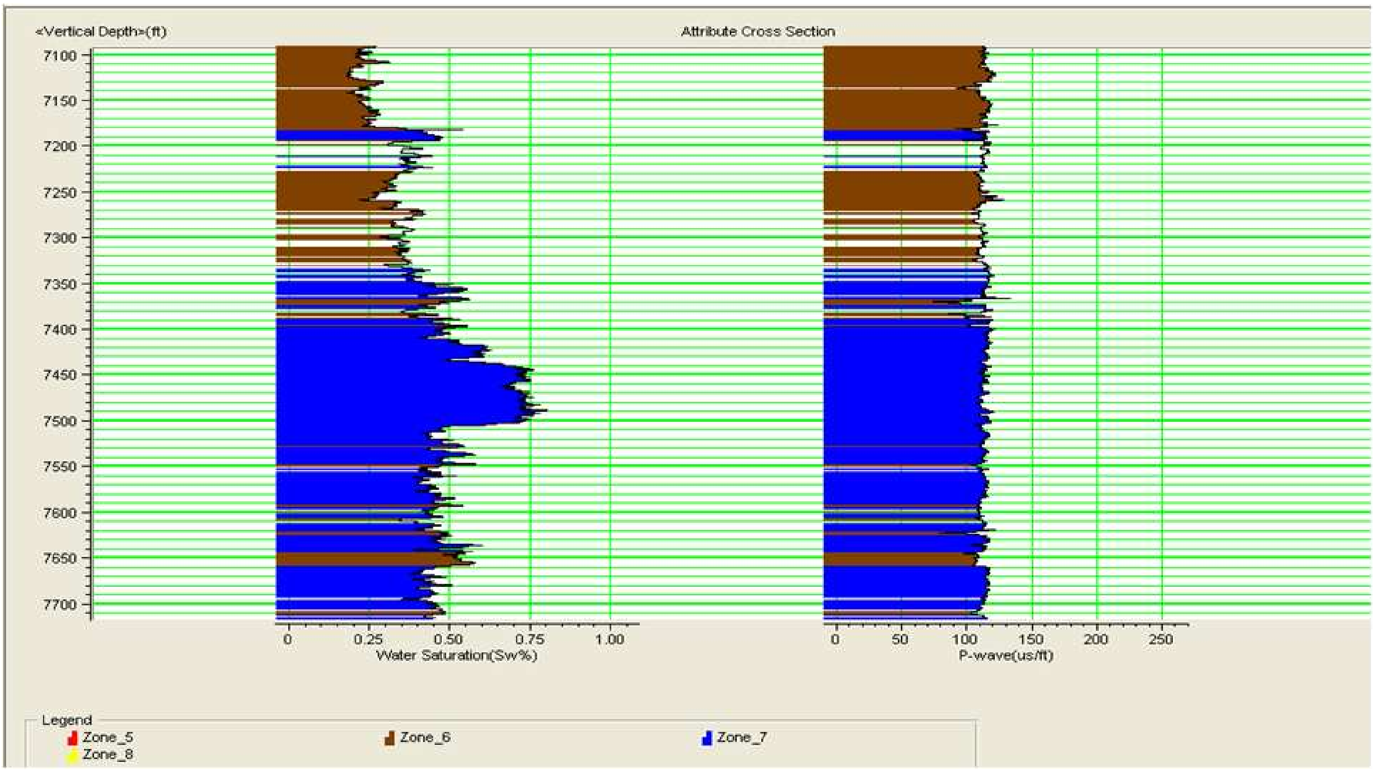
d)


<Vertical Depth>(ft)
Attribute Cross Section
6300
6350
6400
6450
6500
6550
6600
6650
6700
6750
6800
6850
6900
0 0.25 0.50 0.75 1.00
Water Saturation(Sw%)
0 50 100 150 200 250
P-wave(us/ft)
Legend
Zone_5
Zone_6
Zone_7
Zone_8

e)


<Vertical Depth>(ft)
Attribute Cross Section
6900
6950
7000
7050
7100
7150
7200
7250
7300
7350
7400
7450
7500
0 0.25 0.50 0.75 1.00
Water Saturation(Sw%)
0 50 100 150 200 250
P-wave(us/ft)
Legend
Zone_5
Zone_6
Zone_7
Zone_8

f)



g)

Figures 25a - g: Sw vs Vp plot for TMB_4 (Cross section)

Table 5: Representation of the various litho-facies, colour, Vp and Sw ranges

FACIES NUMBER	GIVEN ACRONYM	LITHO-NAME	COLOUR ON PLOT	VP RANGE (FT/S)	SW RANGE (%)
1	EL1	SAND	RED	155 – 235	4.0 - 29
2	EL2	SHALY SAND	BROWN	75 – 155	6.0 – 59
3	EL3	SHALE	BLUE	105 – 160	28 – 81
4	EL4	CLEAN SAND	YELLOW	25 – 100	6.0 - 18

E) POROSITY versus S-WAVE

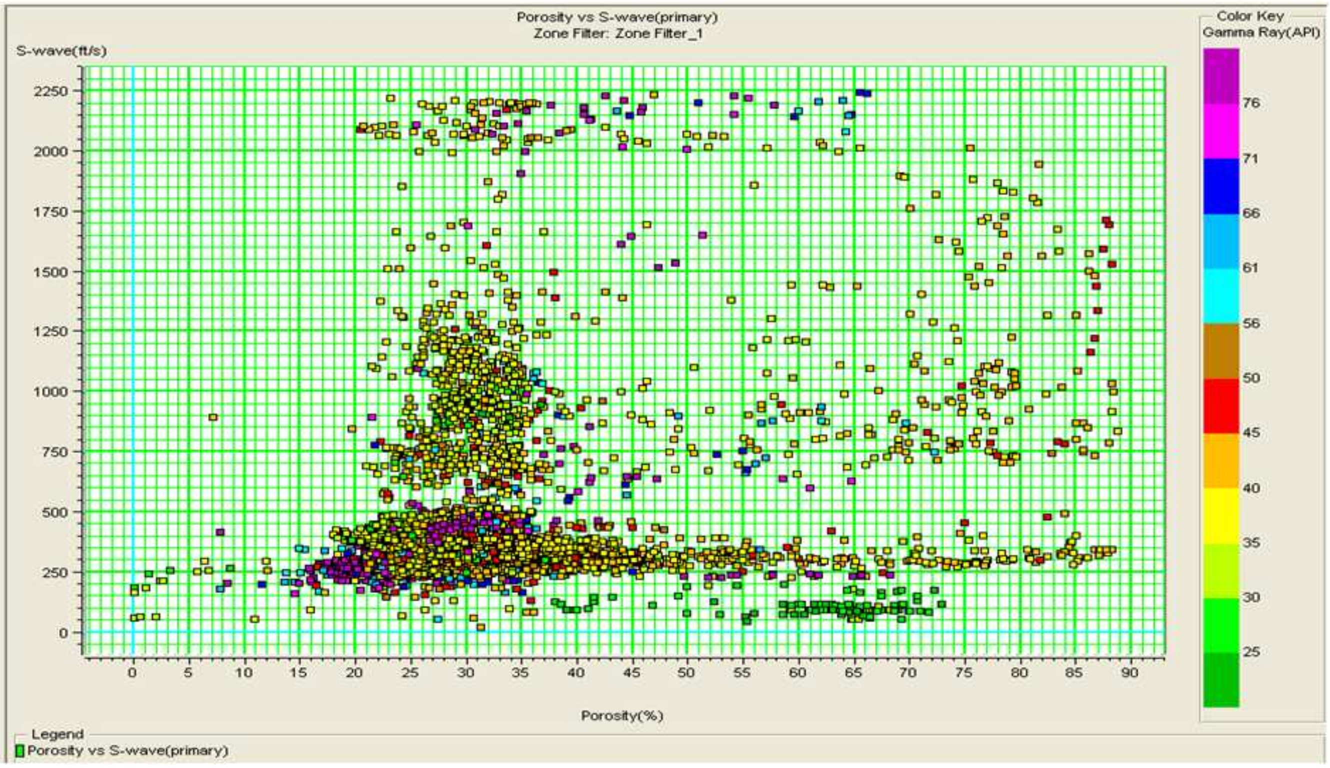


Figure 26a: Porosity versus Vs cross plot for TMB_4 colour coded by GR (before zoning)

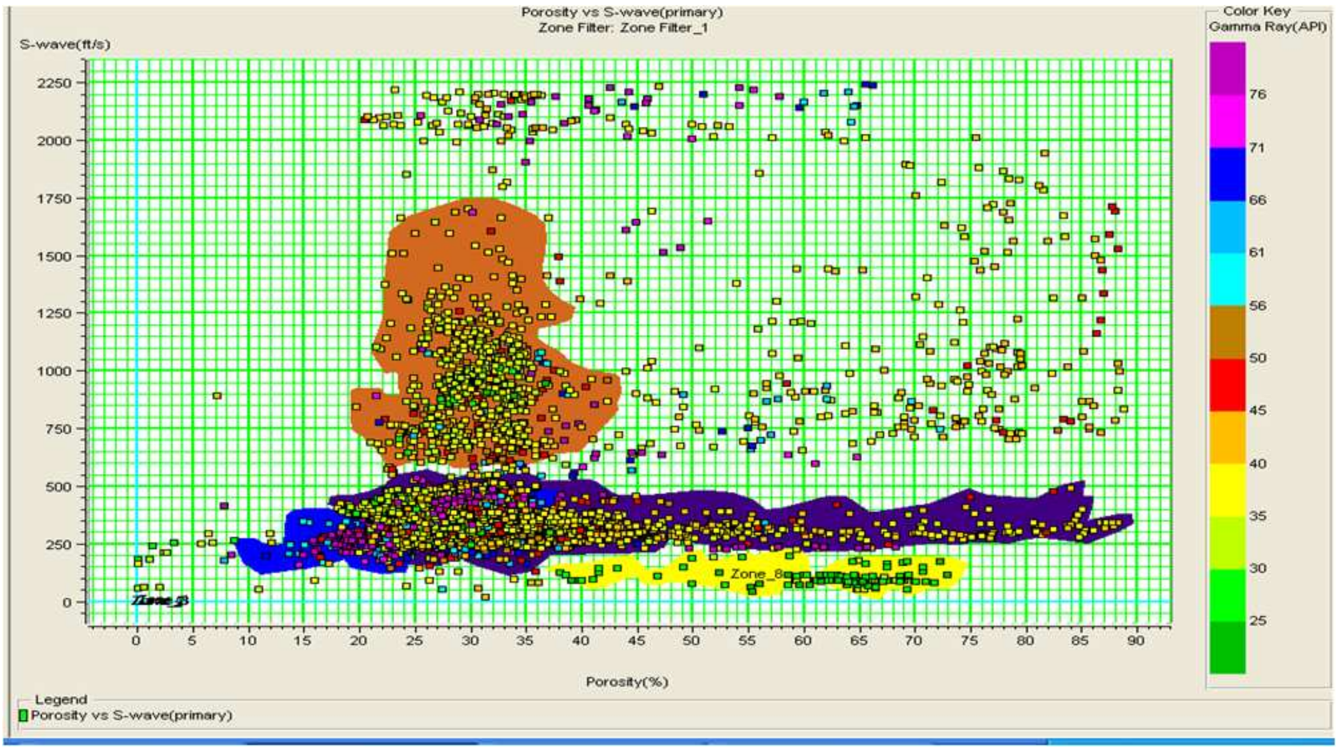
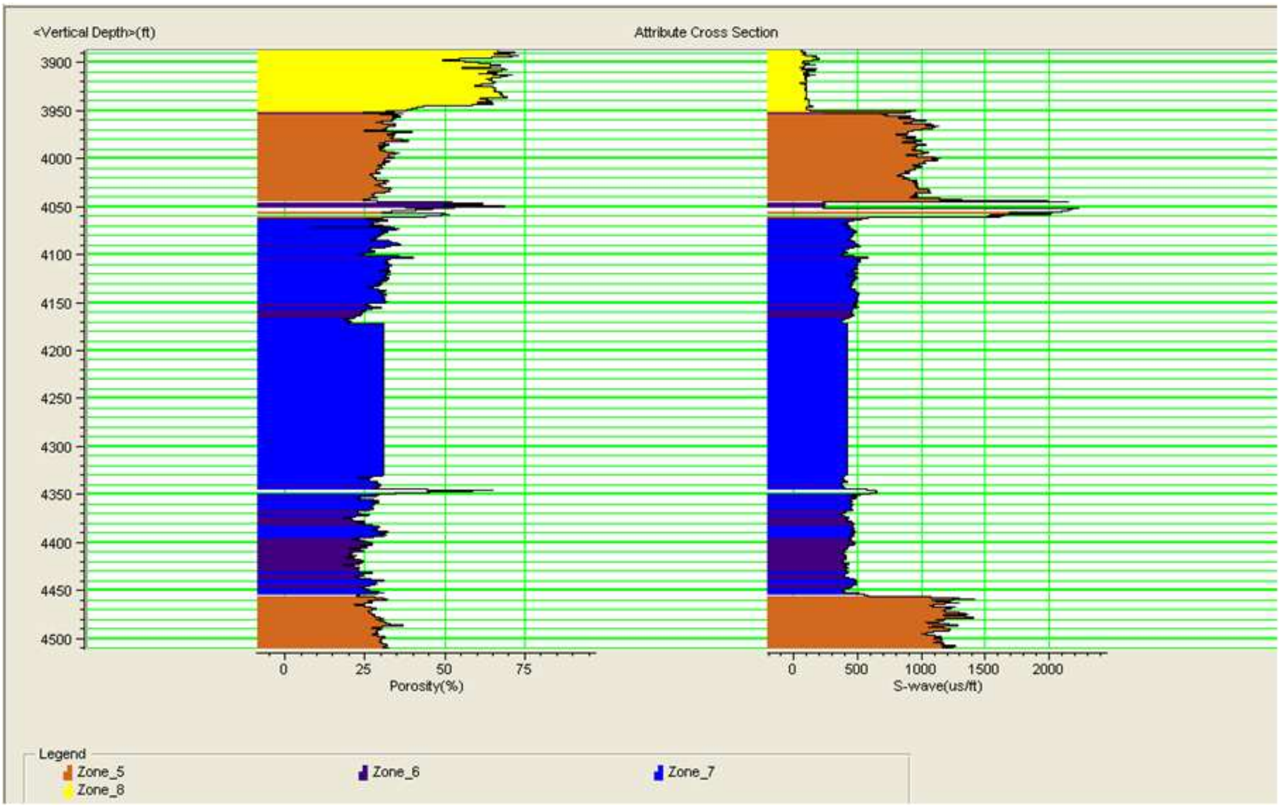
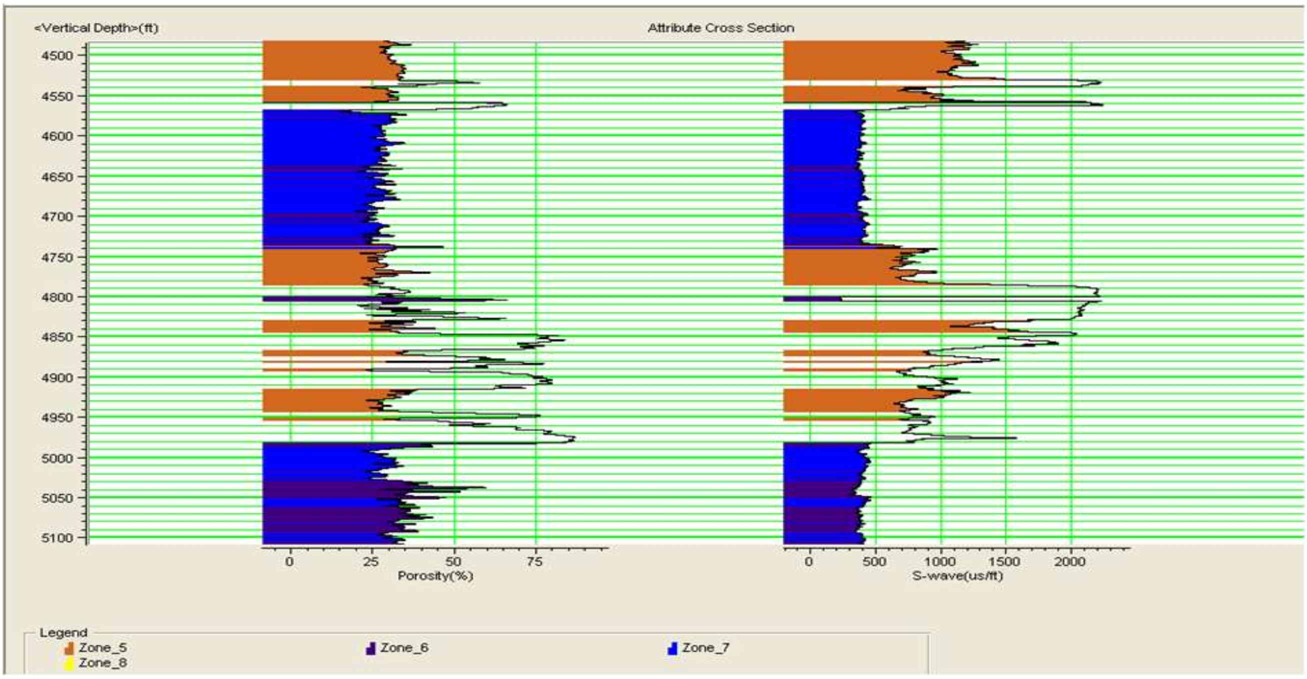


Figure 26b: Porosity versus Vs cross plot for TMB_4 colour coded by GR (after zoning)

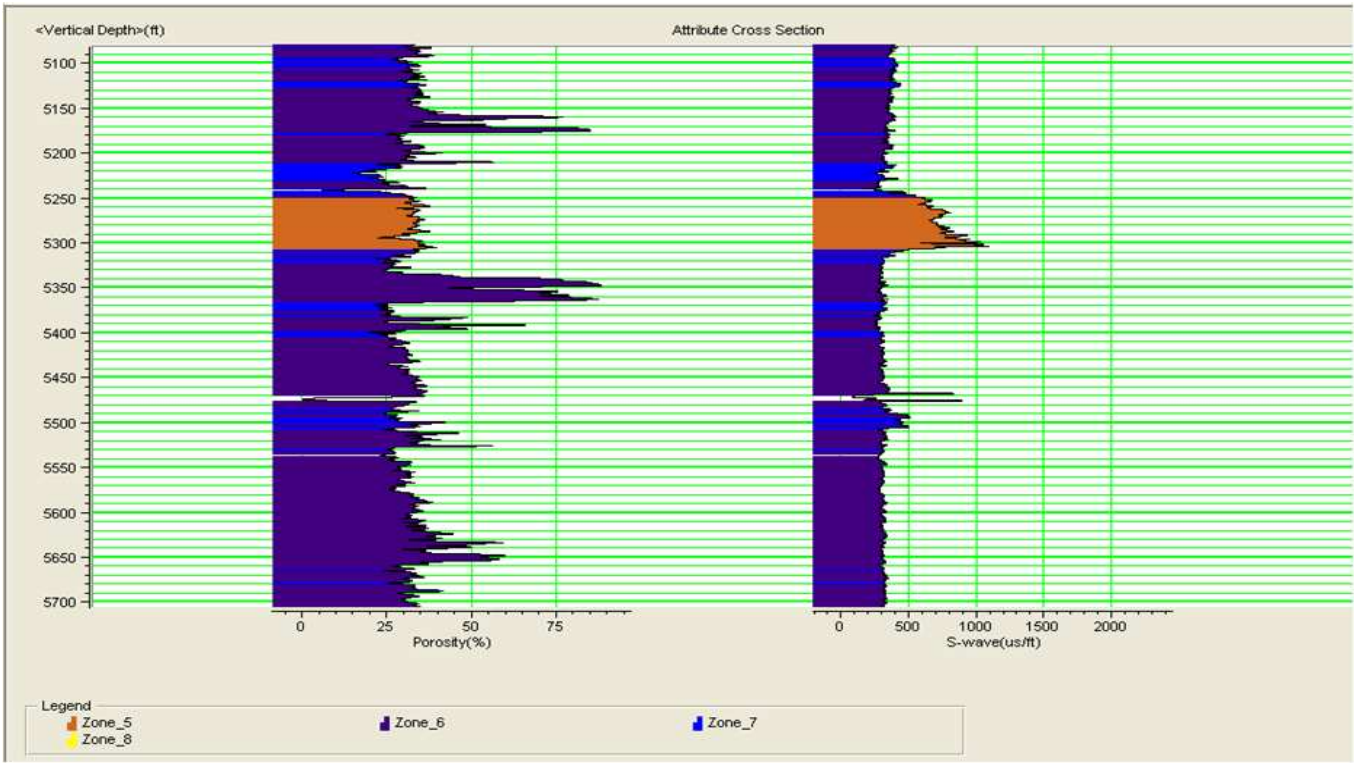
CROSS SECTION



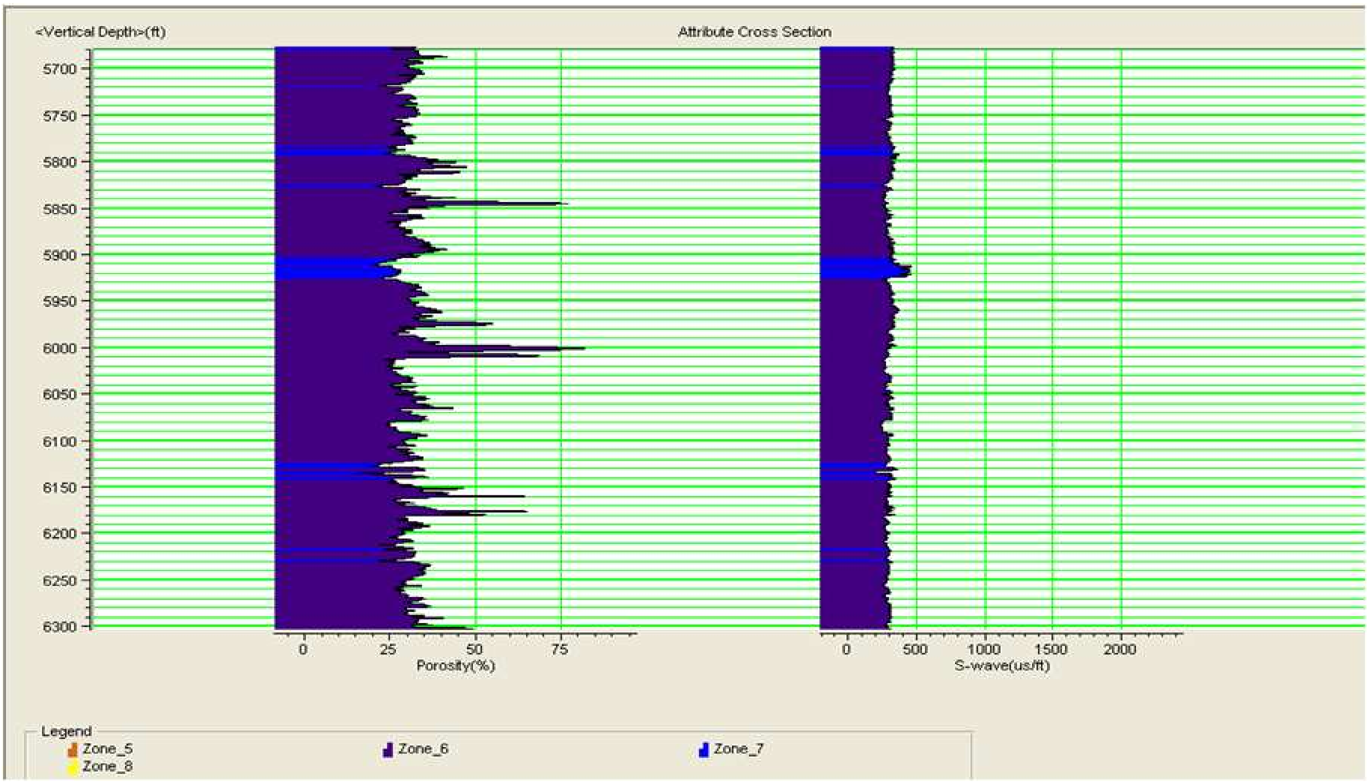
a)



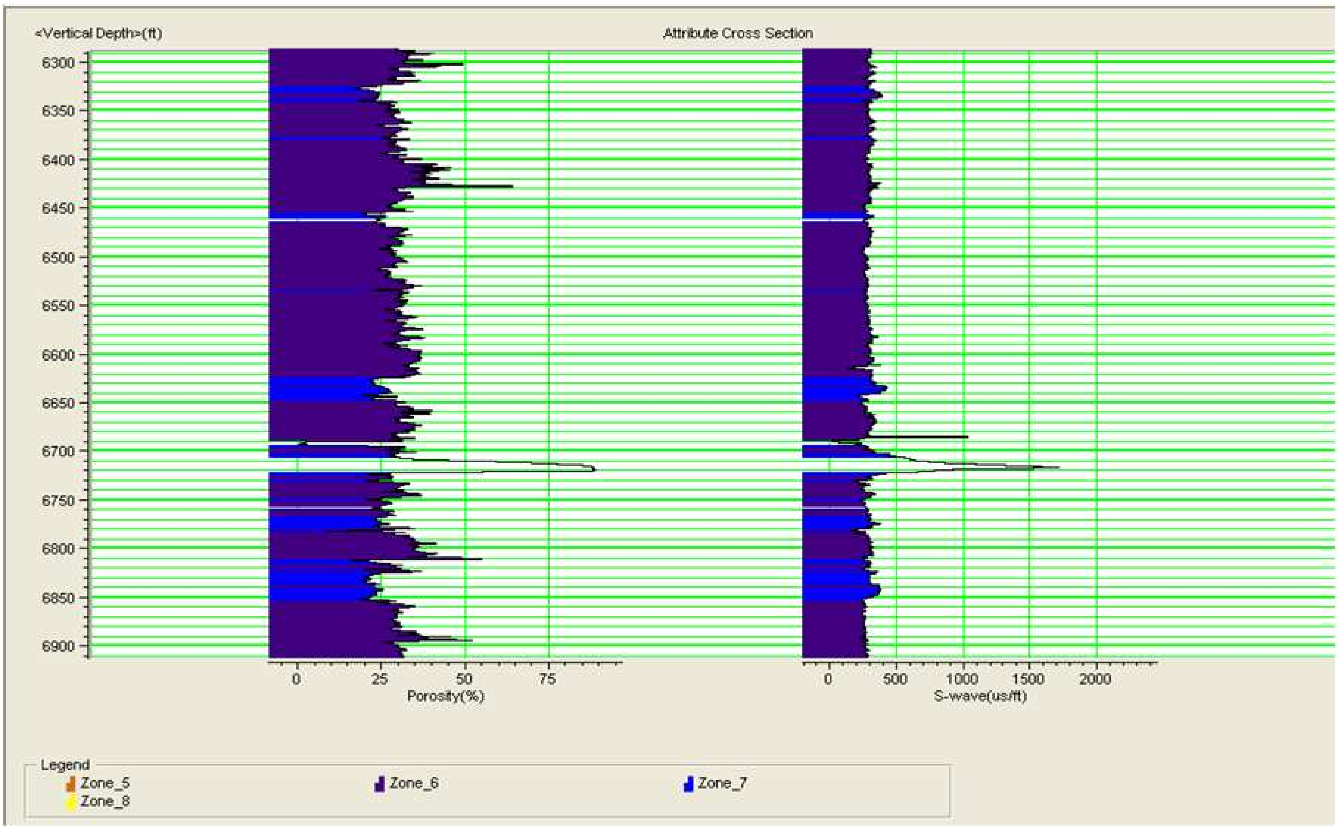
b)


<Vertical Depth>(ft)
Attribute Cross Section
5100
5150
5200
5250
5300
5350
5400
5450
5500
5550
5600
5650
5700
0 25 50 75
Porosity(%)
0 500 1000 1500 2000
S-wave(us/ft)
Legend
Zone_5
Zone_6
Zone_7
Zone_8

c)

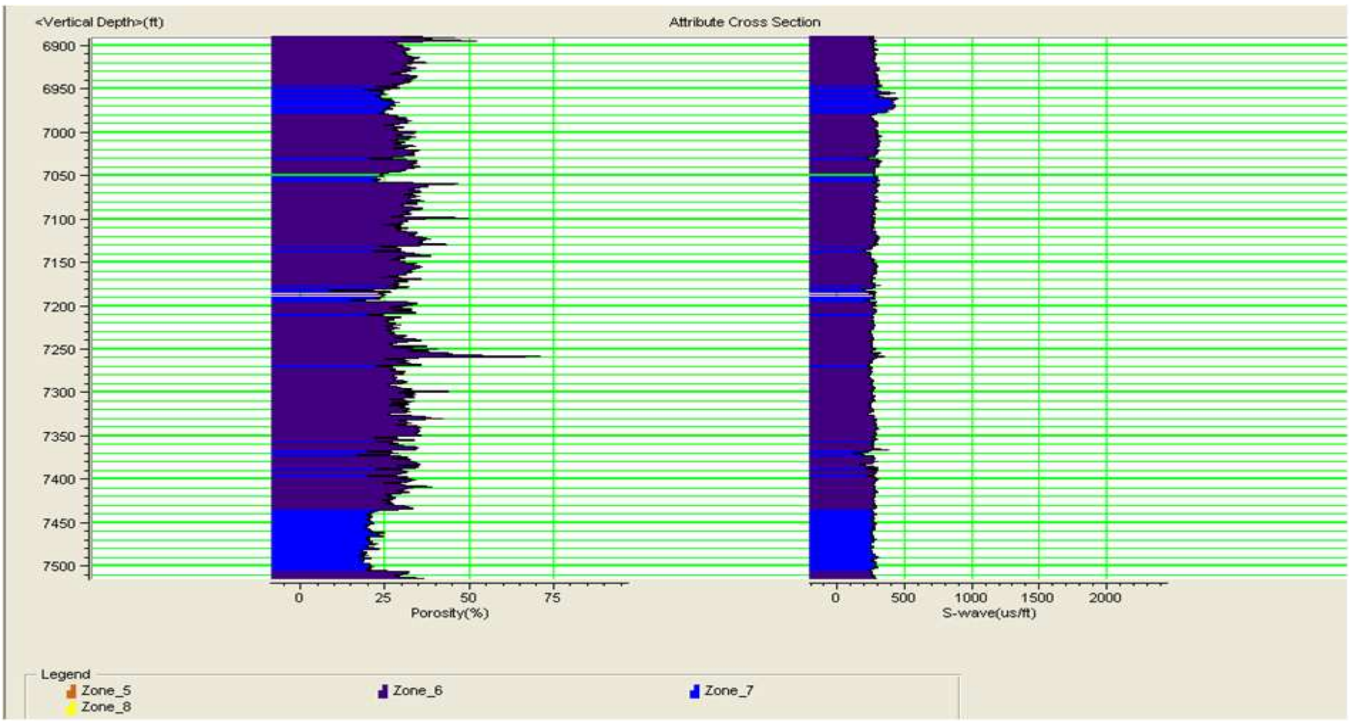

<Vertical Depth>(ft)
Attribute Cross Section
5700
5750
5800
5850
5900
5950
6000
6050
6100
6150
6200
6250
6300
0 25 50 75
Porosity(%)
0 500 1000 1500 2000
S-wave(us/ft)
Legend
Zone_5
Zone_6
Zone_7
Zone_8

d)



<Vertical Depth>(ft)
Attribute Cross Section
6300
6350
6400
6450
6500
6550
6600
6650
6700
6750
6800
6850
6900
0
25
50
75
Porosity(%)
0
500
1000
1500
2000
S-wave(us/ft)
Legend
Zone_5
Zone_6
Zone_7
Zone_8

e)



<Vertical Depth>(ft)
Attribute Cross Section
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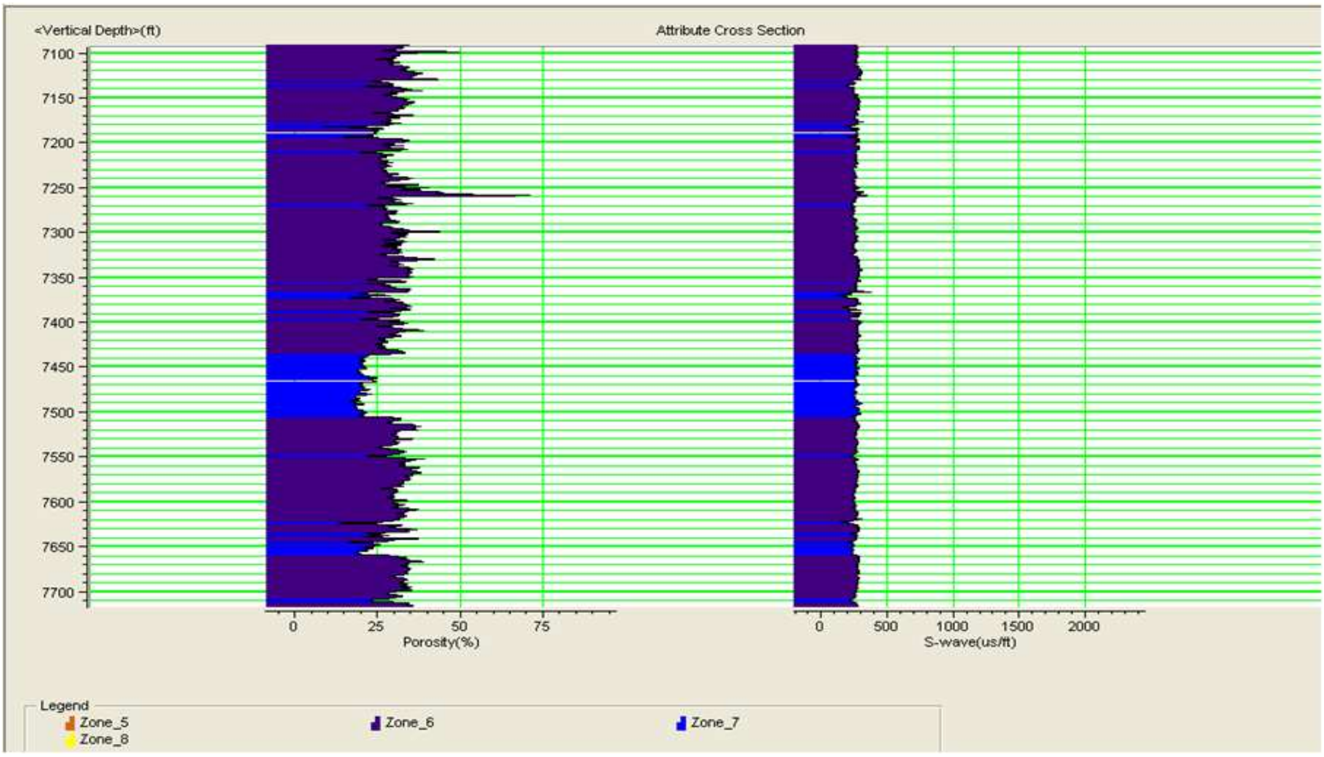
6950
7000
7050
7100
7150
7200
7250
7300
7350
7400
7450
7500
0
25
50
75
Porosity(%)
0
500
1000
1500
2000
S-wave(us/ft)
Legend
Zone_5
Zone_6
Zone_7
Zone_8

f)



g)

Figures 27a - g: Porosity vs Vs plot for TMB_4 (Cross section)

Table 6: Representation of the various litho-facies, colour, Vs and Porosity ranges

FACIES NUMBER	GIVEN ACRONYM	LITHO-NAME	COLOUR ON PLOT	VS RANGE (FT/S)	POROSITY RANGE (%)
1	EL1	SAND	BROWN	520 – 1750	20 - 43
2	EL2	SHALY SAND	PURPLE	100 – 575	17 – 89
3	EL3	SHALE	BLUE	125 – 450	8.0 – 38
4	EL4	CLEAN SAND	YELLOW	25 – 200	38 - 73

F) WATER SATURATION versus POROSITY

For this petrophysical plot, three log-facies coded as EL1, EL2 and EL3 were obtained instead of four as was the case with the petrophysiacal versus elastic property plot.

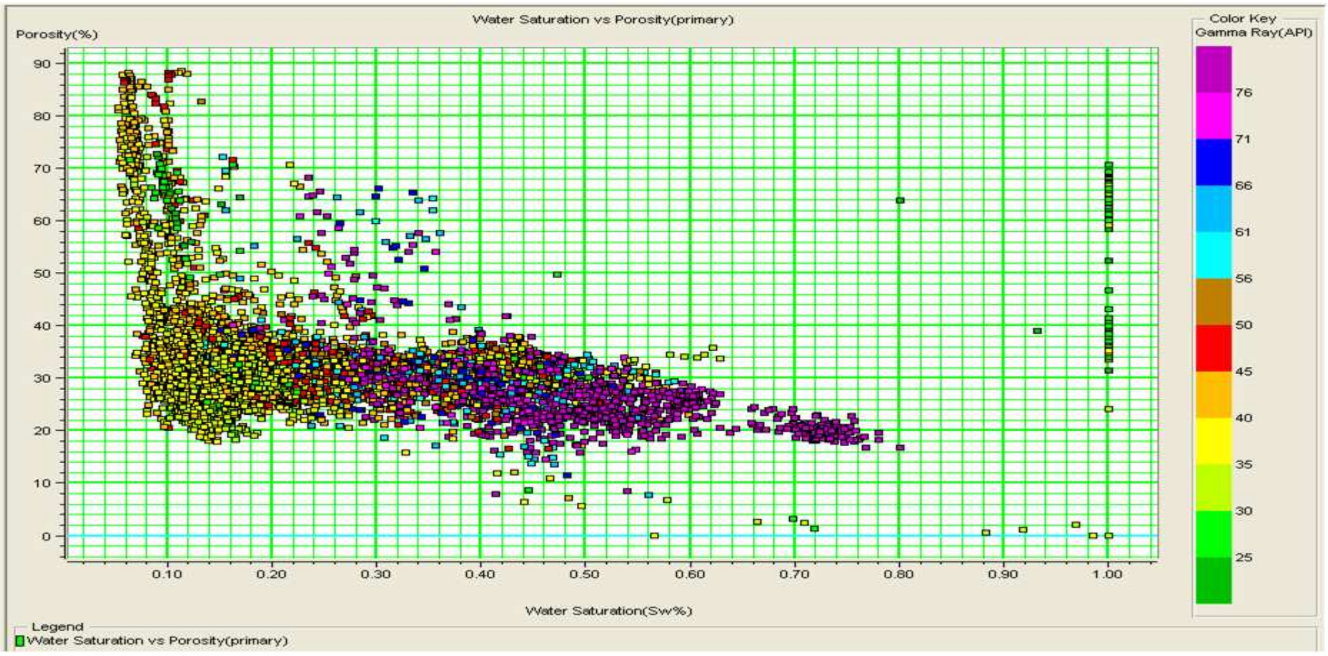


Figure 28a: Sw versus Porosity cross plot for TMB_4 colour coded by GR (before zoning)

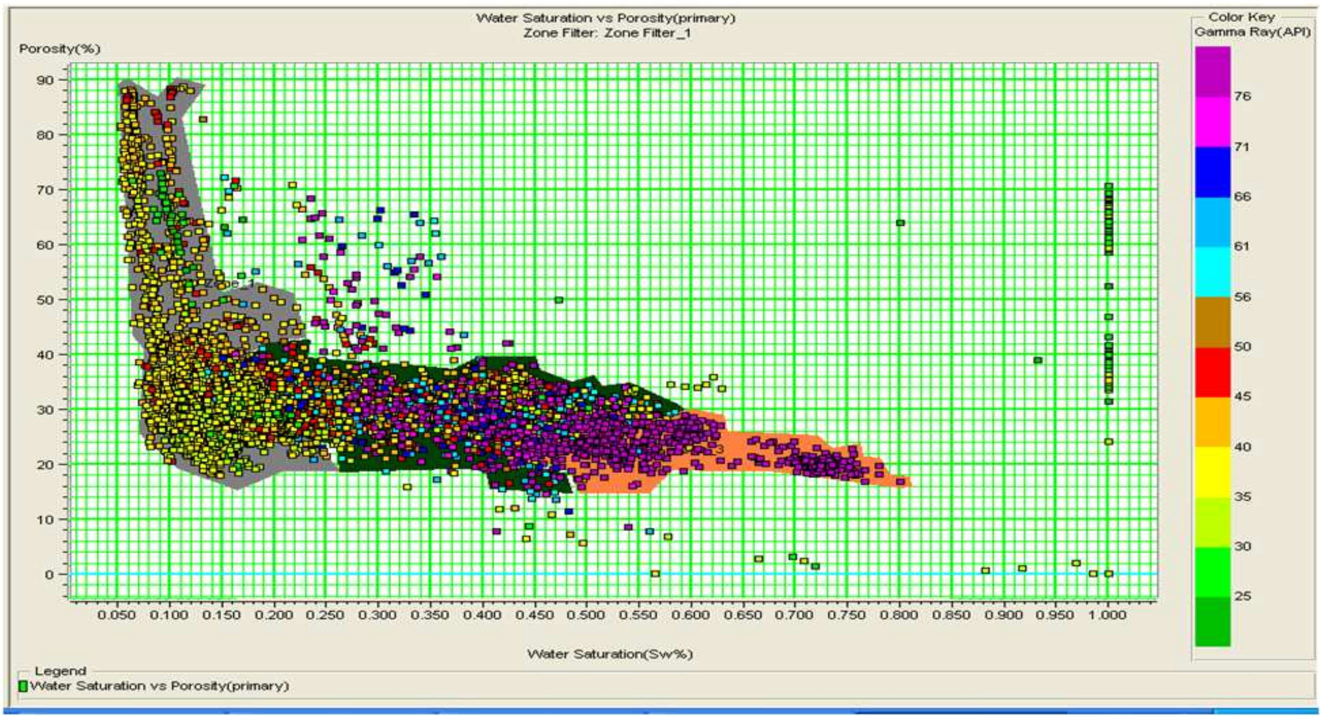
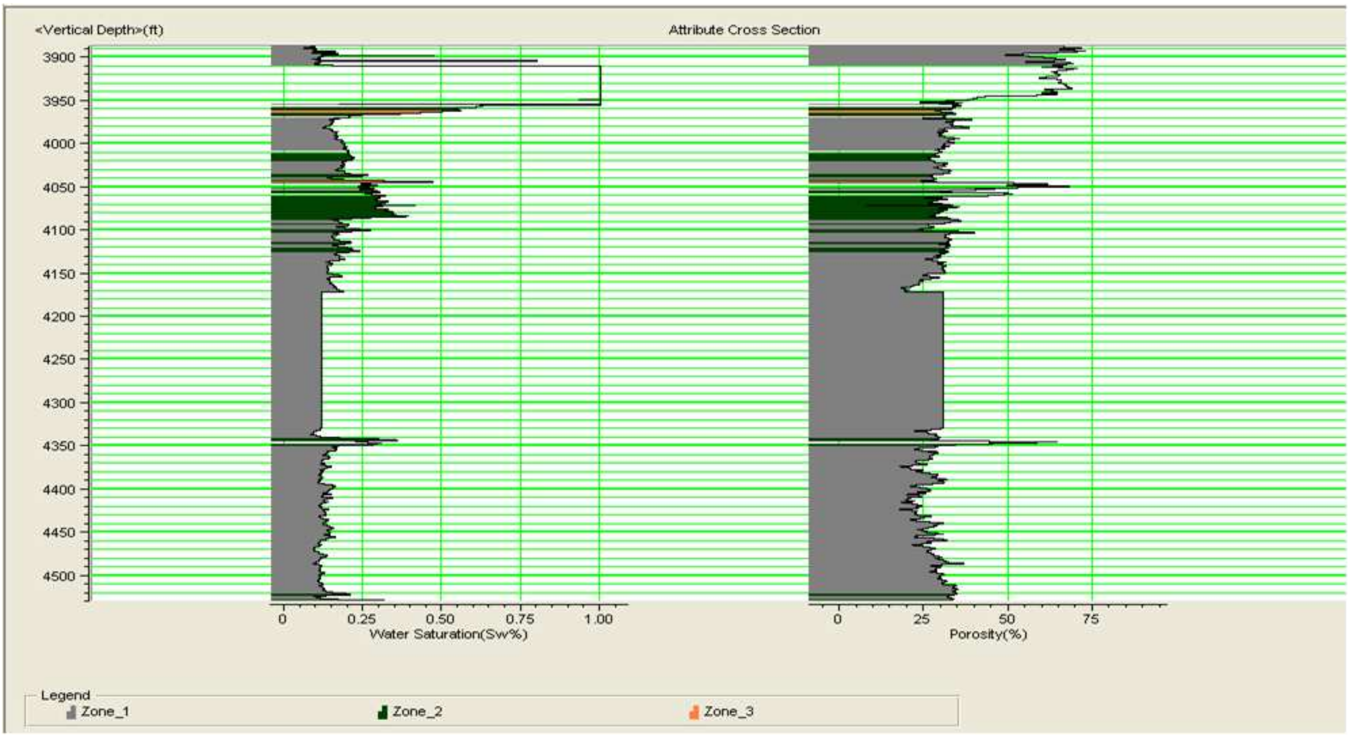
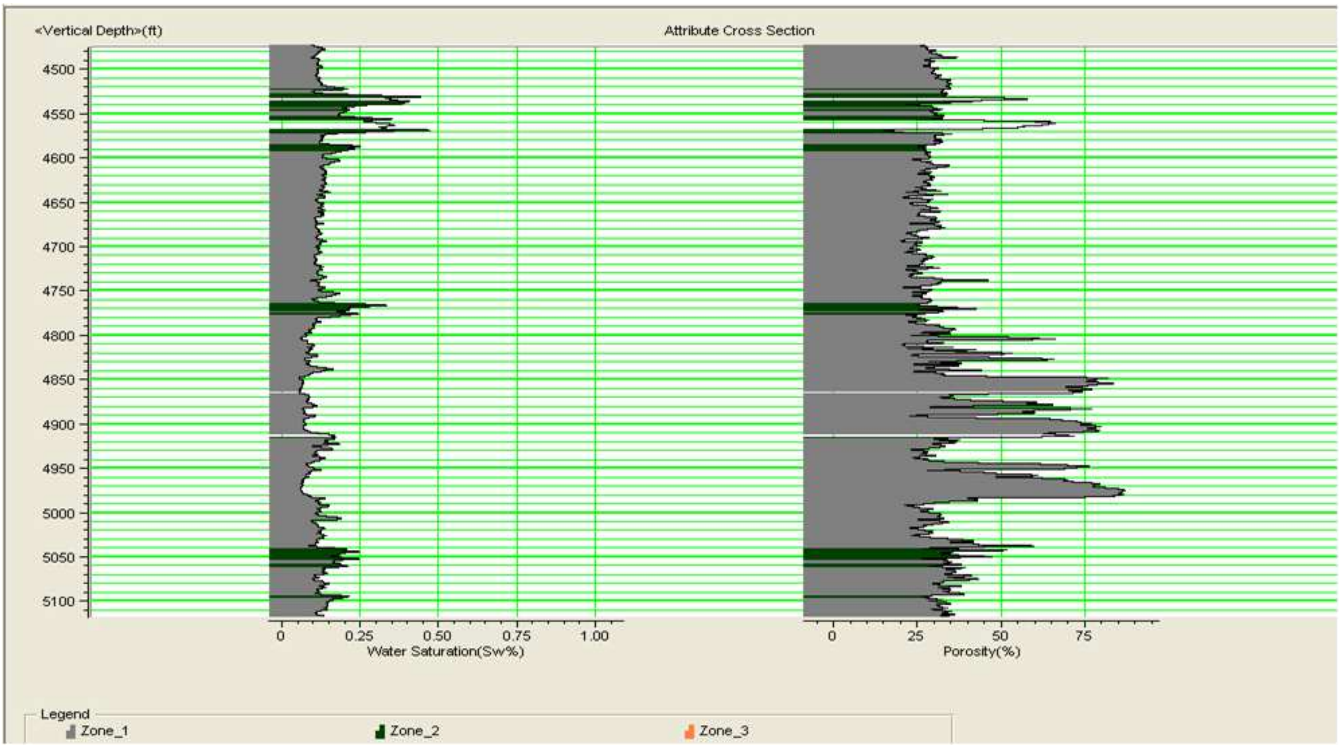


Figure 28b: Sw versus Porosity cross plot for TMB_4 colour coded by GR (after zoning)

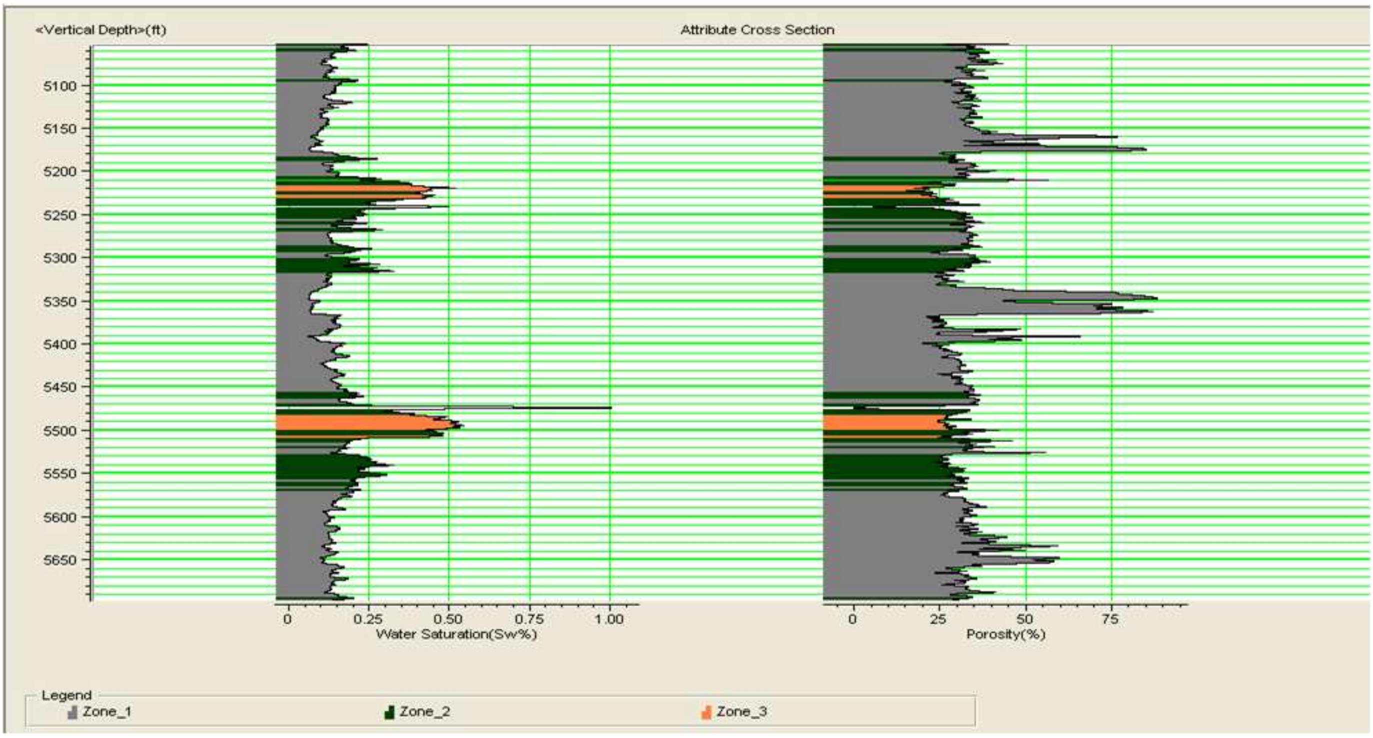
CROSS SECTION



a)

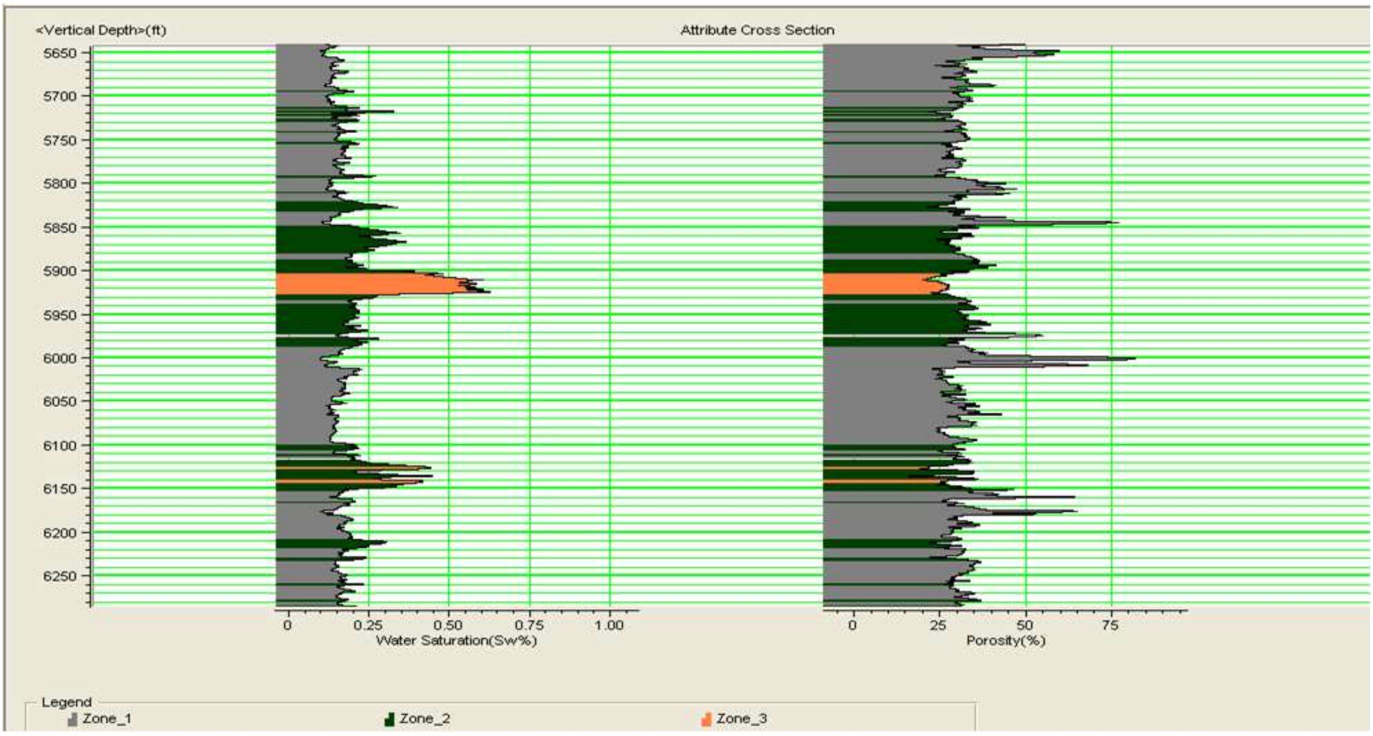


b)



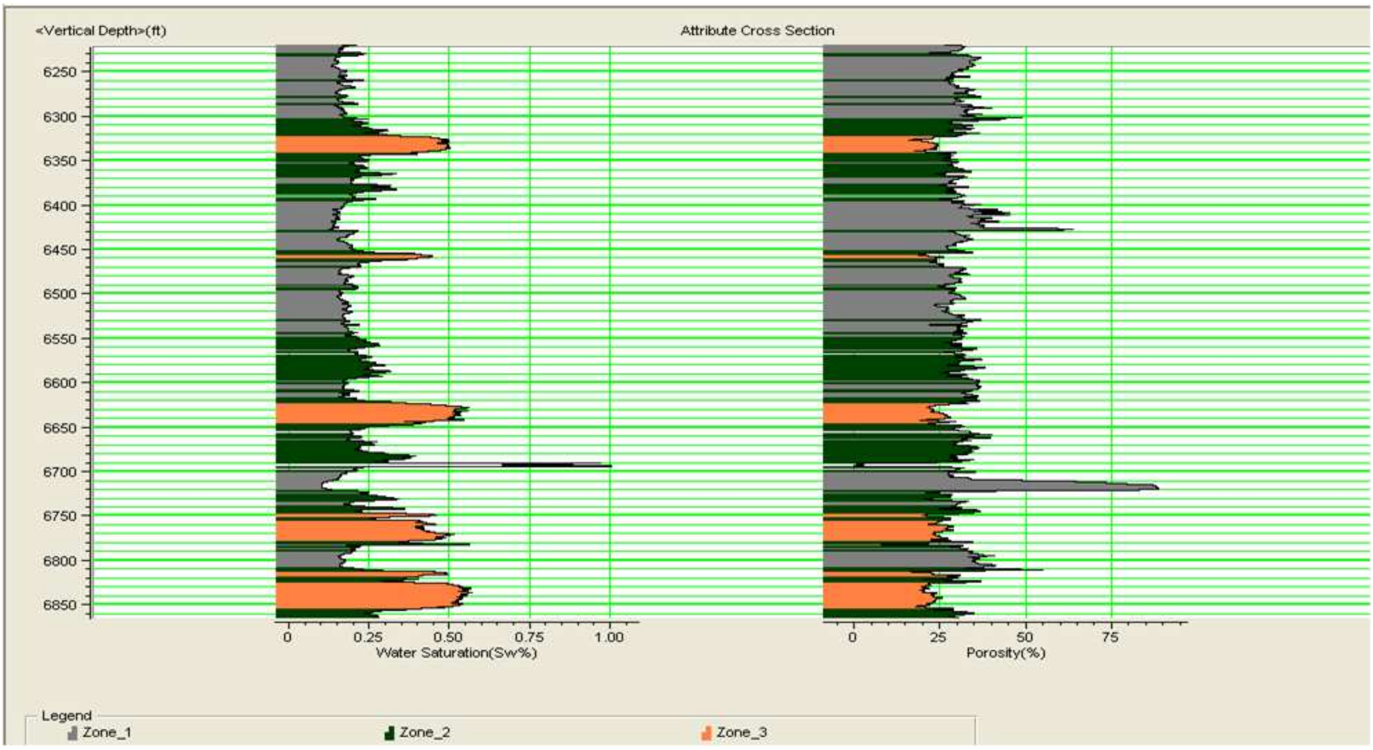
<Vertical Depth>(ft)
Attribute Cross Section
5100
5150
5200
5250
5300
5350
5400
5450
5500
5550
5600
5650
0 0.25 0.50 0.75 1.00
Water Saturation(Sw%)
0 25 50 75
Porosity(%)
Legend
Zone_1
Zone_2
Zone_3

c)



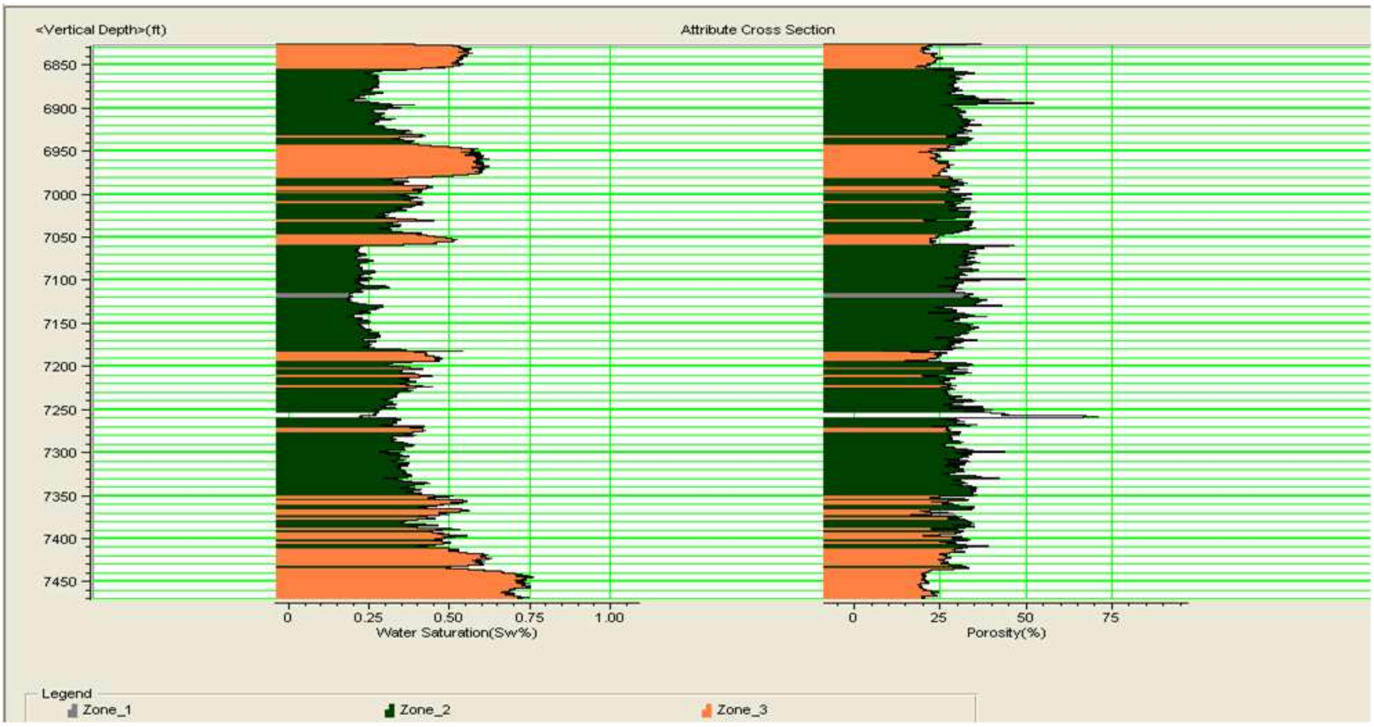
<Vertical Depth>(ft)
Attribute Cross Section
5650
5700
5750
5800
5850
5900
5950
6000
6050
6100
6150
6200
6250
0 0.25 0.50 0.75 1.00
Water Saturation(Sw%)
0 25 50 75
Porosity(%)
Legend
Zone_1
Zone_2
Zone_3

d)



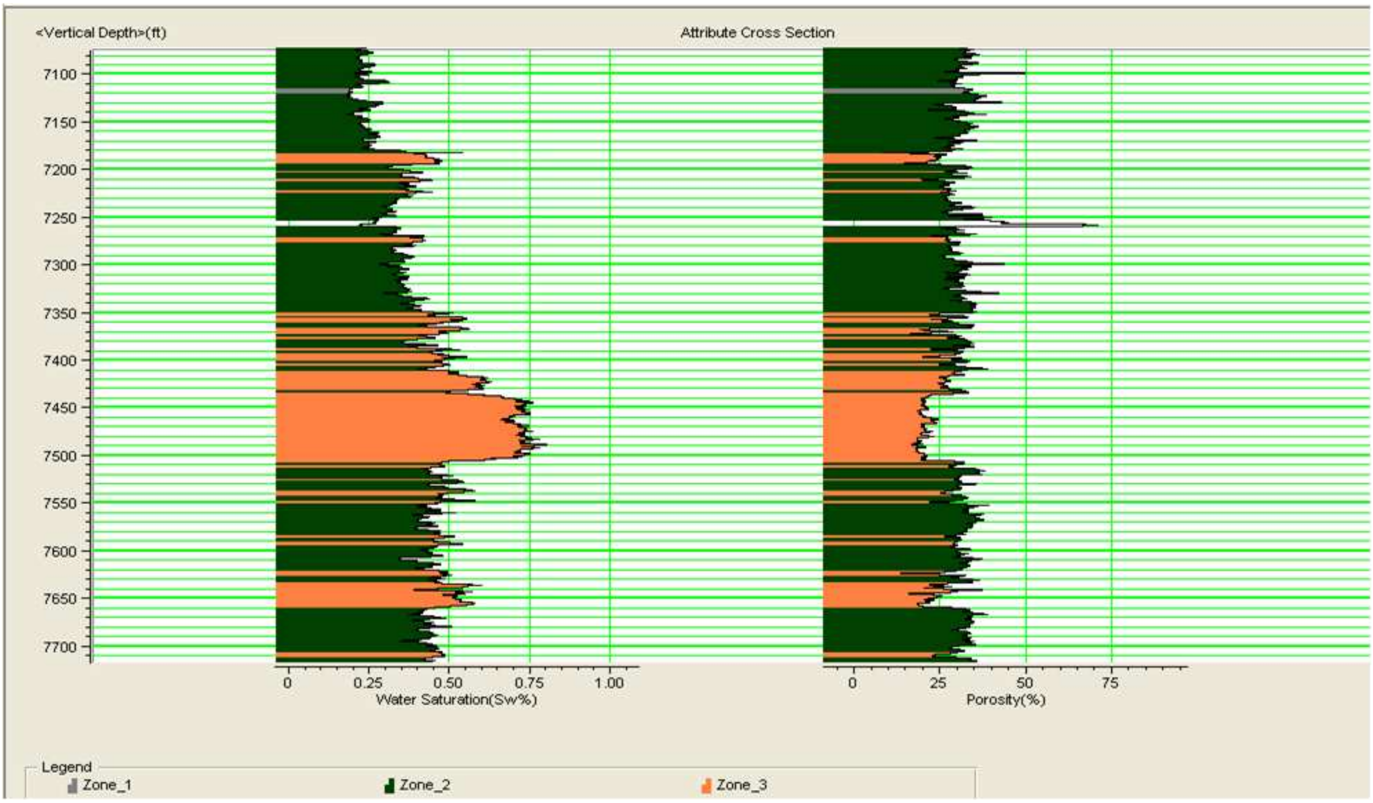
<Vertical Depth>(ft)
Attribute Cross Section
6250
6300
6350
6400
6450
6500
6550
6600
6650
6700
6750
6800
6850
0
0.25
0.50
0.75
1.00
Water Saturation(Sw%)
0
25
50
75
Porosity(%)
Legend
Zone_1
Zone_2
Zone_3

e)



<Vertical Depth>(ft)
Attribute Cross Section
6850
6900
6950
7000
7050
7100
7150
7200
7250
7300
7350
7400
7450
0
0.25
0.50
0.75
1.00
Water Saturation(Sw%)
0
25
50
75
Porosity(%)
Legend
Zone_1
Zone_2
Zone_3

f)



g)

Figures 29a - g: Sw vs Porosity plot for TMB_4 (Cross section)

Table 7: Representation of the various litho-facies, colour, Sw and Porosity ranges

FACIES NUMBER	GIVEN ACRONYM	LITHO-NAME	COLOUR ON PLOT	SW RANGE (%)	POROSITY RANGE (%)
1	EL1	SAND	GREY	5.0 – 26	18 - 88
2	EL2	SHALY SAND	DEEP GREEN	20 – 58	14 - 40
3	EL3	SHALE	BROWN	40 – 80	14 –26

4.1.2 RESULTS FOR TMB_1 (WELL 2)

The results for TMB_1 to be presented are the cross plots for Sw vs Vp and that for Sw vs Porosity. Furthermore, three log-facies were realized from these plots and these included sand, shaly-sand and shale and were coded as CL1, CL2 and CL3 respectively.

A) WATER SATURATION versus P-WAVE

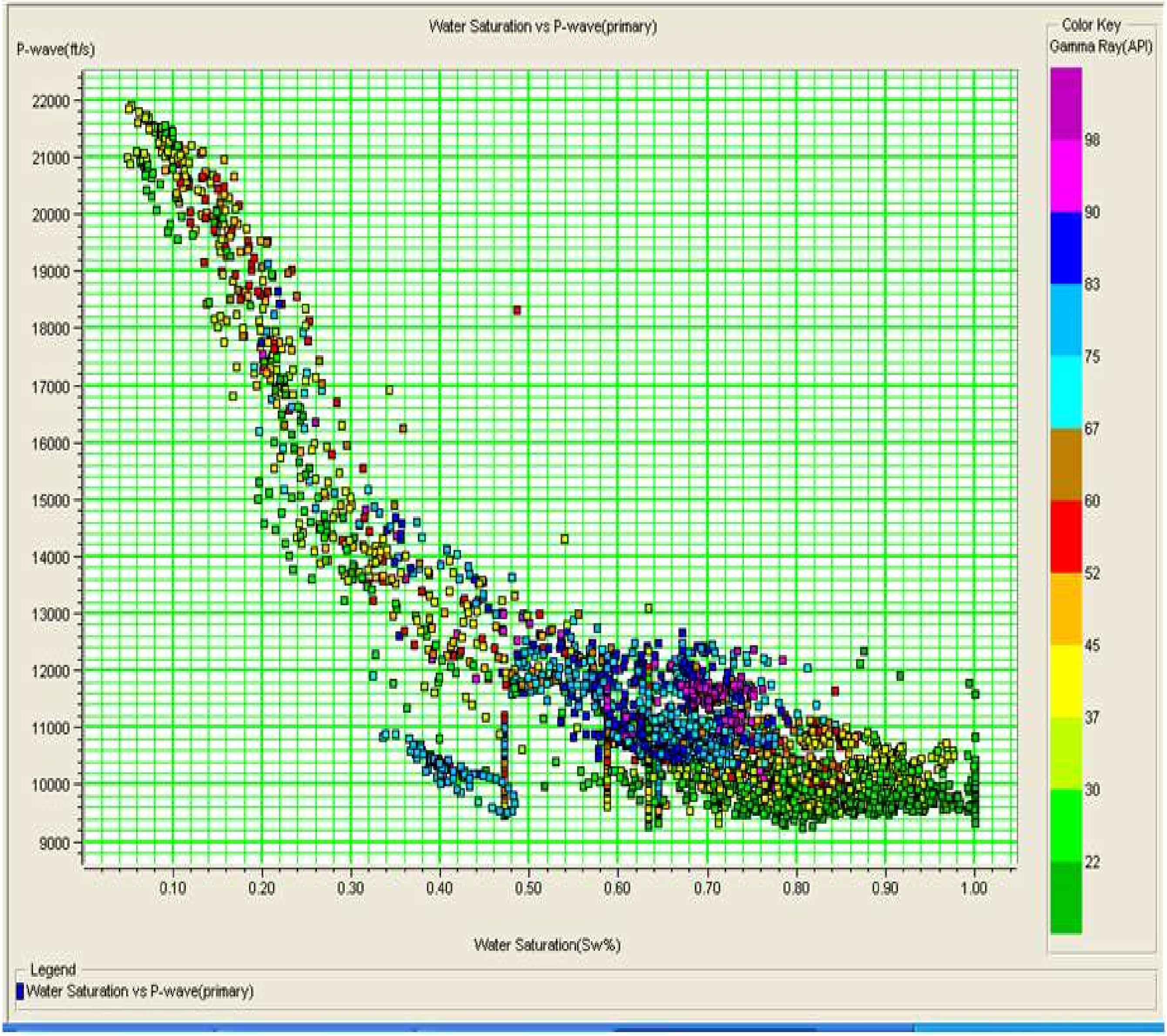


Figure 30a: Sw versus Vp cross plot for TMB_1 colour coded by GR (before zoning)

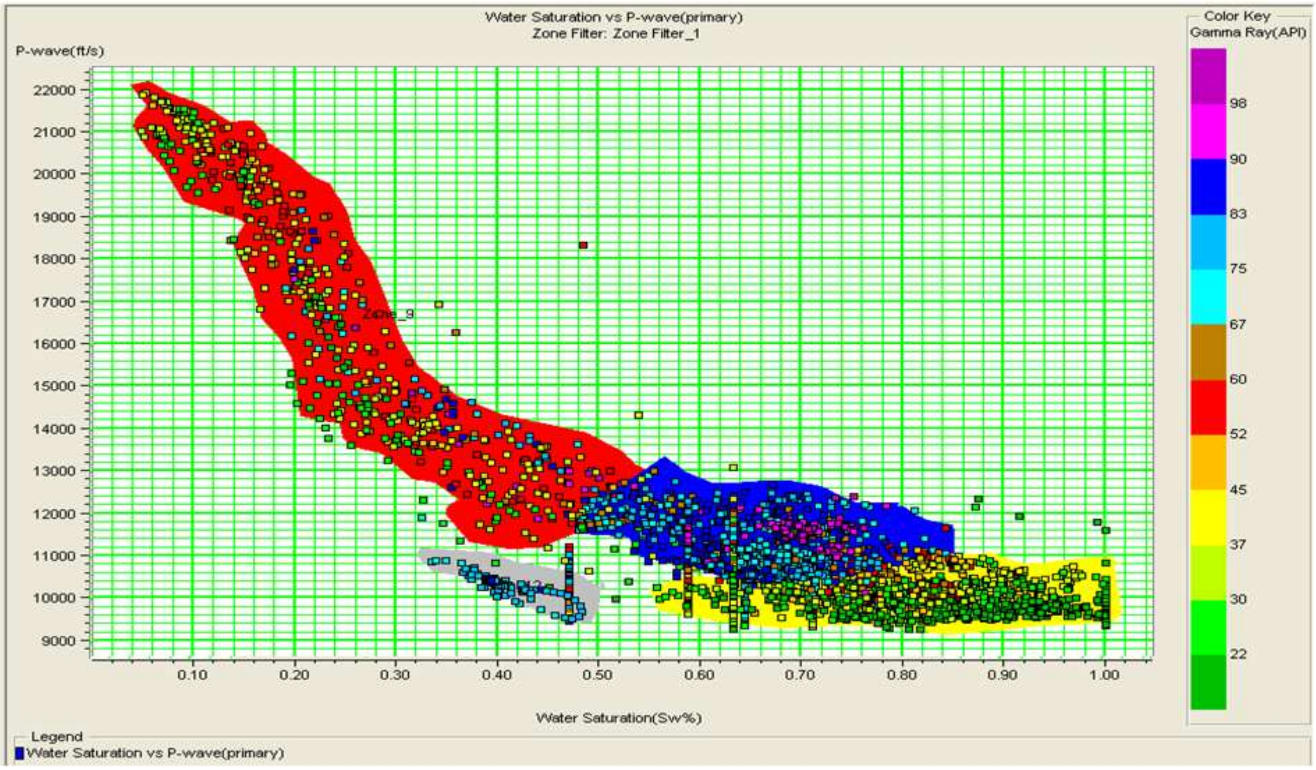
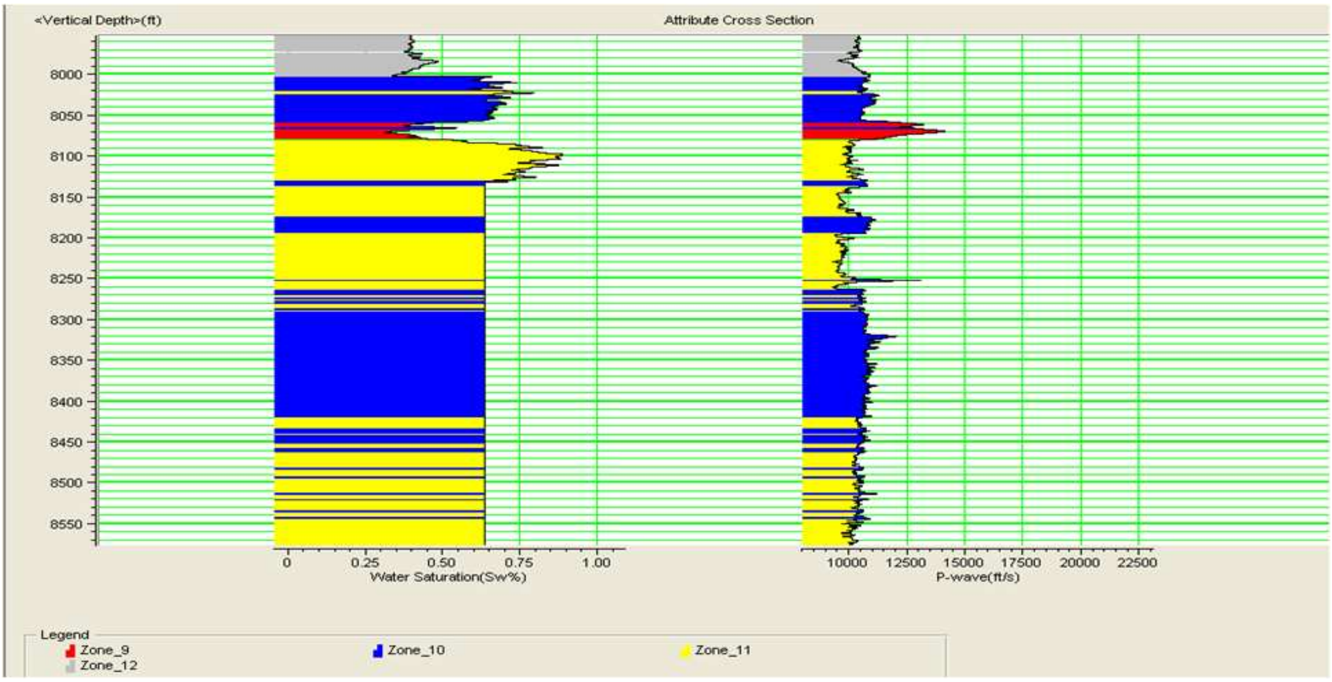
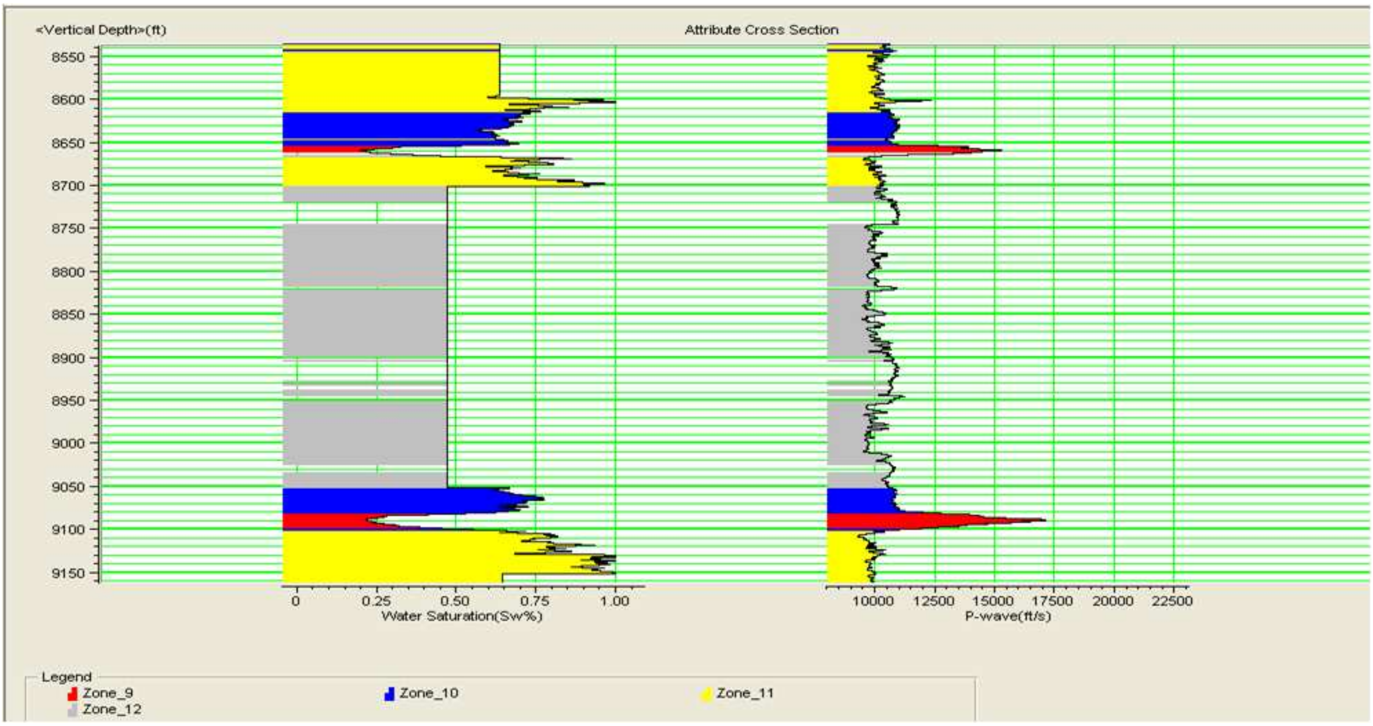


Figure 30b: Sw versus Vp cross plot for TMB_1 colour coded by GR (after zoning)

CROSS SECTION

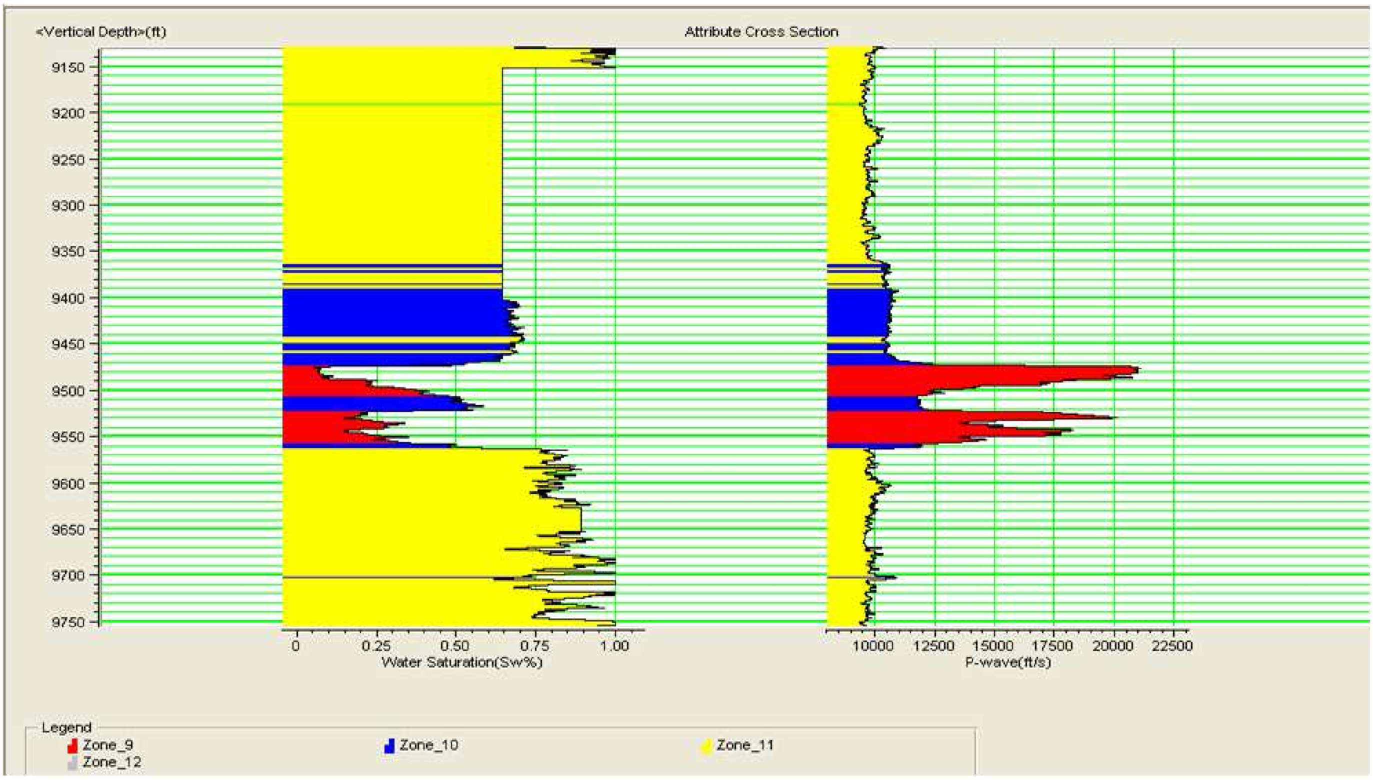


a)



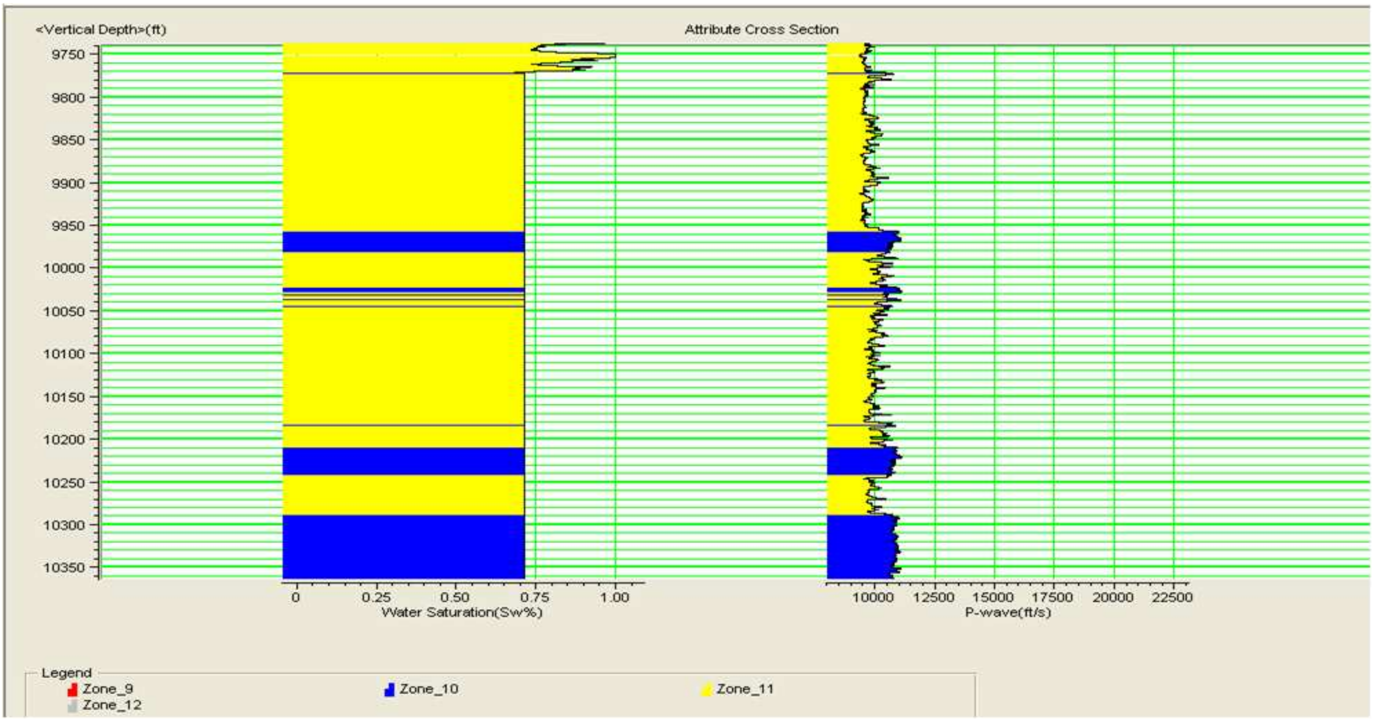
<Vertical Depth>(ft)
Attribute Cross Section
8550
8600
8650
8700
8750
8800
8850
8900
8950
9000
9050
9100
9150
0 0.25 0.50 0.75 1.00
Water Saturation(Sw%)
10000 12500 15000 17500 20000 22500
P-wave(ft/s)
Legend
Zone_9
Zone_10
Zone_11
Zone_12

b)

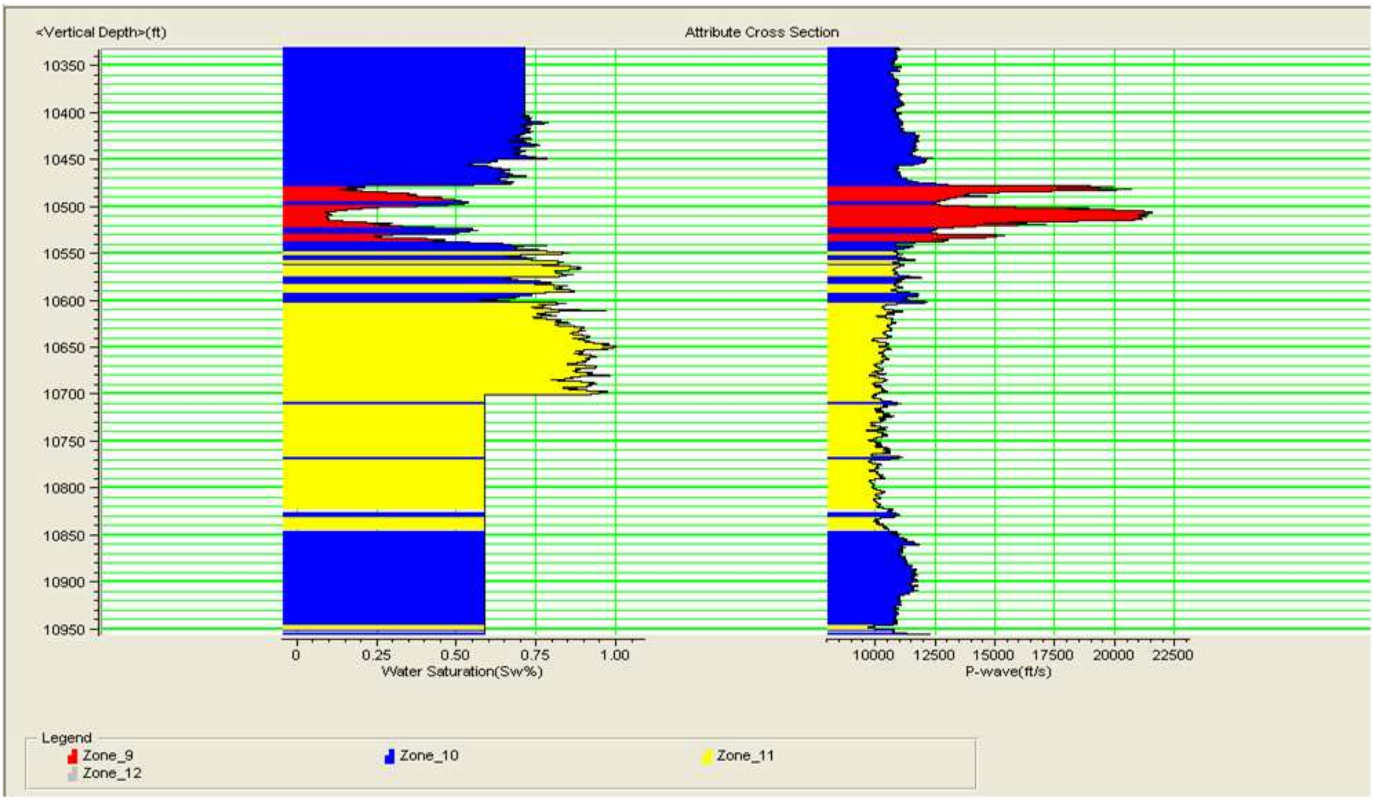


<Vertical Depth>(ft)
Attribute Cross Section
9150
9200
9250
9300
9350
9400
9450
9500
9550
9600
9650
9700
9750
0 0.25 0.50 0.75 1.00
Water Saturation(Sw%)
10000 12500 15000 17500 20000 22500
P-wave(ft/s)
Legend
Zone_9
Zone_10
Zone_11
Zone_12

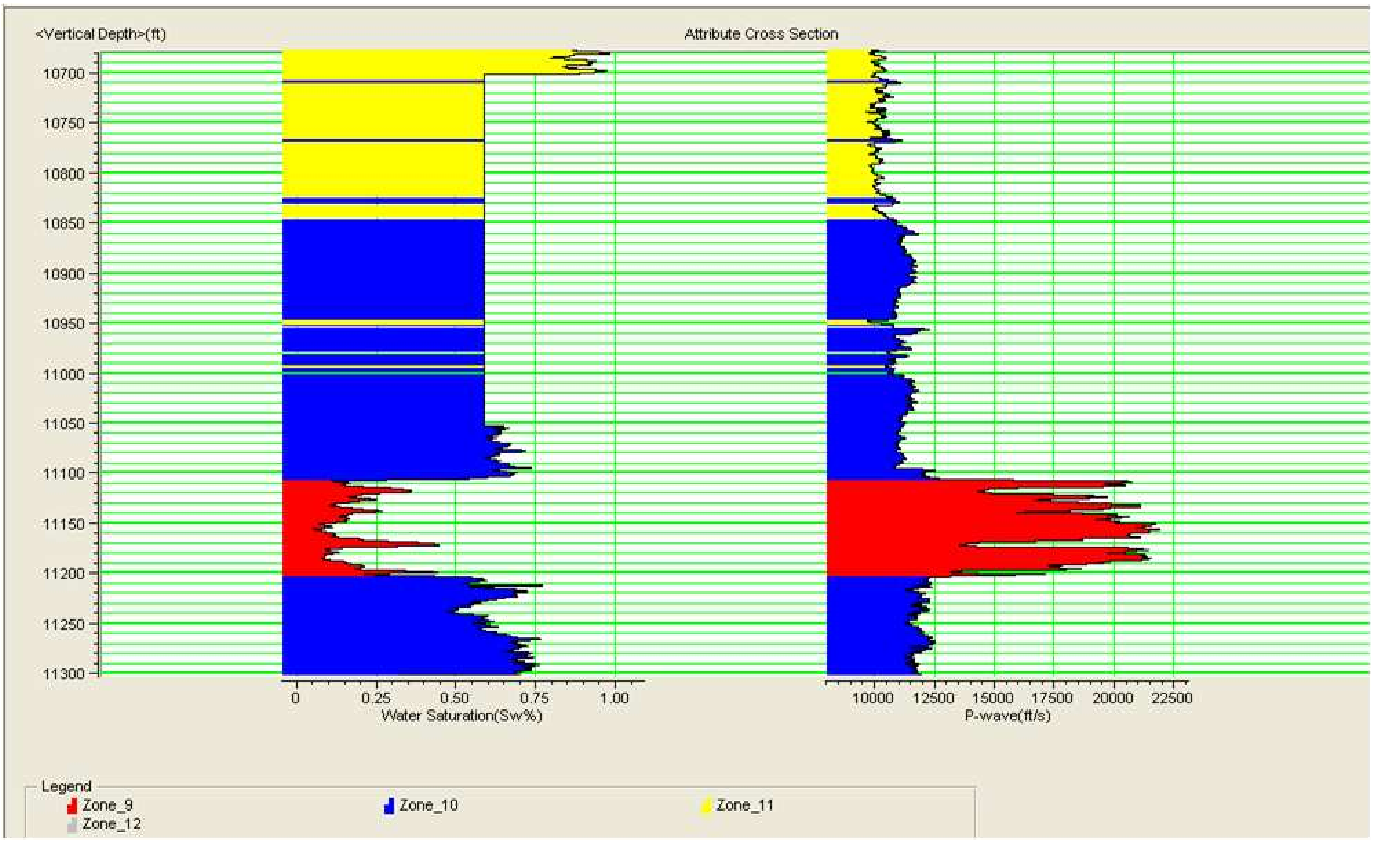
c)


Attribute Cross Section
<Vertical Depth>(ft)
Water Saturation(Sw%)
P-wave(ft/s)
Legend
Zone_9
Zone_10
Zone_11
Zone_12

d)


Attribute Cross Section
<Vertical Depth>(ft)
Water Saturation(Sw%)
P-wave(ft/s)
Legend
Zone_9
Zone_10
Zone_11
Zone_12

e)



f)

Figures 31a - f: Sw vs Vp plot for TMB_1 (Cross section)

Table 8: Representation of the various litho-facies, colour, Vp and Sw ranges

FACIES NUMBER	GIVEN ACRONYM	LITHO-NAME	COLOUR ON PLOT	VP RANGE (FT/S)	SW RANGE (%)
1	CL1	SAND	YELLOW	9200 –11000	56 - 100
2	CL2	SHALY SAND	RED	11200 –22000	5.0 - 49
3	CL3	SHALE	BLUE	10400 –13000	55 – 84

B) WATER SATURATION versus POROSITY

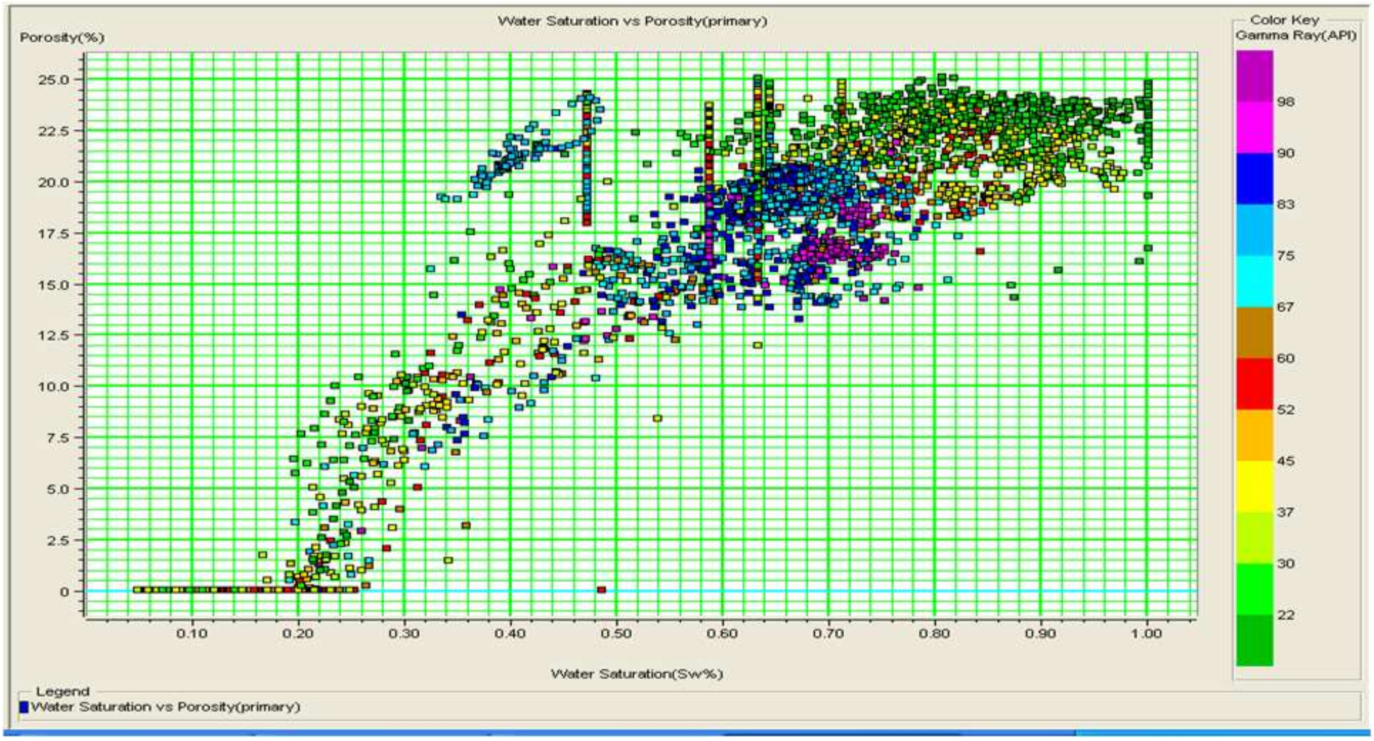


Figure 32a: Sw versus Porosity cross plot for TMB_1 colour coded by GR (before zoning)

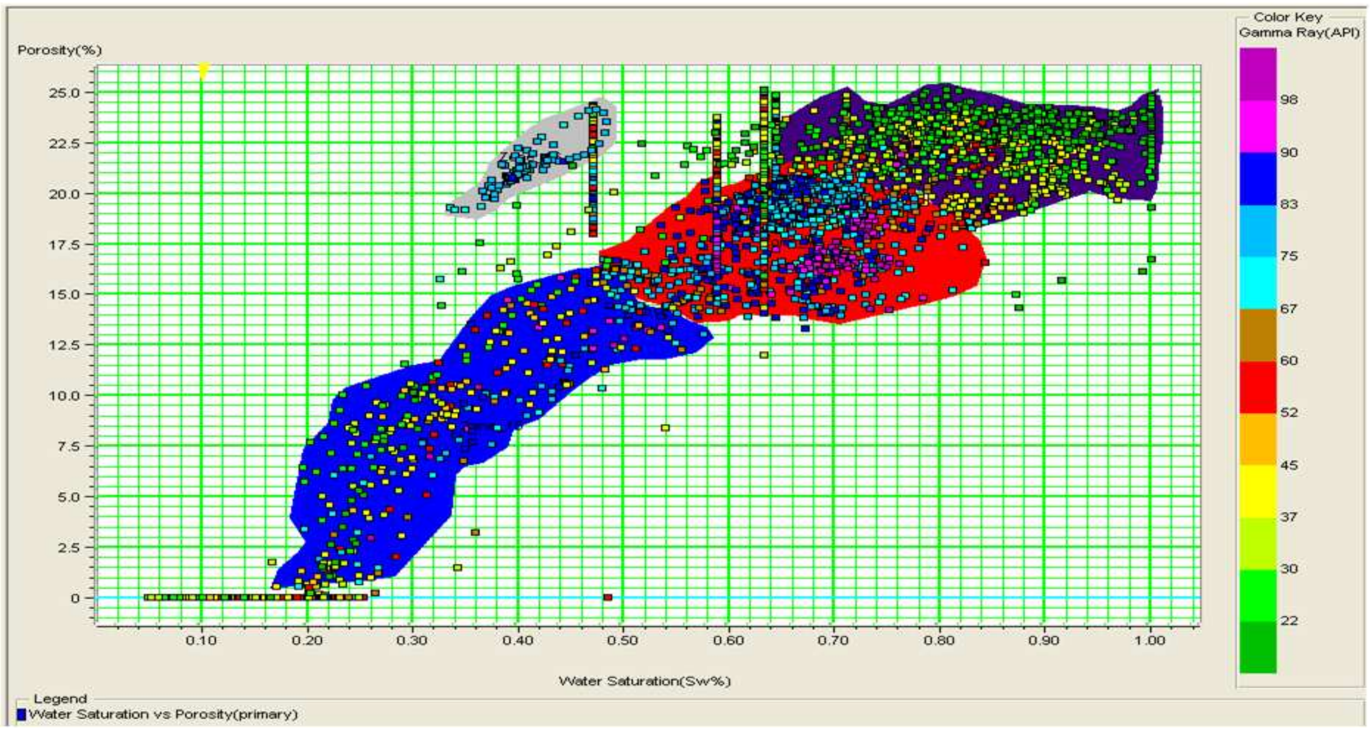
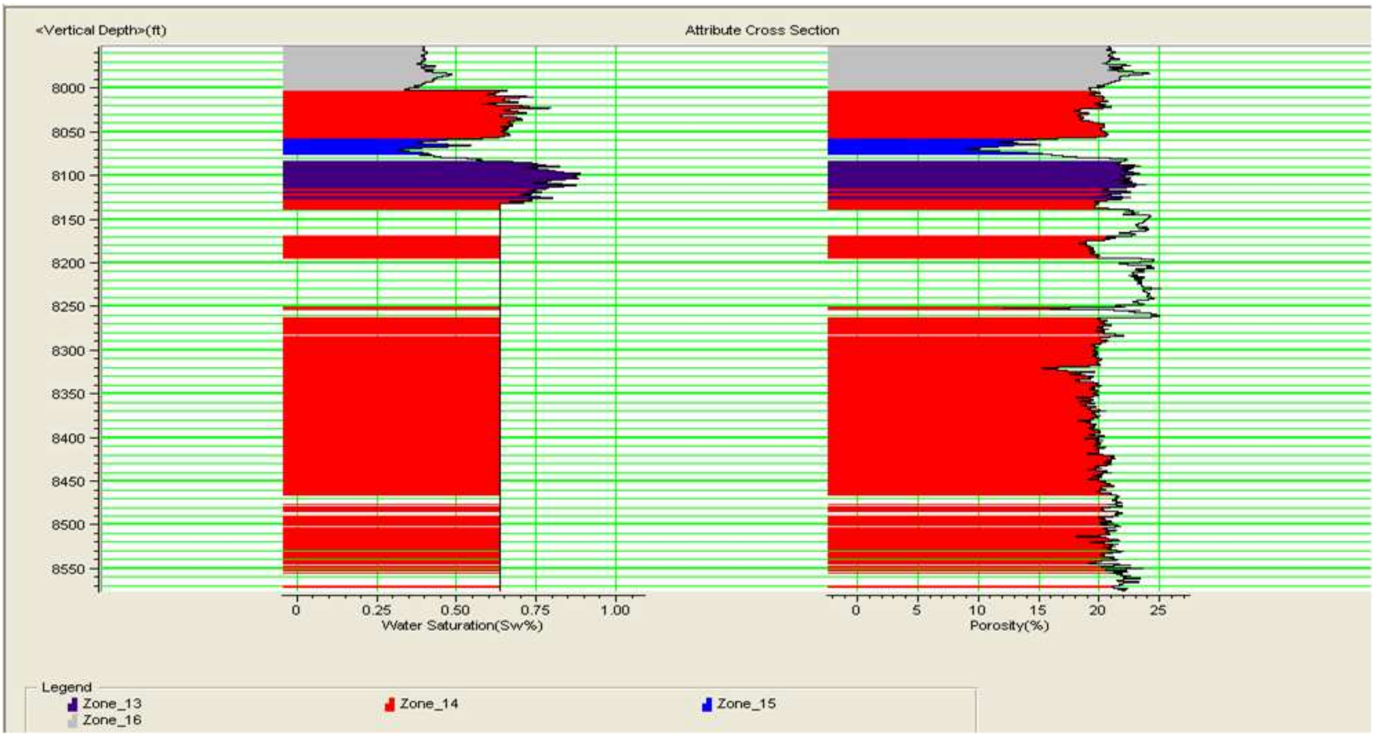
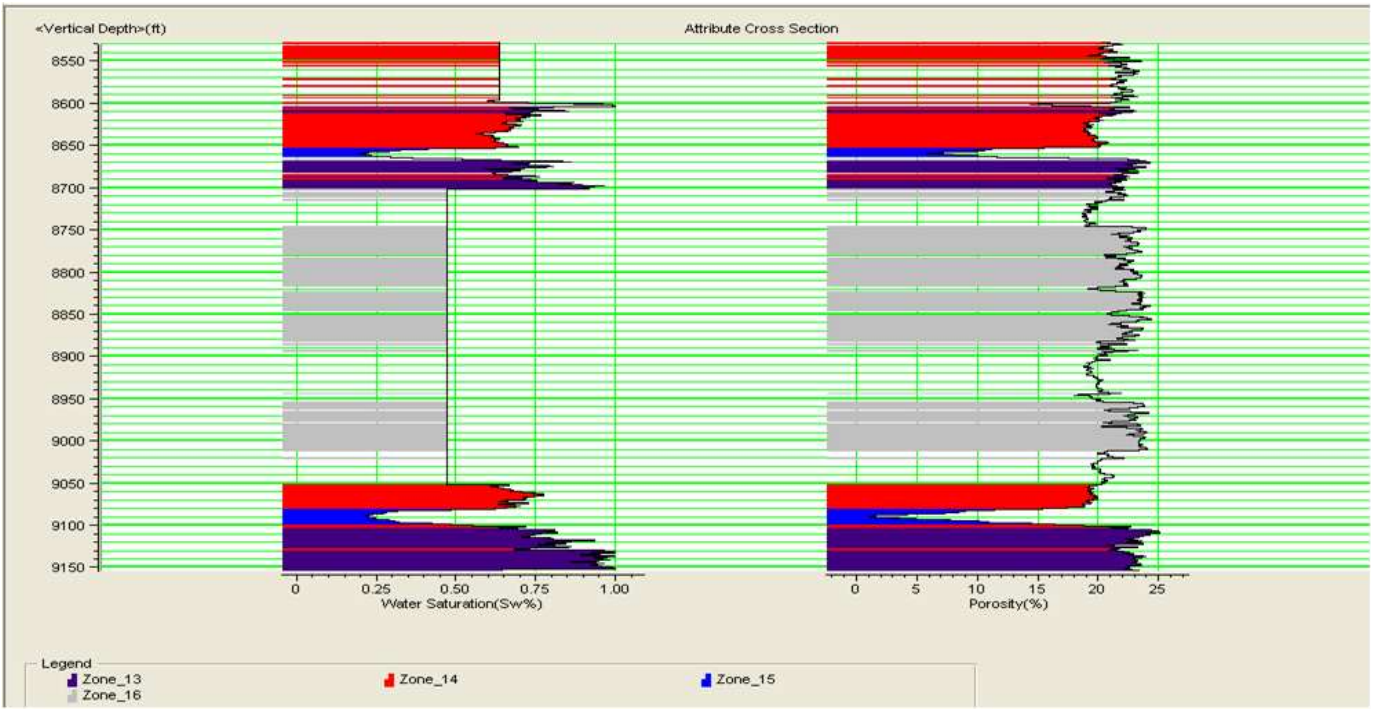


Figure 32b: Sw versus Porosity cross plot for TMB_1 colour coded by GR (after zoning)

CROSS SECTION



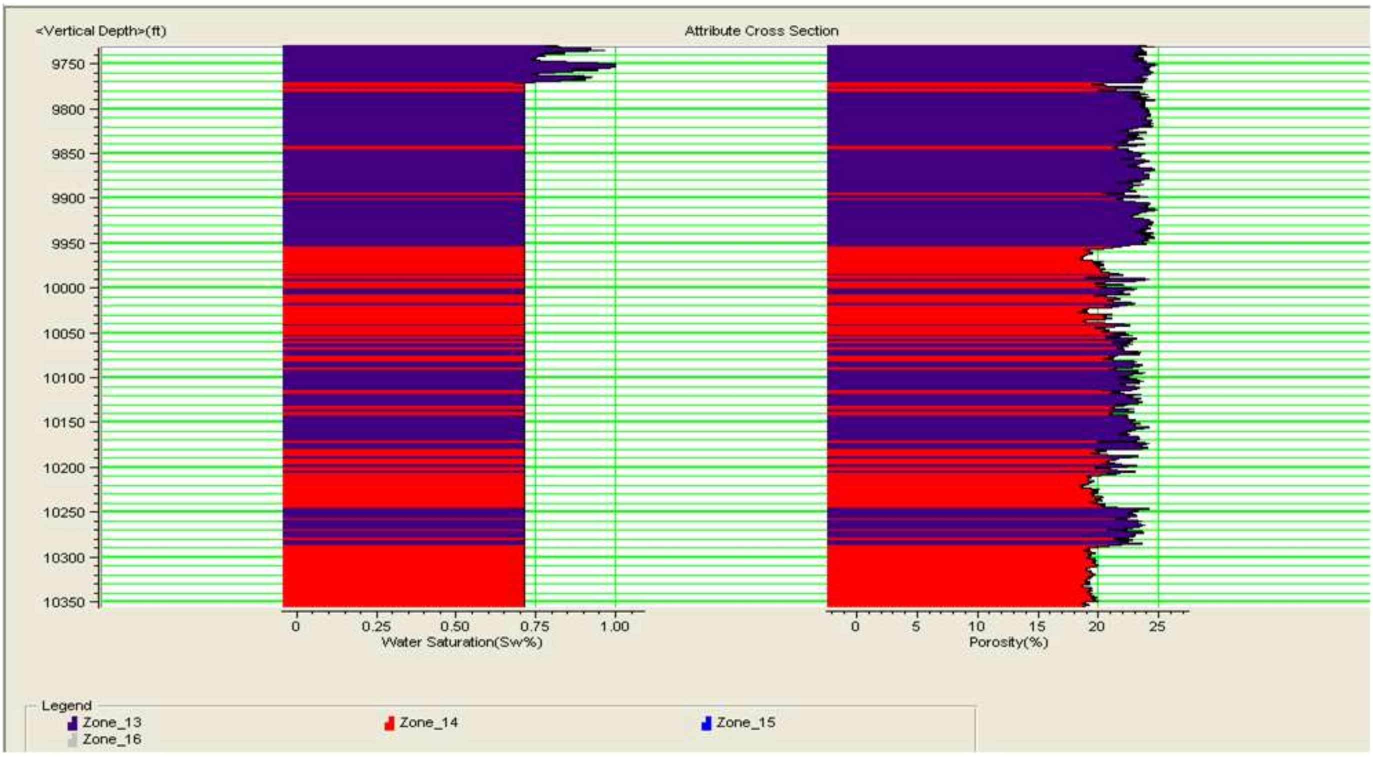
a)



b)

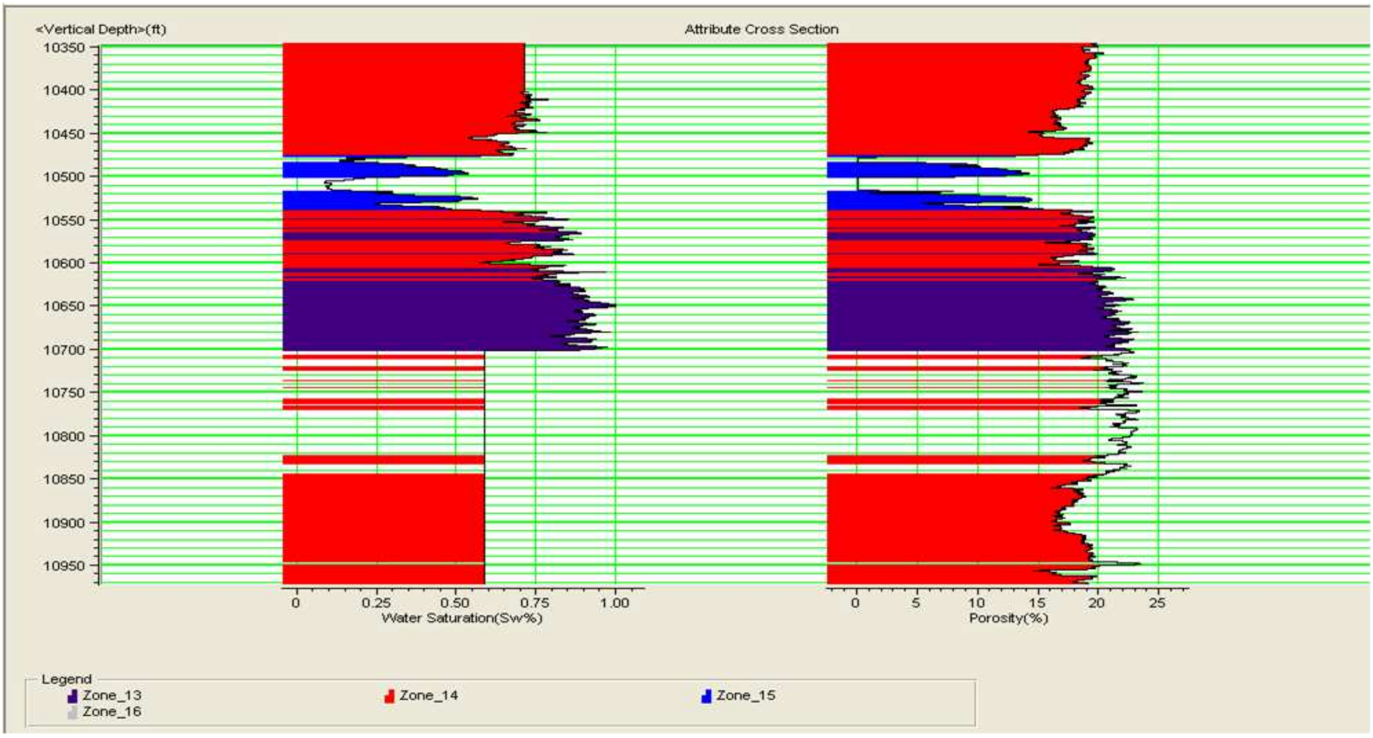
<Vertical Depth>(ft)
Attribute Cross Section
9150
9200
9250
9300
9350
9400
9450
9500
9550
9600
9650
9700
9750
0 0.25 0.50 0.75 1.00
Water Saturation(Sw%)
0 5 10 15 20 25
Porosity(%)
Legend
Zone_13
Zone_14
Zone_15
Zone_16

c)

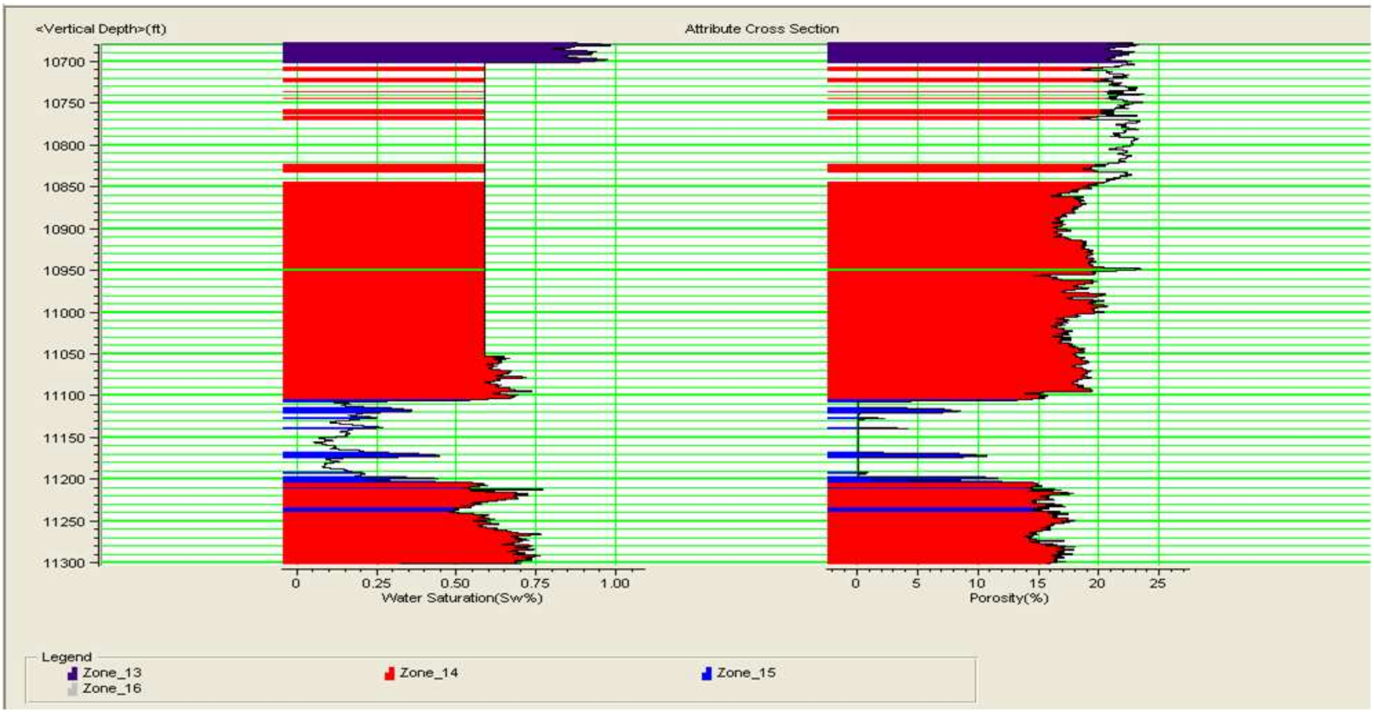


<Vertical Depth>(ft)
Attribute Cross Section
9750
9800
9850
9900
9950
10000
10050
10100
10150
10200
10250
10300
10350
0 0.25 0.50 0.75 1.00
Water Saturation(Sw%)
0 5 10 15 20 25
Porosity(%)
Legend
Zone_13
Zone_14
Zone_15
Zone_16

d)



e)



f)

Figures 33a - f: Sw vs Porosity plot for TMB_1 (Cross section)

Table 9: Representation of the various litho-facies, colour, Sw and Porosity ranges

FACIES NUMBER	GIVEN ACRONYM	LITHO-NAME	COLOUR ON PLOT	SW RANGE (%)	POROSITY RANGE (%)
1	CL1	SAND	PURPLE	64 – 100	18.5 - 25.5
2	CL2	SHALY SAND	BLUE	17 – 56	0.5 – 16.5
3	CL3	SHALE	RED	48 – 84	13.5 – 21

4.2 INTERPRETATION

The interpretation will be patterned according to how the results were presented. In this light therefore, geological, petrophysical and engineering meaning will be carved out of the numerous cross plots previously presented in the results section starting with those of TMB_4 down to TMB-1.

4.2.1 INTERPRETATION OF RESULTS FOR TMB_4 (WELL 1)

Here, the behavior of the different parameters plotted and their resultant contribution to log-facies classification is examined.

The porosity versus Vp/Vs ratio curve gives a scattered plot whose points are colour coded by GR log to clearly differentiate the various litho-types. Therefore, where data points are in cluster and of particular or multiple colors, log-facies can be classified from their zoning. From the plot, four log-facies (EL1, EL2, EL3 and EL4) were inferred based on the general lithology from the GR log. As backed by literature (Rojas E., 2005; Guliyev, G., 2007 and Sukitprapanon P., 2008), a low Vp/Vs value (mostly within the range of 1.6 – 2.0) corresponds to clean sand (absence of shale) which could be gas- saturated and it is the case for this plot. This is because gas is less dense, hence reduces the P-wave velocity significantly when it comes in contact with it, in effect, if Vp reduces, the Vp/Vs ratio also reduces, supported by the fact that Vs does not travel through fluids. This in a way detects the presence of hydrocarbons which when matched with the Neutron porosity log tracts with depth can tell the types of hydrocarbons present. So, from the plot, the facies EL4 zoned with yellow colour has the lowest Vp/Vs ratio and therefore classified as clean sands with a high porosity value of 70% at a depth of 3890ft. Also, the low ratio is an indicator of the other types of hydrocarbons saturated in the sands other than gas. Furthermore, very low Vp/Vs values of <1.5 are also indicators of overpressure zones. This is because high porosities within rock units in a formation means small rock matrix and as a result cannot support the overburden. In such a case, the fluids present will tend to support part of the overburden, resulting to higher-than normal fluid pressure (hence, general increase pressure within the formation), and since fluids impede or reduce the P-wave velocity and S-waves don't pass through them at all, the Vp/Vs value(s) will be very low because of the combined effect of porosity and fluids on the Vp and Vs.

It should be re-iterated that the presence of fluids reduces the Vp/Vs ratio. On the other hand, the EL2 log-facies (shaly-sand) has a highest porosity of 88% corresponding to a Vp/Vs ratio ranging from 2.0 – 3.6 and a depth of 5350ft. The next facies coloured purple has the highest ratio of all the log-facies which range from 3.6 – 8.8 but with a low porosity range from 20 – 40%. This means that the majority of the rock is made of matrix and explains the high Vp/Vs ratio since rocks with high matrix concentration show greater P-waves velocity through them. To this effect, the log-facies was classified as EL1 log-facies with litho-name sand. The last facies is the EL3 facies (shale) is classified based on its relatively high Vp/Vs ratio of up to 3.2. This value is low compared to sands because of the high porosity range (10 - 39). This log-facies is zoned blue on the plot. A carefully observed break in the facies interval within the attribute cross section is due to missing information at those depths. These depth ranges include: 4040 – 4060ft, 4530 – 4540ft, 4560 – 4570ft, 4790 – 4830ft, 4850 – 4870ft, 4890 – 4910ft, 4950 – 4980ft, 5470 – 5480ft, 7610 – 7620ft.

For the Sw versus Vp/Vs, four log-facies (EL1, EL2, EL3 and EL4) and their classification according to the parameters plotted were obtained. As opposed to the porosity versus Vp/Vs plot where the clean sands occur at high porosity values, for the Sw versus Vp/Vs ratio plot the clean sands occur at low Sw values while the case is reversed for shale which occurs at high Sw and low porosity values, meaning they are more saturated with water. This is followed by shaly-sands, sands and clean sands in that order. All these are summarized in table 5. It is worth noting that for both plots the EL4 facies occurs at low Vp/Vs ratios.

The porosity versus Vp and Sw versus Vp plots are still interpreted the same as was done for the two previous plots. The same four log-facies are observed, classified using the same reasons earlier mentioned i.e at low Vp and high porosity values (for porosity versus Vp curve), EL4 log-facies exist while the same log-facies exist (for Sw versus Vp) at low Sw and Vp values. The low Vp values are as a result of high porosity which limits the matrix of the rock and hence reduces the P-wave velocity as it travels through it. Again the shale shows the highest Sw reading for the Sw versus Vp plot at medium Vp values.

The porosity versus Vs plot gives same results as all the plots involving Vp and Vp/Vs ratio. This is because Vs was derived from Vp by transform using Castagner's equation and is expected that it behaves the same as Vp.

For the Sw versus porosity plot which is termed a petrophysical plot, three log-facies are obtained as opposed to four in the previous plots and these are EL1, EL2 and EL3 all corresponding to sand, shaly-sand and shale respectively.

As inferred from the results, the porosity range decreases while the Sw range increases in that order, meaning the sands have highest range of porosity values and shales the lowest. Two key points to be taken note of from this plot are:

- At high porosity values of between 60 – 75, there exist some evidence of clean sand, but is not clearly separated from the normal sands as was the case with plots involving elastic properties

(Vp/Vs, Vp and Vs). For this reason, it is difficult to clearly single it out as one log-facies and this goes a long way to show why only three facies are obtained from this plot. Therefore, integrating both petrophysical and elastic properties brings out these log-facies clearly (see figs.34 and 35).

- Secondly, the sands are not clearly separated from the shaly-sands as was the case with the petrophysical versus elastic property plots. This again limits the demarcation of each log-facies from the other, hence supporting the fact that integrating both petrophysical and elastic properties improves the classification of the log-facies.

In conclusion, the results from TMB-4 bring out clearly the aim of this work which was to optimize and improve log-facies classification by integrating both petrophysical and elastic properties. This differentiates it from the conventional classification which is only based on examination of petrophysical properties, and the improvement is what makes this work unique.

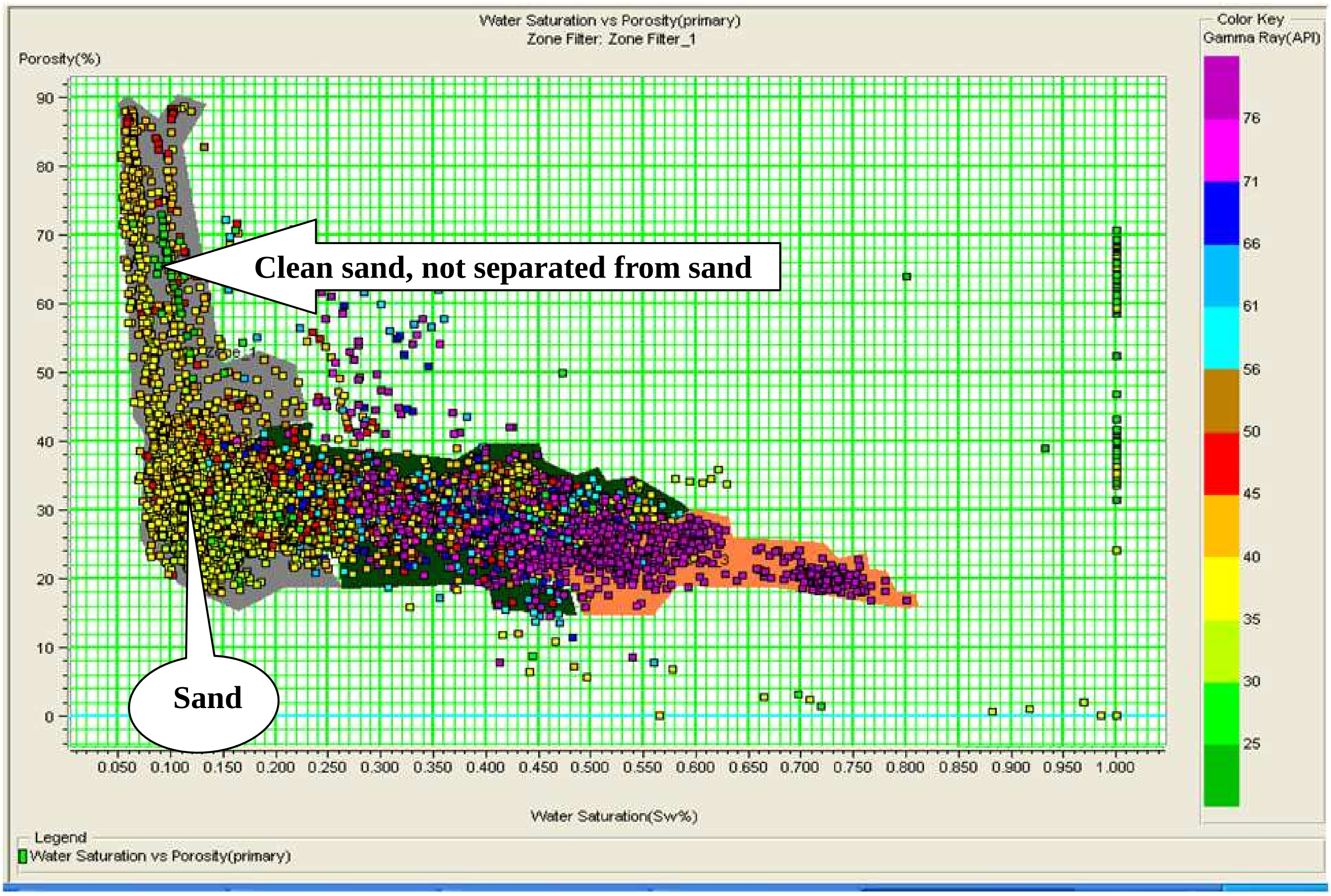


Figure 34: Petrophysical plot (Sw vs Porosity) with no clear-clean sand distinction from the sands.

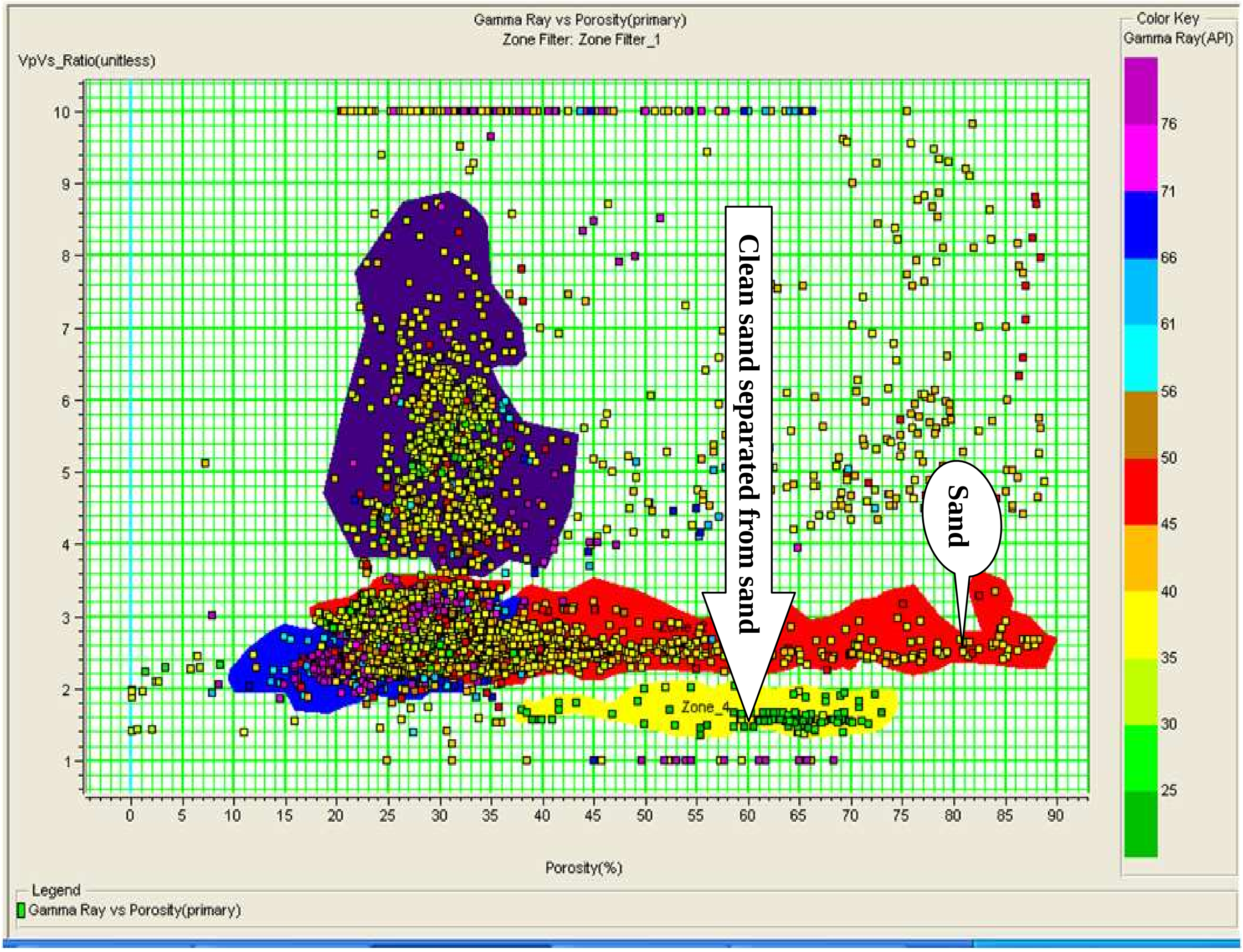


Figure 35: Petrophysical vs elastic property plot showing clear-clean sand separation from sands.

4.2.2 Interpretation of Results for TMB_1 (Well 2)

From the Sw versus Vp plot, three log-facies were obtained which included CL1, CL2 and CL3 representing sand, shaly-sand and shale respectively. The sands here cover a small range of Vp values which mean that they are more porous, presumably reason why they show high Sw values since the numerous pores would easily store water.

Shaly-sands give the highest Vp reading of between 11200 – 22000ft/s. This is because the pores of the sands have been cemented with some of the shale and hence increasing its matrix strength and in effect Vp increases. This shaly-sand to a limited extent cannot be thought of being hydrocarbon bearing, instead, the sands can be suggestive of that. The zone with grey color is a shale lens, because the data points guided by the GR log indicates shale but these points are separated from the main cluster point for the shale and so could be considered a shale lens. It has low Sw values (40 - 48) compared to the other shale zoned blue in colour (55% and above). Supporting that fact that it is a shale lens it is observed that within the cross section, it occurs only at two intervals (at depths between 7950 – 8000ft and 8700 – 9050ft).

The same three facies are shown by the Sw versus porosity plot, confirming the facies relationship with Sw as backed by porosity. The difference between the two plots i.e petrophysical versus elastic (fig. 30a - b) and petrophysical plot only (fig. 32a - b) is that the level of noise is reduced for the former and as a result, improves the classification than the later. Furthermore, the sands though classified as such show some evidence of being clean in the case of the Sw versus Vp plot than the sands for the Sw versus porosity plot. All these still goes to support the fact that integrating both petrophysical and elastic rock properties gives a better classification and interpretation of log-facies which hold the key to building a good and efficient static (geologic) reservoir model. It should be noted that if log-facies are not properly classified in the model building, dynamic reservoir properties like permeability cannot be accurately assigned to the model for dynamic modeling by the reservoir engineer.

In addition the issue of inter-well spacing within the reservoir and that of reconciling log and seismic data can properly be addressed by the objectives of this work. This is a very important part for the reservoir engineer as it concerns the attribution of reservoir properties to every section of the reservoir. This work handles it in the sense that the Sonic log from data can be used to compute Vp which is what the seismic data give. Such computation is done using equations 4a and 4b above and at desired depths.

As a result, the lithology and petrophysical parameters from the well (porosity, permeability, Sw, Density, etc) can be estimated between wells or other sections of the reservoir by matching the calculated Vp on the seismic section and determining its corresponding porosity, permeability, etc, as given by the well logs.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

In this work petrophysical properties from formation evaluation analysis and elastic properties from rock physics models were integrated in order to classify log-facies. In line with this, two wells (TMB_4 and TMB-1) were examined. The plots of petrophysical properties only and those of petrohysical properties versus elastic properties for both wells resulted to three and four log-facies respectively after the interpretation of a series of cross plots. The plots for TMB_4 were validated with those of TMB_1 to test if the trend was the same if the method is applied to other wells and as a result, there was a tie, as the same trend was observed for every plot done for both wells. This led to the conclusion that the procedure used for the log-facies classification can be used for any well.Plots of only petrophysical properties were also produced for both wells and used for comparative purposes. The results demonstrated the improvement in the classification obtained by integrating both elastic and petrophysical data other than using petrophysical data alone as it is usually done. From the Vp/Vs ratios, it means overpressure zones are not encountered in these wells, since none of the values was <1.5.

Furthermore, the log-facies obtained in this research forms the basis on which a good and effective or better still an improved static model for the KK field depends. It follows that, before model validation, the log-facies in place should be well examined if not, flow properties will not be properly assigned to the different layers. So, the aim of this work was to capture this by appropriately classifying the log-facies so that better static models can be produced and subsequent dynamic modeling would be successful. In effect, log-facies classification in static reservoir modelling holds the basis on which efficient modelling (be it static or dynamic) and subsequent production lies.

5.2 RECOMMENDATIONS

Mindful of the fact that excellent research and innovation has to be promoted within the institution, Africa and the world at large, I hereby recommend the following:

- The results obtained could be used to build a static and dynamic model for the KK field to validate the facies optimization.
- Contributions from this work such as Vp/Vs ratios computed through the rock physics transformations should be used to study its effect as an indicator of overpressure zones.
- Further work can be done on the evaluation of the aerial extend of formation properties away from the wellbore using the velocities computed and also tackling the problem related to reconciling seismic and log data.
- From this work, the elastic waves could be used for the estimation of the location of fractures and permeability of hydrocarbon bearing formation as part of further research.
- Lastly, internship should be organized for students to have the opportunity of putting into practice the theory acquired from the classroom.

RELEVANCE OF THE WORK

- This work gives a new approach to log-facies classification by integrating both petrophysical and elastic properties.
- Secondly, work shows an improvement in the log-facies classified by integration of both petrophysical and elastic properties as opposed to the conventional way of classification which is only based on petrophysical parameters (as shown in the results, chapter four).
- It leads to the proper estimation of the proportion of sand in thin heterolithic sequences, which in conventional wire line logs will underestimate.
- Furthermore, the knowledge gained from this work solves or reduces the problem of faulty determination of flow units within layers of the reservoir and hence, assigning inappropriate or incorrect flow parameters like permeability.
- In addition, the work captured rock physics modelling aspects which enhance the understanding of the behaviour of reservoir and non-reservoir zones and correct for some of the problems encountered in well log data.
- The computed Vp/Vs ratios calculated in this work can be used as an indicator for overpressure and gas-saturated zones within the formation. This is also backed by literature (Eugenia, R., 2005). Typically, the presence of gas-saturated sandstones lowers the Vp/Vs even further (Vp/Vs of 1.6 or lower) and overpressure conditions can lower Vp/Vs even more (<1.5).

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APPENDIX

LIST OF SYMBOLS

Table 10: Illustrates the various parameters, their symbols and units as used in the work.

PARAMETER	SYMBOL	UNITS
Total Vertical Depth	TVD	ft
Density	ℓ	g/cc
Resistivity	R	Ω-ft
Constants	C1, C2	Unitless
Porosity	Φ	%
Resistivity of water	Rw	Ω-ft
True Resistivity	Rt	Ω-ft
Density of water	ℓw	g/cc
Density of rock matrix	ℓma	g/cc
Hydrocarbon and fluid Density	ℓh and ℓfl	g/cc
Observed Density from Logs	ℓobs	g/cc
Water Saturation	Sw	%
No plot	χ	
Tortuosity factor	a	Unitless
Saturation exponent	n	Unitless
Cementation exponent	m	Unitless

APPLIED EQUATIONS

These are mainly equations used for the computation of some Petrophysical and Elastic properties from available log data.

PETROPHYSICAL COMPUTATIONS

- DENSITY

$$\ell = C_1\ [Vp]^{0.25}$$ ....Eqn. 1 (Gardner's Equation, 1974)

- POROSIT

$$\Phi = \frac{0.9\sqrt{[Rw \times Rt]} \times (\ell m - \ell h) + (\ell ma - \ell obs)}{(\ell ma - \ell h)}$$ ....Eqn. 2a (Porosity from Density Log)

$$\Phi = \frac{\ell_{ma} - \ell_{obs}}{\ell_{ma} - \ell_{fl}}$$ ....Eqn. 2b (Serra, 1984)

- WATER SATURATION

$$Sw = \sqrt[n]{\frac{a\ R_w}{R_t\ \Phi^m}}$$ ....Eqn. 3 (Archie's empirical formula, 1942)

ELASTIC PROPERTY COMPUTATIONS

- P-WAVE

$$P - wave = C_1 [Depth \times Resistivity]^{\frac{1}{6}}$$ ....Eqn. 5 (Faust's Equation, 1951)

- S-WAVE

$$S - wave = C_1 \times P - wave + C_2$$ ....Eqn. 6 (Castagna's Equation, 1985)

- VP/VS RATIO

$$\frac{V_P}{V_S} = \frac{P - wave\ velocity}{S - wave\ velocity}$$ ....Eqn. 7

LIST OF ACRONYMS

Table 11: Illustrates the various acronyms with their full meaning as used in the work.

ACRONYM	MEANING
AUST	African University of Science and Technology
2D, 3D	Two and Three Dimensions
GR	Gamma-Ray
HEMI	Hemipelagic Shales
LCT	Low Concentration Turbidite
VLCT	Very Low Concentration Turbidite
HCT	High Concentration Turbidite
API	American Petroleum Institute
E D & P	Exploration Development and Production
E & P	Exploration and Production
Vp	Primary Wave Velocity (Compressional velocity)
Vs	Secondary Wave Velocity (Shear velocity)
QC	Quality Check
Sw	Water Saturation
SP	Spontaneous Potential
NPHI	Neutron Porosity
TMB	Tomboy (well name)
CALI	Caliper Log
LITH and DT	Lithology and Sonic Log
RHOB	Bulk Density
LLD	Lateral Deep Log (Lateral Long Normal Log)
LLS	Lateral Shallow Log (Lateral Short Normal Log)
CILD	Compensated Induction Deep Log
SGR	Spectral Gamma—Ray Log
SAV	Start Amplitude Value
EAV	End Amplitude Value
RPM	Rock Physics Model
RPMC	Rock Physics Model Computations
PPC	Petrophysical Property Computations
EL1- EL4	Names for different Log-facies for well 1
CL1- CL4	Names for different Log-facies for well 2

Table 12: Facies occurrence and distribution with depth for Porosity versus Vp/Vs plot for TMB_4 (Well 1)

DEPTH (ft)	LOG-FACIES
3900 – 3950	Clean sand
3950 – 4050	Sand
4050 – 4370	Shale
4370 – 4450	Shaly sand
4450 – 4550	Sand
4600 – 4740	Shale
4740 – 4980	Sand
4980 – 5020	Shale
5020 – 5250	Shaly sand
5250 – 5320	Sand
5329 – 5900	Shaly sand
5900 – 5930	Shale
5930 – 6620	Shaly sand
6620 – 6650	Shale
6650 – 6770	Shaly sand
6770 – 6790	Shale
6790 – 6810	Shaly sand
6810 – 6850	Shale
6850 – 6950	Shaly sand
6950 – 6980	Shale
6980 –7450	Shaly sand
7450 – 7500	Shale
7500 – 7630	Shaly sand
7630 – 7660	Shale
7660 – 7700	Shaly sand

Table 13: Facies occurrence and distribution with depth for Water saturation versus Porosity plot for TMB_4

DEPTH (ft)	LOG-FACIES
3900 - 4050	Sand
4050 - 4090	Shaly sand
4090 - 4520	Sand
4520 - 4590	Shaly sand
4590 - 5040	Sand
5040 - 5060	Shaly sand
5060 - 5210	Sand
5210 - 5030	Shale
5030 - 5320	Shaly sand
5320 - 5460	Sand
5460 - 5510	Shale
5510 - 6620	Shaly sand
6620 - 6650	Shale
6650 - 6750	Shaly sand
6750 - 6790	Shale
6790 - 6810	Shaly sand
6810 - 6850	Shale
6850 - 6950	Shaly sand
6950 - 6980	Shale
6980 –7450	Shaly sand
7450 - 7500	Shale
7500 – 7630	Shaly sand
7630 - 7660	Shale
7660 - 7700	Shaly sand

TIME SCHEDULE OF WORK

The entire work followed a successful defined time frame which ran for ten months and this was to ensure that the work was finished on time. A run-down of the time schedule is presented in tabular form as follows:

Table 14: Presentation of the time schedule of work from start to finish

TIME FRAME	MAJOR ACTIVITY	MINOR ACTIVITY
15TH JANUARY – 31ST MARCH	Idea initialization and development	Reading past work
		Scanning through my courses
		Reading journals
2ND – 31ST APRIL	Findings and discussion of thesis idea with supervisor	Aim of work
		Scope of work
		What the work entails
		Relevance of work
	Adoption of thesis topic	Looking a captivating topic
1ST – 31ST MAY	Preparation of materials	Search for Journals
		Search for articles
		Search for papers
		Search for textbooks, etc
	Initial arrangements for data collection	Calls and other transactions with company

1ST – 15TH JUNE	Start of write-up from preliminary pages	Preface
		Dedication
		Abstract, etc
16TH JUNE – 1ST JULY	Write-up of chapter one (Introduction)	Problem description
		Objectives of study
		Scope of study
		Motivation for the study
2ND JULY – 2ND AUGUST	Write-up of chapter two (Literature Review)	Location of study area
		Formation evaluation
		Elastic waves
		Rock physics
		Seismic reservoir characterization
		Log-facies classification
		Construction of a geologic model
3RD – 8TH AUGUST	Final discussions with supervisor on laboratory work	Deliberations on what is to be done and the things needed
	Preparations for trip to UNN Nsukka	Arrangement of materials and finances to carry along
	Conclusions for data collection	Trip to company for data

	Methodology layout	Mastering the various steps involved in the methodology
8TH AUGUST	Trip to UNN	
9TH – 28TH AUGUST	Lab work	Input of data into softwares
		Editing of data
		Scenarios simulation
		Cross plotting and cross section analysis, etc
29TH – 30TH AUGUST	First discussion of results with supervisor and appropriate corrections	How to classify the log-facies Number of log-facies and names The log-facies interpretation
31ST AUGUST	Return from UNN to AUST	
1ST – 10TH SEPTEMBER	Methodology write-up	Write-up on acquisition and log data gathering from the field
		Write-up on loading, importation and QC of data
		PPC
		RPMC
		Log-facies classification
11TH – 20TH SEPTEMBER	Results Write-up	Putting into writing all the results obtained from the analysis
21ST -29TH SEPTEMBER	Conclusion and Recommendations	Summary of the study

		What could be drawn for the work
	First editing of entire work	
30TH SEPTEMBER	Submission of work to supervisor for corrections	
1ST- 10TH OCTOBER	Continuous editing	
11TH – 20TH OCTOBER	Final corrections	
21ST- 25TH OCTOBER	Final print-out of work	
	Reading all through the work	
	Submission of work	