An Integrated Approach Towards Better Understanding The Distribution Of Reservoir Properties Through Petrophysical Analysis And Well Correlation Of Kohat And Potwar Sub-Basins, Pakistan

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In The Name Of ALLAH, The Most Merciful and The Most Beneficent.

<u>Submission Certificate</u>

This is to certify that **<u>Mr. Kashif Sohail</u>** submitted this thesis entitled "**An integrated approach towards better understanding the distribution of reservoir properties through petrophysical analysis and well correlation of Kohat and Potwar Sub-basins, Pakistan"** is here by approved for the submission of M. Phil. degree in Geology (Session 2016-2018).

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Dedication

I wish to dedicate my research to my beloved parents because without their support, wisdom, care and guidance I would not have the goals I have to strive and be the best to reach my dreams. They always prayed for my success and prosperity and provided me all the facilities in my life. My Mother always supported me in every ups and downs of my life and my educational carrier. Today what I am is due to my parent's countless prayers and love.

My loving teachers, who are very inspiring personalities for me and who helped me to do this work

They all always inspired me to achieve higher brilliance to assemble my educational career.

Kashif Sohail

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I am very grateful and wish to pay my personal gratitude and tribute to Mr. Raja Fahad, Aosaf Hassan and Beicip-Franlab Support, who provided me with their valuable information, guidance and encouraged me at each and every step.

I am obliged to express special thanks to my loving, caring and respected parents who supported me and provided me through all possible resources with great patience throughout the duration of study.

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Abstract

In this study, efforts are made to relate formations related to depth in 3 wells, petrophysical analysis, Electrofacies analysis, behavior of seismic velocities with the different rock types, source rock identification and behavior of logs with the input of fluids.

This thesis consists of two parts, one is related to geology and the other is based on geophysics. In first part we discussed about the correlation of different lithologies variation with depth. Correlation is done between three wells Chanda_deep_01, Chanda 02 and Esa Khel-01. Two wells have many formations in common to each other this include Chanda-deep-01 and Chanda 02 because of their location. While Isa-khel-01 have not similarity in formation as compare to other two wells. Electrofacies plays an important role for the discrimination of different facies related to mineralogy. The prediction of Electrofacies is done on the basis of log behavior. Five facies are identified and marked in the reservoir. Results of Electrofacies reveal Limestone as the reservoir rock.

In the second part, geophysical aspects of the well data are taken into account. This includes observation of seismic velocities variation through different lithologies. Sudden decrease in velocity is observed at Samanasuk limestone level (4499-4579m) which is main reservoir. Estimation of TOC helps in delineation of source rock. Lockhart Limestone is marked as a source rock which shows very good TOC of 12%. At the end, Gassmann's Fluid Substitution is carried out. Curves of velocity and density are generated at different saturations level. This is a 4-D analysis which incorporate time lapse in characterization of reservoir which helps in estimation of hydrocarbon reserves.

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Chapter # 01

INTRODUCTION

1.1 Introduction

Geology being the most attractive field all around the world and a lot of researches has been established during past decades and Pakistan being the most fascinating part among the different countries on the globe. Number of geological events and a lot of researches has been carried in different regions of Pakistan. Different companies working on different projects for analyzing the geological events and for exploration of hydrocarbons and minerals. It has a great importance in oil and gas sector too. With the passage of time the movements of plates in the subsurface of earth, building of mountains and many other geological phenomena are all apart related to geology. Geologically Pakistan has been eminent because of its great mountains, widespread glaciers, devastating earthquakes and large succession of Salt Range (Read and Watson, 1968).

For the relationship between different types of strata under the earth crust the term correlation is used and this correlation is done between two or more area to study the presence and equally distribution of different type of lithologies, fossils relationship and many other features. Generally there are two ways of correlation one is to correlate the physical characteristics of lithology, we can say it a physical correlation and in other, we can compare the presence of different types of fossils in different strata. It is consided an important technique as it gives information regarding changes that take place with the passage of time in earth history and also give information about signs by which change occurred. There are different divisions of time such as eras; periods and epochs in geological time scale on the basis of this we can do correlation easily (Rudman and Lankston, 1973).

Electrofacies also play an important role for the determination of high density and low-density regions in required areas. The plot between the porosity and permeability and the collection of different points can be very helpful in the determination of reservoir rocks. The description of depositional environment and to determine the quality of reservoir rocks and to characterize the heterogeneity for different geostatistical models, electrofacies have an important role. Initially non-supervised approach methods are used for the determination of electrofacies by assigning different logs such as neutron log, effective porosity log, gamma ray log and density log. These electrofacies analysis can be used for studying seismic attributes, for analysis of core data and many other studies and these techniques can generally be applied to many geological settings. (Ye and Rabiller, 2000).

Rock properties and their relation with gasses, liquids, hydrocarbons etc., petro physics has a great importance. Accumulation of hydrocarbons and determination of reservoir rocks in the subsurface and to determine the quantity of hydrocarbons, different properties of rocks can be studied such as determination of porosity, permeability, volume of shale, volume of hydrocarbons, saturation of water and many other rock properties. Different methods are applied for the acquisition of data and well logging and for the determining different types of logs. Every log has its importance and property to determine different features regarding subsurface geology. (Mavko et al., 2009).

An integrated work between Geology and Geophysics is done for the determination of other properties like fluid substitution. Total Organic Carbon (TOC) is the best tool for the identification of the source rock. Many methods are there to find TOC such as Rock Eval Pyrolysis, through Logs etc. (Schumacher, 2002). Fluid substitution plays an important role for the identification and estimation of hydrocarbons reserves. This technique helps us in determining how much hydrocarbons are left for the production. We can estimate the time for the well to produce hydrocarbon. Fluid substitution is an important tool in the field of Geophysics. The main method to find Fluid Substitution is Gassmann’s Fluid Substitution method. (Adam et al., 2006) The detail of which is discussed in my dissertation.

1.2Objectives of Work

The main objectives of my thesis are as follow:

- To correlate different lithologies based on depth in different wells located at different location. It gives information about the similarities and dissimilarities of features in wells that are to be correlated.
- Electrofacies analyses play an important role to identify the mineralogy of the subsurface and we can easily identify the presence of different facies based on

behavior of log. Different logs show different behavior in facies. Supervised Approach has been used to identify Electrofacies.

- Petrophysics is also the most important tool for the identification of reservoir rocks and properties. It is done for the identification of different parameters like volume of shale, saturation of hydrocarbons, and saturation of water by using different logs to identify the reservoir rocks and the zones where we can determine the presence of hydrocarbon.
- Application of Basic Rock Physics on given Data for the identification of seismic velocities, Vp and Vs and by using this result, separation and presentation of different lithologies like sand stone, lime stone, shale, dolomite etc.
- Total Organic Carbon (TOC) also plays an important role in the field of geology. The main purpose to find TOC is the identification of Source rocks.
- Gassmann's Fluid Substitution is also the main part of this thesis. This is done for the estimation of hydrocarbon reserves by comparing the change in densities and velocities. As the behavior of Log values shows variation due to the presence of water and other fluids. So, by giving different percentages of fluid to be injected we can easily estimate the hydrocarbon reserves. It is the best tool for the quantification and identification of fluids in a reservoir rock.

1.3Location of the study area

This work is done on the area of Kohat and Potwar Sub basins of Upper Indus Basin. Geologically and Geophysically this area has a great importance. Many companies did a lot of researches in this area and a lot of production is done. This work is done on the wells that are drilled by Oil and Gas Development Company Limited (OGDCL), Chanda-deep-01 in year 2000, Chanda-02 in year 2005 and Isa-Khel-01 in year 1993. The total area of Indus Basin is about 1.1 million km^2 that is shared by Pakistan, China, India and Afghanistan. The major portion (about 52%) of Indus Basin is in Pakistan. This area has also a great importance in the field of agriculture. Many tributaries are present that includes Ravi, Beas, Sutlej, Jhelum, Chenab Gilgit, Shigar and many more.

Chanda-Deep 01 and Chanda 02 are in Kohat region while Isa Khel-01 is in Mianwali region of Upper Indus Basin. With the help of EasyTrace software this data can be used to identify different properties.

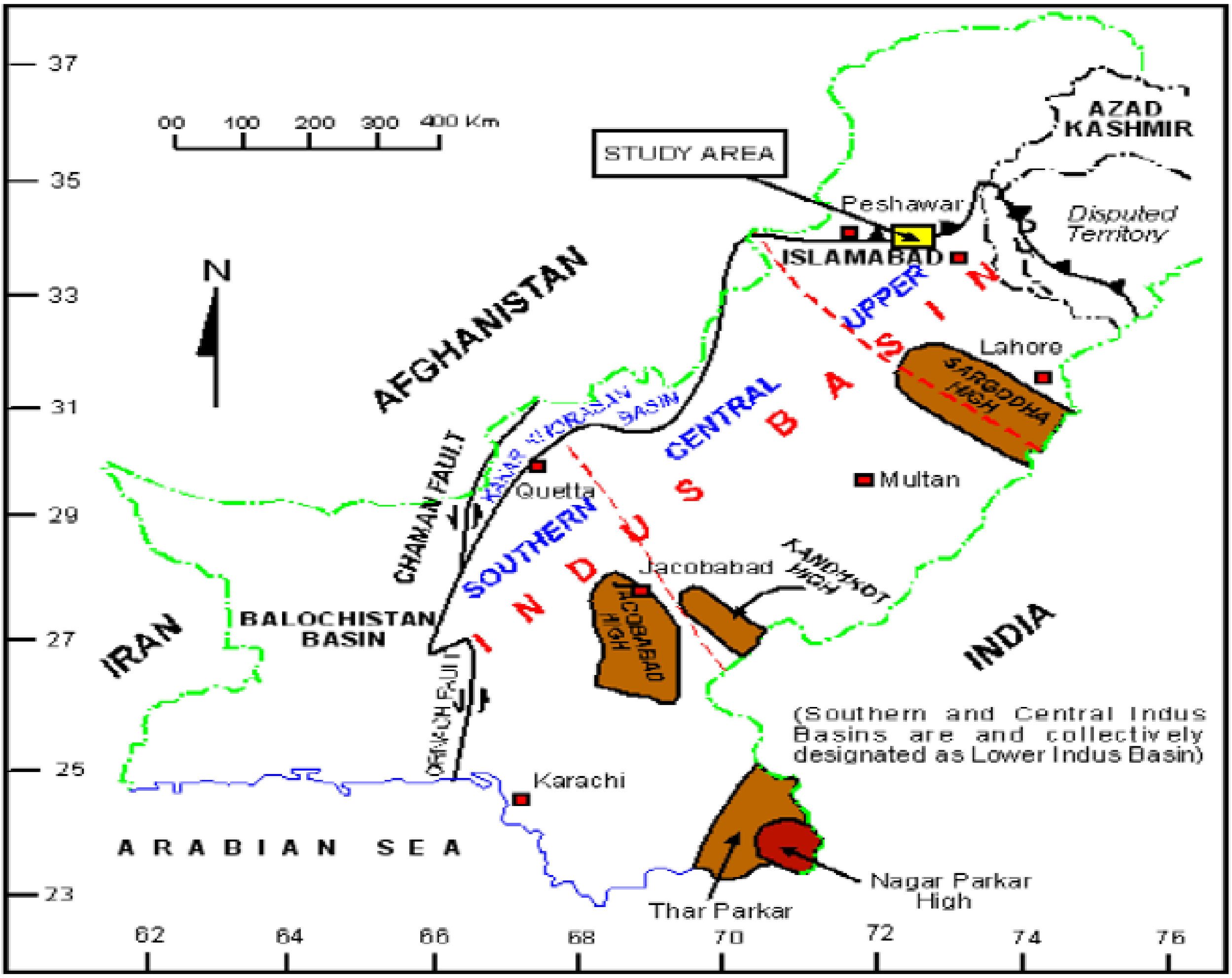


Figure 1.1 Structural map of the Kohat Plateau, northern Pakistan (modified after Khan et al., 1986; Gee, 1989).

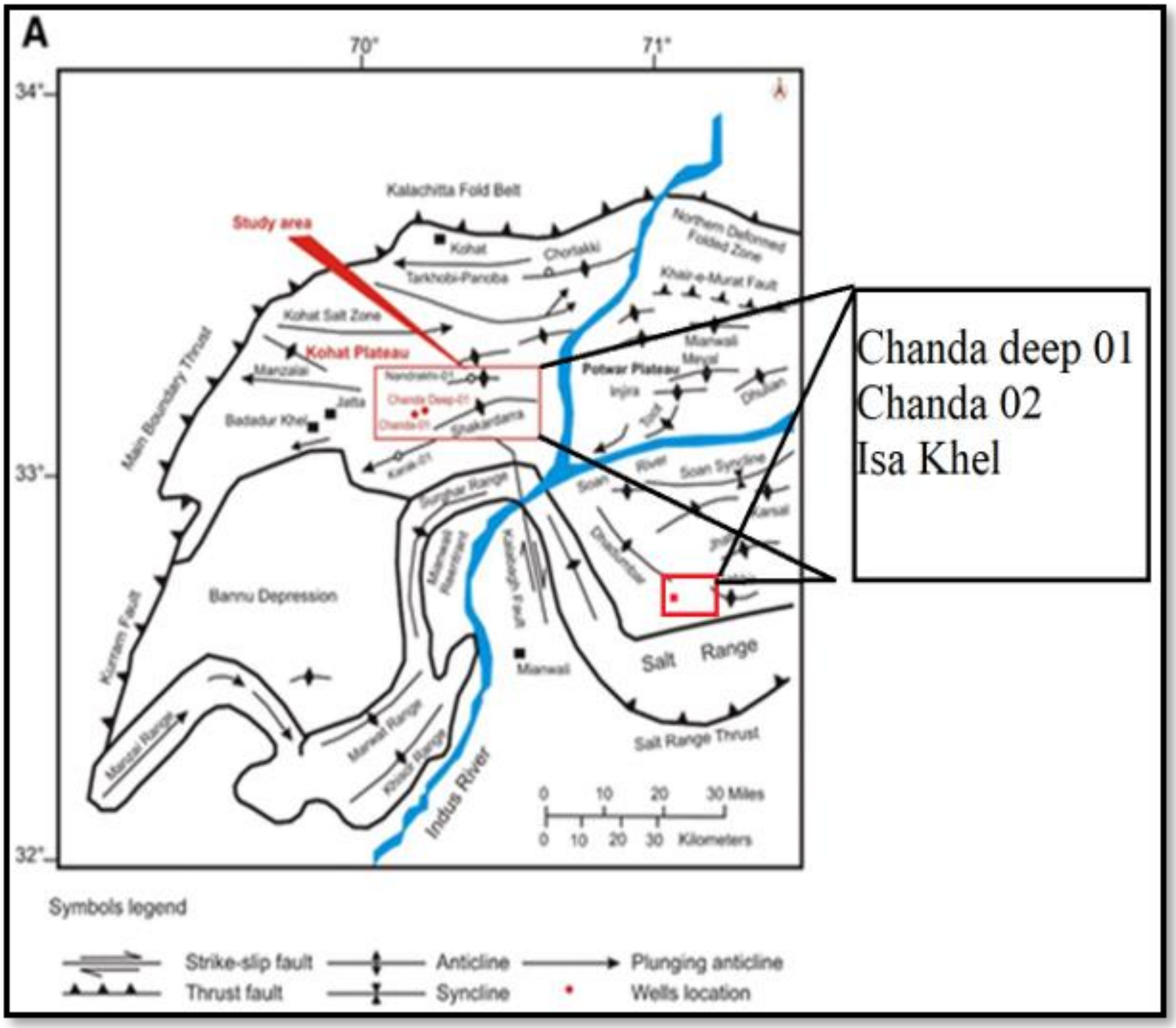


Figure1.2 Structural map of the Kohat Plateau, northern Pakistan (modified after Khan et al., 1986).

Chapter # 02

GEOLOGICAL SETTINGS

2.1 Regional Tectonics

Geologically Pakistan is divided into three major types of sedimentary basins that are Indus Basin in the east, Baluchistan Basin in the west and Pishin Basin in the northwest. (Middlemiss, 1896). Different fault zones are there separating these basins from each other. Ornach-Nal transform fault zone separates Indus Basin from Baluchistan Basin. Location of Pishin Basin is between Indus and Chaman transform fault. There are number of sub-basins, fold belts anticlines, monoclines having variable styles of structure that results from different geodynamic conditions, have been identified in Indus Basin and Baluchistan Basin. (Wynne, 1873).

In the northern area of Pakistan, the development of mountain belts including Himalayas, Karakorum and Hindukush are the result of presence of three lithospheric plates namely Indian, Eurasian and Arabian. The tectonic history is recorded by the rock units having age ranging from Precambrian to Recent. The Main Karakoram Thrust (MKT) also known as northern suture zone while the Main Mantle Thrust (MMT) also known as the southern suture, it separates terrains form Indian Plate. In the southern boundary of Lesser Himalayas there are fold and thrust belt of Kala Chitta Range. (Cotter, 1993) In the south of Himalayan collision zone there are Salt Range, Kohat Plateau and Potwar Plateau. This is an active fold and thrust belt that is bounded in the north by MBT and in the south by Main Frontal Thrust (MFT). Jehlum Fault that is left lateral, strike-slip fault bounds the Salt Range and Potwar Plateau in the east. There is no sharp boundary in the western part of Potwar Plateau. The EW trending thrust in the northern part of the Potwar Plateau extends to the area of Shakardara area in the Kohat Plateau while some part of west of Cis-Indus Salt Range Potwar Plateau is marked by the Kala Bagh Fault. (Emas, 1951).

Our area of study is in Upper Indus Basin with Kohat-Potwar sub-basins. The Kohat-Potwar foldbelt lies in the northwest of the Indian plate. It is structurally defined as petrophycial region. This region is further divided into major structural divisions that are North Potwar Deformed Zone, the Salt Range, the Soan Syncline, the Bannu Sub-basin, the Kohat Plateau and the Trans-Indus Ranges. In the Upper Indus Basin, the structure style generates multiple petroleum prospects (Latif, 1970). These structures are generated by the result of compressional tectonics at foreland margin, extensional tectonics and the up lift in the platform areas. Both

Kohat and Potwar Sub-basins are basically comprised of thick beds of sedimentary successions ranging age from Pre-Cambrian to Quaternary. These basins are mostly comprising of silicates, carbonates and clays etc. and they are separated at various stratigraphic units by unconformities (Shah, 2009). The location of study area is given in the figure below as:

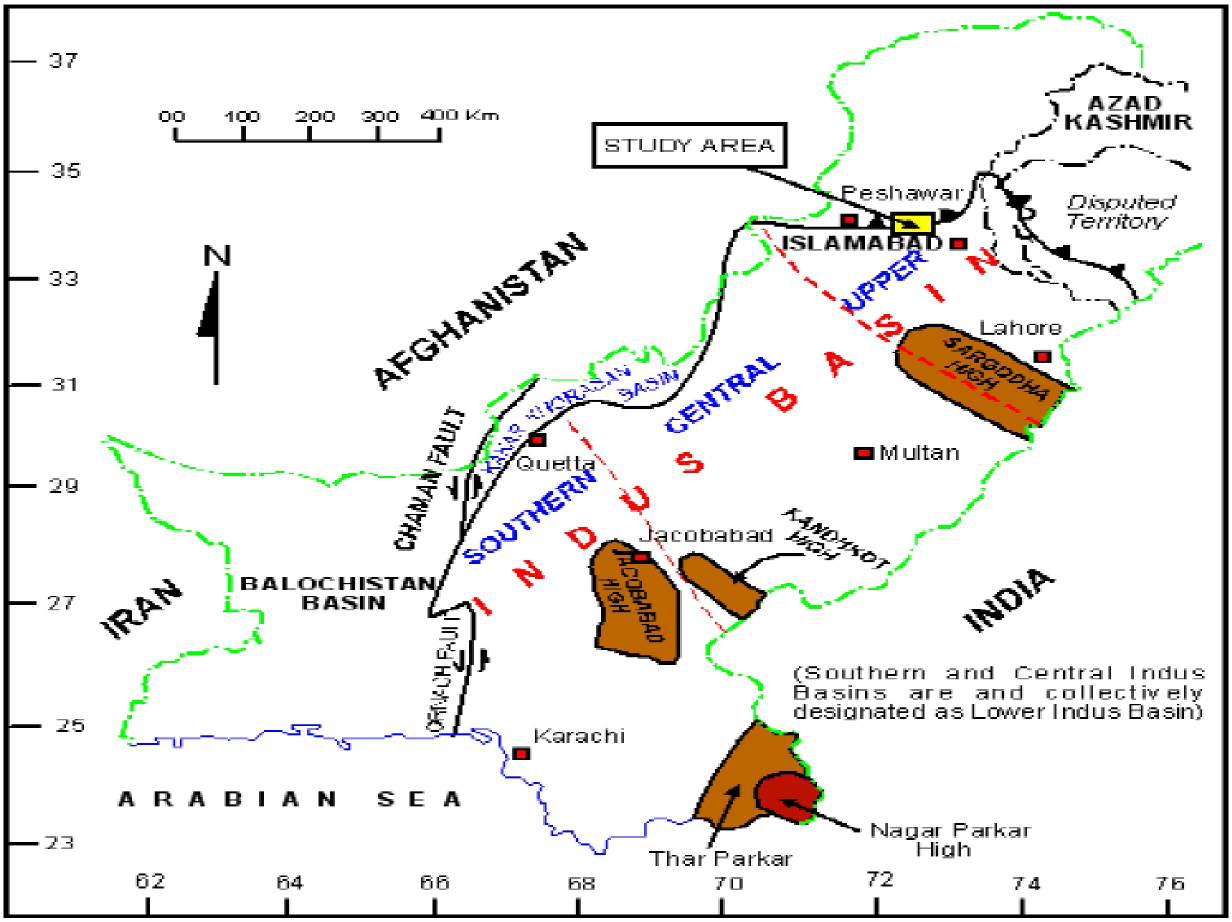


Figure 2.1 Basinal Division Map of Pakistan by Arshad Maqsood Malik, University of the Punjab Lahore.

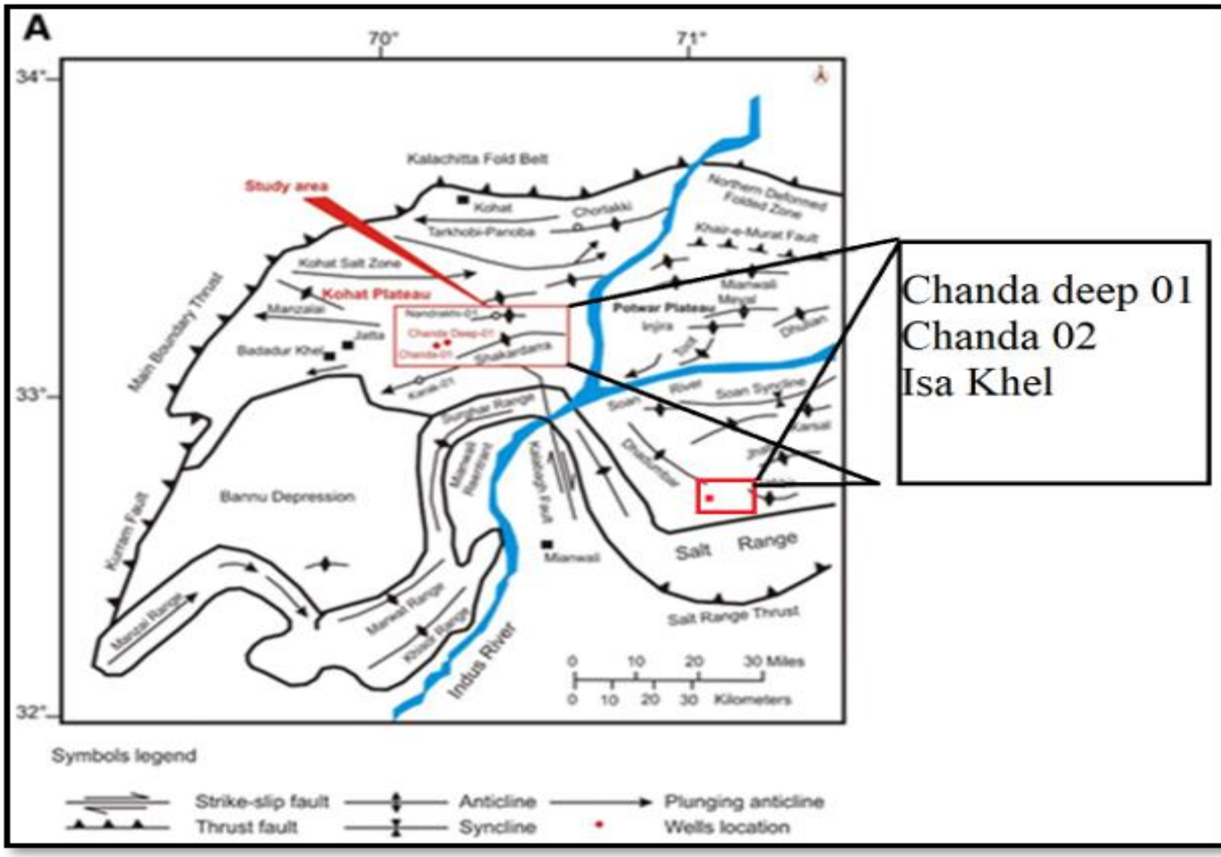


Figure 2.2 Tectonic map of the Kohat Plateau, northern Pakistan (modified after Khan et al., 1986; Gee, 1989).

2.2 Geology of the Study Area

2.2.1 Structure Style

The Kohat-Potwar plateau on the southern part of Himalayan and Karakoram orogenic belt is a result of compressional tectonics after Indo-Eurasian collision. The Kohat-Potwar plateau is bounded at north by Kalachitta Hills. The Salt Range and Trans-Indus Range marks the boundary at south. The western boundary is mark by Kurram-Parachinar Range. The River Indus separates the Kohat-Potwar Plateau by the Eastern side named as Potwar area and the Western side as Kohat area. The Kohat region in northern Pakistan area is one of the complex tilted plateau and also sometimes seems as “Cuesta” region with its complicated structural attribute, for example, moderate-steeper dip which may form asymmetrical structures due to large number of wrench-tectonic thrust/overthrust, rejuvenated and normal faulting. large numbers of duplex structure also have been marked in the area. The Kohat and Kuldana Formations are the only representatives of the Middle Eocene in the Kohat Plateau.

The north and northwestern area of Kohat have more tight and deformed structures as compared to the south and southeastern areas due to rotational activity. The whole Kohat region like Potwar is composed of imbricate wrench faults and these imbricate faults are gentle in the Potwar area while steeper in the Kohat area. The eastern part of the Kohat Plateau formed duplex structure in Kohat Formation. The western part of the area has more tectonic damages as compare to east part of Kohat region. The study area is comprised of fold and thrust belt assemblages which are thin skinned structures superimposed by thick-skinned structures. The major part of the plateau is dominated by compressional structures; however, the strike-slip faulting is confined to the southern Kohat plateau.

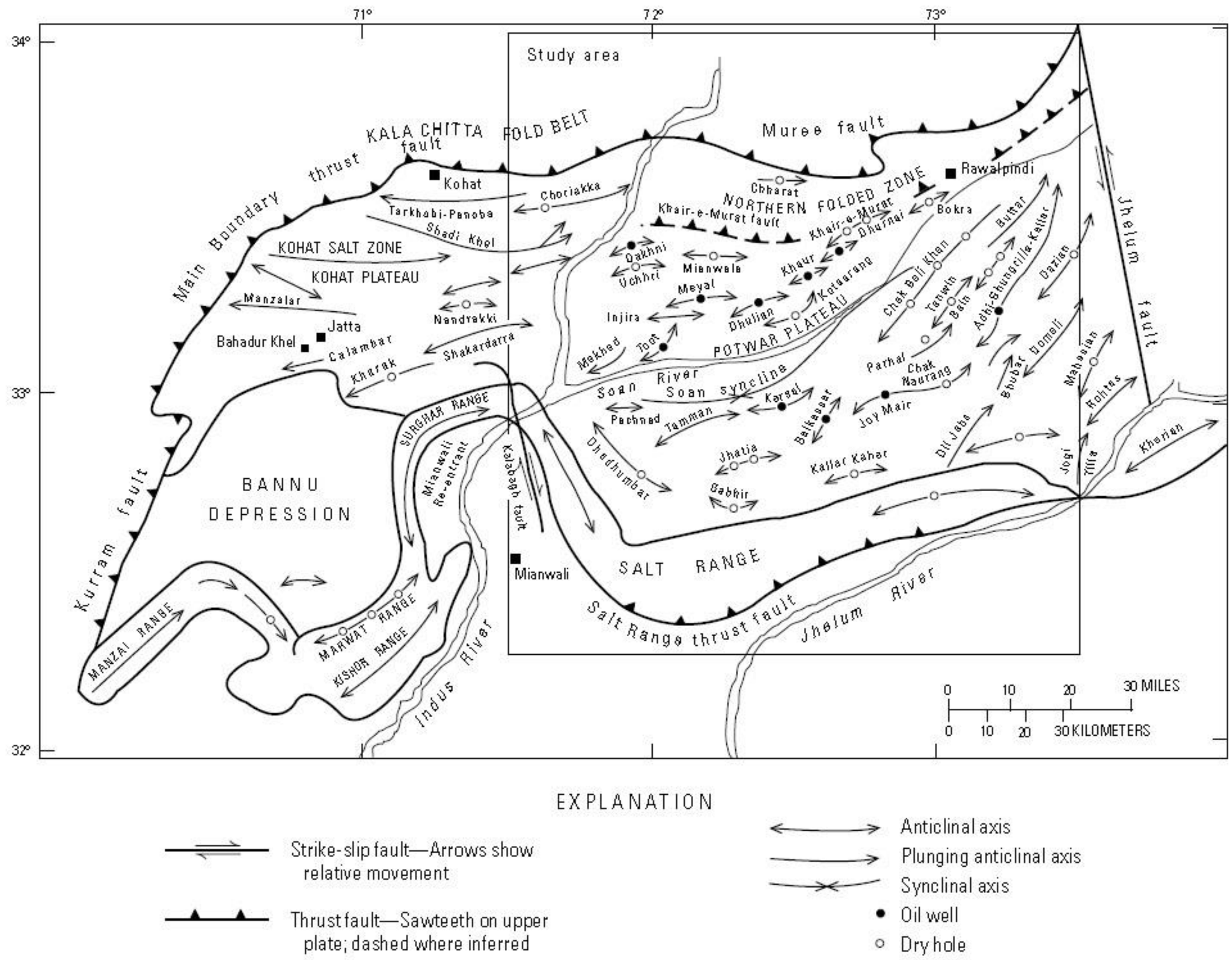


Figure 2.3 Structure map of Kohat Potwar, Northern Region of Pakistan (after Khan, 1968; Gee, 1989).

2.2.2 Stratigraphy

The stratigraphy of our area is divided into three Eras:

(a) Paleozoic Stratigraphy

(b) Mesozoic Stratigraphy

(c) Cenozoic Stratigraphy

PALEOZOIC STRATIGRAPHY

Paleozoic Stratigraphy includes following formations:

Wargal Limestone

Middle Productus Limestone was the first name of this formation. Later (Teichert, 1967) changed its name to Wargal Limestone. In the Central Salt Range its type locality is near Wargal Village. The Wargal limestone consist of dolomite with little sandstone and thick bedded limestone. It is identified by grey to dark grey color or pale yellow. The Wargal Limestone is conformably underlain by the Chhidru Formation and overlain by the Amb Formation. Based on foraminifers age of Late Permian is assigned to it.

Chhidru Formation

Chhidru formation name suggested by (Dumbar, 1993) and its old name was Upper Productus Limestone. Its type locality is in Western Salt Range near Chhidru Nala. The Chhidru Formation is mostly composed of dolomite, at some places it contains shale deposits and also contains thin to medium bedded limestone. It is identified by dark grey color. The upper part of this formation is highly fossiliferous that contains fine grained to medium grained sandstone beds while the lower part is mostly composed of calcareous sandstone, sandy limestone and minor amount of phosphate nodules. The Chhidru Formation is underlain by the Mianwali Formation and overlain by the Wargal Limestone. Based on fossils present in this formation, Late Permian age is assigned to it.

MESOZOIC STRATIGRAPHY

Mesozoic Stratigraphy includes the following formations:

Mianwali Formation

"Mianwali Series" name is suggested by (Gee, 1995) later on this name was modified by (Kummel, 1996) as "Mianwali Formation". It is located in the western part of Salt Range in Mianwali region. The Mianwali Formation is divided into three members as:

- Kathwai Member: It is 4-5 meters thick. This member consists of beds of dolomite, some amount of shale and fine layers of limestone.
- Mittiwala Member: Thickness of this member is about 100 meters. It consists of brownish grey limestone, shale and siltstone.
- Narmia Member: The thickness of this member is about 25 meters. It contains greenish grey silty shale, with thin beds of dolomite and dolomitic limestone. The limestone is light grey in color, hard and compacted.

The Mianwali Formation is conformably underlain by Tredian Formation while it is overlain by Chidru Formation. Triassic age is assign to this formation.

Tredian Formation

(Gee, 1945) suggested its name as "Tredian Formation". This formation also consists of two members:

- Landa Member: It is the lower member that consists of micaceous and reddish grey to greenish grey sandstone and also some amount of shale. The thickness of this formation is about 20-29 meters.
- Khatkiara Member: It is the upper member of this formation that consists of massive and thick bedded of white sandstone. Thickness of this member is about 40-60 meters.

The Tredian Formation in conformably underlain by the "Kingriali Formation" and overlain by the "Mianwali Formation".

Kingriali Formation

Kingriali Formation was named after "Kingriali dolomite" by (Gee, 1945). In Khisor Range its type locality is near Kingriali Peak. It consists of massive beds of dolomitic limestone with light grey to brown in color with inter beds of dolomitic shales and marl. The thickness of this formation is about 75-105 meters. The Kingriali Formation is conformably underlain by the Datta Formation and has lower contact with the Tredian Formation. Late Triassic age is assigned to this formation.

Datta Formation

The old name of this formation was "variegated Stage" by Gee but after this, its name was changed to "Datta Formation". The location of this formation is in Surgher Range near Datta Nala. This formation consists of mainly sandstone, siltstone and some amount of shale is also present in this formation. It also contains layers of coal and laterite beds. It is identified by orange black to yellowish brown color. The Datta Formation is unconformably underlain by the "Hangu Formation" and sharply overlain by "Kingriali Formation". The age of this formation is Jurassic.

Shinawari Formation

The name "Shinawari Formation" was given by (Fatmi and Khan, 1966). It is located near Shinawari Village in the western side of Samana Range in Kohat District. The lithology of this formation is mainly composed of thin bedded limestone, some amount of calcareous and non-calcareous shale with nodular marl and calcareous sandstone. It is identified by brownish grey to grey in color. Shale of this formation is dark to brownish grey in color. The Shinawari Formation is transitional contact with the Datta Formation in the lower part while it is conformably underlain by the Datta Formation. The age of this formation is Jurassic.

Samana Suk Formation

(Davies, 1930) gave the name to this formation as "Samana Suk Formation". This is mostly found in Samana Range. The lithology of this formation is mostly composed of medium to thick bedded limestone with little amount of marl and calcareous shale. This formation is overlain by the Shinawari Formation and this contact is transitional in nature while it is underlain by the Chichali Formation. Jurassic age is also assigned to this formation.

Chichali Formation

(Danil and Chik, 1961) suggested its name as Chichali Formation and in 1967, Shah described it as belemnite beds for the rocks from Salt Range. (Latif, 1970) suggested the name as “Spiti Shale” for the Chichali Formation. The type locality is near Chichali pass in Surghar Range. The lithology of this formation is mainly composed of brown sandstone, glauconitic shale and silty sand. On the basis of their lithology this formation is divided into three members. Lower member is sandy, shale grading upward into greenish black and bluish black brown. It also contains fossiliferous Sandstone with phosphate nodules. Middle member is identified by dark grey glauconitic, calcareous and fossiliferous sandstone while the upper member is un fossiliferous glauconitic sandstone. The Chichali formation is gradational and conformably underlain by the Lumshiwal Formation and overlain by the Samana Suk Formation with disconformable contact. The age of this formation is Cretaceous.

Lumshiwal Formation

Firstly, Gee described its name in 1945 as “Lumshiwal Sandstone” further Stratigraphic Committee of Pakistan amended its name as “Lumshiwal Formation” because of variation of lithology from area to area. The type locality of this formation is near Lumshiwal Nala. Lithology of this formation composed of cross beds of massive Sandstone with sand and glauconitic shale. The Lumshiwal Formation is underlain by the Kawagarh Formation and this contact is disconformable while it is overlain by the Chichali Formation and this contact is conformable and gradational. On the basis of fossils present in this formation a Cretaceous age is assigned to it.

CENOZOIC STRATIGRAPHY

Cenozoic Stratigraphy includes the following formations:

Hangu Formation

The Stratigraphic Committee of Pakistan assigns the name as the Hangu Formation also characterized as Hangu shale and Hangu Sandstone. The type locality of the Hangu Formation is situated in the south of Fort Lockhart having Latitude 33º 33´ 44” N and Longitude as 71º 44´ E and this formation is well exposed in Dhak Pass in the Salt Range. In Kohat area the Hangu Formation consists of white, light grey and reddish-brown sandstone with the intercalation of grey colored shale and rarely conglomerated lenses. In the Salt Range and in Trans Indus Range, the Hangu Formation is comprised of sandstone of dark grey color, carbonaceous shale and some nodular Limestone. This formation overlies many Mesozoic and Paleozoic rocks in many parts of Kohat and Potwar basin. An early Paleocene age is assigned to this formation on the basis of presence of micro-palentological fossils.

Lockhart Limestone

The name "Lockhart Limestone" is introduced for the Paleocene Limestone in the Kohat area and it is exposed near Fort Lockhart having latitude of 33º 26´ N and longitude of 70º 30´ E.(Davies, 1930). In Trans-Indus Ranges and Salt Range, Lockhart Limestone is comprised of grey to light grey, medium bedded with little amount of grey marl and in the lower part containing bluish grey calcareous shale. Paleocene age is assigned to this formation on the basis of presence of micro-fossils. In Kohat area, the Lockhart Limestone is identified by grey to medium grey, medium to thick bedded limestone. In adjoining area of Hazara and Kala Chitta the limestone is dark grey and black in color, containing intercalations of marl and shale. This limestone gives bituminous odor on fresh surface. This is well exposed in Kohat Potwar area. The Lockhart Limestone is conformably overlain by Hangu Formation and transitionally underlain by the Patala Formation and contains abundant foraminifers.

Patala Formation

(Davis and Pinfold, 1918) named it as Patala for Patala Shale and dignified by the Stratigraphic Committee of Pakistan. It has a great exposure in the Kohat and Potwar area also in the Salt Range. The type locality of this formation is at latitude of 32º 40´N and longitude 71º 49´E. It is mostly comprised of marl and shale having sandstone and limestone as subordinate. The shale bearing rocks have dark greenish gray, calcareous and carbonaceous and marcasite nodules. From place to place this formation shows some variation. The yellowish and brown sandstone characterizes the upper part of the Patala Formation. In area of Kohat this formation has dark grey shale content which is intercalated with argillaceous limestone beds. In Upper Indus Basin thickness of the Patala Formation varies from 20-180m. The Patala Formation has conformable contact with overlain the Lockhart Limestone. It is highly fossiliferous that have abundant mollusks, foraminifers and ostracodes. On the basis of these fossils the Late Paleocene age is assigned to this formation.

Jatta Gypsum

(Gee, 1945) suggested the name for the upper part of Kohat Series, and then (Meissner, 1970) suggested its name as "Jatta Gypsum". The type locality of this formation is near Kohat area. Lithology consists of massive beds with greenish white and hard gypsum and thin beds of clay with green, purple and red color. The thickness of this formation ranges from 30 to 40 meters. Jatta Gypsum is underlain conformably by Panoba Shale and overlain conformably by Kuldana Formation. Early Eocene age assigned to this formation.

Kuldana Formation

Many names were given to this formation like "Kuldana beds" by (Wynne et al., 1974), Kuldana Series by (Middlemiss, 1869) and Pinfold in 1918 named it as "Varigated Shale". Finally "Kuldana Formation" name is formulized by the Stratigraphic Committee of Pakistan. Location of this formation is near Kuldana Village in the north of Murree Hill. Formation is consisting of shale and marl of brown to pale grey color with irregular beds of sandstone, limestone and conglomerate with bleached dolomite. The Kuldana Formation is underlain by the Kohat Formation while it is overlain by the Jatta Gypsum. The upper contact is conformable and the lower contact is disconformable. Middle Eocene age is assigned to this formation.

Kohat Formation

"Kohat Shale" name is suggested by (Eames, 1951) with three subdivisions of "Nummlitic Shale", "Kohat Limestone" and "Sirki Shale" later on (Meissner et al., 1952) suggested its name as "Kohat Formation". The type locality of this formation is near Kohat-Khushal Ghar Highway in Kohat Region. The lithology of this formation is limestone of thin beds and shale at the base of greenish color. It is 70 meters thick in the south of Lachi in the Kohat area. The Kohat Formation is underlain by Habib Rahi Formation while overlain by Kuldana Formation. The both upper and lower contact are conformable. Eocene age is assigned to this formation.

Murree Formation

(Wynne, 1974) suggested its name as “Murree Group”, (Lydekker, 1883) named it as “Murree Beds”, and Pilgrim named it as “Murree Series” and then Stratigraphic Committee of Pakistan suggested its name as “Murree Formation”. This formation consists of clay of dark red and purple color, sandstone of purple to greenish grey color having medium to coarse grain sandstone. Shale is also present with marl. The common things in sandstone are the veins of calcite and quartz. The Murree Formation is underlain by the Kamlial Formation while it is overlain by the Kohat Formation. The upper contact is transitional while the lower contact is unconformable. Miocene age is assigned to this formation.

Kamlial Formation

(Pinfold, 1918) named it as “Kamlial Beds”, and then Stratigraphic Committee of Pakistan assigned its name as “Kamlial Formation”. The location of this formation is in the southwest of Kamlial Village in District Attock. It consists of sandstone of purple grey to red color and medium to coarse grained. Red shale is also identified in this formation. The most extensively distributed formation in Kohat-Potwar area is the Kamlial Formation. This formation is underlain by the Chinji Formation and overlain by the Murree Formation. Both the upper and lower contacts are conformable. Middle to Late Miocene age is assigned to this formation.

Chinji Formation

First name of this formation was “Chinji Zone” suggested by (Pilgrim, 1913) and then (Lewis, 1937) suggested its name as “Chinji Formation”,which was finally accepted by the Stratigraphic Committee of Pakistan. The location of this formation is in the south of Chinji Village in District Attock. The lithology of this formation consists of fine to medium grained sandstone, clay of red color, yellowish grey sandstone is present in the formation, it also identified in different colors like whitish grey and grey color of fine to medium grain size. The Chinji Formation is underlain by Nagri Formation while it is overlain by Kamlial Formation. The upper contact is transitional while the lower contact is conformable. Late Miocene age is assigned to this formation.

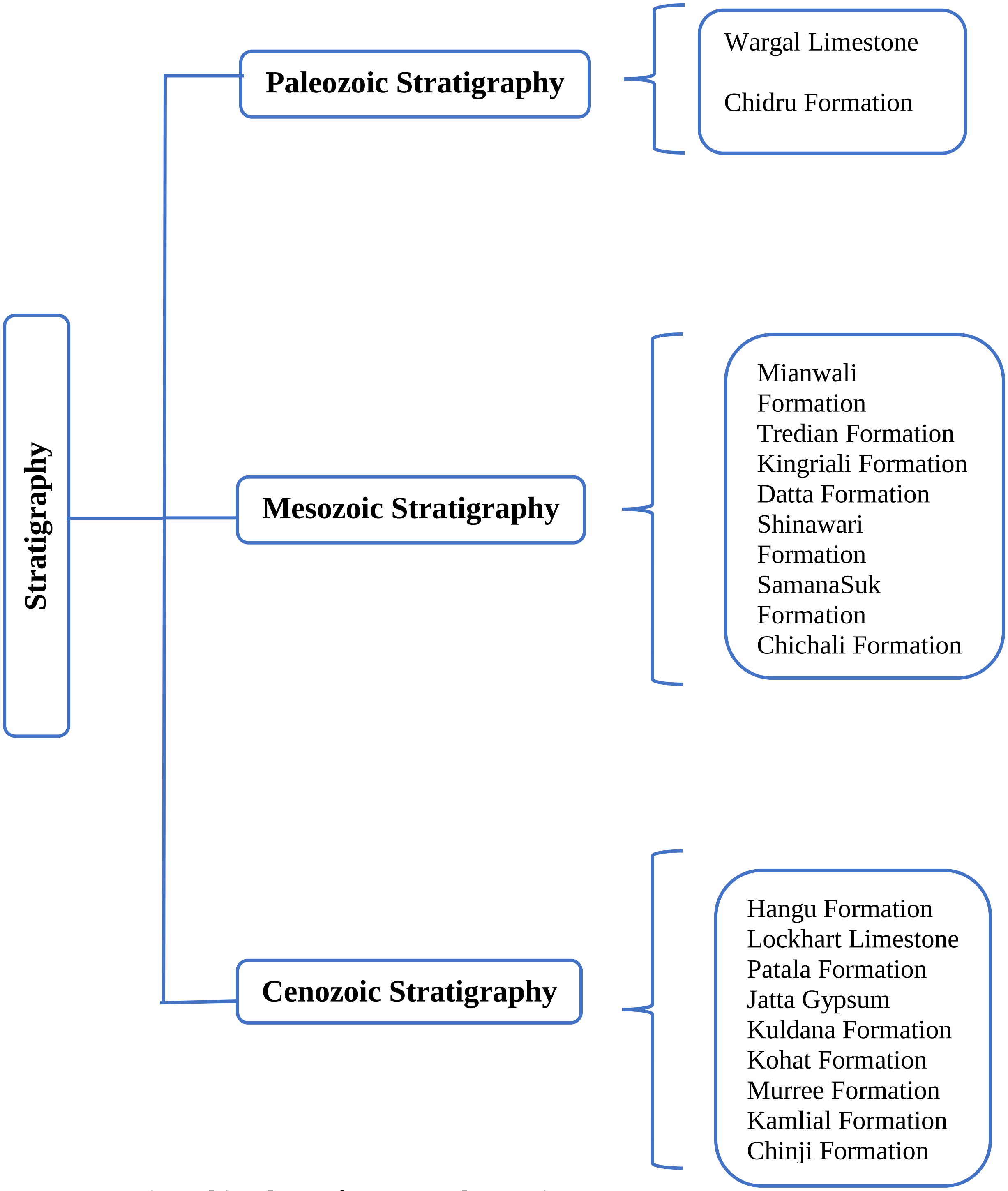


Chart 2.1: Stratigraphic Chart of Upper Indus Basin.

2.3 Petroleum system of the study area

Hydrocarbon Potential

There are many source rocks present in the Upper Indus Basins having age ranging from Pre-Cambrian to Paleocene. The Lockhart lime stone showing good potential for hydrocarbons, similarly the Datta sandstone also have potential and many other formations are considered as a good source rocks in Kohat-Potwar area of Upper Indus Basin.

Source Rock

Many source rocks were identified in the Kohat-Potwar sub-basin and the surrounding areas from Infra Cambrian age to Eocene. The shale of Patala Formation and shale of the Lockhart Limestone are considered as the main source rocks of Kohat-Potwar area. The value of Total Organic Carbon (TOC) in Upper Indus Basin ranges from 3.75% to 20%. The TOC value of Patala shale of Paleocene age ranges up to 10.73 % showing good potential for oil and gas in Kohat-Potwar Basin. The coal and coaly shales in the Patala Formation and the Datta Formation also show good source rocks.

Reservoir Rocks

There are good reservoirs rocks present in the Upper Indus Basin having age ranges from Infra Cambrian to Miocene. In Kohat region the Samana Suk Formation is considered as a reservoir rock through petrophysical analysis, other reservoir rocks are identified as the Lockhart Limestone and the Datta Formation. The clastic and carbonates of age Infra Cambrian are targeted as reservoir rock, clastics of Permian, Middle Jurassic, Lower Cretaceous, Upper Paleocene, Lower Eocene and Miocene are also considered as a reservoir rock in Upper Indus Basin.

Seal Rock

The good seal rocks in Upper Indus Basin are the thick layers of shale and evaporate of age Infra Cambrian. Inter bedded shales, mud stone and siltstone act as a seal for Cambrian reservoirs. Intraformational shale and Limestone act as a seal to Mesozoic and Cenozoic Reservoir. Miocene shales and Paleocene shales in Patala Formation act as a regional seal in our study area.

Trapping Mechanism

In Kohat –Potwar area both types of traps are possible either structural trap or stratigraphic trap. The eastern part of Potwar represents local pop up structure and thrusted anticlines. The northern part of Potwar area has Duplex Geometry, where the potential targets are thrusted anticlines. In Kohat area there are very complex deformation styles because of the strike slip movement. Possibly this area is represented by flower structures, pop-up structure, anticlines and fault propagated folds etc. Sub thrust traps are also the result of tectonic disturbance.

Chapter # 03

METHODOLOGY AND DATABASE

3.1 Work Flow

This thesis has two parts, first is related to Geology and second is related to Geophysics. In the first part different methods are used for the best output of my results that includes EasyTrace and Techlog software and the results on data given by DGPC. Well correlation is done by using well tops, here we make a separate file from well tops file to upload it on software, and then by using this file the correlation is done. Similarly, the identification of Electrofacies is done by uploading data and using different logs i-e NPHI, POTA, THOR, RHOB etc. by applying non-supervised approach, on the results we apply cut off on a fix density, then based on different densities we can separate many Electrofacies. Different cross plots of logs show different behavior with different lithologies.

In the second part, Basic Rock Physics is done by finding the velocities of seismic wave i.e., Vp and Vs. With the help of sonic log and then based on these values we can give the ranges of velocity in different lithologies to show them separately. In basic rock physics we can separate different lithologies on the basis of velocity variation. Total Organic Carbons is also calculated by using logs. At the end Fluid Substitution is done by giving input Las file of different logs. The behavior of log is different in water and other fluids, firstly we find the behavior of logs in given data then by giving different input values of fluid we can detect the change of behavior to find the best match of file. On the basis of this process we can fine the hydrocarbons reserves in given well.

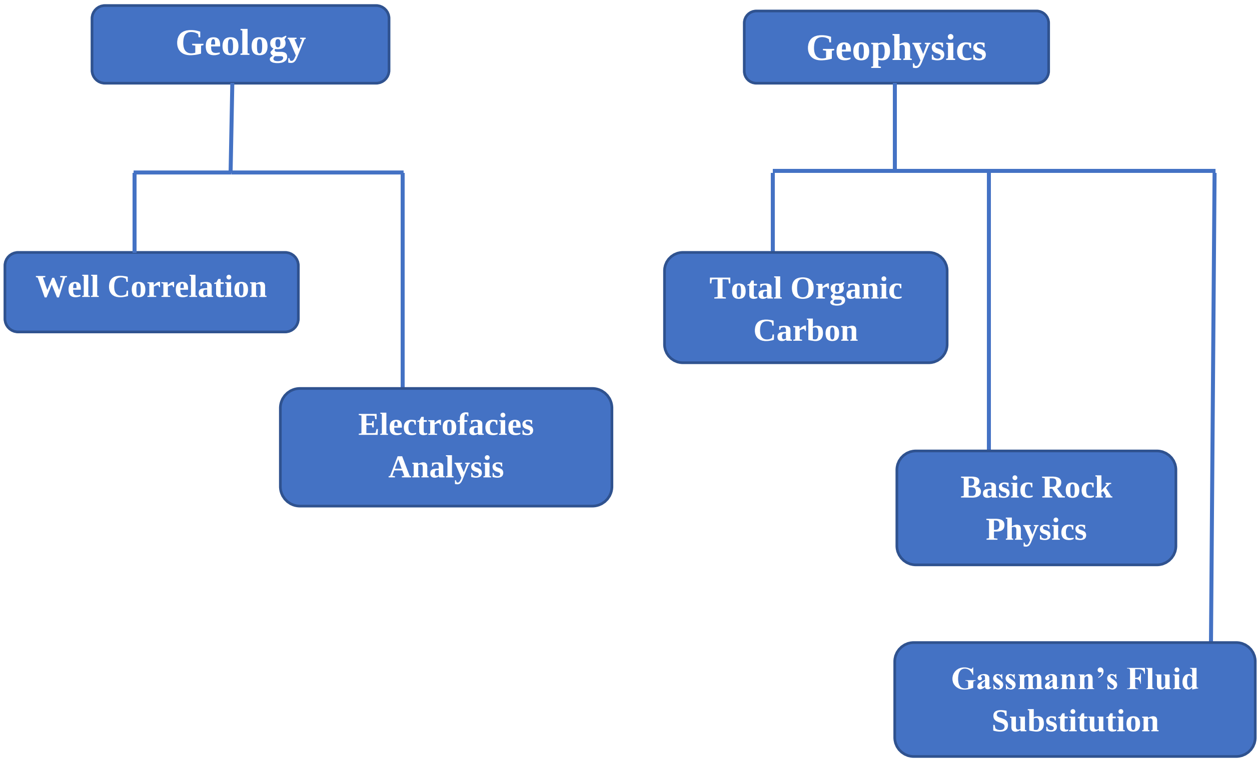


Chart 3.1: Division of different mechanisms included in this dissertation.

3.2 Introduction of Software used

EasyTrace

EasyTrace software is a part of Open Flow Suit that deals in different software's such as Cougar Flow, Puma Flow, Temis Flow etc.

EasyTrace Software is 1D data editing and processing tool. It is multi-disciplinary software used for featuring under a very productive package and a verity range of functions which are very useful for Geologists, Geophysicist as well as Reservoir Engineers. Data obtained from Well is in different formats i-e LASS, LASS.2, ASCII, SEG-Y etc. having different rate of sampling. This data requires suitable processing for geological and geophysical modeling. Our main study is to locate Reservoir rocks and this reservoir characterization requires specific log editing and processing, for example we can determine rock-type through log data, seismic signatures, density factor and many more information we get from log interpretation. The main workflows of EZT (EasyTrace) are as follow:

1) Data Management:
    i) It can import and export the major formats of Well Logs used in industries.
    ii) Processing of 1D type of any data: discrete or continuous, cores and SCAL, markers or time and depth domain with different sampling.
    iii) Easy edition of data, various functions available for processing and calculation.

2) Main Geoscientific Functionalities:
    i) It includes geophysical-oriented functions includes simulation of signals, filtering and smoothing of log trace, log correction, velocity estimation and AVO/AVA modeling.
    ii) Gives best results regarding to wells issues like TOC estimation, rock physics, pore pressure prediction.
    iii) Supervised and non-supervised approach for geological purposes also gives best results for water saturation modeling and core analysis integration.

3) Data Display:
    i) EasyTrace displays data in the form of logs, histograms, cross plots or SCAL curves.
    ii) Data displayed is enhanced and include interactivity between logs.

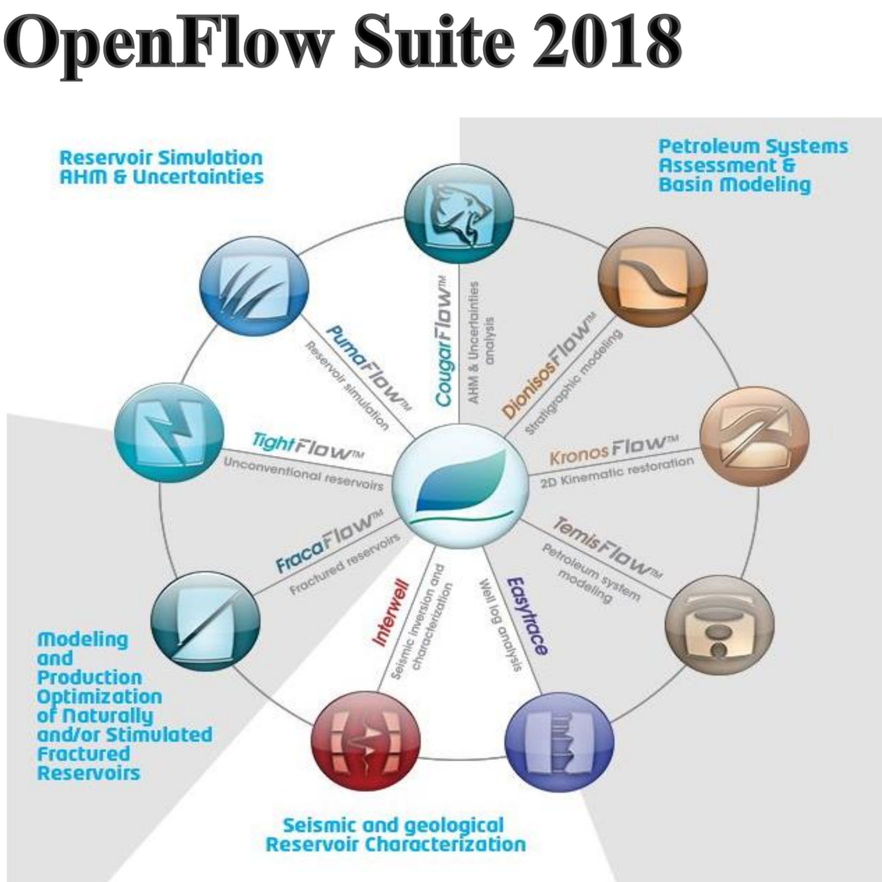


Figure 3.1 Different Softwares of Open Flow Suit.

Figure 3.2 EasyTrace Software Version 2017.2.

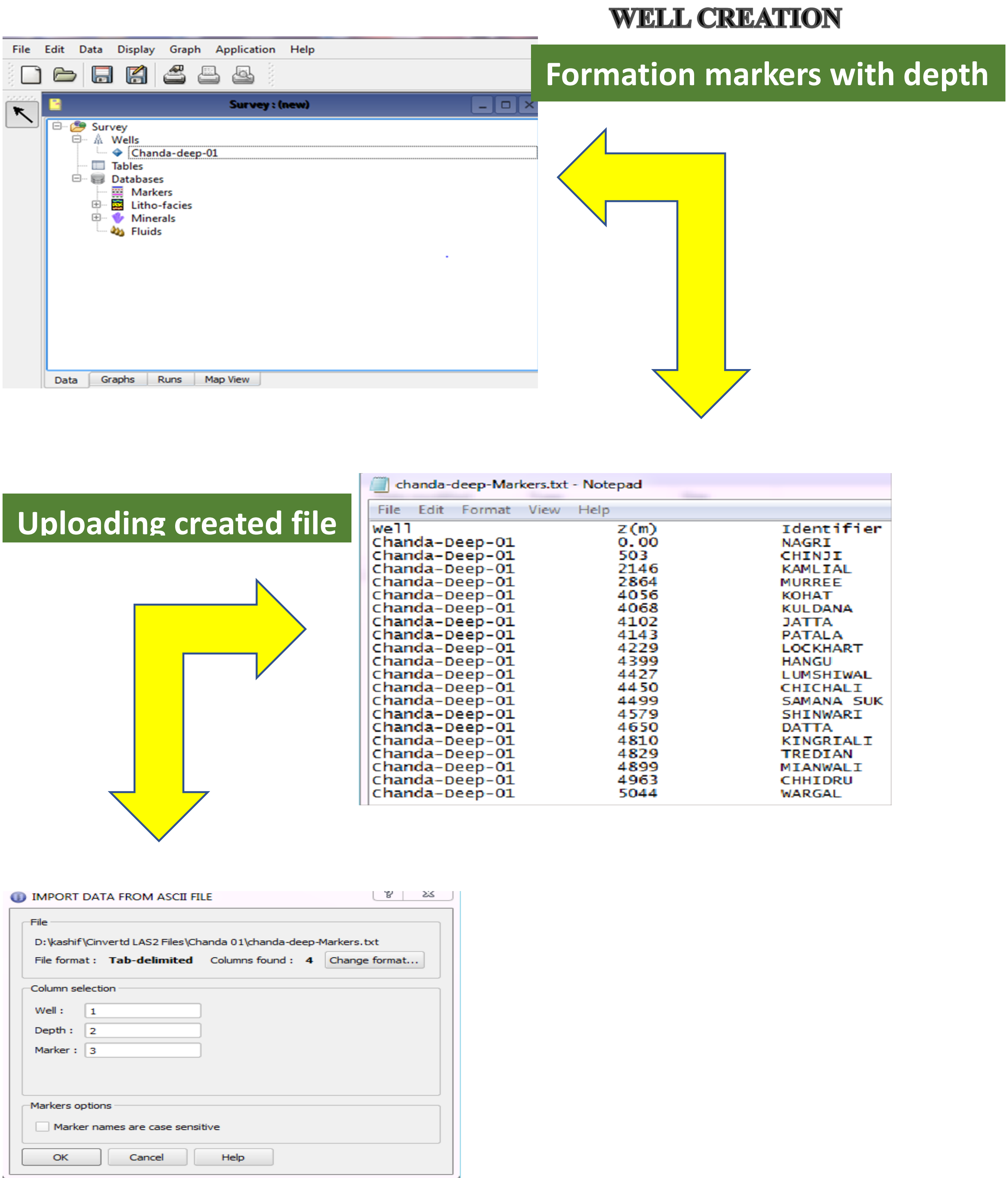
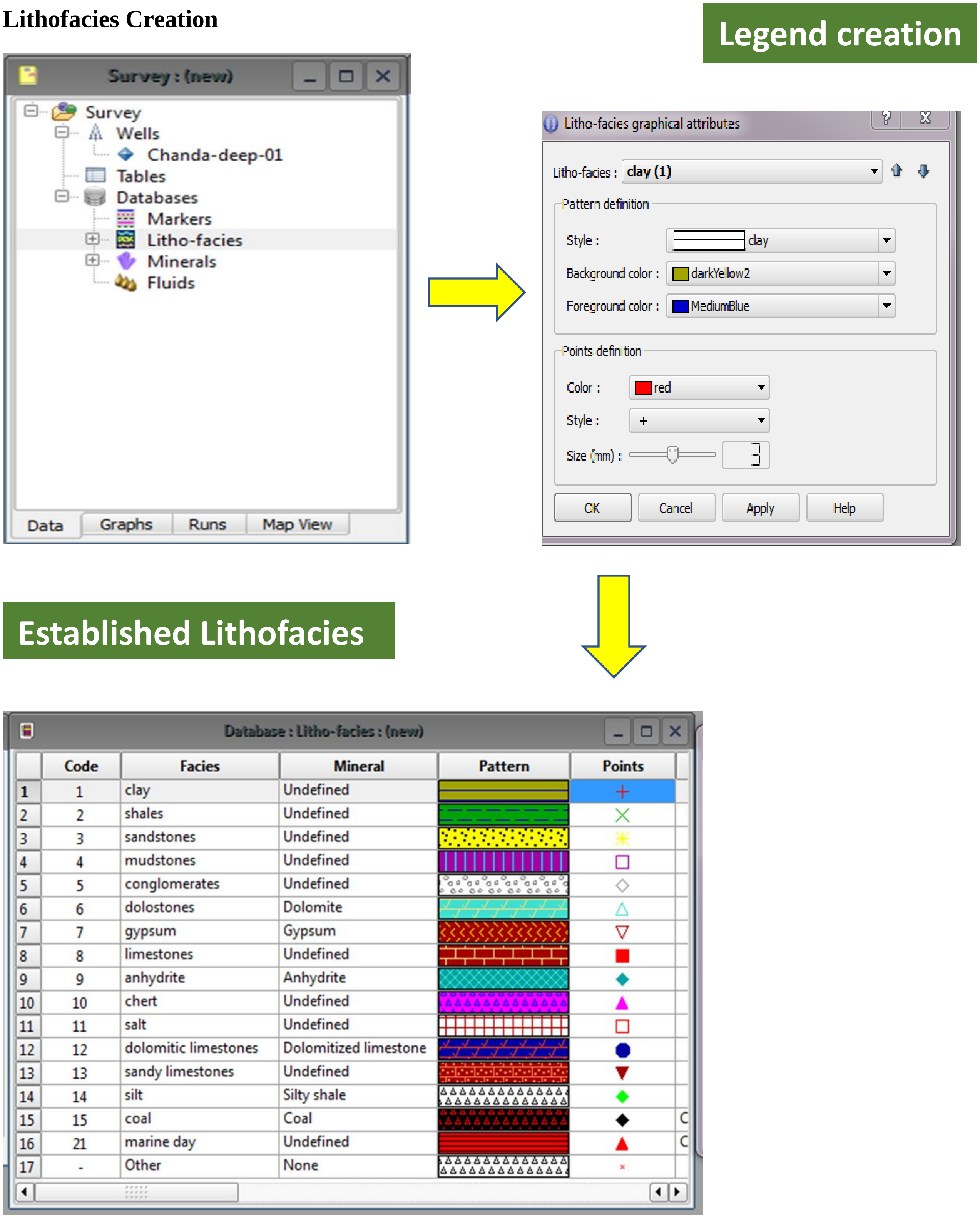


Figure 3.3 Working Mechanism of EasyTrace Software.

Lithofacies Creation



	Code	Facies	Mineral	Pattern	Points
1	1	clay	Undefined		
2	2	shales	Undefined		
3	3	sandstones	Undefined		
4	4	mudstones	Undefined		
5	5	conglomerates	Undefined		
6	6	dolostones	Dolomite		
7	7	gypsum	Gypsum		
8	8	limestones	Undefined		
9	9	anhydrite	Anhydrite		
10	10	chert	Undefined		
11	11	salt	Undefined		
12	12	dolomitic limestones	Dolomitized limestone		
13	13	sandy limestones	Undefined		
14	14	silt	Silty shale		
15	15	coal	Coal		
16	21	marine day	Undefined		
17	-	Other	None		

Figure 3.4 Established Lithofacies on EasyTrace.

UPLOADING LAS FILES – Chanda Deep 01

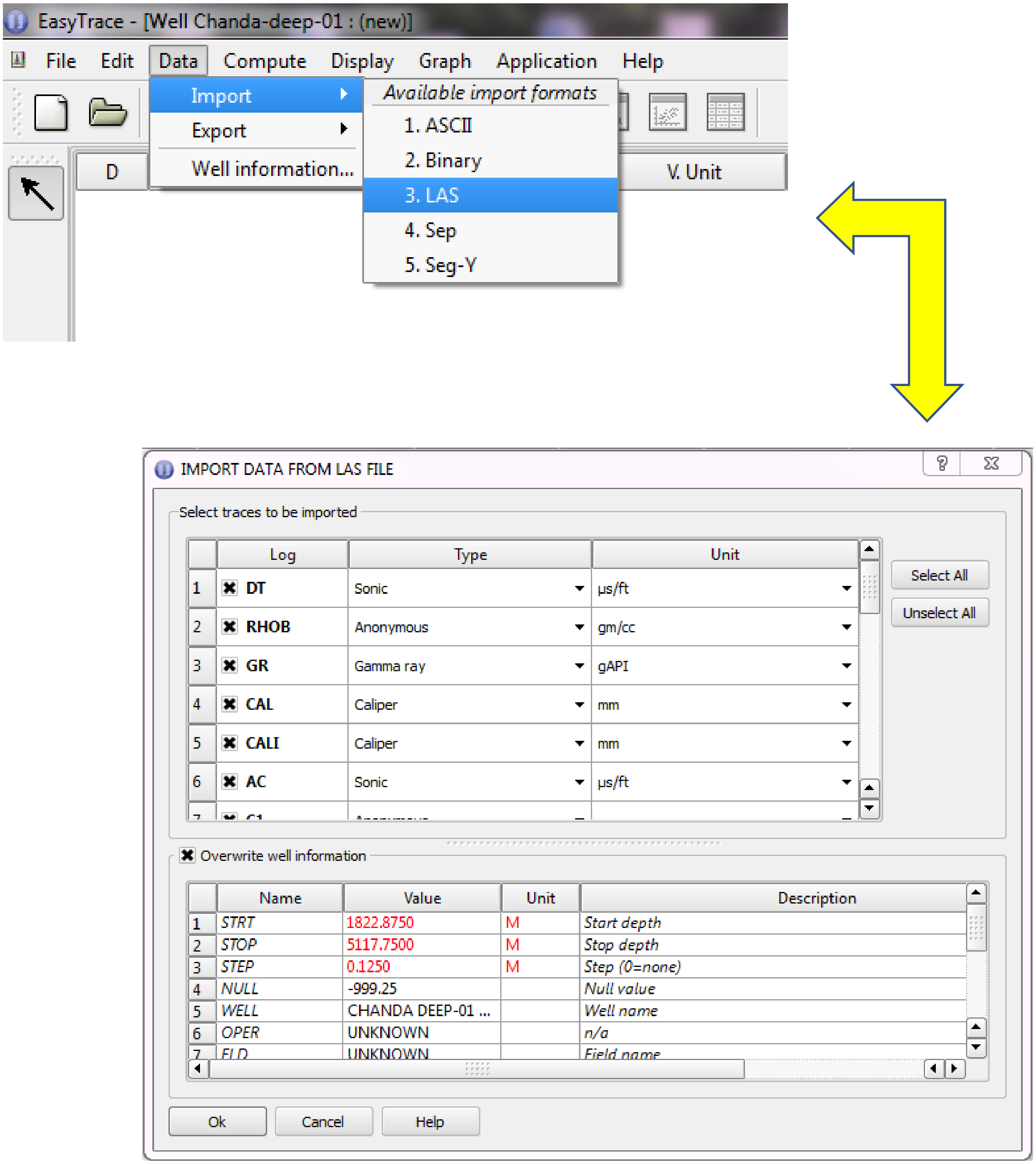


Figure 3.5 Uploading LAS File in EasyTrace Software.

TRACE DISPLAY

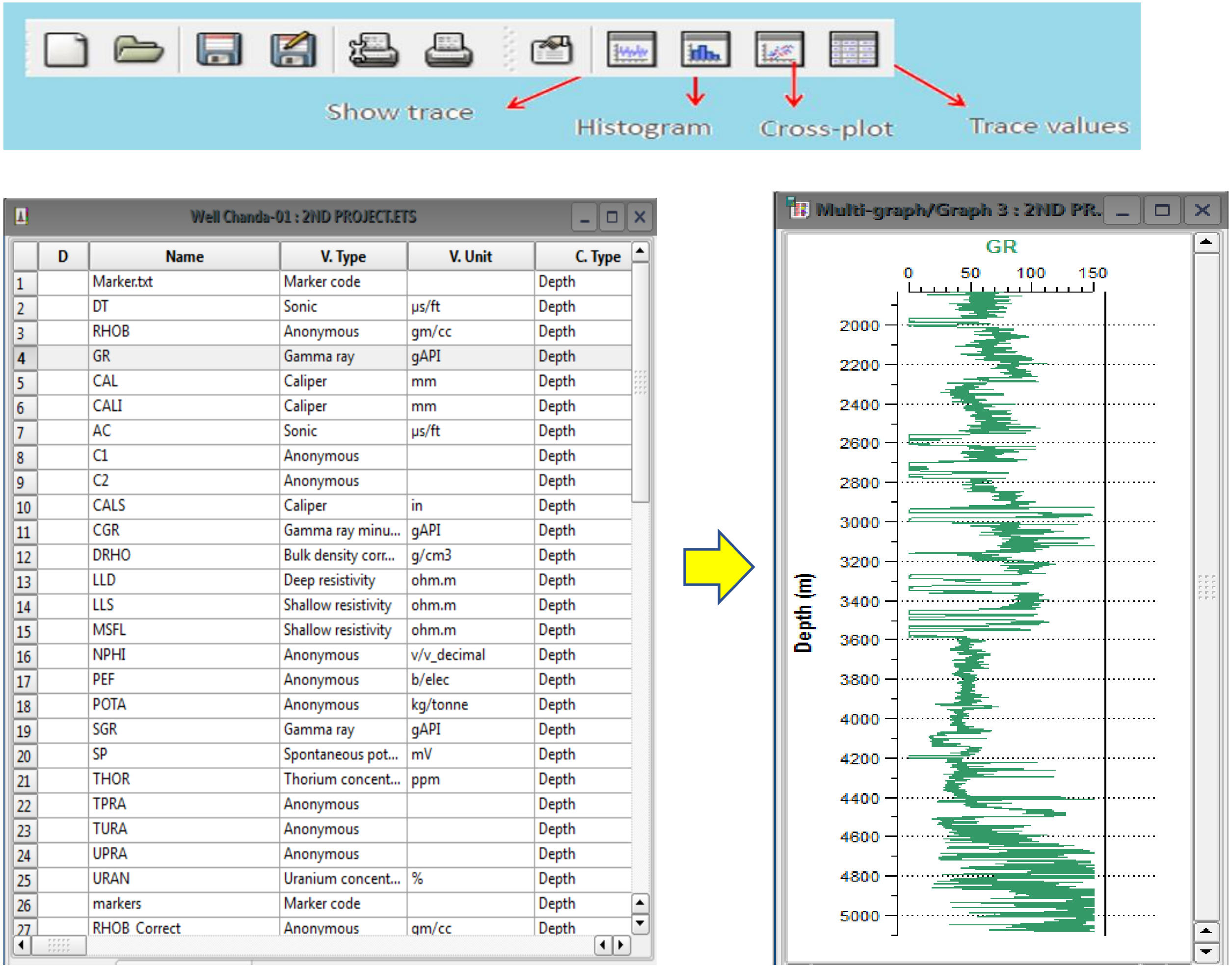


Figure 3.6 Trace Display of GR Log on EasyTace.

3.3 Database

Data used for thesis work is provided by Land Mark Resources (LMKR) with permission of Director General of Petroleum Concession (DGPC). This data includes:

LAS File, Headers and Well Tops of Chanda-Deep-01, Chanda 02 and ISA-Khel

Chapter # 04

RESULTS

4.1 Electrofacies Analysis

Data of Well-Log in LAS format is combination of depth values (z) and that log is related to each value of depth and can be represented as:

[X] = […. (Xij) ....]

Here X log is represented and "j" and "i" are the points for which the value of log is to be measured.

Samples given are in a p-variable hyperspace and in this hyperspace every axis is linked to the measuring tool. So electrofacies is nothing it is just the group of depth values (z) in space. The geological meaning of electrofacies is a priori known and from core data it must be interpreted.

Display of samples in log hyperspace:

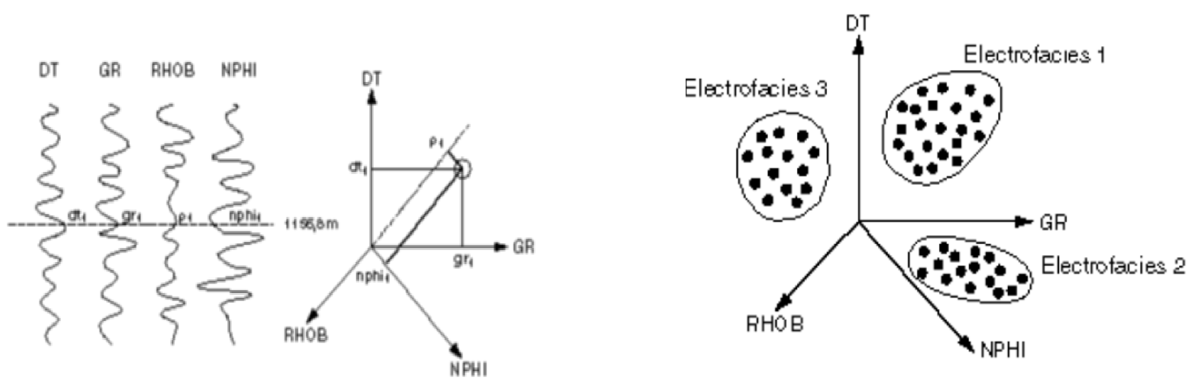


Figure 4.1 Electrofacies Display in Log Hyperspace.

Electrofacies are generated by combining the numerical analysis of data with the standard interpretation of geological logs. Then we use geological knowledge about porosity and density and using well log data we can predict the maximum and minimum values of density as well as porosity for the prediction of reservoir. We can develop a cross plot between different logs to generate results. (Ye and Rabiller, 2000).

Electrofacies depends upon the value of "z" in space, at first we have to check the logs to locate values of "z" by this we calibrate the logs and then these logs will be corrected in depth. Among different logs Geologist have to select the most suitable log as some logs don't provide much help for interpretation. It's better to choose firstly 3 or 4 logs which are standard (eg: RHOB, NPHI, GR) then for other evaluation these can be validated. Here we used THOR, NPHI, POTA and RHOB; we didn't use SGR as it might be dismissed with its spectral component. Data obtained from different measurements with different units so for its geometric analysis this data can be compared and this can be done when we have data from different measurements and having same units, mostly data is standardized by default but this normalization distort the data and if data to be compared have the same units then this normalization step is not important. EasyTrace allows the best view of cross plot or logs which allow an interactive interpretation of data and to choose the best parameters.

Here we have calculated the relation between DT log (density log) and Neutron Porosity Log (NPHI) to classify the Electrofacies of given wells by which we can calculate the maximum concentration of density and porosity as shown in Figure.

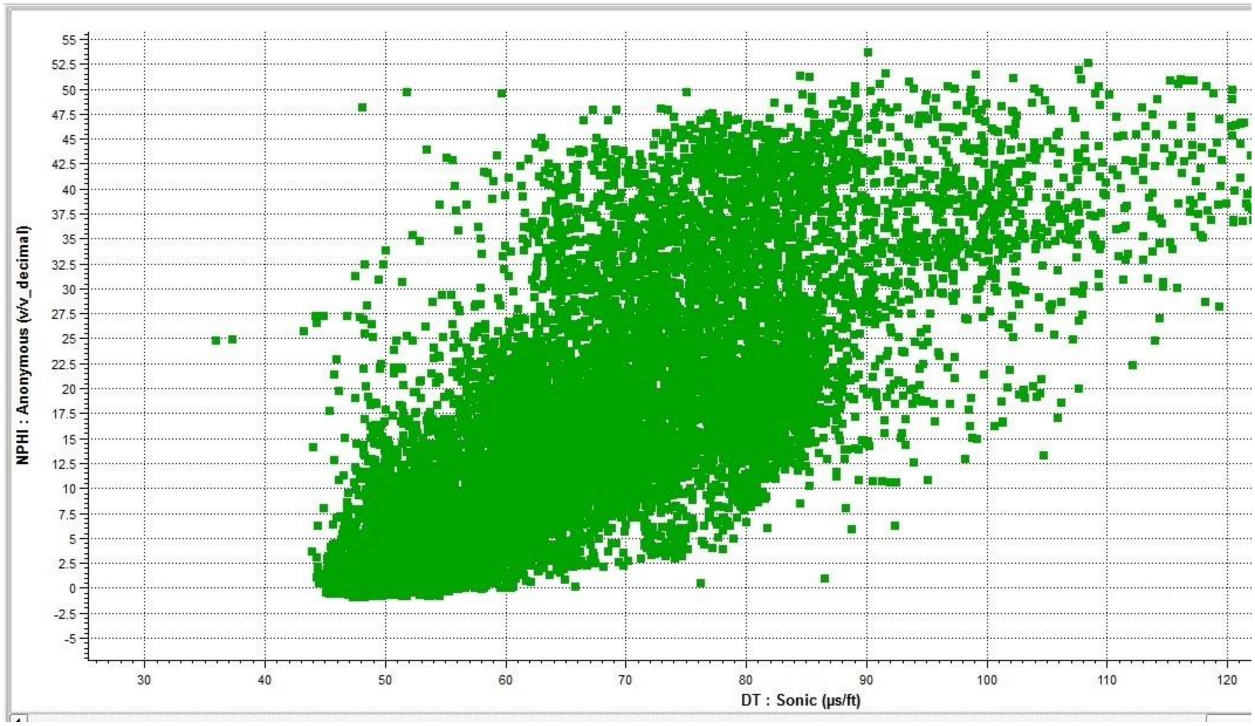


Figure 4.2 Clustering of points using NPHI and DT Log in Chanda Deep 01.

We can classify Electrofacies be using EasyTrace, and this software offers two different type of classification methods:

- Supervised Approach
- Non-Supervised Approach

Here we apply the Non-Supervised Approach.

4.1.1 Non-Supervised Approach:

A non-supervised approach for density can be divided into three main steps

- Density Function Estimation,
- Density Function interpretation: number of classes, creation of the training samples,
- Data point assignment.

4.1.2 Density Function Estimation:

As an electrofacies is just the gathering of points having high and low density in the log hyperspace, so they are separated by the area having high and low density. By identifying and studying the change of density at different points, it is possible to identify different zones and number of sets. Then density can be divided into number of classes according to the density peaks. (Lee and Datta-Gupta, 1999).

In statistics the probability density function (pdf) f(x) is the most important concept. This describes the random distribution of variable X and gives result of its associated probabilities by using the formula:

$$P\ (a<X<b) = \int_a^b f(x)dx \qquad \forall\ (a<b)$$

The result can be displayed by histogram as:

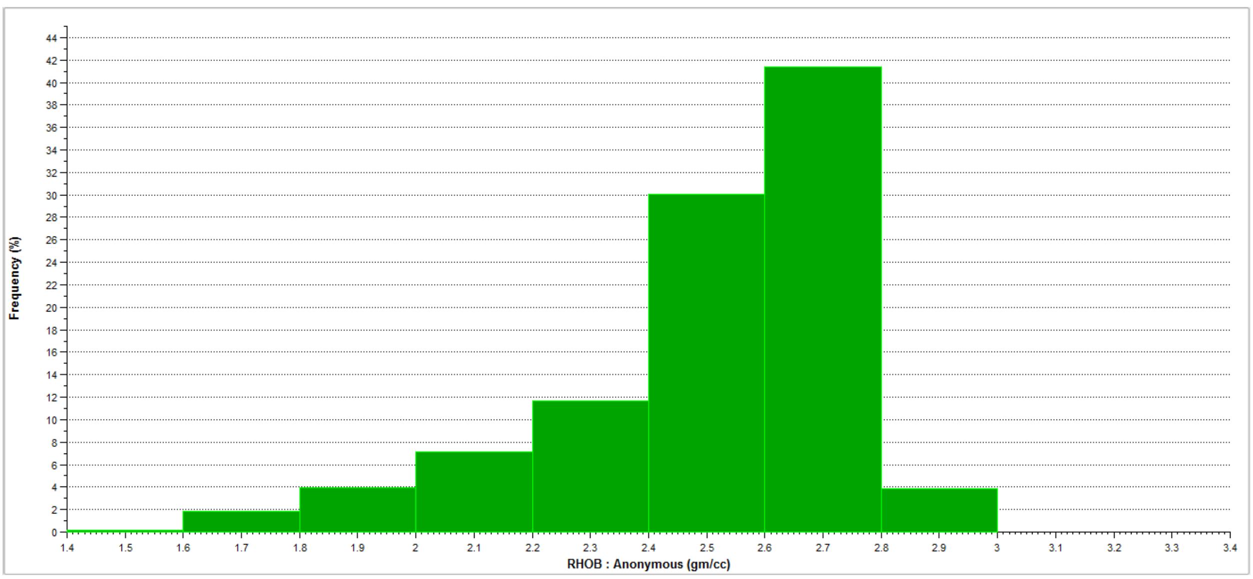


Figure 4.3 Histogram of different facies in Chanda Deep 01.

But this histogram does not the good presentation of density estimator as for a particular value the number of samples are not displayed, this only present the number of samples that fall in an interval:

$$f\ (\dot{x}) = \frac{fi}{h} \qquad \forall x \text{ in the interval of length h}$$

For more accurate estimation of density, EasyTrace can allows two methods

- The Kernel Method
- The K Nearest Neighbour Method.

4.1.3 The Kernel Method:

In this method the function f(x) can be approximated be using formula:

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} K.\frac{x-xi}{h} \qquad (x) = (n \text{ samples } \{x1,,xn\})$$

Here we suppose K(x) = 1 and if range of x is [-1/2;1/2] and 0, then K is the indicator function on [-1/2;1/2]. Total number of samples present in the moving interval is represented by f(x) and K is the Kernel Function. By using this method the estimation is much better as compare to histogram but still we have discontinuous function so we add a continuous kernel function to make it smoother to display different density regions. There are two functions for kernel function; a Gaussian kernel and an Epanechnikov kernel. Mostly we use Gaussian kernel and they are given by formula as:

Gaussian Kernel:

$$K(u) = \frac{1}{\sqrt{2}}\exp(-\frac{u^2}{2})$$

An Epanechnikov kernel:

$$K(u) = \frac{3}{4\sqrt{5}}.(1-\frac{u^2}{5}) \qquad \text{For } |u| < \sqrt{5}\text{ , otherwise 0}$$

The second formula is complicated but the mathematics it has, have interesting properties so we use here the Gaussian kernel. In the above mentioned formula the "h" is known as "smoothening Parameter" and it is directly related to density if the value of h is too small then the density function will be rough and if it has high value then the function of density will be over smoothed.

4.1.4 The K-Nearest Neighbour Method (KNN)

In this method the given number is "k" and this indicates the k nearest number of samples around "x". Suppose the distance between "x" and most distant of its neighbor is dk(x) then the density function in following is given by:

$$f(x) = \frac{\alpha}{dk(x)} \qquad \text{Where } \alpha \text{ is a constant value}$$

This indicates the inverse relation between dk(x) and x, where the value of dk(x) is small the density will be high as there are a lot of points located near "x" and if the value of dk(x) is high then density will be low as very few points will be located near "x".

The density function of above method is not estimated in uni-dimensional space but it can be estimated in p-dimensional space by using the p-log. If we use only one variable then the density function obtained is curve. If we use two variables the density obtained is in peak form like a topographic surface, so as we use more variables for density it will be difficult to recognize. However, there are different methods to recognize density peaks. By this method Kittler used the following ways to estimate the density:

- A random point is chosen.
- To calculate the slope in all direction he defines a neighboring method.
- Greatest slope is used to move next points as far uphill.
- This process is continued unless density peak is obtained.
- And by the same way the points moving downhill are selected to identify the density zone.

Firstly, we have to define the scale for electrofaceis to identify. We have defined 7 types of electrofaceis with different presentation.

Here we have applied Kernel method then K nearest neighbors' method as it is easier to obtain parameters and it is more reliable. The density can be shown is the form of graph as shown in figure:

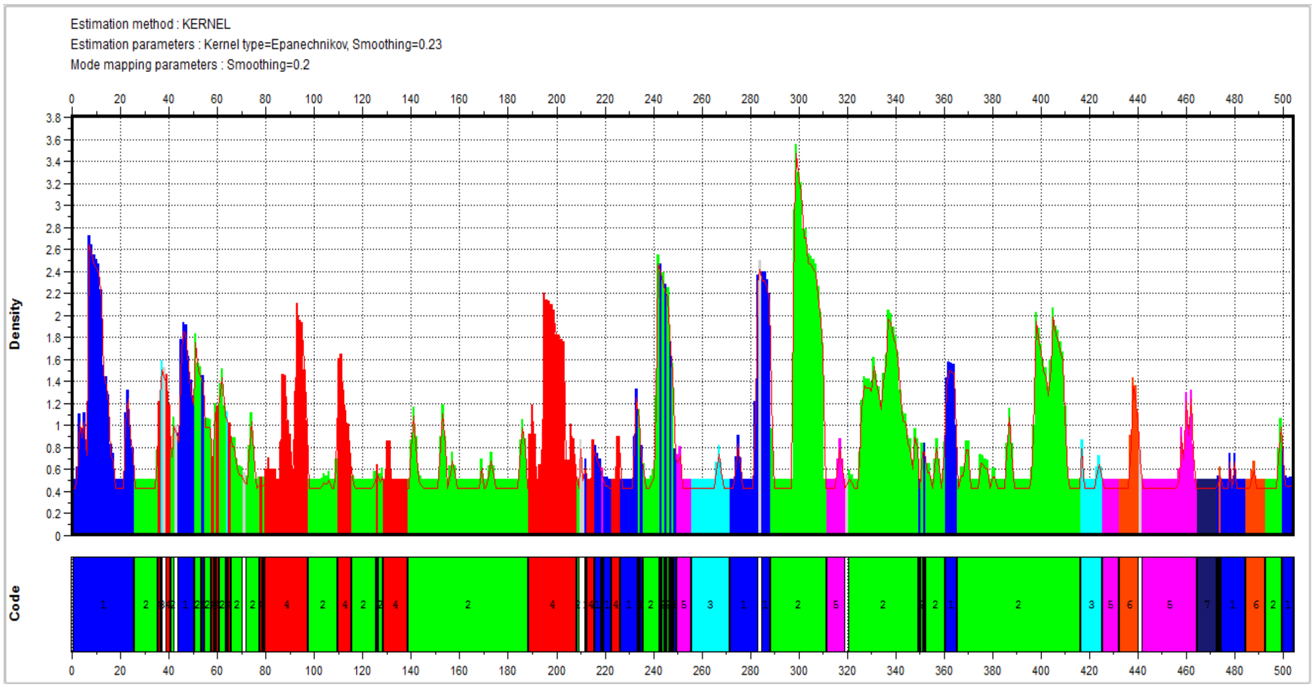


Figure 4.4 Densities of different facies with respect to clustering of points.

We have divided this curve into different zones showing different variation in density with respect to depth. The density is along y-axis and the distribution of point (x) is along x-axis with depth. Cut off is applied over the density of 0.5, then we have marked 7 different types of electrofacies. Then plotting them with different logs we can identify the nature of facies either there is clay, sandstone, limestone etc. if we plot the histogram of these values of density we can easily identify different facies. By showing these facies on 2D plot we get this plot that differentiates these facies with color in Figure:

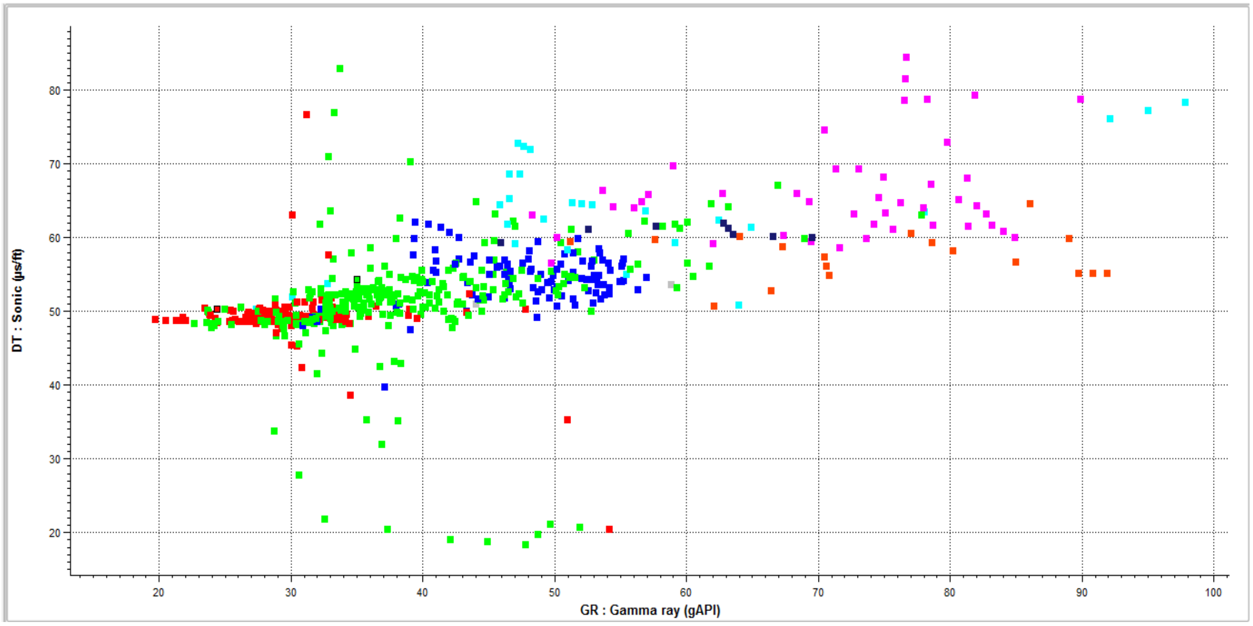


Figure 4.5 Dispaly of Electrofacies and their clustering.

Here we have differentiated 8 types of facies with different colors. By marking the zones from them we can easily identify them and interpret them as shown in figure:

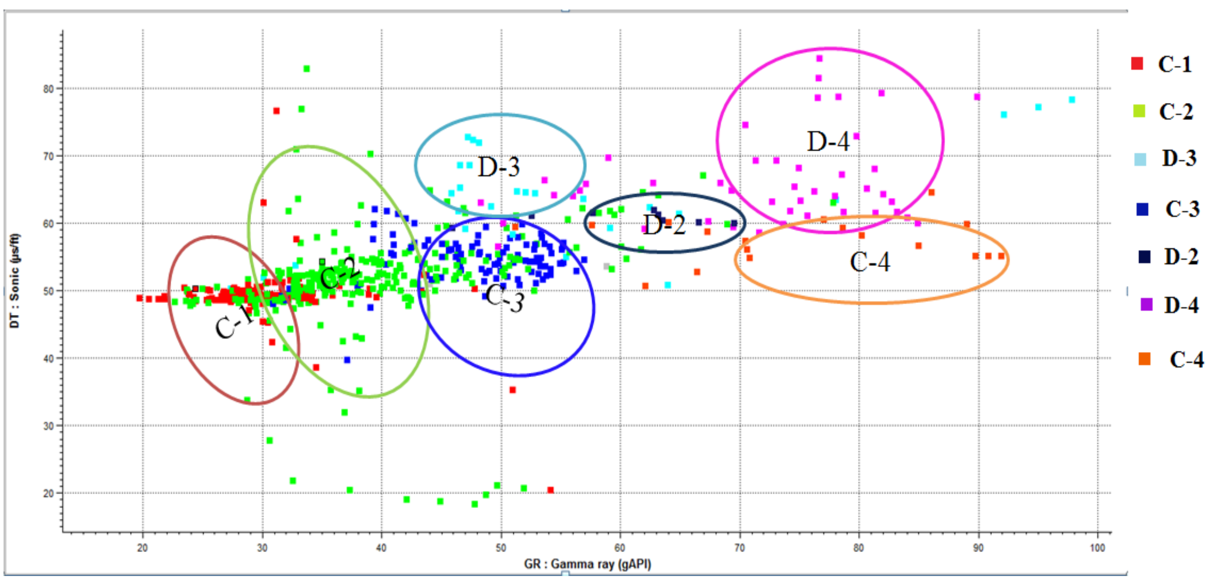


Figure 4.6 Marked Seven Electrofacies in Chanda Deep 01.

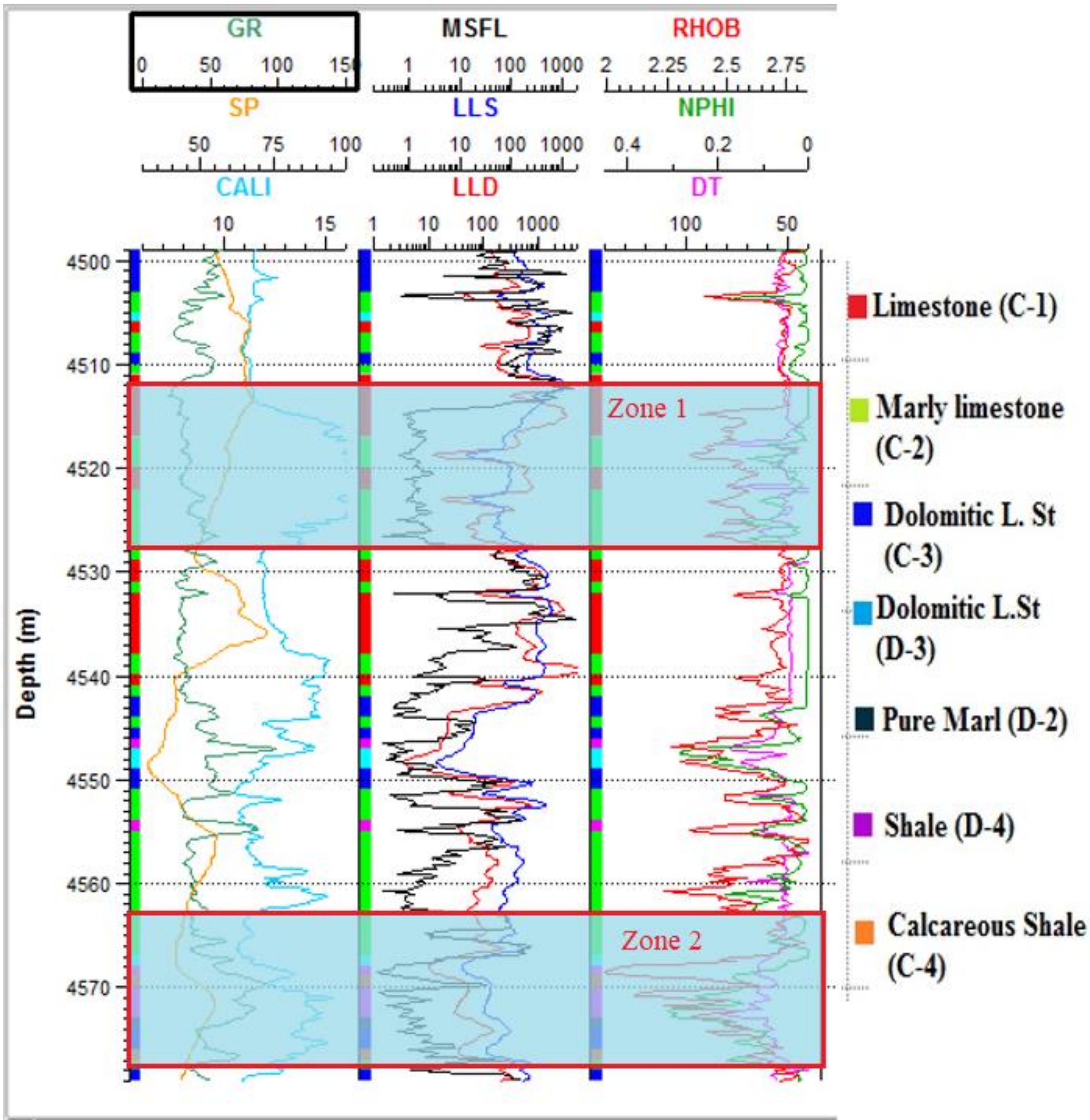


Figure 4.7 Electrofacies in Log Hyperspace with depth in reservoir zone of Chanda Deep 01.

A Direct Validation Tool:

After choosing the assignment methods these training samples are kept as non-allocated points. The efficiency of this method can be evaluated by calculating the percentage of well assigned samples which are allotted to their actual class.

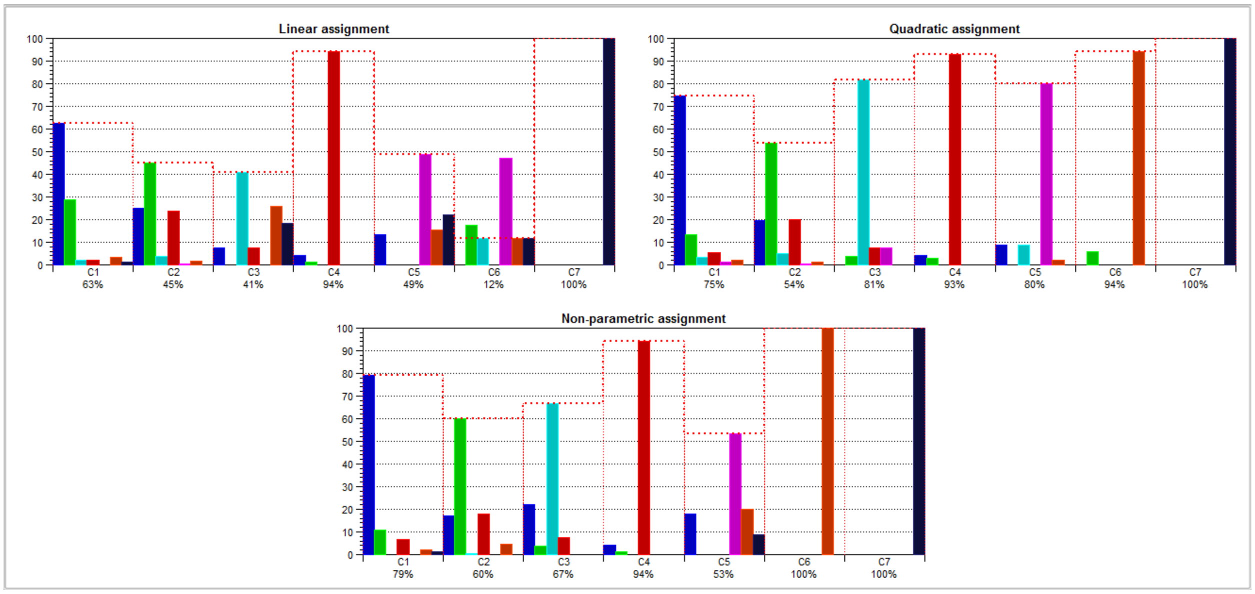


Figure 4.8 Display of Direct Validation Tool of all Facies.

A Cross Validation Tool:

In this method before making the classification rules the sample is taken out of the training sampels and the seprated sample is re-allocated using these rules. This is the more realistic method to find the classification efficency, it will be more pessimistic but realistic. This method is intersting in both cases i-e linear as well as quadritic, but only when points to be determine are not in a large number. This method can be presented in this picture as follow.

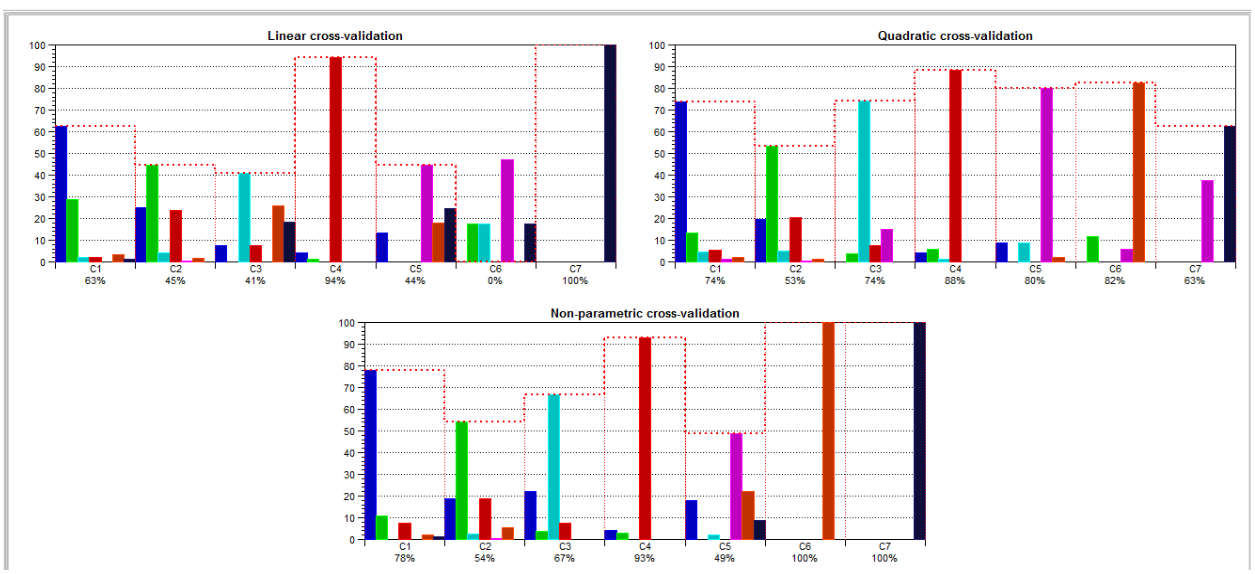


Figure 4.9 A Cross validation tool of all Facies.

EasyTrace also allows to visualize the variables on the basis of discrimination performance and this criteria worls for linear hypothesis which uses the Huygens theorem, defined as:

$$T = B + W$$

In this equation

T: total variance and covariance matrix.

B: matrix of interclass variance and covariance which is computed between classes matrix.

W: varriance and covariance within the classs matrix.

Above all three principles were computed in each step.

- The squar of average canonical correlation based on matrix to be studied.
- The Wilks' Lambda = detW/detT.
- The eigen values of the matrix under study.

Canonical Correlation and Wilks' Lambda

To access the global quality of the discrimination these two factors were studies.

- If the value of Wilks' Lambda is small then the value of canonical correlation, the discrimination will be better.
- And if both the parameters have equal valuee, their values changes inversely when the variables are introduced.

The Eigen Values of ($T^{-}1$).B

The eigen value of each ($T^{-}1$).B presents the discriminatory power of each factorial axis. If it has a large value near to 1 then it allows a good discrimination and if the eigen value is small or near to zero, then it allows not much intrest.

They can be interpreted by the following figure:

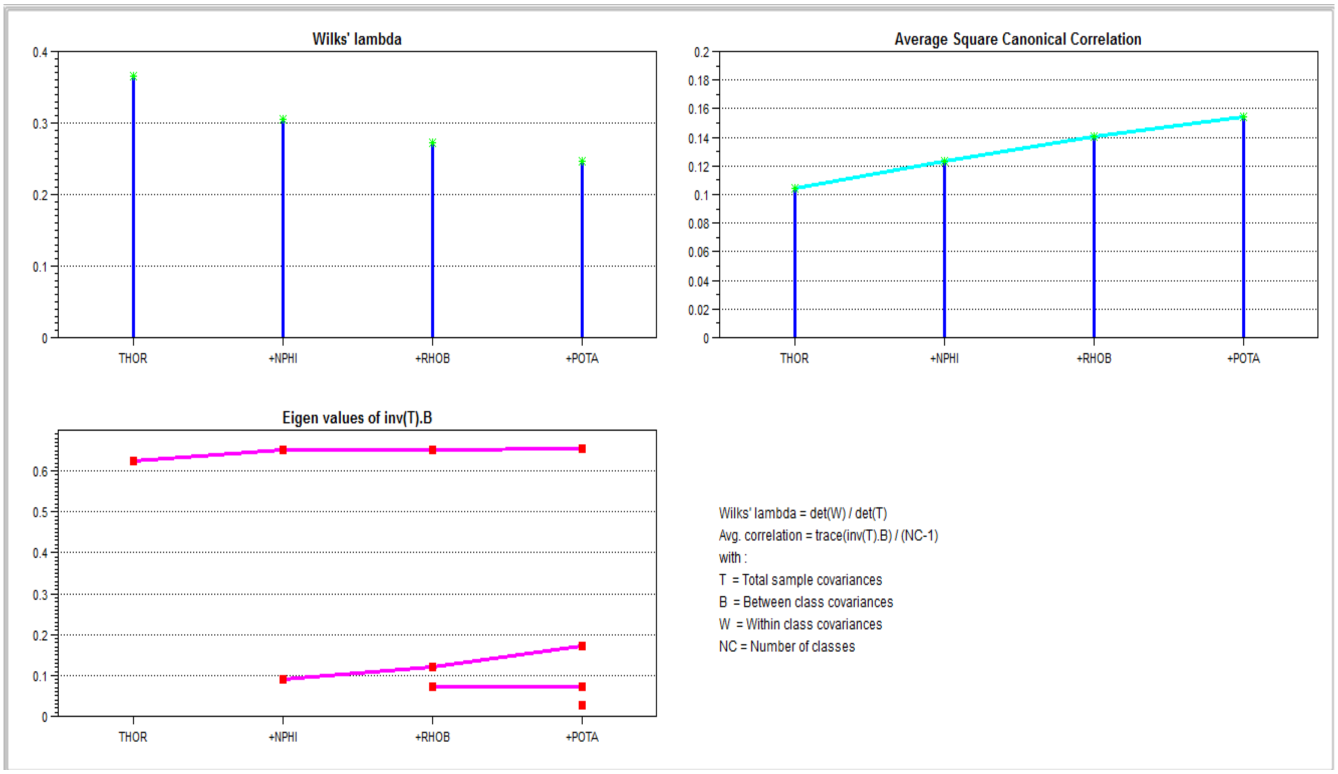


Figure 4.10 Canonical Correlations and Wilks' Lambda.

4.1.5 Supervised Approach

While considering a supervised approach we have training samples which comes from the interpretation of geologist priori data. The table for different classes is given which is a part of geological apriori, then the classification function is shaped according to these training samples. Using this function for classification all points all points were assigned a specifin class.

During the classification of non-supervised approach all classes and the training samples were decided form the density log for interpretation but in supervised approach we use the newely built training samples then define their different classes. Everything is known as in non-supervised approach in the discriminant analysis in this supervised approach we have to choose the hypothesis either linear quadritic or non-parametric.

During the non-supervised approach a geologist cannot identify the class of coal, by using the non-supervised approach those points are not detected which are scattered they can only be identified if they forms a statistical population. But in supervised the characteristics of points are close to the coal and they will be assigned to the class of coal. These all results depends upon the training samples so these samples are very important.

4.1.6 Supervised Or Non-Supervised Approach:

For the prediction of facies both methods can be used together, even we have a priori data information we can run both supervised and non-supervised approaches, and we can ensure the better control for the prediction of facies. For better understanding for the distribution of samples in a log hyperspace a non-supervised approach is used. Similarly a supervised approach can be the good method for priori data interpretation. In practical works, using the non-supervised approach we cannot identify the coals which are an important for study purpose. Similarly using the supervised approach we cannot properly identify the classes for the density function. Therefore both of the methods can be used.

4.2 Petrophysical Analysis and Well Correlation

4.2.1 Correlation

The correlation in geology is the technique according to which we can inaugurate the relationship between different strata of earth crust. Depending upon different features to be determined, correlation is divided into different kinds:

Lithological Correlation: this refers to the relationship between lithology of different wells and the position of lithostratigraphic position.

Fossil Correlation: this refers to the relationship between beds having same kind of fossils and their bio stratigraphic position.

Chrono-Correlation: this refers the correspondence in ages of different formation and in their chronostratigraphic position.

Correlation, for geologists is the main task specially when they have in oil and gas sector and it is also helpful in mining as well as hydrology. The most important data that is used for correlation is obtained from cores, well logs and cutting. Among these parameters well logs are most useful as they are continuous long readings and they are also balanced measurements and commonly available in field for number of wells. (Van Wagoner et al., 1990).

Different logs are used for finding different types of correlation. Logs obtained from field are sensitive to rock properties and fluid present in them. In circumstance most of them are more sensitive to fluids then the secondary parameter will be lithology so by using this technique we obtained lithostratigraphic correlation. Gamma ray log (GR log) and spontaneous potential log (SP log) are mostly used by geologists for correlation because these logs are commonly available and they contain sufficient amount of lithological signal. In the same way a lithofacies correlation can also be obtained if the above mention logs are shared with logs having textural information about bedding from borehole data or magnetic resonance logs. The most important use of borehole data and dip meters is to gain information about structure; this data is tied into seismic lines and can be concluded away into well correlation and maps.

Lithostratigraphic logs are consider as the most important logs for lithostratigraphic correlation but no logs, however present the mineralogical and lithological composition better than nuclear spectroscopy log because these logs are insensitive to the fluids present in the rocks. Gamma ray log is also important to lithological changes, but thorium, uranium and potassium are also among the important natural radioactive elements that occur as a noticeable element in rock-forming minerals. Through potassium log we can detect presence or minerals like mica, illites and potassium feldspar. Without change in any major lithology thorium and uranium logs occur for example slightly increase in heavy minerals in oil and tar reserves. Hence only gamma ray is not always useful in well correlation, for good lithological correlation this gamma ray measurement is naturally broken and thus potassium and other logs can be used for better correlation. (Rudman and Lankston, 1973).

Here we have data of three wells Chanda-Deep-01, Chanda-02 and Isa-Khel-01. Correlation is done between these wells by using different logs. Many formations are common in all these wells and some are common in individual well.

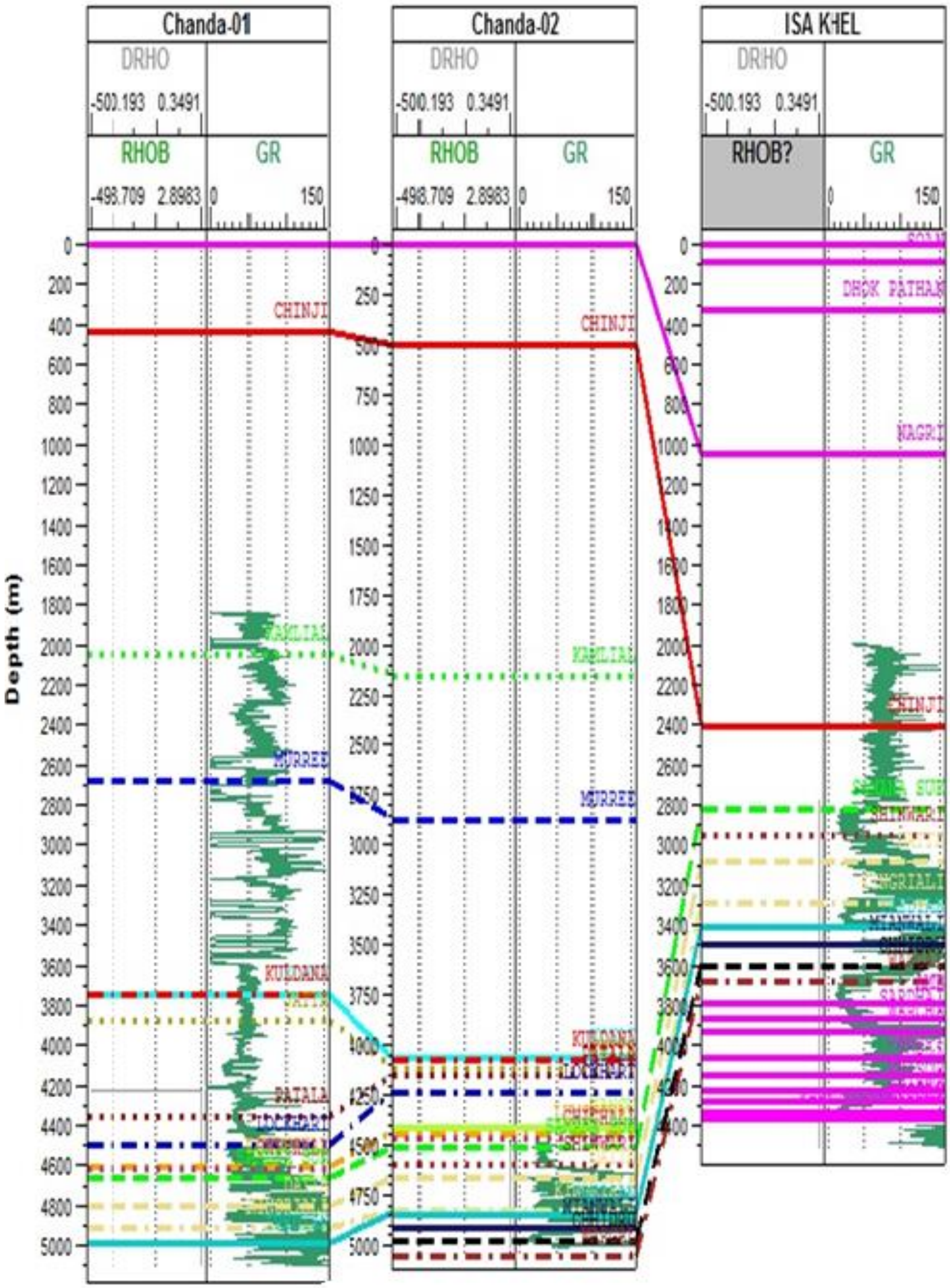


Figure 4.11 Correlations between Chanda-Deep-01, Chanda-02 and Isa-Khel.

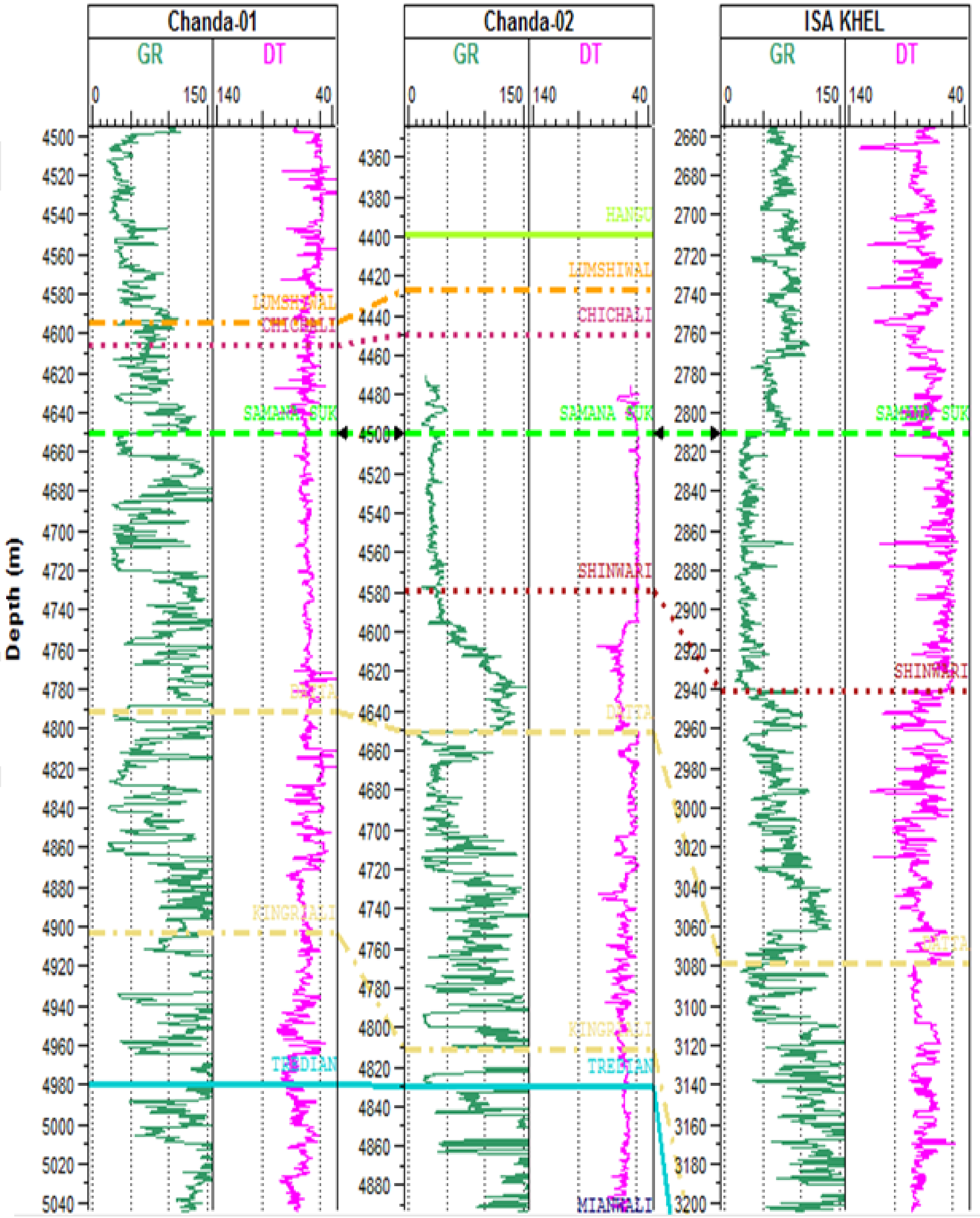


Figure 4.12 Correlation of different formations.

4.2.2 Well Logging

Well Logging is the French Word which means "electrical coring". Well logging can be defined as a record of many characteristics of rock formation measured by different devices in the bore hole. Well logging is a technique of making a record of geological formations penetrated by a borehole. The visual inspection of different samples that are brought to the surface can be helpful for log measurement and these are logs are known as geological logs and geophysical logs can be measured physically by lowering instruments into the well. In any phase of well's history well logging can be done. In oil and gas industry these logs are helpful to study rock properties and fluid properties to find different hydrocarbon zones in geological formations. The interpretation of these measured logs from well logging is made to locate depth zones containing oil and gas.

By using logging tools we can determine electrical, electromagnetic, acoustic, radioactive, nuclear magnetic resonance and many other properties of the rocks and the hydrocarbons they contain. These logs can also be helpful to define porosity, permeability, pore geometry, physical rock's characteristics, we can also determine depth and thickness of different zones and we can distinguish between oil, gas and water in the reservoir. By using densities by log we can estimate the hydrocarbon reserves. Well logging is the oldest and most used method that depends on the geophysical properties of rocks. (Hearst and Nelson, 1985).

4.2.3 Types of Well Logs

There are different types of well logs that include:

4.2.3.1 Spontaneous Potential Log:

The Spontaneous potential logging also known as Self Potential or SP logging can be done to characterize properties of rock formation. It can measure electrical current that occurs naturally in the boreholes and this electrical current is a result of difference of salinity between the formation water and bore hole mud filtrate. SP log are used as indicator approximate 26 permeable beds that also includes determination of permeable sands and impermeable shales and also for locating bed boundaries. This can be done by using two electrodes, an electrode in the borehole and reference electrode at the surface. It is rarely useful in offshore environments.

The electrical current in the formation can be determine by measuring small electric potential (measured in mill-volts) between depths in the borehole and voltages at ground surface. The change of voltages in the well bore is caused by buildup of charge. Clay and shales will generate one charge and permeable formation such as sandstone will generate an opposite one. This buildup of charge is caused by the difference in the salt content of formation water and drilling fluid.

4.2.3.2 Electrical Resistivity Log:

Electrical resistivity logs are used to measure the bulk resistivity of the formation. Resistivity is defined as the degree by which a substance resists the flow of electrical current. Different rocks have different values of resistivity. The resistivity of sedimentary rocks can be determined by the rock components and geometry. Resistivity is directly related to porosity and fluid present in these pores. Fresh water, hydrocarbons and rocks are all insulator to electric current. Porous rocks that contain saline water have low resistivity values and a non-porous rock or the rocks bearing hydrocarbons has high resistivity values. Resistivity measures the amount of salinity of water present in the formation. As hydrocarbon bearing rocks have high resistivity values so this log is useful for determining the type of fluids in the formation and it is also used as an indicator of lithology of formation.

4.2.3.3 Gamma Ray Log:

The gamma ray log is used to measure the natural radioactivity of the formation. High energy gamma rays are emitted by the decay radioactive elements. This log normally reflects the shale content in sedimentary formations because of the presence of most of radioactive elements in clay and shales. Shales mostly have relatively high gamma radioactive response and this gamma ray log is taken as good measurement for grain. Thus coarse-grain sand containing little mud will have low value of gamma ray while a fine mud will have a high value of gamma ray. Shale has high GR log reading while clay-free clean sandstone and carbonate rocks have low GR readings. Naturally alpha, beta and gamma radiations are emitted form a radioactive substance but it is practical to measure only the gamma radiation in a well bore.

Some rocks and naturally radioactive and they contain some unstable elements. Uranium-Radium series, Thorium series and Potassium 40 are the elements that are contributing the major portion of the natural radiation in sedimentary rocks. In both cased and open well, gamma ray log can be run. No matter the nature of presence of fluid in the bore hole the gamma ray log can be obtained.

4.2.3.4 Density Log:

The density log provides information about the bulk density of a formation along the depth of borehole. Bulk density is the function of a mineral forming a rock matrix and fluid present in the pore spaces. This log is also used to calculate porosity. Different lithologies can be determined by using density log, the bulk density of different materials are shown in the following table.

Rocks	**Bulk Density (g/cm3)**
Sandstone	2.65
Coal	1.2-1.8
Halite	2.05
Limestone	2.75
Dolomite	2.87
Anhydrite	2.98

Table 4.1: Bulk Density values of different rocks.

4.2.3.5 Sonic Log:

Sonic log is a tool that provides information about the formation’s interval transit time and this transit time is a measure of formation’s capacity to transmit seismic waves. Sound speed in the formation is measured by this log and it is related to both, porosity and lithology of the rocks that are being measured. If we know the lithology of a formation we can determine its porosity by using this log. The value of sonic log of different rock units are as given in table below.

Rocks	Interval Transit Time (µsec/ft)
Sandstone	51-56
Limestone	47.5
Dolomite	43.5
Anhydrite	50
Halite	67

Table 4.2: Sonic log values of different rocks.

4.2.3.6 Neutron Log:

Neutron log is basically used for the description of porous formation to determine their porosity. This log responds by the presence of hydrogen in the formation, it can measure the concentration of hydrogen ion in formation. The formation in which clay is not present and the porosity is jam-packed with water or hydrogen, then this neutron log measures the pores filled with liquid.

Electrically neutrons are neutral particles, and they have mass that is approximately identical to the mass of hydrogen atom. The neutrons are emitted continuously from a source of radioactive material, and then this neutron collides with the atom of hydrogen. Neutron atom loses some of its energy on each collision, and this lost energy depends upon the relative mass of nucleus. This process includes three basic processes:

Neutron Emission, Neutron Scattering and Neutron Absorption.

Log Type	Units	Parameters measured
Spontaneous Potential Log (**SP)**	mV	Spontaneous electrical current
Gamma Ray Log (**GR)**	API	Natural radioactivity
Resistivity Log (**ER)**	ohm m	Resistance to electric current
Sonic Log (**DT)**	µs/ft	Velocity of sound propagation
Density Log (**RHOB)**	g/cm3	Reaction to gamma ray
Neutron Log (**NPHI)**	v/v	Reaction to neutron

Table 4.3: Log types with units and their measured parameters.

4.2.4 Petrophysics

Petrophysics is the study of rock properties and the interaction of rocks with gasses, fluids, hydrocarbons and aqueous solution. By this study we can determine the reservoir rock, for reservoir containing hydrocarbons in the subsurface must have porosity (φ) and permeability (k). So these properties are the fundamental to characterize the reservoir rock. Different types of petrophysical properties includes porosity (φ), permeability (k), density (ρ), hydrocarbon saturation (So, Sg), water saturation (Sw), thermal and electrical conductivity etc. (Rybach & Buntebarth., 1982) The most common petrophysical properties are discussed below.

4.2.4.1 Porosity (φ):

Porosity is the ratio of number of pores (Vpores) in the rock to the total bulk volume of rock (Vb):

$$\Phi = \frac{\mathrm{V(pores)}}{Vp}$$

It depends upon the orientation, shape, angularity, surface, texture and degree of cementation and also the grain size distribution that makes the rock unit. Porosity is further divided into two types

- Primary Porosity (φp)
- Secondary Porosity (φs)

Primary Porosity is defined as the porosity that develops at the time of deposition of strata and maintains after the compaction of strata. This includes:

- **(a)** Inter crystalline porosity-spaces in the rock units, this type of porosity is developed mainly due to chemical precipitation of sedimentary rocks like dolomite, limestone etc.
- **(b)** Intergranuler / interpartical porosity-spaces between grains, this type of porosity characterizes clastic sedimentary rocks like shale, sandstone etc.

Secondary Porosity is developed by the result of geological processes like dolomitization, fracturing and diagenesis etc. it is developed after the deposition of sediments. It includes

- **(a)** Solution porosity that is developed from the channels as the rock dissolves the hydrothermal solutions and

(b) Fracture porosity (φf), it is the fracture related porosity in the reservoir rocks that develops under the tension caused by the tectonics activity such as folding and faulting.

4.2.4.2 Calculation of Porosity

Porosity can be calculated by using different logs, using these logs we can calculate density porosity (φD), neutron porosity (φN), total porosity (φT) and effective porosity (φe) by using the formulas given below:

- Density Porosity (φD)

  The density porosity is calculated by

$$\Phi(D) = \frac{(\rho m - \rho b)}{(\rho m - \rho f)}$$

Here ρf = fluid density

ρb = bulk rock density

ρm = rock matrix density

Some common rock fluid densities are given in the table as below:

Fluid	**Fluid density (ρf)**
Fresh water	1
Salt water	1.1 – 1.2
Hydrocarbon	0.8 – 0.9

Table 4.4 : Rock matrix densities.

- **Neutron Porosity:**

  Neutron porosity is calculated by using formula:

$$\phi N = (1.02 * \phi N\_log) + 0.0425$$

Where

ϕN_log = NHPI log response.

- **Total Porosity:**

  Total porosity (ϕT) can be calculated by using formula:

$$\phi T = \frac{(\phi D + \phi N)}{2}$$

  Where

  ϕD = Density Porosity.

  ϕN = Neutron Porosity.

- **Effective Porosity (ϕe):**

  Effective Porosity (ϕe) can be calculated by using formula:

$$\phi e = \phi T * (1 - Vsh)$$

  Where

  ϕT = Total Porosity.

  Vsh = Volume of shale.

4.2.4.3 Volume of Shale

Volume of shale gives information about the amount of shale present in the formation. Among the sand and carbonate, shale is more radioactive therefore Gamma ray log is used to calculate the volume of shale in the formation having porosity and this volume of shale is expressed in percentage or percentage.

As it is calculated by Gamma ray so first we have to calculate the maximum and minimum value of GR from the log response then these values are used to find the volume of shale by using formula:

$$I(GR) = \frac{(GRlog - GRmin)}{(GRmax - GRmin)}$$

Where

GRlog = log response in the zone of interest, API units.

GRmin = minimum value of GR log.

GRmax = maximum value of GR log.

IGR = gamma ray index.

After calculating these parameters the volume of shale can be calculated by:

Vsh = 0.083 * ($2^{2.7}$ GR) – 1

4.2.4.4 Water Saturation (Sw)

Water saturation is the amount of pore spaces, occupied by the liquid (formation water). To calculate the water saturation, firstly we have to determine the resistivity of water (Rw) then by using Archie equation to find the water saturation. Mathematically it can be calculated as:

$$R_{mf} \text{ at } 75^{o}\text{F} = R_{mf\ temp} * (\text{temp} + 6.77)/\ 81.77$$

Correction of Rmf to 75 ºF

$$K = 60 + (0.133 * T_f)$$

$$\frac{R_{mfe}}{R_{we}} = 10^{-\frac{ssp}{k}}$$

$$R_{mfe} = \frac{146 * R_{mf} - 5}{337 * R_{mf} + 77}$$

Rmfe formula if Rmf at 70 F < 0.1 , Rmfe = 0.85 Rmf, Rmfe formula if Rmf at 750 F

$$R_{we} = \frac{R_{mfe}}{R_{mfe}/R_{we}}$$

$$\text{Rw } 75^{o}\text{F} = \frac{77 * R_{we} + 5}{146 - 377 * R_{we}}$$

Rw at 75 ºF formula if $R_{we} < 0.12$

R_{we} at 75 ºF = - [0.58 - $10^{0.69*R_{we}-0.24}$]

Rw at 75 ºF formula if R_{we} > 0.12

Rw at formation temperature = Rw at 75 ºF * $\frac{81.77}{(T_f+6.77)}$

Rmfe = Equivalent resistivity.

Rmf = Resistivity of mud filtrate.

Rw = Resistivity of equivalent of water.

Using above mentioned method the resistivity of water can be calculated then by using Archie Equation we can fine the value of water saturation by using following formula:

Sw = $[\left(\frac{a}{\phi^m}\right) * \left(\frac{Rw}{Rt}\right)]^{1/n}$

Where

Sw = water saturation.

Rw = water resistivity.

Φ = porosity.

m = cementation factor.

a = (constant) Rt = log response (LLD).

4.2.4.5 Hydrocarbon Saturation (S_{hc})

It can be defined as the saturation of hydrocarbons like oil and gas in the formation. It is expressed as a percentage of volume of pores. It can be calculated by logs by using these given formulas as below:

$\boldsymbol{S_{hc}}$ **= 1 –** $\boldsymbol{S_w}$

OR

$\boldsymbol{S_{hc}}$ % **= 1 –** $\boldsymbol{S_w}$%

Where

Shc = So + Sg

If Sg = 0, then Shc = So

Sw = Saturation of water.

4.2.4.6 Well Log Interpretation

For well log interpretation we used different logs such as GR, LLD, NPHI and SP log etc. On the basis of these logs we have categorized different reservoir zones by identifying the behavior of logs. Reservoir can be identified where the value of GR log is low, value of SP log low, but high value of NPHI and LLD. We can also identify the reservoir zones by identifying the cross over result of LLD, LLD and MSFL. The marked zones are shown in the figures given below as:

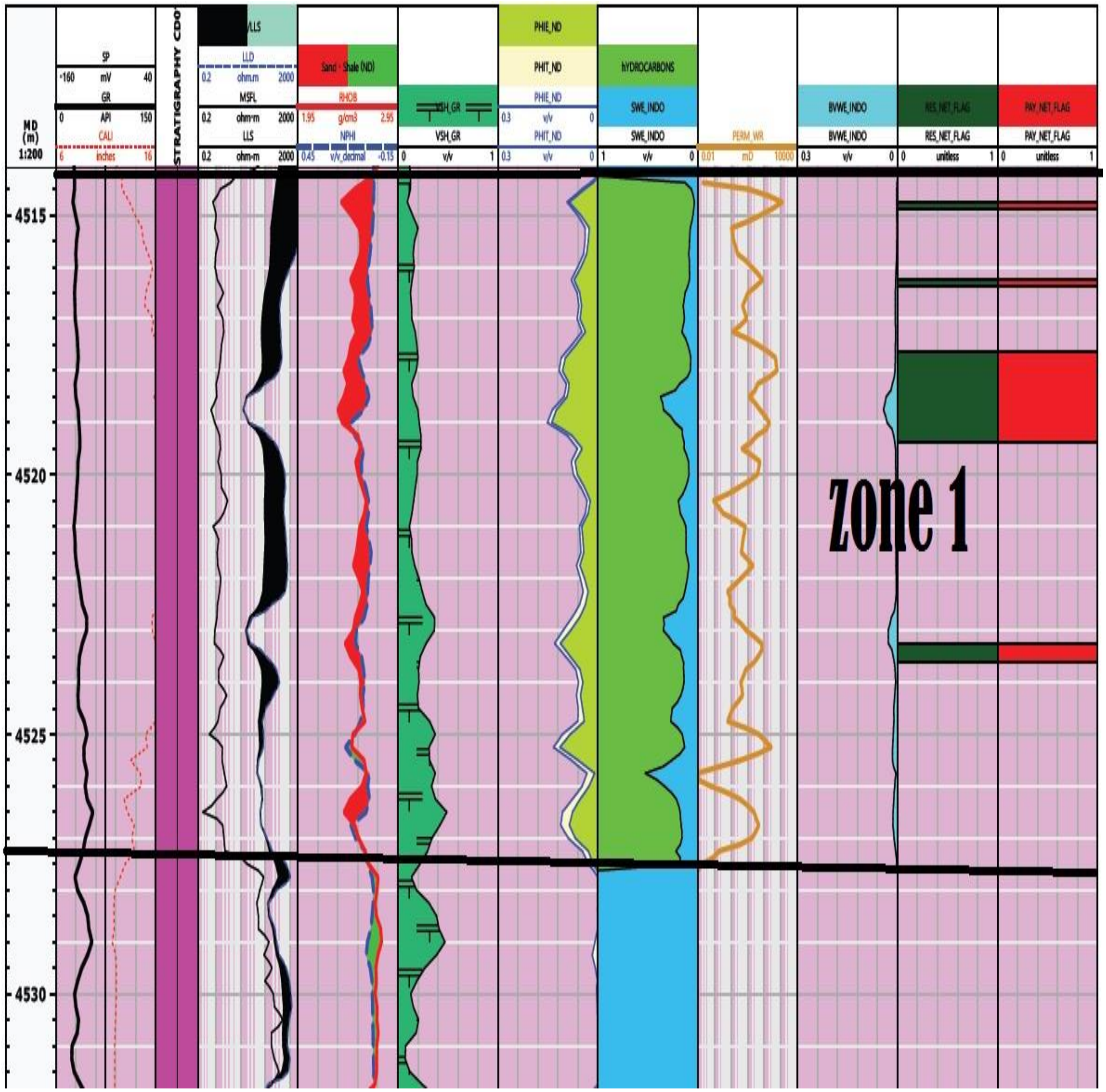


Figure 4.13 Zone 1 of SamanaSuk Formation on Chanda Deep 01.

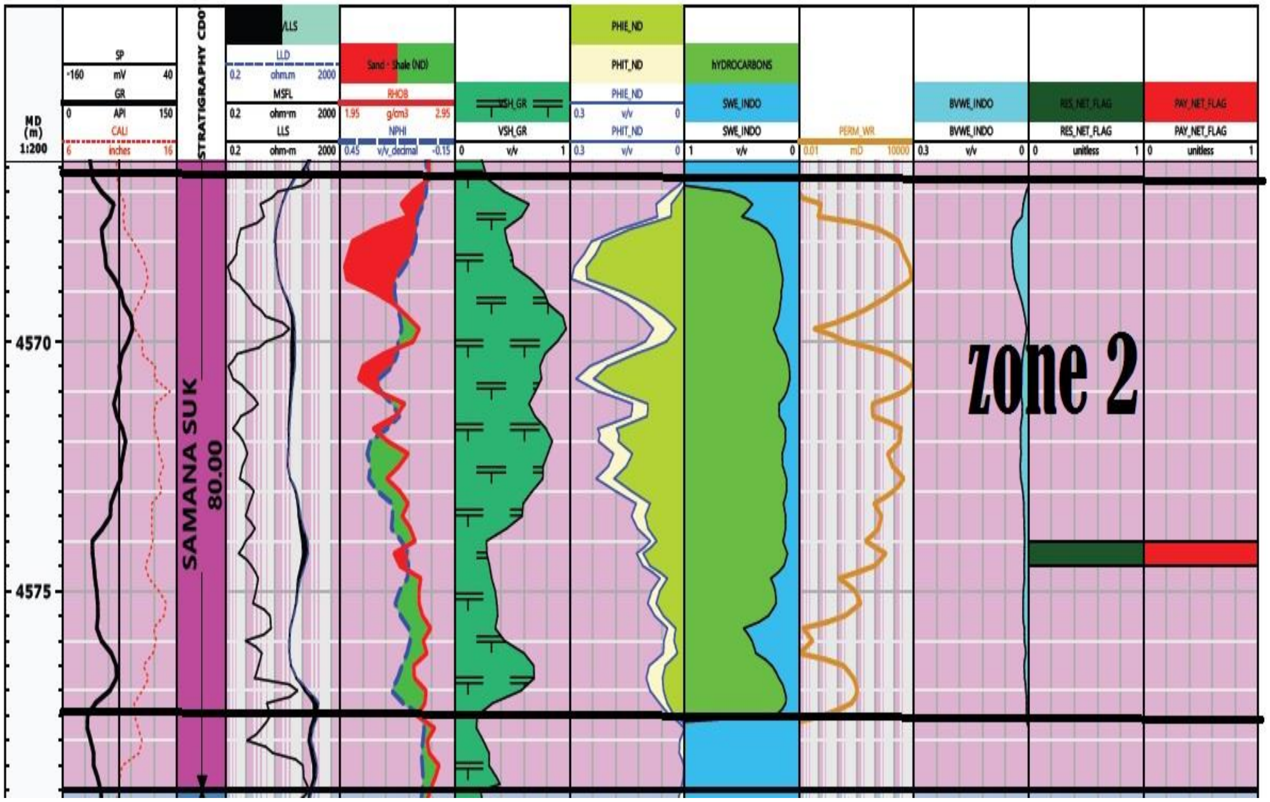


Figure 4.14 Zone 2 of SamanaSuk Formation of Chanda Deep 01.

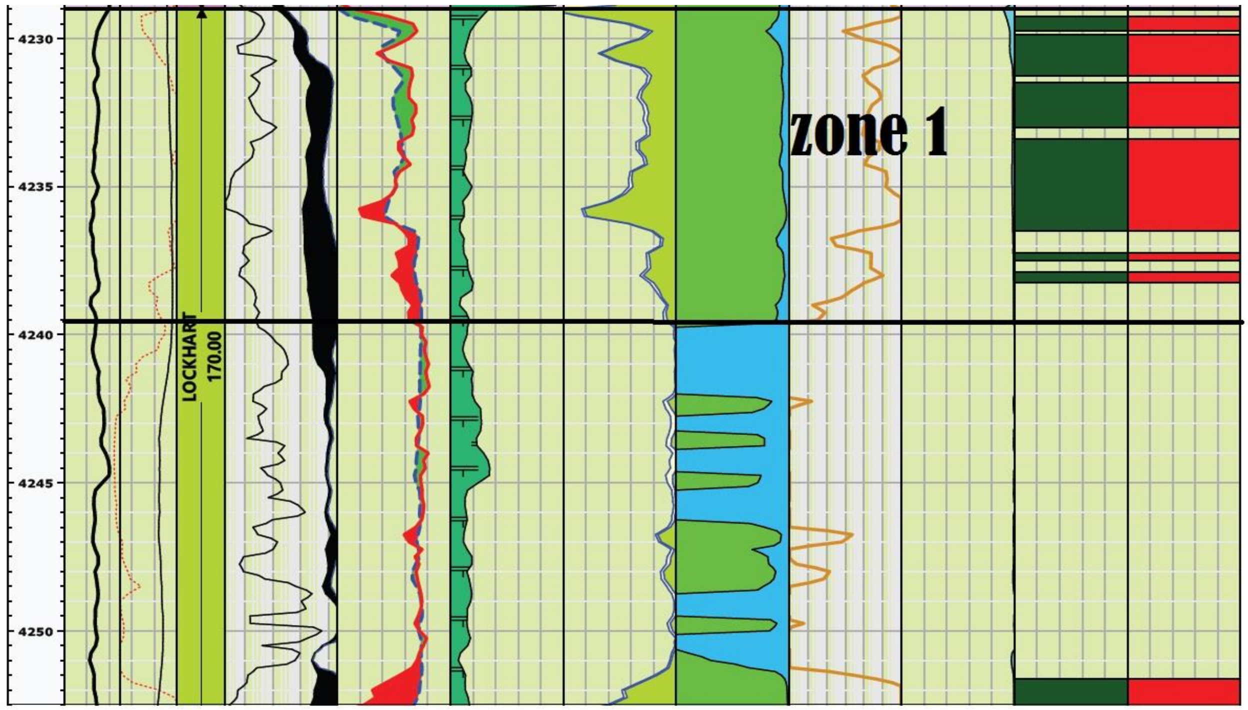


Figure 4.15 Zone 1 of Loakhart Limestone of Chanda Deep 01.

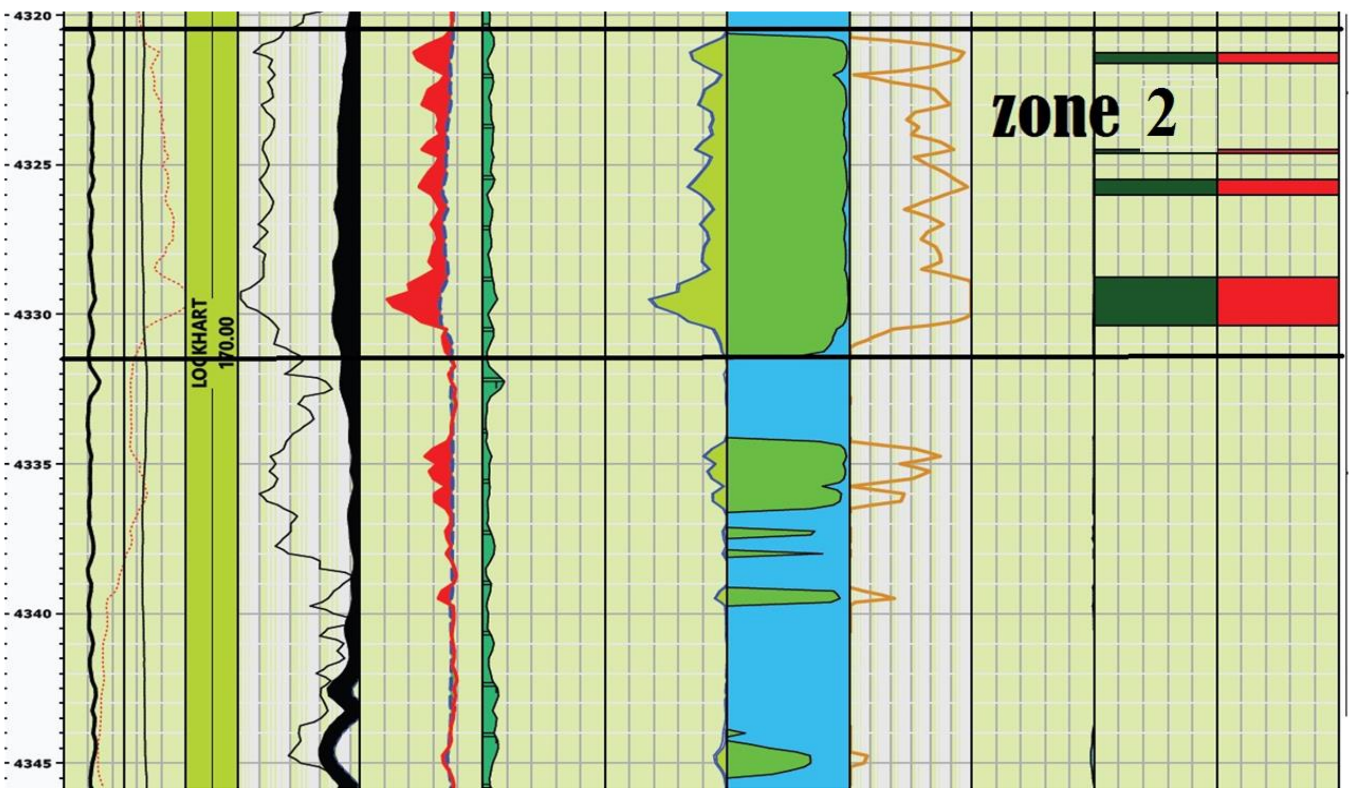


Figure 4.16 Zone 2 of Lockhart Limestone of Chanda Deep 01.

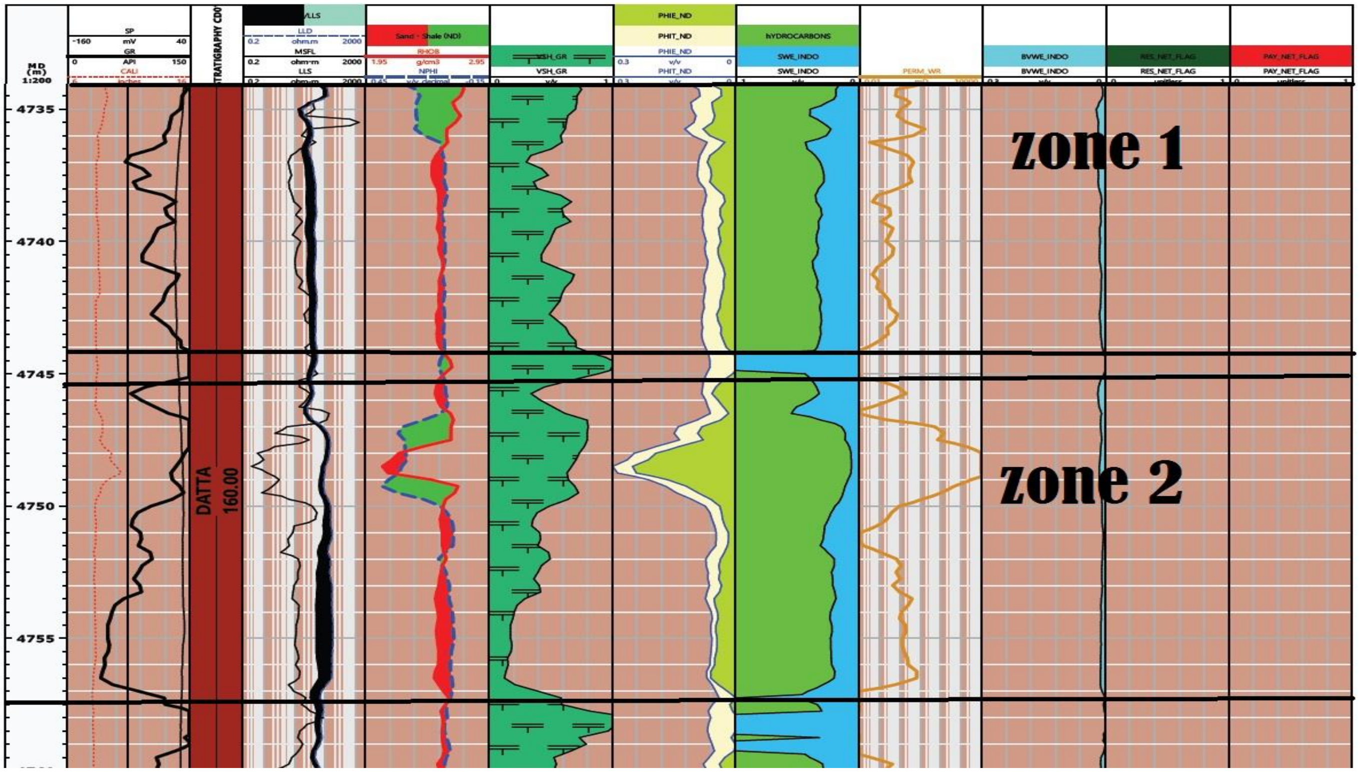


Figure 4.17 Zone 1 and Zone 2 of Datta Sandstone of Chanda Deep 01.

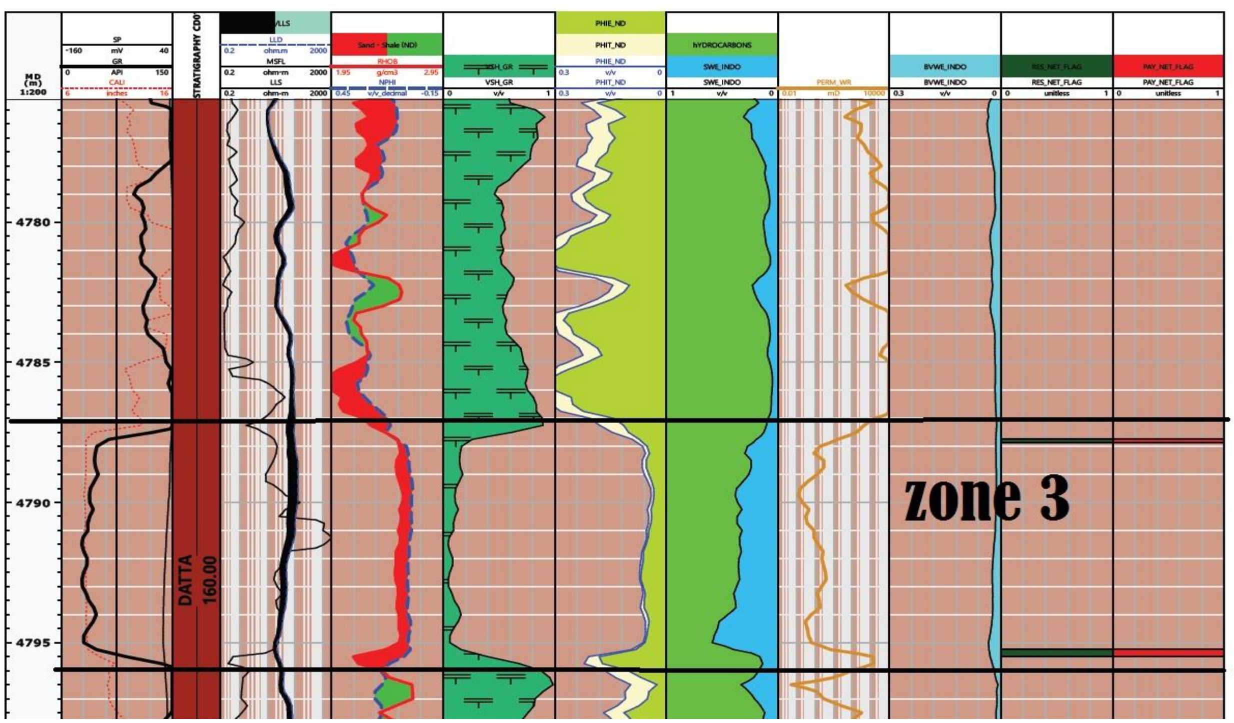


Figure 4.18 Zone 3 of Datta Sandstone of Chanda Deep 01.

4.3 Geophysical interpretation

4.3.1 Basic Rock Physics

Introduction to Rock Physics

Rock physics is the study to characterization depends upon the behavior of propagation of seismic waves. This seismic response indicates the composition of different rocks either they are brittle or ductile etc. Rock physics is an important component in the production, development and oil and gas exploration. This study provides best relationship to understand and connect different properties of rock with petrophysical, geochemical and seismic data. These rock properties includes mineralogy, permeability, porosity, fluids present in pores, pore shape, pore pressure, different stresses and overall architecture of rock like fractures, joints laminations etc. Seismic waves are very sensitive to rock parameters. The main focus in rock physics is to relate seismic-to-reservoir properties. (Mavko et al., 2009).

For characterization and monitoring of reservoir rocks, Rock Physics has much importance for the estimation of properties of different rocks. The most reliable method that is effective to obtain subsurface data is seismic data, because seismic attributes depends upon the various rock properties like porosity, permeability, fluid properties, saturation of fluids etc. There are many methods that link seismic velocities Vp and Vs to the porosity of rocks. This has been proven form these models that the velocities decreases with the increase of porosity and the shear moduli and effective pressure decreases with increase of porosity. This all phenomena depend upon the type of rocks. The laws that relates rock physics to the properties of rocks obtained from:

(a) Core measurements where the seismic velocities, densities and porosities are measured simultaneously from rock sample.

(b) Data of well log that includes saturation, densities, mineralogy, velocities and porosity curves.

Here some of the keys are discussed for which the rocks properties affect the seismic velocities. These properties will be:

Lithology	Porosity
Pore Fluid	Clay Content
Temperature	Pressure

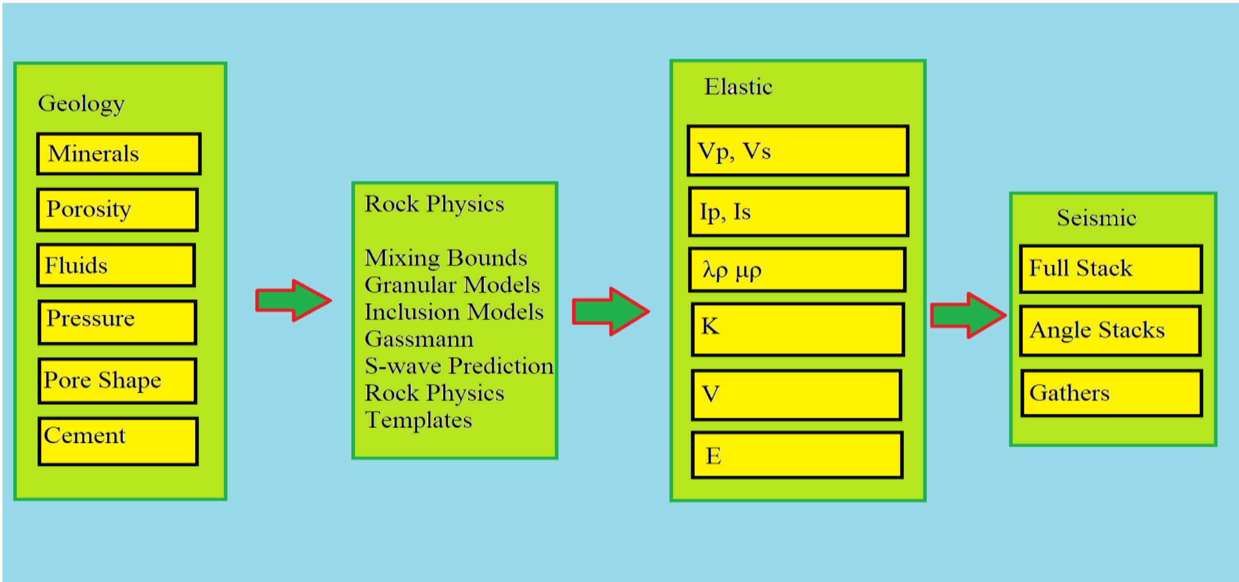


Figure 4.19 General use of Rock Physics.

4.3.1.1 Effect of Lithology on Velocity

Characteristically the primary velocity Vp is higher in carbonates as compare to sandstone. Vp has a wide range of values in shales. Both the p-waves and s-waves decreases in the rocks having soft lithology. Generally the velocities depend on the density and elastic moduli that are given by the following formula:

$$\mathbf{Vp} = \sqrt{\frac{K+\frac{4\mu}{3}}{\rho}} \quad \text{and} \quad \mathbf{Vs} = \sqrt{\frac{\mu}{\rho}}$$

On these properties one can differentiate and characterize the rocks and properties of rocks. The seismic velocities through different lithologies can be shown in the given figure as:

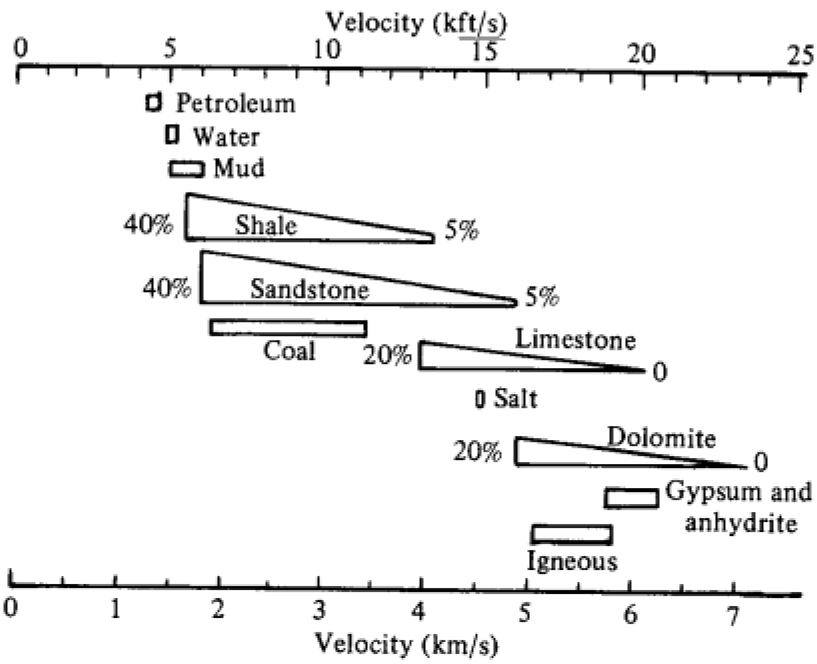


Figure 4.20 Velocities through different rocks (Faust., 1951).

4.3.1.2 Effect of Porosity on Velocity

Generally, we have decrease of velocity with the increase of porosity but the main factor in this explanation is pore shape. In rock physics modeling pore shape plays an important role and it is idealizing as an elliptical in shape, and this shape is described by Aspect Ratio. According to this ratio if we compare rocks that have similar porosity, but both have different pore shape then the rocks that have fat pores have high velocities and rocks with thin pores have less velocities.

4.3.1.3 Effect of Pore Fluids on Velocities

The rock unit is saturated with fluids that are incompressible or viscous have high bulk modulus then the rocks that have fluids that have highly compressible gas while the shear modulus leftovers unchanged when the fluid is saturated. There is less change of velocities for stiff rocks and more change for soft rock.

4.3.1.4 Effect of Clay Content on Velocity

They high clay content in the rock units reduces the velocities, the effect of clays mainly depends upon the type of clay mineral, its position in the rock microstructure and also the inter-relationship between clay-mineral and porosity. The interrelationship between porosity and clay content causes the non-linear variation of velocities.

4.3.1.5 Effect of Temperature and Pressure on Velocity

The effect of temperature is typically more noticeable in case of hydrocarbon properties, while velocity is dependent on effective pressure. The velocity increases with the increase of effective pressure due to stiffness of rocks and increasing the bulk modulus.

In our given data we have applied basic rock physics to differentiate between shales and sandstones by giving the ranges of velocities of Vp and Vs and then noticing the behavior of velocity through sandstone and shales. These can be given in the figure as follow:

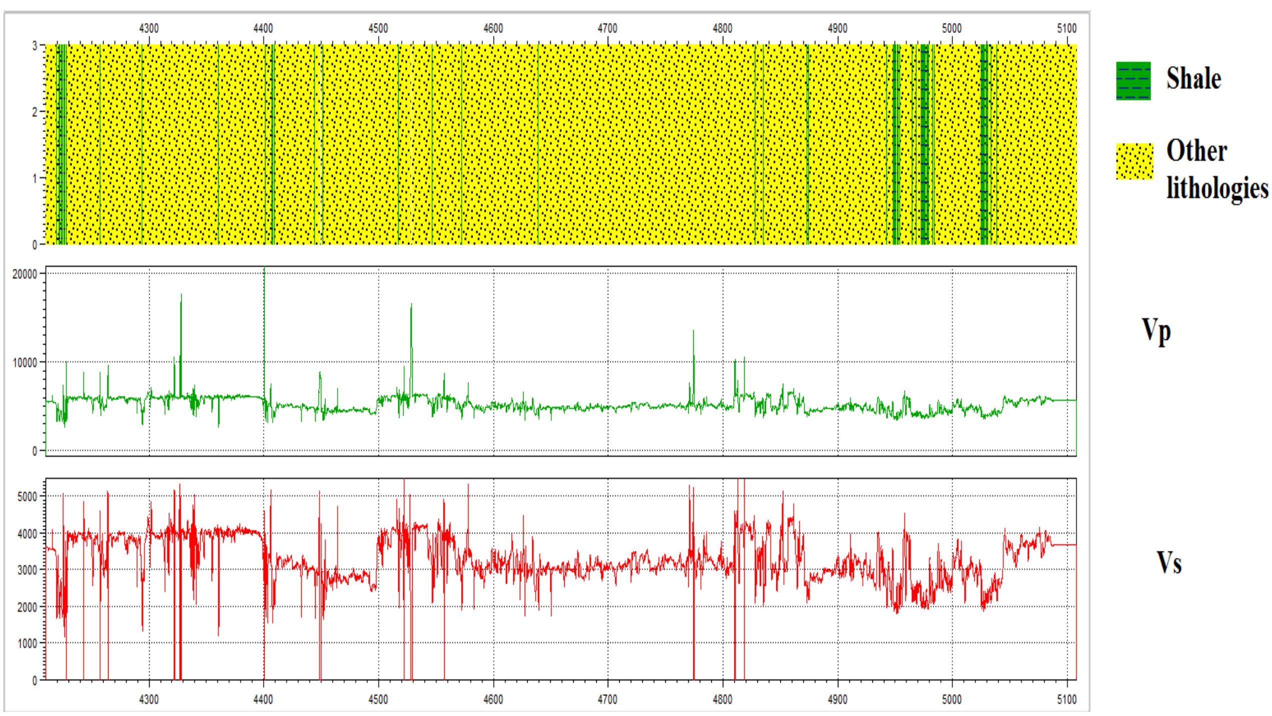


Figure 4.21 Change of Seiemic velocities (Vp and Vs) through different lithologies.

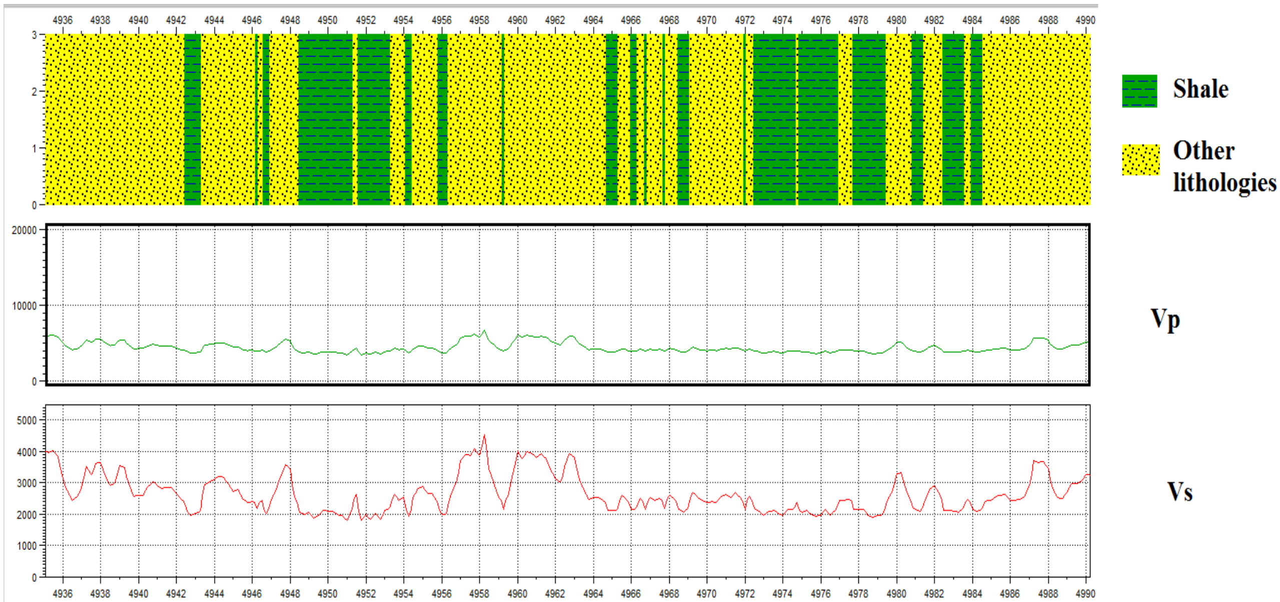


Figure 4.22 the Change in Behavior of Seismic velocities from shale and other lithologies.

4.3.2 Total Organic Carbon (TOC)

Introduction to TOC

The TOC stands for the Total Organic Carbon. It refers to the amount of organic carbon present in the soil or in the geological formations. Particularly the TOC is used to determine the source rocks in the petroleum play. The value of TOC varies from 0% to 10% or sometimes 12% or 15%. For shales gas reservoirs the value of TOC is considered as 2% although some geoscientists state that the rocks having high value of TOC that is round about 10% indicates the possibility of kerogen filling pores. The depositional environment controls the amount of TOC in source rocks. TOC is measured by different processes that includes Rock Eval Pyrolysis or by using well data, form logs we can fine the value of TOC to find the reservoir rocks. (Schumacher, 2002).

Source rock is a fine-grained rock that is rich in organic matter and capable to generate crude oil and natural gas after the change of heat below the earth curst. The hydrocarbons then move toward the more porous and permeable rock formation where they settle down and accumulated to make oil or gas reservoirs. The potential source rocks are those rocks that are not exposed to the temperature of about 100ºC while the actual source rocks are those in which the generation and exclusion of hydrocarbons have accord. In solids and sediments basically three main types of carbon are present. They are (1) Elemental Carbon, (2) Inorganic Carbon and (3) Organic Carbon. The quality of carbon presents depends upon the partitioning and bioavailability of different sediments that are associated to contamination. The three types of carbons are discussed as below:

(1) **Elemental Carbon Form** includes charcoal, soot, coal and graphite. They are mostly formed by the incomplete combustion of organic matter in different sediments and soils. This has been done by different geologic sources or dispersion of carbon during the process of mining etc.

(2) **Inorganic Carbon Form** is derived from parent material sources. They are presents typically in carbonates, the two most common carbons that are found in these carbonates are Calcite ($CaCo_3$) and Dolomite [$CaMg(CO_3)_2$] although other forms of carbons are also present like siderite $FeCO_3$ etc it depends upon where the soils are formed and where they are located. Due to agriculture input, calcite and some extent of dolomite are mostly present.

(3) **Organic Carbon Form** is the naturally occurring form of carbon that is derived by the deposition of plants and animals. The amount of carbons increases with the increase of deposition of contaminating material through the process of anthropogenic activities.

4.3.2.1 Methodology

Several methods are there to find the value of TOC, Log-Based method is one of them. Log based measurement includes different logs that are gamma-ray log, uranium log, nuclear magnetic resonance, neutron log, density log and resistivity log. Each method based on physical measurements and its sensitivity to organic matter.

Here in the Upper Indus Basin in Chanda-Deep-01 well we used the well data to determine the value of TOC to determine the source rocks. The results can be shown in the figures given below as:

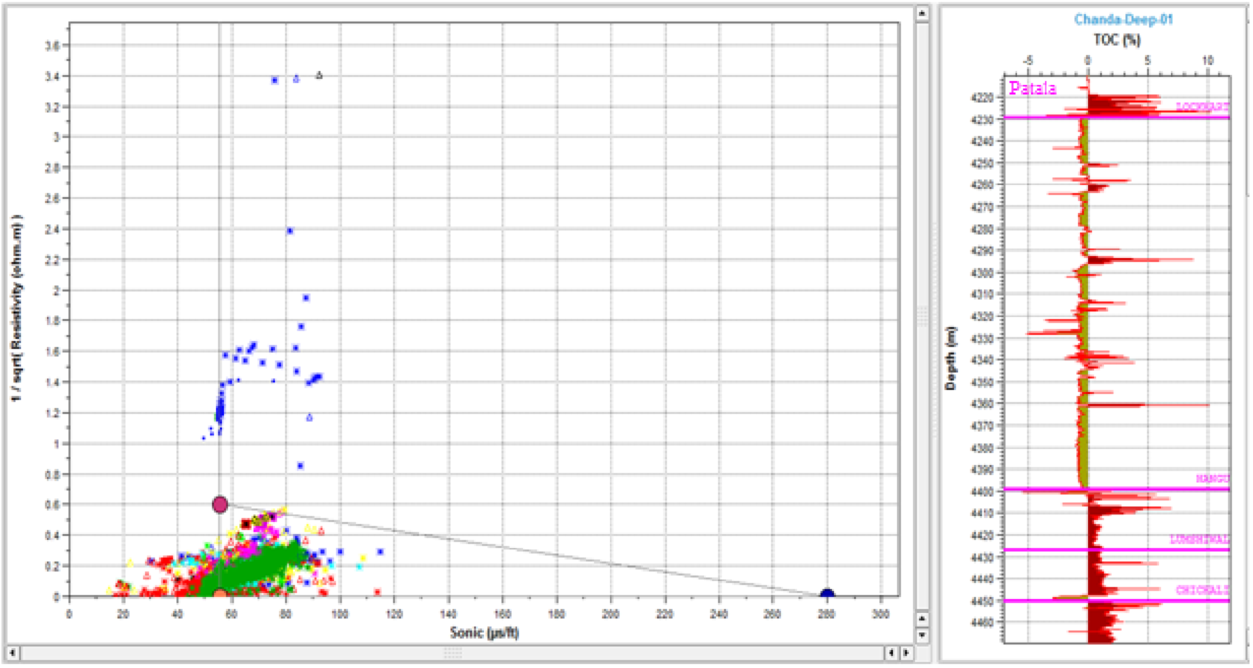


Figure 4.23 Determination of Source Rock (Patala Formation) in Chanda Deep 01.

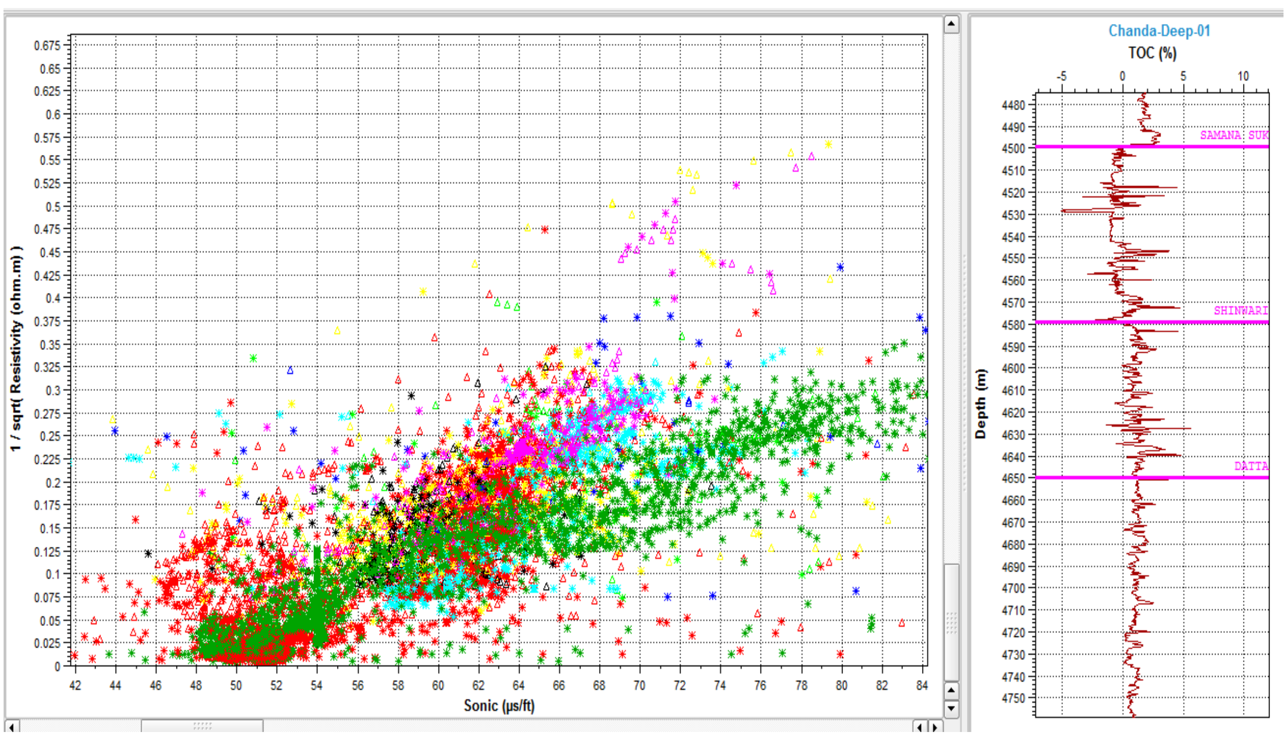


Figure 4.24 Other Source rocks that might be considered in Chanda Deep 01.

4.3.3 Fluid Substitution

Introduction

In Seismic Rock Physics, Fluid Substitution plays an important role which provides the tool for the identification of fluids in the reservoir and the quantification of fluids in the reservoir rocks. Rock Physics has a great importance to relate seismic with hydrocarbons to characterize reservoir. Fluid substitution is based on the modeling of behavior of fluids on rocks velocities and the change of densities with respect to substitution of fluids. Gassmann's Equation is the most used equation for this process. Many authors have discussed the limitation, formulation and strength of this equation like (Batzle and Wang, (1992)) (Wang, (2001)), (Smith et al., 2003).

Basically, Fluid substitution is 4-D analysis that helps to make difference between Bulk Modulus and Shear Modulus with condition that shear modulus does not depends upon the fluid pressure. The change in seismic response, during the expansion of hydrocarbons depends upon the saturation level of the fluids.

The main objectives of fluid substitution are to model the seismic velocities and reservoir densities at given temperature, pressure, porosity, mineral type etc. and to relate the saturation of fluids like that 100% of water saturation or hydrocarbons with the saturation of oil and gas. By using known density and rock moduli we can determine the velocities of seismic of an isotropic material while the Vp and Vs can be calculated by using:

$$\mathbf{Vp} = \sqrt{\frac{K + \frac{4\mu}{3}}{\rho}}$$ and

$$\mathbf{Vs} = \sqrt{\frac{\mu}{\rho}}$$

In the above given equations, Vp and Vs are the P-wave velocity and S-wave velocity respectively while the K and μ are the bulk density and shear density and ρ is the mass density.

Densities of saturated rocks are can be computed by using mass balance equations. Moduli are another factor that can be computed after fluid substitution and this factor can be calculated by using Gassmann's equation.

4.3.3.1 Gassmann's Equation

The Gassmann's Equation gives the relationship between bulk modulus of rocks to its pores, fluid properties and pore frames. The Gassmann's Formulation is given by the following equation:

$$K_s = K_d + \Delta K_d$$

$$\Delta K_d = \frac{K_\circ (1 - {K_d}/{K_\circ})^2}{1 - \phi - {K_d}/{K_\circ} + \phi \times {K_\circ}/{K_f}}$$

$$\mu_S = \mu_d$$

In the above-mentioned equation:

$K_\circ$ is the bulk moduli of the mineral grain, K_f is the bulk moduli of fluid, K_d is the bulk moduli of dry rock and K_s is the bulk moduli of saturated rock frame, while ϕ, μ_S *and* μ_d are the porosity, and shear modulus of saturated rock and dry rock respectively. According to this equation the fluid present in the pores will affect only the bulk modulus but do not affect the shear modulus. The assumption for the derivation of Gassmann's equation includes:

(1) The porous material should be an isotropic, homogenous, elastic and monomineralic.

(2) The pore spaces should be in pressure equilibrium and are well connected.

(3) The source medium should be a closed system in which no pores-fluid movements occur across the boundaries.

(4) There should be chemically interaction between rock and fluid.

4.3.3.2 Gassmann's Fluid Substitution via EasyTrace Software

The Gassmann's Fluid Substitution uses the theory to create the new density and velocity log. This theory describes the phenomena of wave propagation in the fluid filled porous solid by using the mathematical relationship between the various rock properties. The steps in EasyTrace software to find different parameters are discussed as below. Firstly we will give different percentages for the substitution then identify the behavior of density and velocity log as shown in figures:

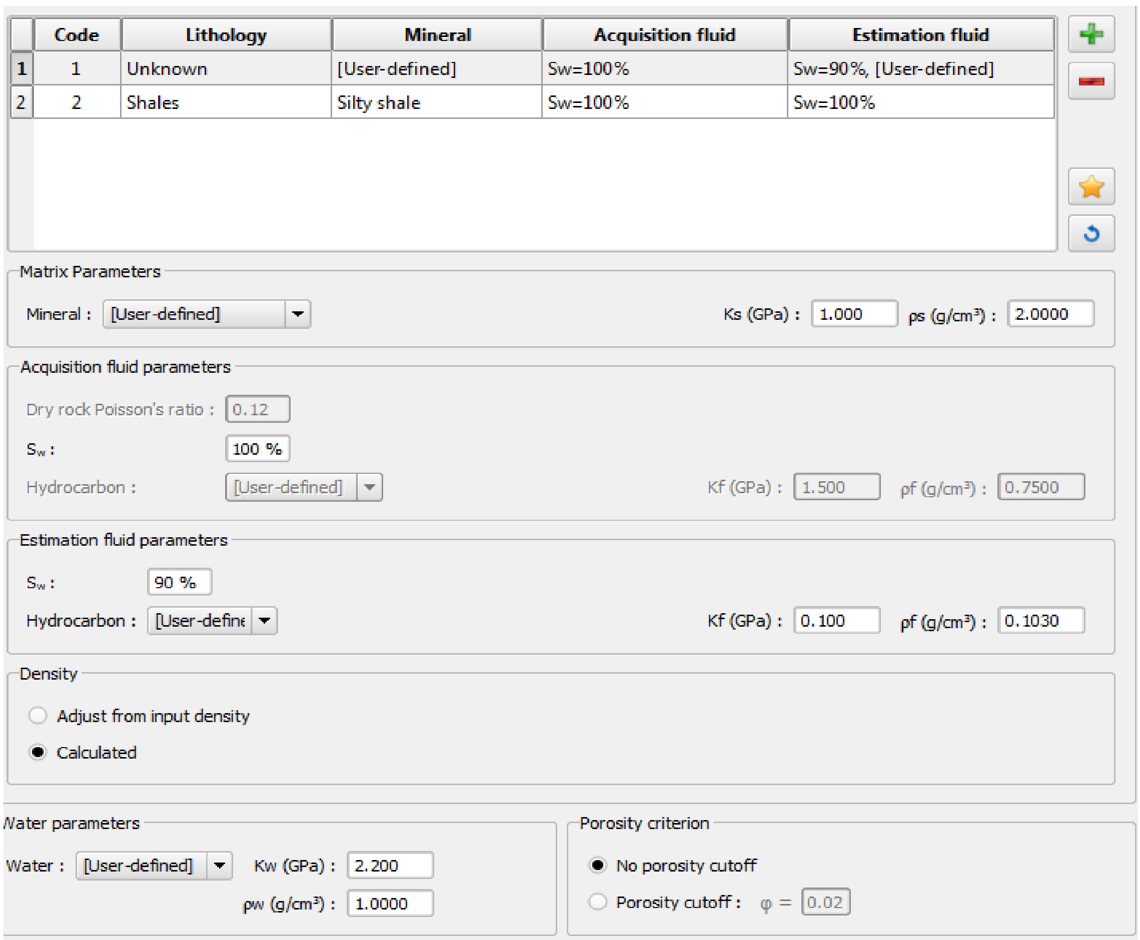


Figure 4.25 Input of saturation levels for 10%.

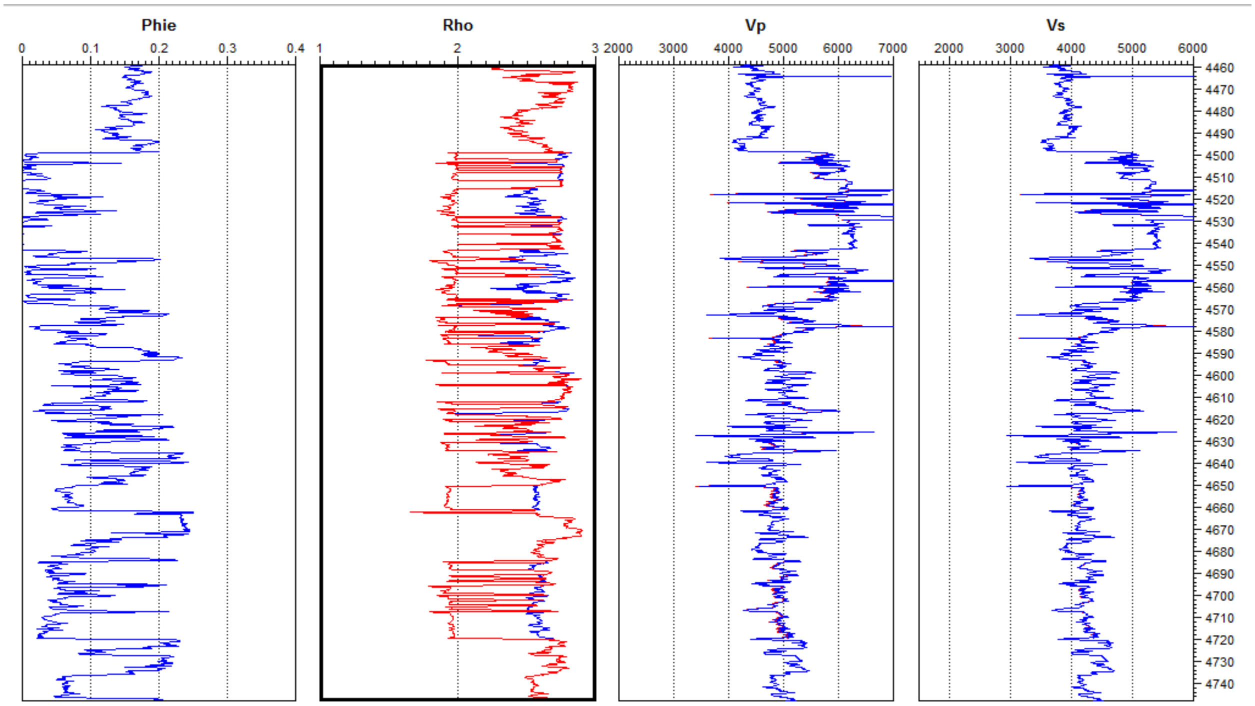


Figure 4.26 Saturated curves of 10% Fluid Substitution.

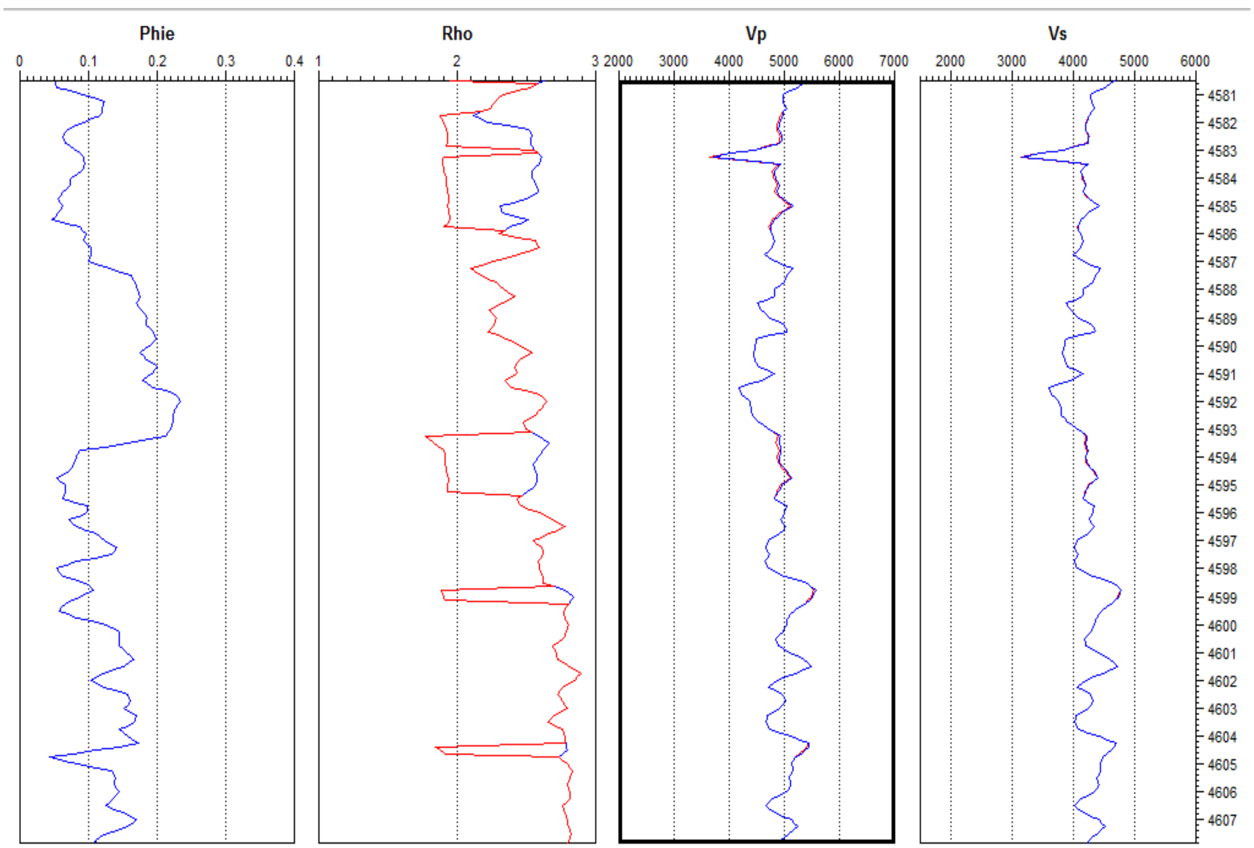


Figure 4.27 Zoomed display of 10% saturation level.

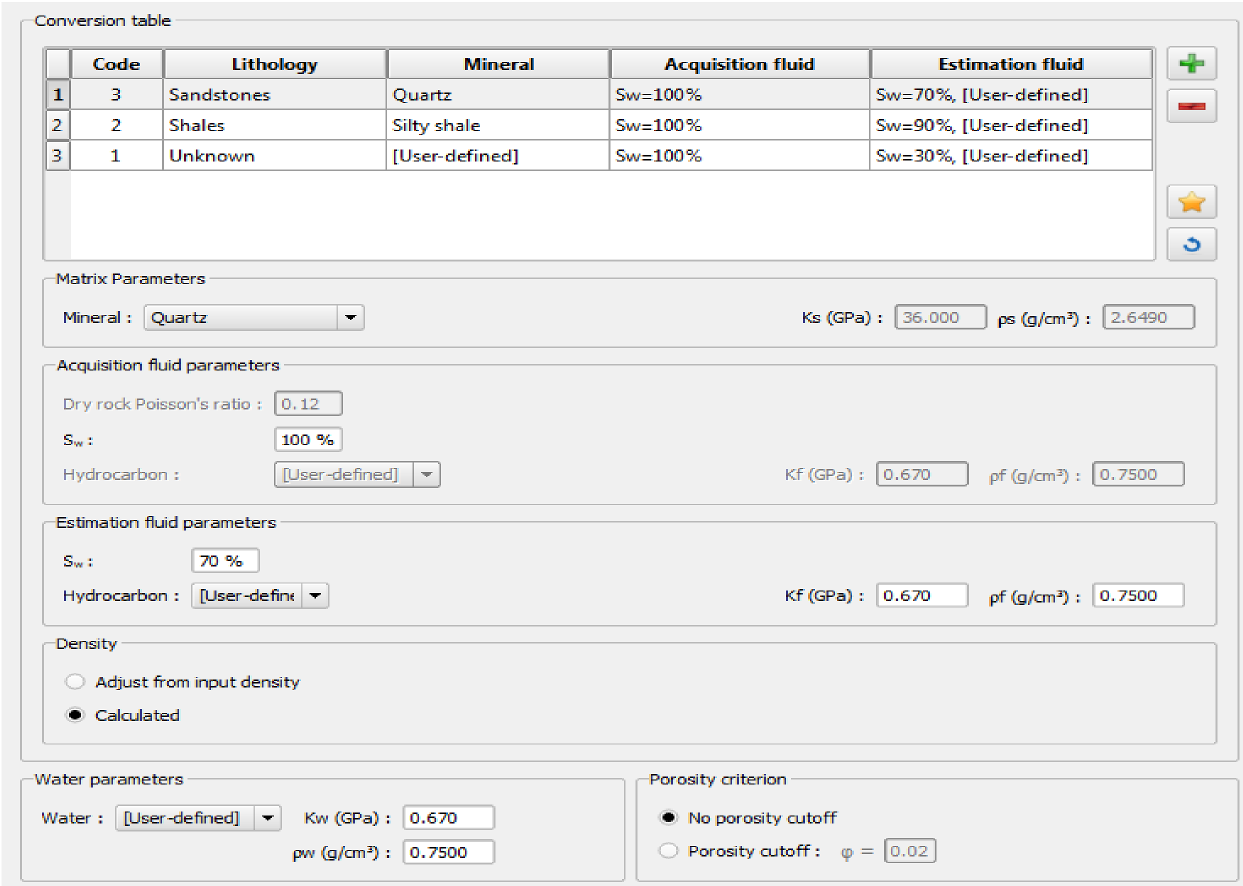


Figure 4.28 Input of Saturation level for 30%.

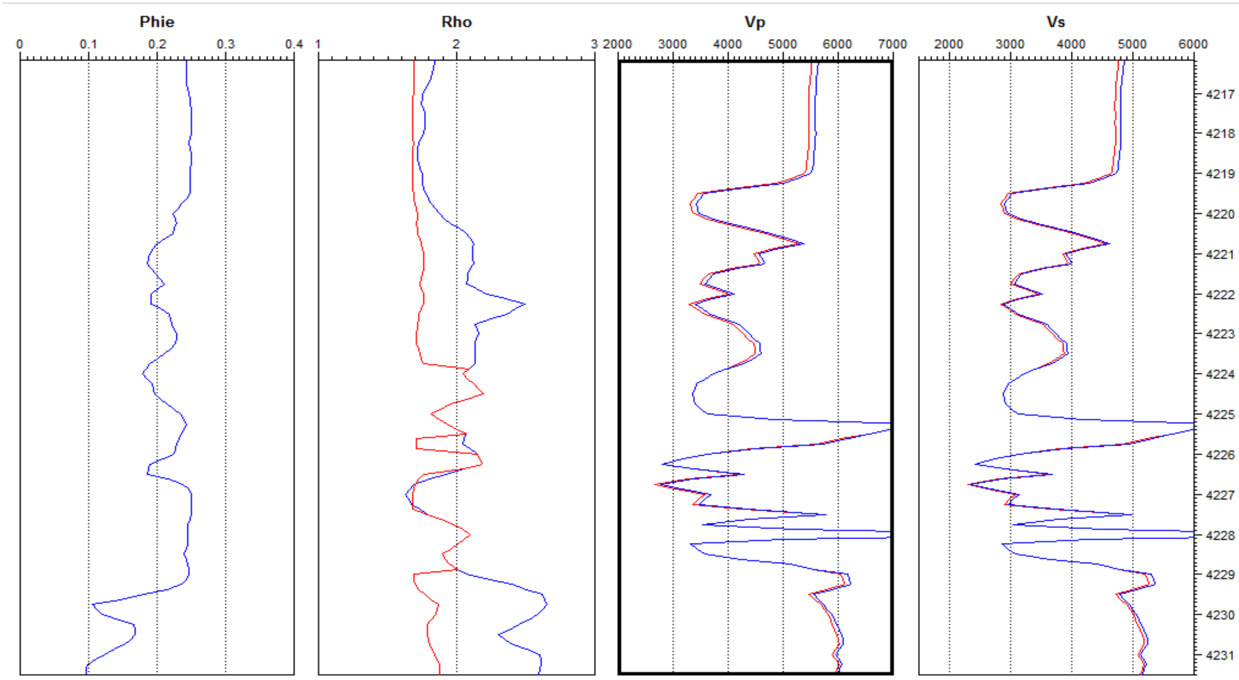


Figure 4.29 Saturated curves of 30% fluid substitution.

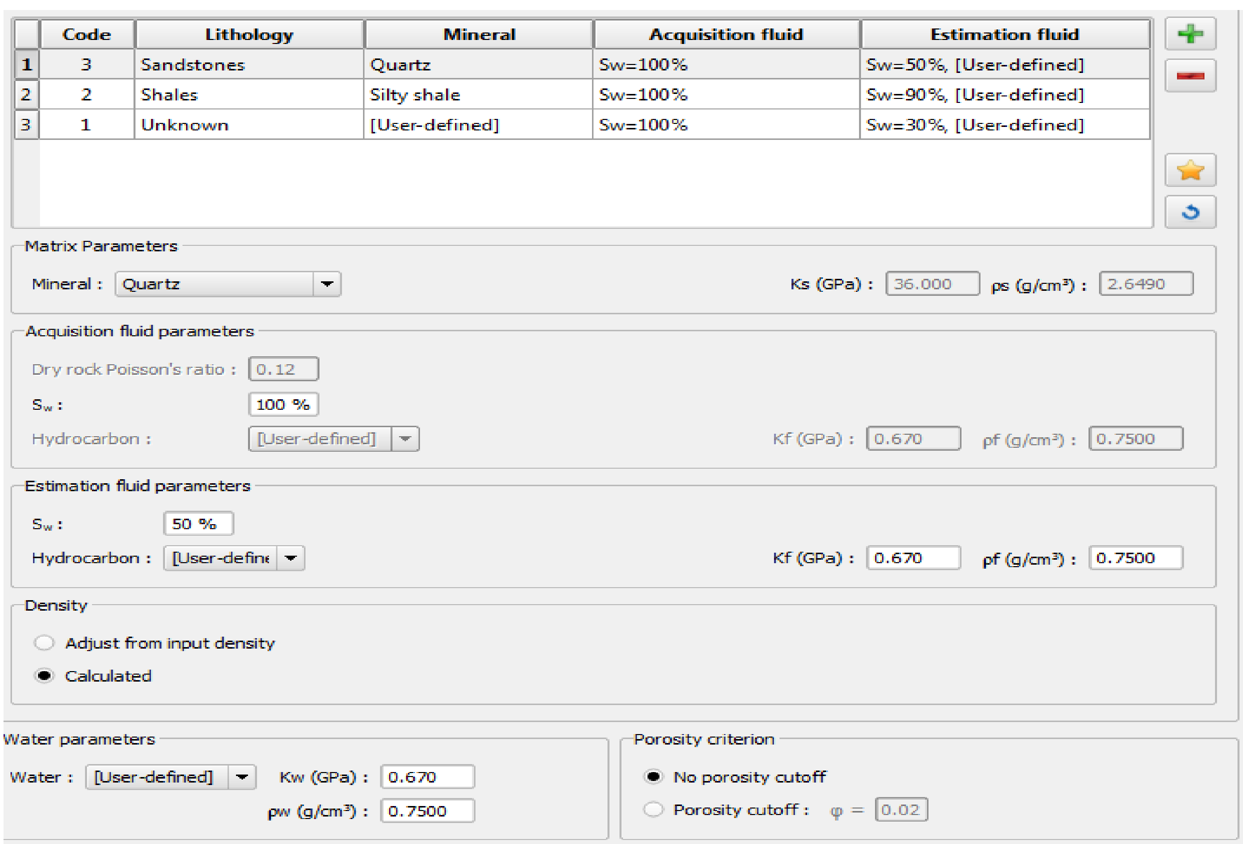


Figure 4.30 Input of Saturation level for 50%.

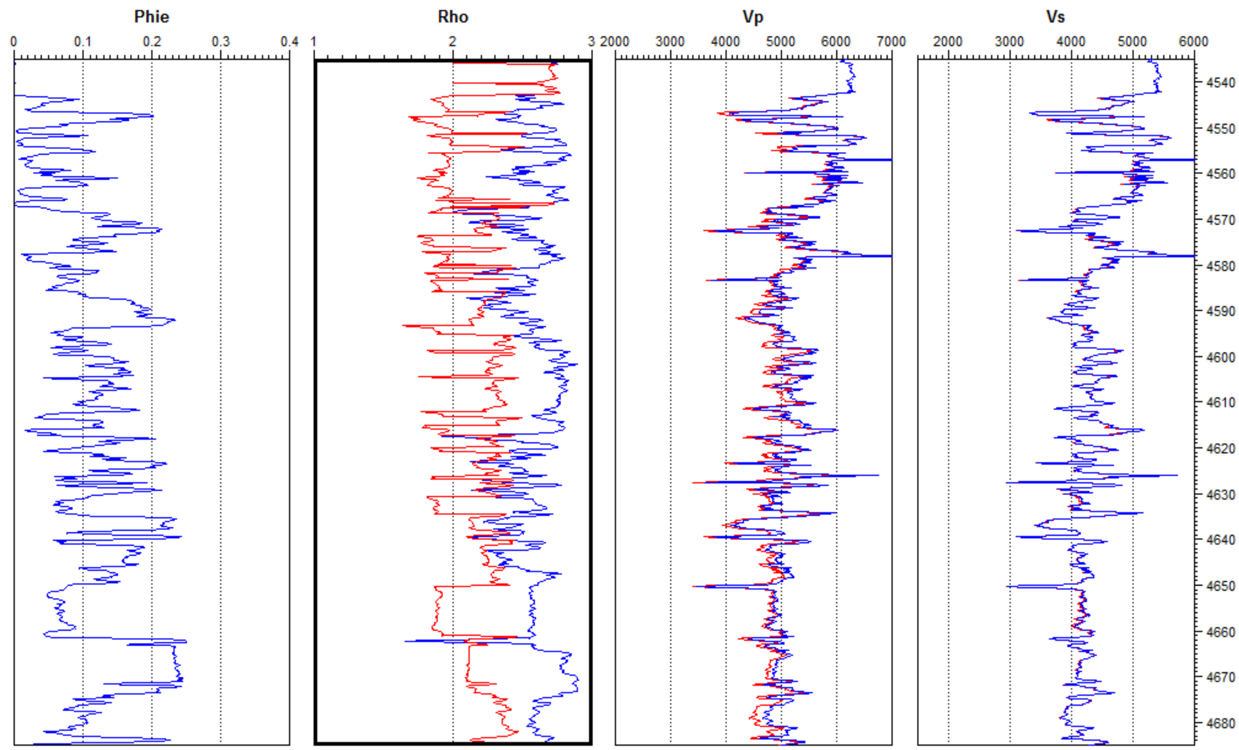


Figure 4.31 Saturated curves of 50% fluid substitution.

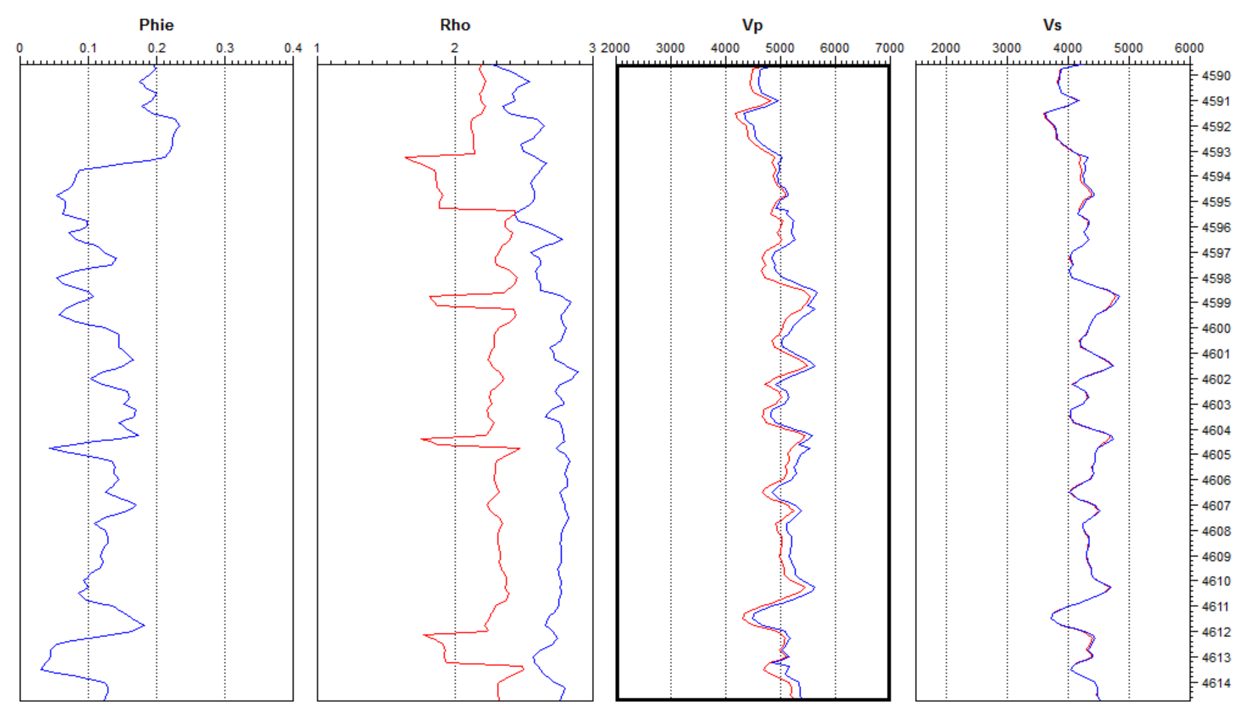


Figure 4.32 Zoomed curve of 50% fluid substitution.

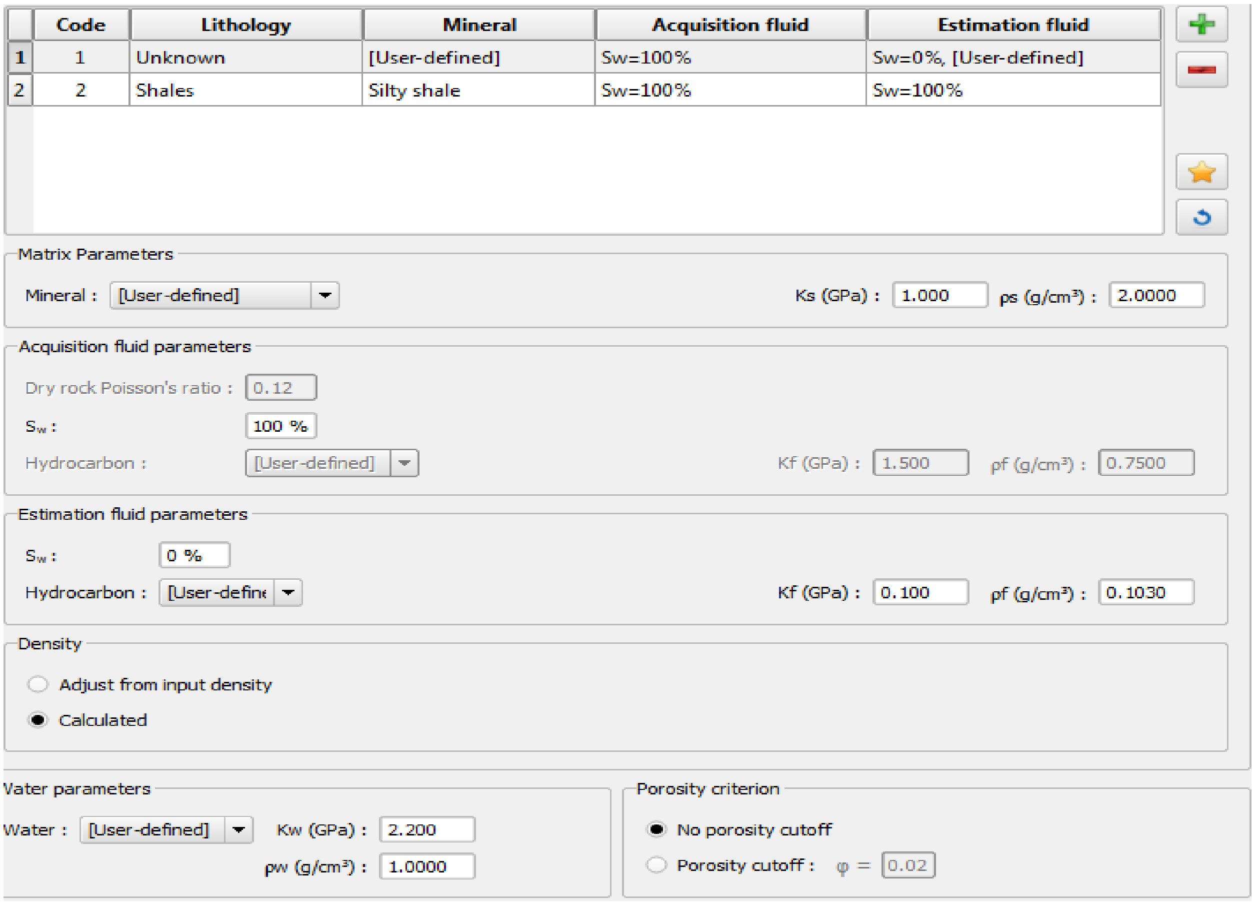


Figure 4.33 Input of Saturation level for 100%.

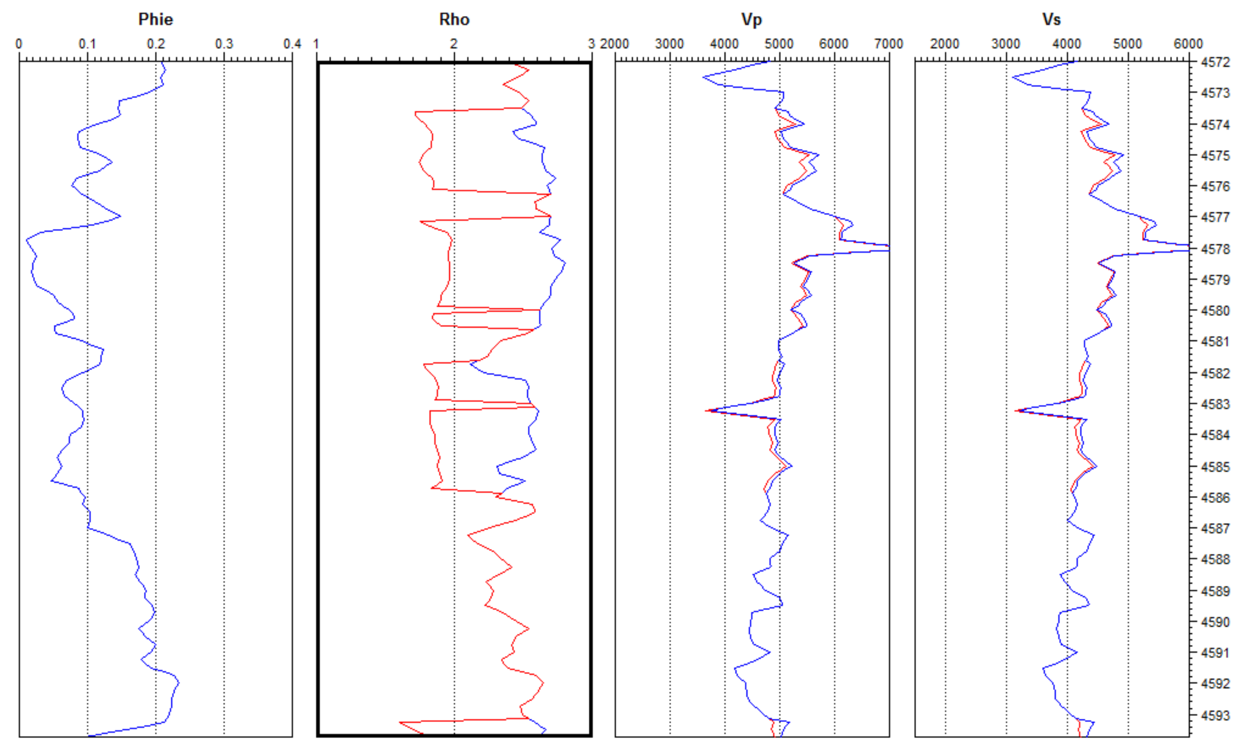


Figure 4.34 Saturated curves of 100% fluid substitution.

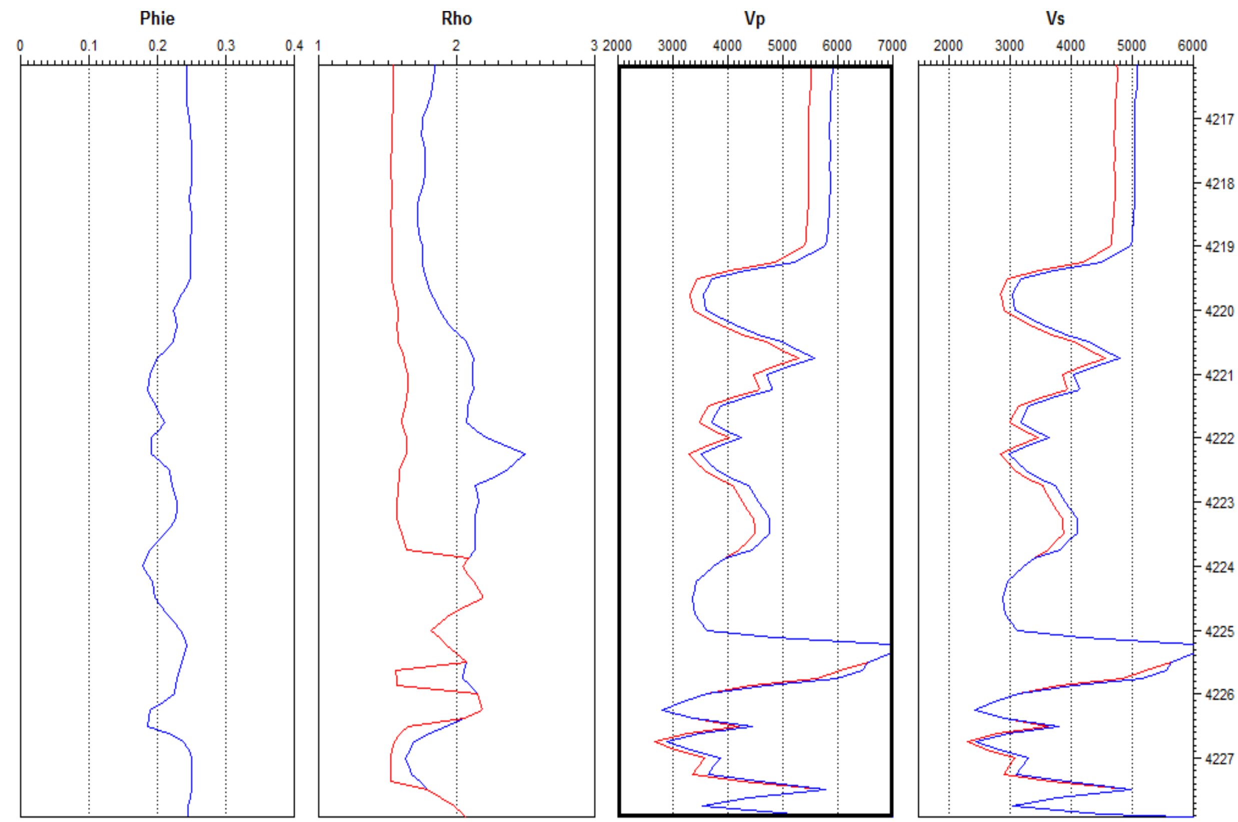


Figure 4.35 Zoomed curves at 100% fluid substitution.

Chapter # 05

DISCUSSION AND INTERPRETATION

Petrophysical Interpretation of Well

In Chanda-Deep-01 different formations were analyzed and evaluated to identify different possible reservoir zones. Different zones are marked on the basis of log behavior, porosity, permeability and water saturation. In Chanda-Deep-01 the producing formation is the SamanaSuk formation present at the depth of 4499m and has thickness of 80m. In this formation we have noticed the decreasing trend of GR Log. In the above given Figure 4.5 and 4.6 two zones were marked as zone 1 and zone 2. In these zones the petrophysical parameters are as follow:

Vsh < 30%
Sw < 60% and
Porosity > 07 %

According to these parameters we calculated that the volume of shale is less than 30%, saturation of water is less than 60% and porosity is greater than 7%. By these factors we identified that the Samana Suk Formation is our reservoir rock.

With the same parameters we can say that other reservoir zones will be the Lockhart Limestone and Datta Formation. As shown in Fig 4.7 and 4.8 we noticed the same decreasing trend of GR Log, the crossover of LLD and LLS we can identified the reservoir zone as zone 1 and zone 2 of the Samanasuk Formation. Here also we detect the high value of hydrocarbon saturation as compare to water saturation. So this is possible reservoir area.

Third reservoir rock we can say will be Datta Formation as it also shows the same behavior as discussed above. In the figure 4.9 and 4.10 three zones were analyzed as zone 1, zone 2 and zone 3 in which we can identify the good petrophysical properties that give information of reservoir zones. In all these formations the producing formation is Samanasuk Limestone. Oil and Gas Development Company Limited (OGDCL) is working on this well. This well has total depth of 5500m.

Properties of other zones marked as reservoir zone are

Zone 1 of SamanaSuk Formation

Sw	26%
Sh	74%
Phi_e	9%
Vsh	27%

Zone 2 of SamanaSuk Formation

Sw	20%
Sh	80%
Phi_e	12%
Vsh	38%

Zone 1 of Lockhart Limestone

Sw	13%
Sh	87%
Phi_e	11%
Vsh	17%

Zone 2 of Lockhart Limestone

Sw	48%
Sh	52%
Phi_e	9%
Vsh	41%

Zone 1 of Datta Sandstone

Sw	36%
Sh	64%
Phi_e	8.5%
Vsh	13%

Table 5.1 Petrophysical properties of Different zones of Reservoir rocks in Chanda Deep 01.

Electrofacies Analysis

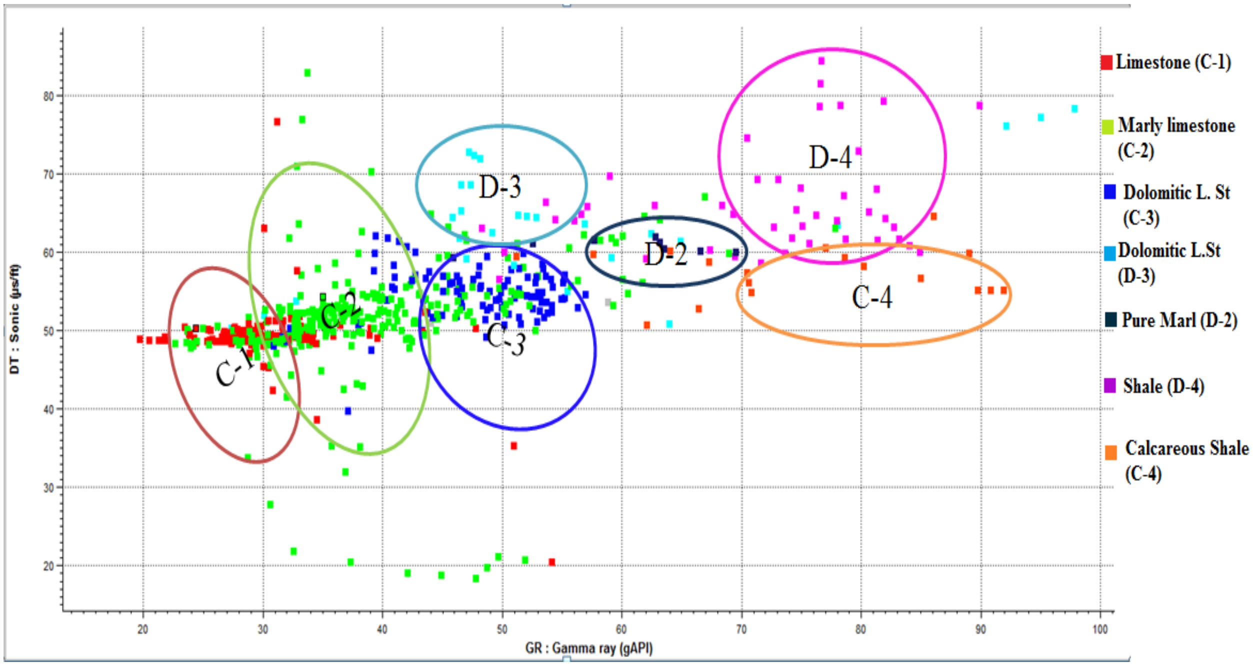


Figure 4.1 Seven Electrofacies in reservoir zone of Chanda Deep 01.

In the above mentioned graphs we have marked 8 facies named as C-1, C-2, C-3, C-4, D-2, D-3 and D-4. We can differentiate them on the basis of log behavior. Here we have made plots between GR Log and DT Log. Rhob log is not taken under consideration as there are caves present in our reservoir area and the thickness is very less so GR and DT logs are more suitable for the identification of Electrofacies.

Firstly we define C-1. C-1 facie is our clean Limestone as we see the Low value of Sonic log that is approximate 50 and low value of GR log that is round about <35. We recognize the alternate bedding of this facie at different depth. Mostly it is present in the upper portion of the reservoir. In the lower part it is not present. In the upper part it is about 9m thick with alternate bedding. It is represented in Red color in the graph and curves.

Secondly we define C-2 facie. C-2 facie is marked as Marly Limestone. Here we observe the increasing trend of GR log but the value of Sonic log (DT log) is low. This shows the presence of radioactive material. It is the dominant lithology in our reservoir area. This also indicates the presence of Hydrocarbons, as the crossover of Resistivity log (LLD and LLS) shows the good results. C-2 has thick beds with alternate bedding. This is spread in the whole reservoir with variation in thickness. It is represented as Green color in the graph and curves.

Third we define C-3 facie. It is defined as Dolomitic Limestone because of dolomitization process. This is observed as the value of GR log is increasing because of this increment delay time is also increasing. In the process of dolomitization present the increasing trend of radioactive material. So, on the basis of this behavior it is marked as Dolomitic Limestone. It also has alternate thin beds. It is shown in blue color and it is mostly present in the upper middle and lower part of reservoir.

Then we define D-3 facie. It is also named as Dolomitic Limestone, but it is hydrocarbon bearing limestone because we observe the increasing values of both Sonic log and GR log. It is present in the middle lower part of the reservoir with thin beds. It is shown in cyan color in the graph and curves.

Fifth facies is defined as D-2 facies. It is the least facie present in our reservoir zone and it is defined as pure marl. Its clustering is very less. Here we see that the value of GR log is constant, but the value of Sonic log is increasing. It is present in the lower most part with very thin bed. It is shown in blackish blue color in the graph and curves.

After D-2 we defined D-4 facie and it is marked as Shale as the value of Gamma Ray log is high up to 85 and the value of sonic log is also very high. As shale is a loose material and we get high values of Gamma ray log. It also has thin beds in the lower part or reservoir. It is shown in purple color in graph and curves.

In the last we define C-4 facie and it is marked as Calcareous Shale. As it also has a high value of Gamma ray log and high value of Sonic log. The presence of carbonates increases the rate of compaction that’s why the delay time increases. It also has very less concentration and extent in the reservoir zone, present at the lower part of the reservoir area. It is presented as orange color.

The table for the range of values of different facies is given as follow:

DT Range	GR Range	Facies Code
18-30	18-30	A-1
18-30	31-45	A-2
18-30	46-60	A-3
18-30	61-90	A-4
31-45	18-30	B-1
31-45	31-45	B-2
31-45	46-60	B-3
31-45	61-90	B-4
46-60	18-30	C-1
46-60	31-45	C-2
46-60	46-60	C-3
46-60	61-90	C-4
61-90	18-30	D-1
61-90	31-45	D-2
61-90	46-60	D-3
61-90	61-90	D-4

Table 5.2 Ranges of GR and DT log of all Electrofacies in Reservoir Zone of Chanda Deep 01.

Rock Physics

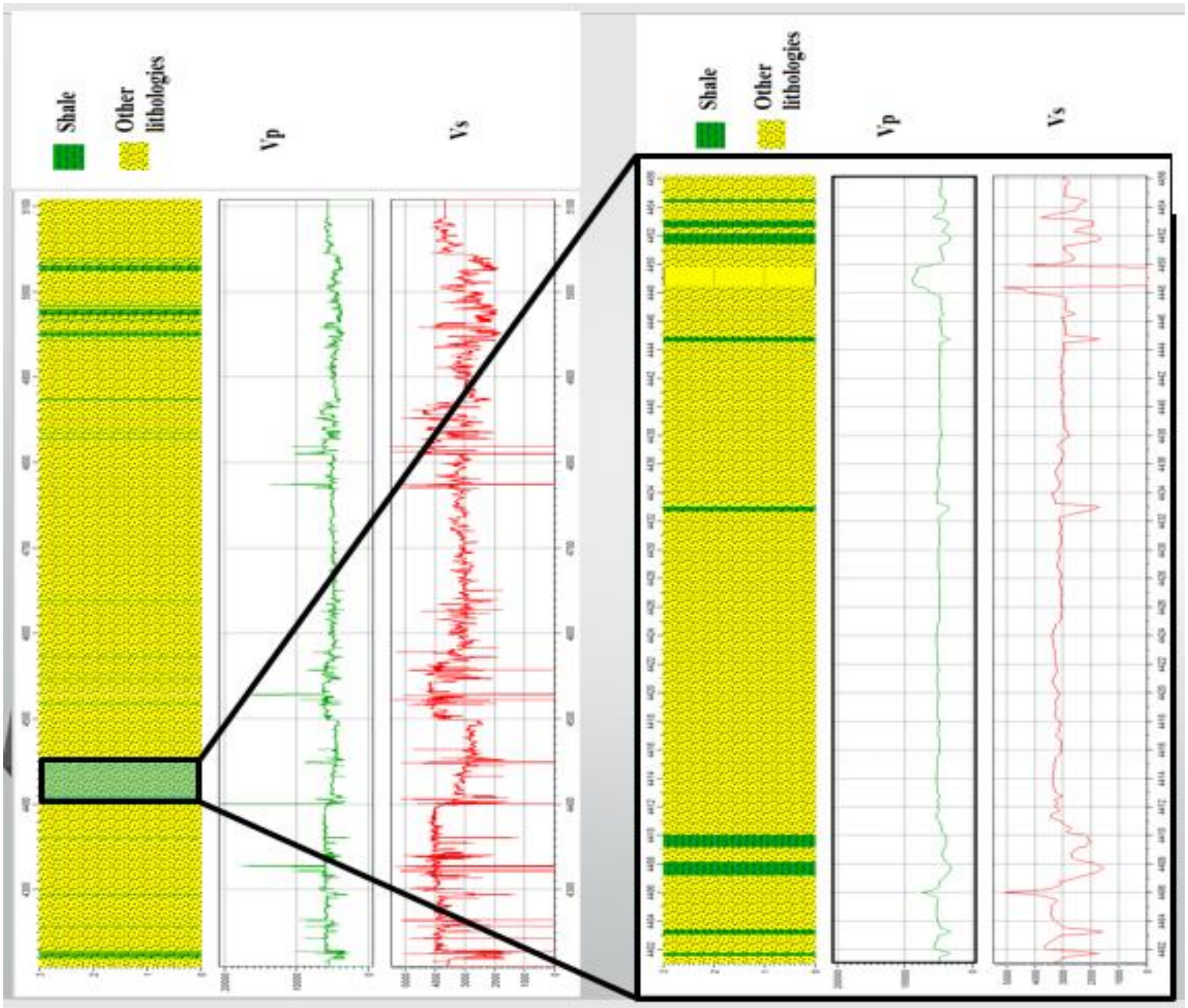


Figure 5.2 Behavior of Seismic waves (Vp & Vs) form different lithology's.

Results and Interpretation

In the above given figures the green color represents the shale content and yellow color represents the other lithologies. Here we see that the velocity decreases in shale content because it is a fine grained rock that is the mixture of clay minerals and small fragments of other minerals that includes quartz calcite etc. and in the above texture we can explain that high clay content decreases the velocity so here we see the decrease of seismic velocity. Similarly for sandstone or other lithologies the velocity is increasing as the presence of a clastic sedimentary rock that is composed of sand sized minerals includes quartz or feldspar. For example, Sandstone is a porous rock to store different fluids as is has a large porosity which means that it has fat pores so we discussed previously that fat pores have high velocities so here in the given diagram we can see the increase of velocity through sandstone. We can also identify the presence of reservoir with the help of behavior of seismic waves with respect to well.

Total Organic Carbon (TOC)

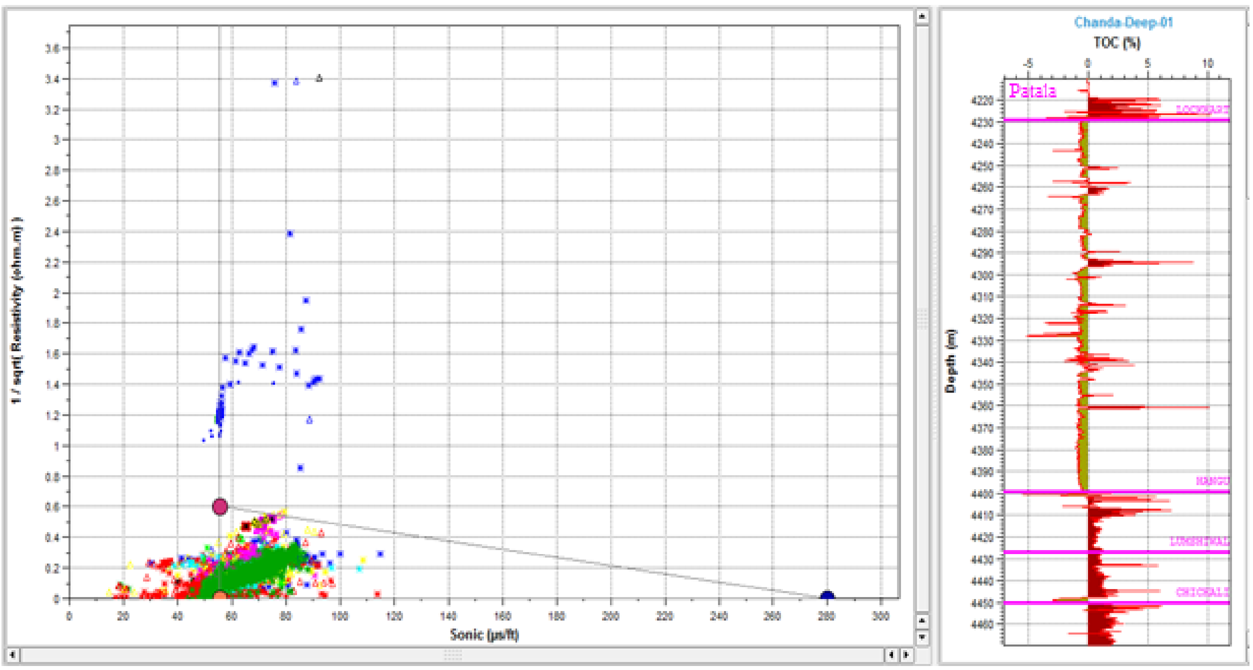


Figure 5.3 TOC Determination of Chanda Deep 01.

Results and Conclusion

From logs the value of TOC ranges from 0.5% to 15% but good source rock has value approximately ranges up to 10%. From the above given pictures, we can see that the value of TOC is good (approximately 10%) in Patala Formation so we can say that this is our source rock. Based on analysis we can also say that other source rocks are may be Lockhart Limestone. Datta Sandstone is not a good reservoir as it has less value round about 3% TOC. But in this area, source rock is Patala Formation and when we look upon our result we also have a good value in Patala Formation. So this will also be our source rock.

Fluid Substitution

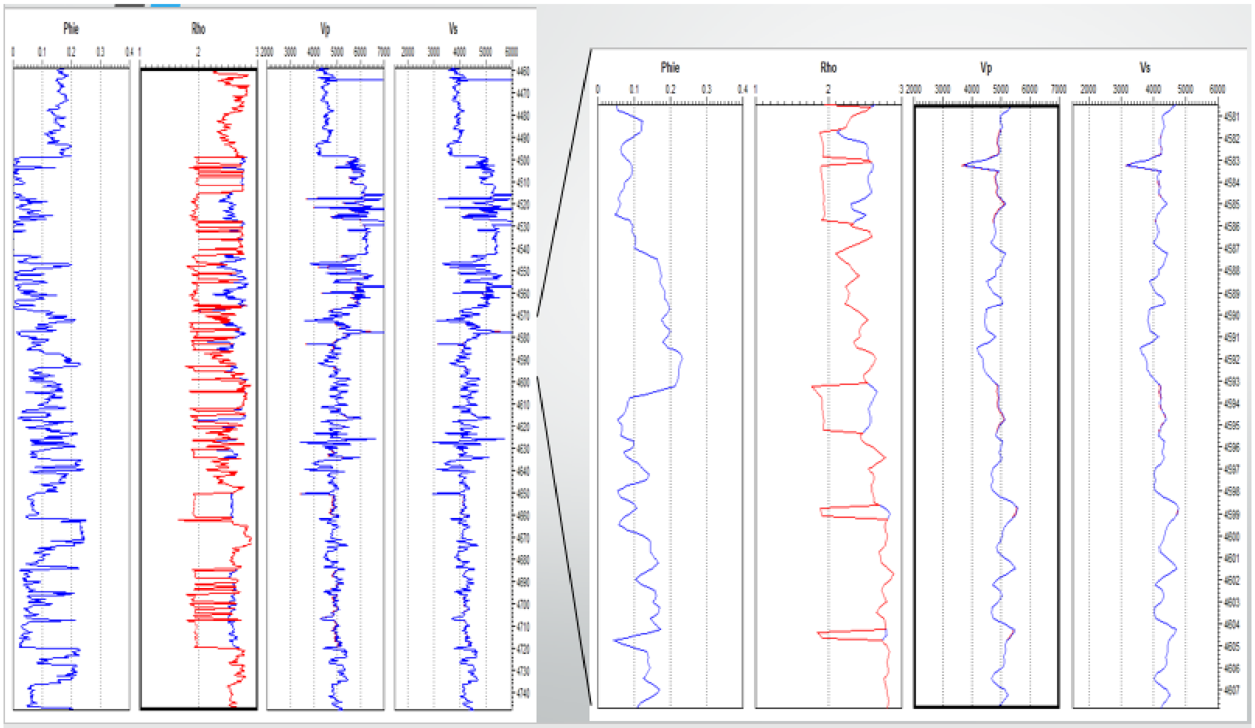


Figure 5.4 Fluid Substitution with 10% saturation level.

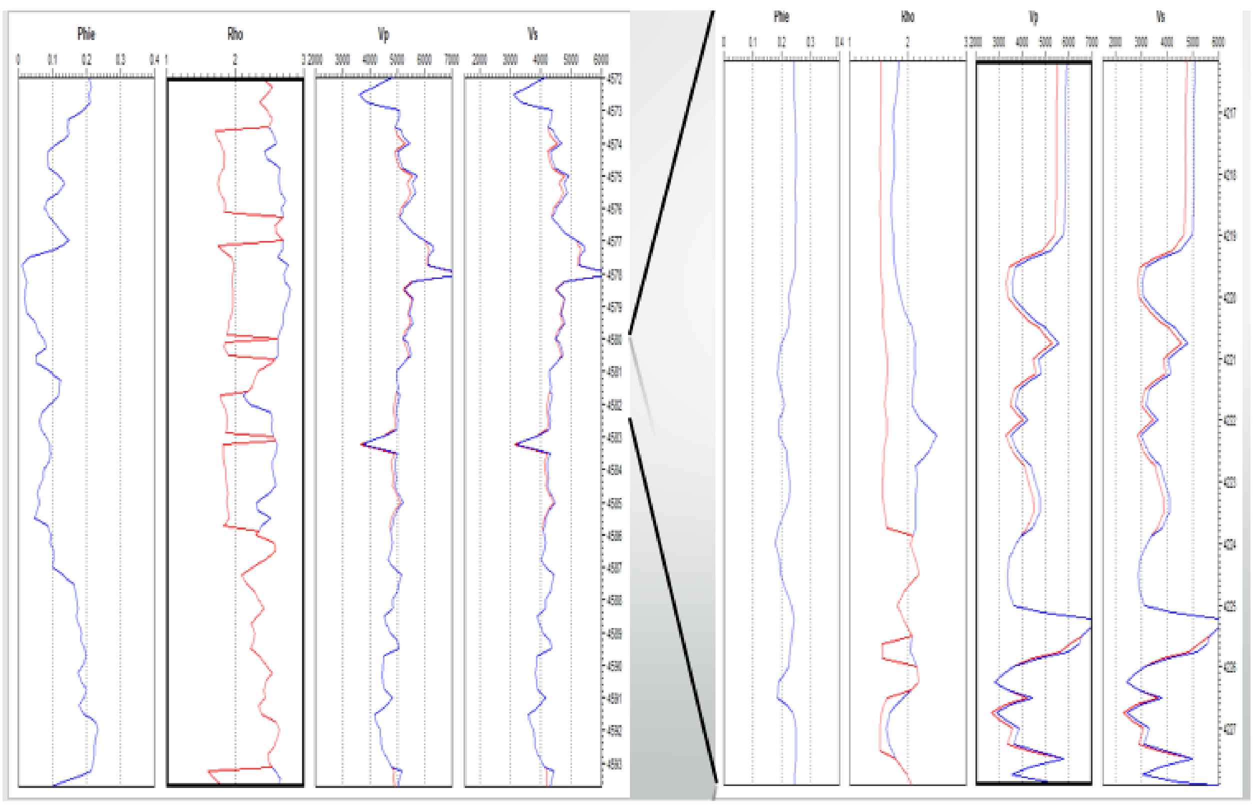


Figure 5.5 Fluid Substitution with 70% saturation level.

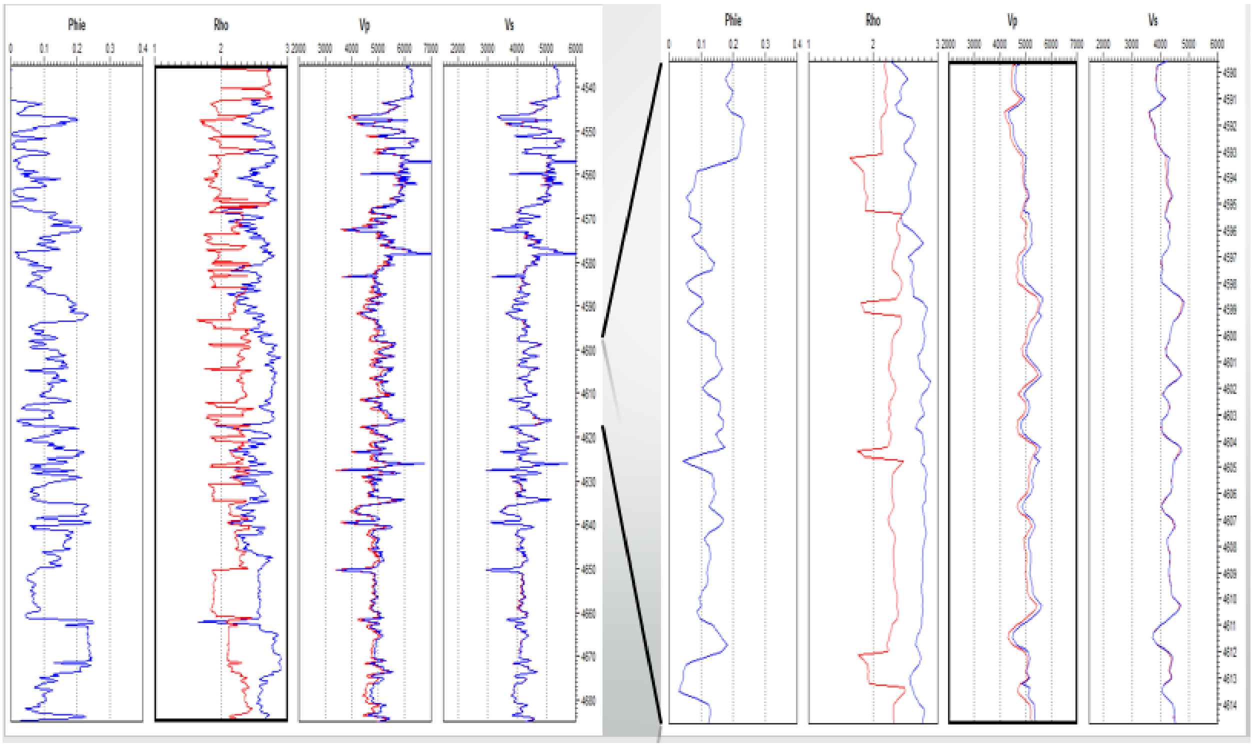


Figure 5.6 Fluid Substitution with 100% saturation level.

Gassmann's Fluid substitution gives information about the estimation of hydrocarbon reserves. In the above given figures we observed the change in the behavior of curves as we give input values at different fluid substitutions. As we know that the velocity of seismic waves are greater in solids as compare to liquids because solid rocks are compacted and the pores are interconnected with each other so due to this compaction the density of rock becomes greater. Whenever there is presence of fluid the velocity of seismic waves becomes less. This phenomenon is observed in the above given figures. In the first case, 10% water saturation has been set. This shows little decreasing behavior of density and velocity curves, this behavior is directly related to the presence of water which is comparatively less dense.

Similarly in next we set water saturation value to 30% this also shows the decreasing behavior of density and velocity curves. The decrease in the values is due to the presence of less dense water. In the next the saturation of water has been set to 50% and 100% respectively, the all output results shows the decreasing trend of density and velocity curves.

All the results shows the decreasing trend of curves so if we get the current values of Logs and compare it with the given saturation we can estimate the hydrocarbons reserves where the curves are best matched.

Chapter # 06

CONCLUSIONS

- Based on present studies, it is concluded that Upper Indus Basin has a great importance for Geological and Geophysical researches, there is much similarity in formations of different wells in Kohat and Potwar region.

- Based on petrophysical analysis, it is concluded that Samana Suk formation is the potential reservoir in Chanda-deep well, while other formations also showed positive reservoir characters (i.e., Lockhart Limestone and Datta Sandstone).

- Six electrofacies were identified on the basis of clustering of points and behavior of log that are: Limestone, Marly Limestone, Dolomitic Limestone, Pure Marl, Shale and Calcareous Shale.

- Rock physics properties were studied that show different behavior of seismic waves in different lithologies, velocities are less in shale as compare to sandstone, limestone.

- Based on TOC (about 10), which shows Lockhart limestone as potential source rock in the studied wells.

- Finally, fluid substitution provide information about the reserve estimation based on change in the behavior of density log and velocity log and comparing it with the original given data present at the given time. But in our case, due to paucity of data, it was not possible to calculate total reserves of hydrocarbons.

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