PETROPHYSICAL ANALYSIS AND FACIES MODELING OF LOWER GORU FORMATION OF KADANWARI FIELD

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M.PHIL GEOLOGY

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A thesis submitted in partial fulfilment of the requirement for the degree of Master of Philosophy in Geology

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CERTIFICATE

This dissertation is submitted by **Samya Ashraf** D/O Muhammad Ashraf is accepted in its present form by the Department of Earth Sciences, Quaid-i-Azam University Islamabad as it satisfies the requirement for the award of M.Phil. Degree in Geology.

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Dated:

ACKNOWLEDGMENT

All praise to Almighty Allah who gave me courage and made me able in completing my thesis work successfully. I offer my gratitude to last Prophet Muhammad (PBUH).

I am also extremely grateful to my honorable supervisor **Dr. Matloob Hussain** for their wide knowledge and logical way of thinking have been of great value for me. Their personal guidance has provided a good basis for this study. I must acknowledge the cooperation of all my teachers whose direction and support have been the source of my success.

I would like to pay my colossal respect to Muhammad Bilal Malik. This work could never have been completed without him. Most of the credit of IP software support goes to him.

I would like to acknowledge my friends for their help and suggestions during my work. I do express my sincere thanks to Palwasha Shahzad Rathore for sincere guidance, help, moral support and encouragement

I am thankful to my parents for moral and financial support. I am indebted to my loving parents, who encouraged and motivated me to face the challenges of life during my academic career. I am also highly indebted to my brothers and my sister and specially my seniors for their love and cooperation.

Last but not the least, I am thankful to all my friends and fellows who encouraged and motivated me throughout my academics.

Samya Ashraf

M.Phil. Geology

2020-2022

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Abstract

Exploration geosciences are greatly influenced by computational technology. Machine learning and other computational technologies are used for analyzing and arranging large data sets with minimum efforts. This technology can provide information about subsurface that is not approachable by other means and it is useful for hydrocarbon exploration. Since, data of subsurface is vast and quite difficult to handle, machine learning effectively manages the data and provides predictions by using techniques like self-organizing map (SOM).

Middle Indus basin is known for heterogeneity and vast hydrocarbon reserves. Lower Goru Formation of Middle Indus Basin acts as a reservoir while Sembar Formation acts as source rock and Upper Goru Formation acts a seal rock. Since Lower Goru Formation has alternating layers of lithology, this formation is known for its lithological heterogeneity. Alternating layers of Lower Goru Formation are divided into further sections by OGDCL and OMV. OGDCL divided formation into Upper sand, shale and marl sequence, Basal sands, Talhar shale and Massive sandstone.OMV divided the respective formation into intervals as A, B, C, D and E interval. Petrophysical analysis for efficient identification of lithology and curves is done, followed by electrofacies analysis using Self Organizing Map technique. Study was for KADANWARI-01, KADANWARI-03, KADANWARI-10 and KADANWARI-11.

By petrophysical analysis it is estimated that E and B sand zones are main reservoirs. For E zone shale volume is 15-20 %, effective porosity 10-12 % and water saturation 25-30 %. For B zone shale volume is 8-10%, effective porosity6-8% and water saturation is 30-35%. Self organizing map technique (SOM) is used to determine electrofacies by dividing the data into twenty clusters and later on four clusters were developed by hierarchical clustering. There clusters are used for classification. SOM maps displayed 2D facies map. Results of SOM technique are analyzed by comparison with petrophysical analysis and accuracy is found. Hence this technique can be used for reservoir estimation. Lithological identification by SOM can reduce the risk associated with hydrocarbon exploration.

Chapter 1

INTRODUCTION

KADANWARI GAS FIELD is located in the Middle Indus Basin. Middle Indus basin is located between two regional extensive highs. Mari-Kandhkot High is present to the northeast of Middle Indus basin and Jacobabad-Khairpur High is present to the southwest of Middle Indus basin.

1.1.Exploration history

This field shown in figure 1.1 was discovered in 1989 and brought on stream in 1995. Field operation started and 2D seismic data was acquired. It was initially operated by Lasmo and after 2003 this well is operated by OMV Pakistan. In KADANWARI GAS FIELD eleven wells have been drilled.

1.2.Petroleum system

Producing reservoirs in this field are Lower Goru sands of Cretaceous age and the sealing is by transgressive marine shales of Upper Goru while Sembar shale act as source rock. Mainly structural traps are present. Significant potential can be indicated by structural and stratigraphic traps in mature fields meanwhile all essential elements of hydrocarbon trapping mechanism are present.

Significant amounts of available potential can be exhumed from structural and stratigraphic fairways of virgin plays in mature fields wherein conventional elements of hydrocarbon trapping mechanisms are well established. Study area has negative flower structure due to rifting and drifting (Kazmi. Jan., stratigraphy of Pakistan).

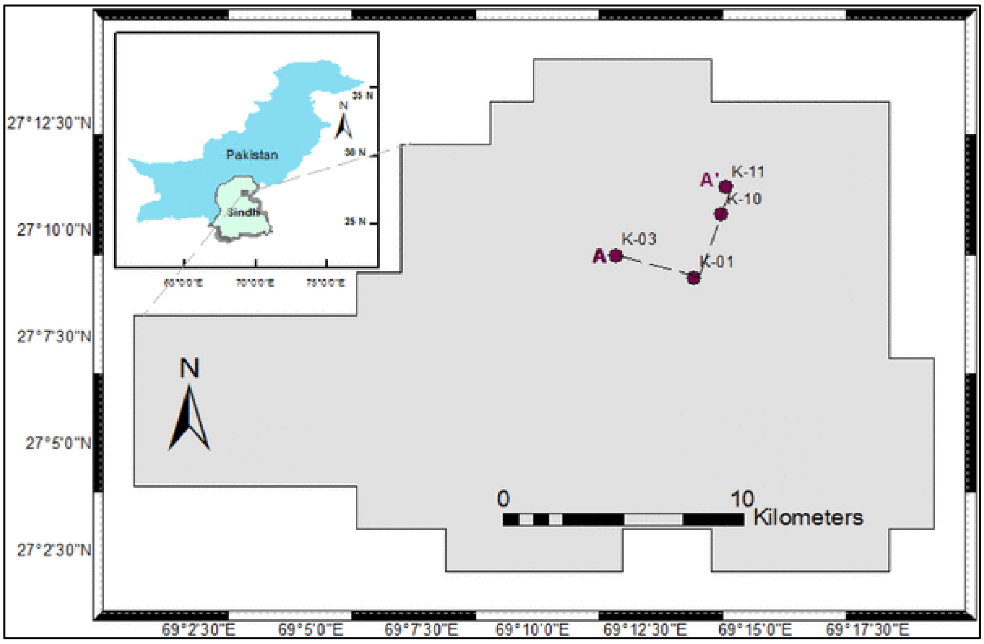


Figure 1.1: Location of study area

1.3.Objectives of study

Main objective is detailed study of petrophysical parameters to determine importance from petroleum aspect. Electrofacies are determined by using Self Organizing Map technique (SOM) and later on comparative analysis is used to estimate accuracy of each technique. In study area objectives include:

- Petrophysical analysis for finding out petrophysical curves, volume of shale, porosities and saturation of water of Lower Goru Formation.
- Reservoir characterization by Facies modeling using machine learning with Self Organizing Map technique (SOM) to identify the potential of E and B zones of Lower Goru Formation of KADANWARI FIELD.
- To analyze the results of Self Organizing Map technique (SOM) as compare to petrophysical analysis for E and B zone of Lower Goru Formation of KADANWARI FIELD.

1.4.Location

The KADANWARI FIELD is located in North-East of Karachi. This field was discovered in northern area of Sindh in 1989. Later on, this well was evaluated by three wells during period of 1990-1991. Production started in September 1995. KADANWARI FIELD is located on the southeastern flank of the regional Jacobabad High (Kazmi and Jan 1997) as shown in figure 1.2. Study area is on the southernmost of Middle Indus Basin .Coordinates of study area are 27°7′46″N 69°13′36″ latitude and 27°7′46″N 69°13′36″E longitude.

Figure 1.2: Location map of the study area (Scotese 1999)

1.5.Data description

Data used for petrophysical analysis and curves was obtained from Directorate General of Peetroleum Concession (DGPC). Data was in form of .las files. These files represented wirelogging data as function of depth with geological strata. Different tools were used for analysis of data for example Gverse is used for petrophysical analysis. Well logs include Gamma Ray log (GR), Spontaneous Potential log (SP), Neutron-Porosity log (NPHI), Density log (RHOB), Resistivity log (LLS, MSFL, LLD) and Sonic log. IP software is used for electrofacies analysis.

1.6.Methodology

Well log analysis is a useful technique to evaluate the petrophysical parameters of the reservoir. Well logs have been used to get more information and accuracy in evaluating a reservoir (Abd El-Gawad 2007).

With provided data Total Organic Content, volume of shale and vitrinite reflectance can be evaluated. Poisson’s ratio and porosity are among the main properties to be evaluated**.** To find out ∆ log R technique suggested by Bowman can be used. Water saturation and hydrocarbon saturation as well as identification of payzone with approximate thickness can be evaluated.

1.7.Significance of research

Petrophysical estimation of data is essential for identification and assessment of reservoir. Petrophysical estimation provides many properties such as lithology, porosity, clay volume, grain size, water saturation and permeability. Electrofacies modeling is also an objective of this research. This research will provide a relation of machine learning to electrofacies by using Self Organizing Map technique (SOM).

1.8. Climate and Physiography

The study area lies in Thar region. It is mostly consist of barren, irregular and roughly parallel sand dunes. There is shortage of potable water and the soil has extraordinary salinity (OGDCL, 1995, Pakistan petroleum prospects). Climate is as of tropical desert that is why study area is quite hot during summer days but comparatively cooler at nights. Hottest month of year in study area are April, May and June meanwhile coldest months in study area are December, January and February. The mean maximum temperature is 280^0C. The mean minimum temperature is 90^0C (Kemal, A, 1992, Geology in Pakistan). There is a fluctuation in the amount of rainfall. Yearly average of rainfall for some areas is as low as 100mm. Rainfall is mostly between July and September. This is a period of South-West monsoon. (Atif Bukhari, 2012, Geography of Pakistan)

Chapter 2

GEOLOGY AND STRATIGRAPHY

Pakistan has three basins including two main basins Indus Basin and Baluchistan Basin and one smaller basin Pishin Basin. Each of these basins passed through different geological episodes in different ages. Later on, these basins were tied during Cretaceous/Paleocene age. Basins tied together along Ornach-Nal/Chaman fault (Kadri, 1995). Indus basin is mainly extending in Eastern part of Pakistan while in western part of India with an aerial extension of about 873000 km^2. Further subdivisions of Indus basin on basis of structural regime and petroleum prospect are as following:

a) Upper Indus Basin (Kohat sub-basin and Potwar Sub-basins)
b) Middle Indus Basin (Suleiman sub-basin)
c) Lower Indus Basin (Kirthar sub-basin)

2.1. Regional tectonics

Middle Indus Basin/ Sulaiman Range

Kadanwari well is located in Middle Indus basin. The Middle Indus basin is separated by Jacobabad high and Mari Kandhkot high from the Lower Indus basin and it is separated from Upper Indus basin by Sargodha High and Pezu uplift in North. Tightly folded, uplifted and faulted rocks of Triassic to Cenozoic age are present in Suleiman Range. According to Kadri (1995); from East to West, Middle Indus is divided into following broad tectonic divisions:

1) Punjab Platform
2) Suleiman Depression
3) Suleiman Fold belt

In East of Middle Indus basin Indian shield is present while in West there is marginal zone of Indian plate. Sukkue rift is present in South of Middle Indus basin,

Punjab Platform

Kadri (1995) described that it is a monocline in Eastern part of Middle Indus basin. This monocline is dipping towards Suleiman depression. Punjab platform is least effective by collision between tectonic plates. In Punjab Platform no outcrops of sedimentary rocks are present. Although most prominent stratigraphic pinch outs in Pakistan are present in Punjab Platform. Numbers of wells have been drilled there.

Suleiman depression/Suleiman foredeep

The Suleiman depression is also called Suleiman fore-deep. Suleiman depression is defined as area of subsidence. This depression has transverse orientation. Suleiman depression was formed by collision of tectonic plates. This depression has Zindapir inner folded zone on Western side meanwhile Maribuggti folded zone on South side. Due to flow of Eocene shales during tectonic collision some anticlines were formed. These anticlines are indicated by seismic evidences of burial (Kadri, 1995).

Suleiman Fold Belt

Suleiman fold belt has disturbed anticlinal features. This is a tectonic feature located relative to the closure zone (Kadri, 1995). Strata in fold belt are of Paleocene to Eocene age. Lithostratigraphic facies vary from North to South and from East to West. Fold belts tend to occur as long, narrow belts running more or less continuously for great distance. These belts are usually irregular and curved and are marked by intense lateral compression. The rock strata are folded and contain low angle thrust faults. Along belts mostly shallow-water marine sediments are found. The youngest mountain-chains are situated along the continental borders.

In the West of Himalayas a tectonically active, broad and gentle fold thrust belt is present. This belt is known as Suleiman lobe (Sarwar & Dejong, 1979). It is formed by transpression. Transpression in West of Himalayas is caused by left lateral strike slip fault along Chaman fault and thrusting of Western terminal on Indian subcontinent (Lawrence et al.1988, Farah et al. 1984, Quaitmeyer et al.1984). These anticlines are basically detachments formed by strike-slip movement

2.2. Global Tectonic history

Orogeny is process of mountain building and it is also known as tectonic revolution. There are basically three stages of orogeny:

1. Initial stage
2. Second stage
3. Final stage

According to tectonic episodes in table 2.1, during initial stage geosynclines were created and sediments were subsided and accumulated. During second stage folds and faults were formed and during final stage mountains were formed. In Late Protozoic age, Gondwanaland supercontinent had intra-cratonic rifting. Later on, another rifting event occurred in Permian-Triassic age. Indian plate separated from Afghan, Africa and Seychelles cratonic elements in the last phase of Mesozoic rifting. After that phase a plate convergence of Indian plate with Eurasian plate occurred in Cenozoic age and this convergence is still going on (Kemal et al, 1991).

This convergence resulted in opening of major faults including Kirthar basement fault, Suleiman basement fault and Jehlum basement fault. Movement of these blocks is the reason of different tectonic patterns on basement blocks (Bannert and Raza, 1992). These diverse geological events are main factor in deposition of Infra Cambrian Eocene source and reservoir rocks and presence of stratigraphic and structural traps.

The Kirthar Fore deep has sediments thickness aggregating over 15 km and faulted eastern boundary with Thar Platform. The sediments deposited in this depression appeared to be Paleocene aged (Ali et al., 1995).

Table 2.1: Summary of important tectonic events occurred on global level

AGE	TECTONIC ACTIVITY
Permian-Middle Jurassic	Separation of Gondwanaland
Middle Jurassic	East Gondwanaland is separated from Africa
Late Jurassic	Indian plate is separated from Africa
Cretaceous	Madagascar separated from India
Paleocene	Indian plate separated from Seychelles
Eocene	Indian plate collided with Eurasia
Early-Late Miocene	Post-rift down-wrapping started
Late Miocene	Karachi Platform developed
Early Miocene	Plate reorganization
Oligocene	Filling of basin
Early Cretaceous	Formation of Karachi trough and marked by KT boundary

2.3. Regional tectonic history

Gondwanaland was rifted during Paleozoic age. This rifting was caused by basaltic magma as magma crumpled the overlying lithosphere. This tectonic bending formed faults and caused divergence and movement of sea floor spreading with thinning of lithosphere. On the basis of literature review, the understudy area is divided into three tectonic episodes. These episodes are shown in figure 2.1.

1. In phase 1, during Middle Jurassic age, exenstional forces broke the upper crust into blocks. These blocks were later on separated by active faults. Later on stretching of initially rifting part stopped and this was indicated by hiatus in Late Jurassic age. This rifted crust later on formed Indus basin failed rift.
2. Phase 2 began in Early Cretaceous age. This phase indicates the deposition of sediments on drifting crust.
3. Phase-3 initiated in Late Cretaceous age. Continental crust was subsided and Mesozoic sediments were being deposited in Indus basin.

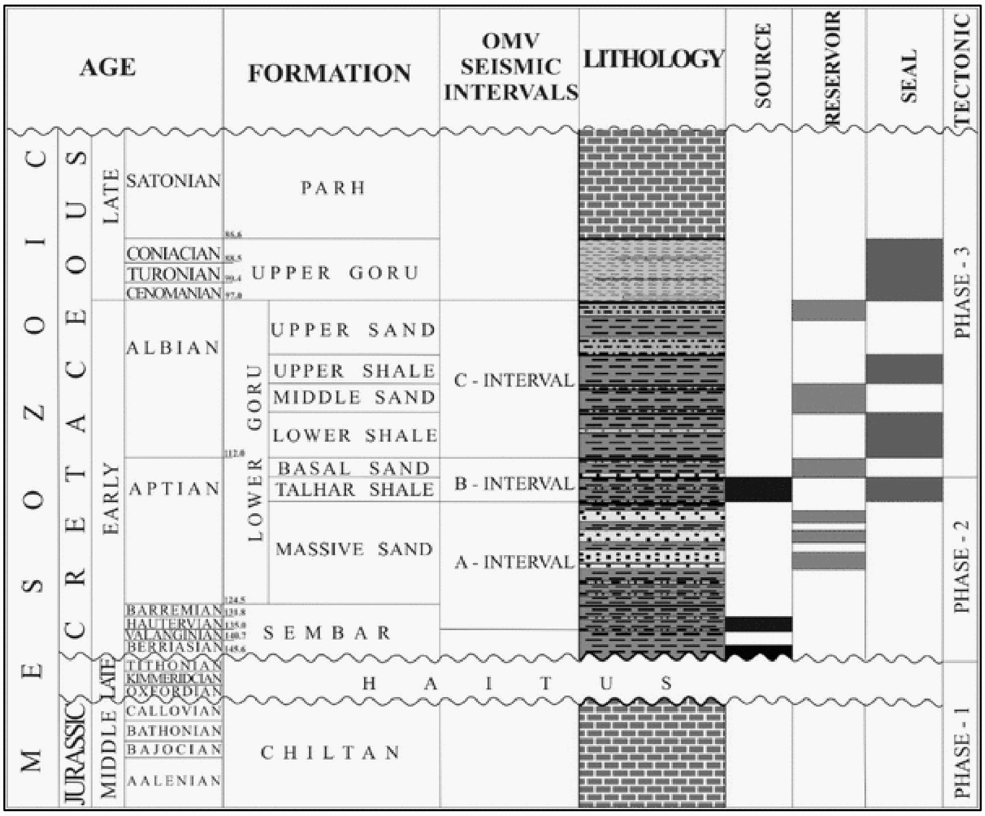


Figure 2.1: Regional tectonic history

2.4. Folds and faults

KADANWARI FIELD has faults and dip closures alongside well are shown in figure 2.2. Most prominent faults are wrench faults. These faults divide the KADANWARI FIELD in to blocks. These blocks formed horst and graben structure. KADANWARI-01 acted as graben. This graben in bounded by KADANWARI-03 as horst in East and KADANWARI-10 and KADANWARI-11 as horst in West. Moving towards North there would be stratigraphic trap and decrease in reservoir quality. Petroleum traps are complex combination of faults and dip closures. Reservoir quality decreases while moving towards North.

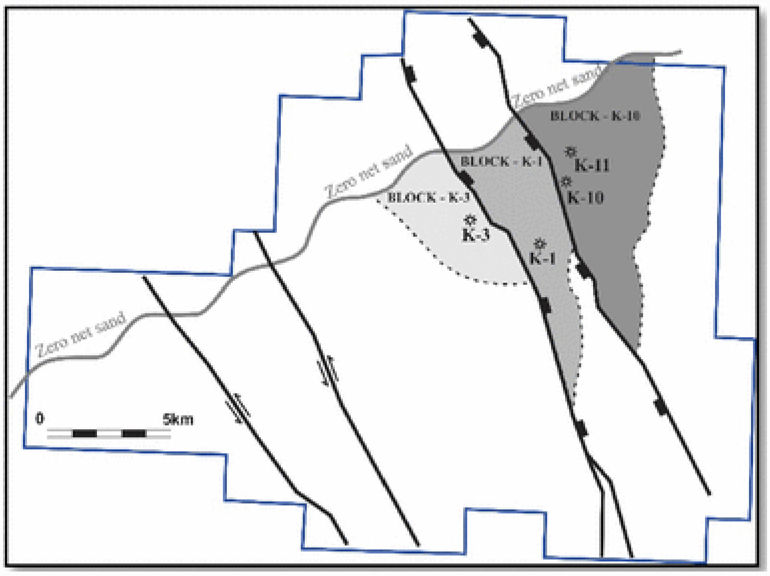


Figure 2.2 Faults in KADANWARI FIELD

2.5. Stratigraphy of study area

It mainly includes formations of Mesozoic age. Formations in KADANWARI FIELD are Chiltan Formation, Sembar, Lower Goru, Upper Goru and Ranikot Formation as shown in figure 2.3.

Chiltan Formation: It is a limestone of Jurassic age.

Sembar Formation: This formation belongs to early Cretaceous age. Lithology includes black shale, siltstone, argillaceous limestone, nodules and sandy shale at the base. This formation is mainly deposited in deep marine environment. Marine organisms of Cretaceous age such as Belemnites, Forams and Ammonites are present in Sembar Formation. This formation has conformable upper contact with Goru Formation and disconfirmable lower contact with Mazar Drik Formation.

Lower Goru Formation: It is a member of Goru Formation. It is of early cretaceous age. Lithology of Lower Goru Formation includes sandstone, marl, and siltstone with subordinate shale. Colors of limestone can vary from grey to white and from translucent to transparent. Siltstone has color variations as well. Siltstone is fine to medium grained. Sandstone is fine grained. Limestone is soft to medium hard.

Lower Goru formation is a promising reservoir. This formation has wide range of lithologies and the formation can be divided into four sections according to OGDCL classification as following:

a. Upper sand, shale and marl sequence

This sequence as indicated by name has shale, sandstone, marl and rare but still there limestone. Shale is of grey color and splintery to flaky in nature. Shale is fissile and pyritic. Sandstone is of white color with grain size in range of fine to very fine grains. Sandstone is translucent to transparent in nature. Siltstone is in range of grey to white color with argillaceous sometimes micaceous and calcareous chemical composition. Siltstone shows blocky appearance. Marl is in range of grey to white in color and arenaceous in chemical composition. Marl is hydrophilic and rarely to moderately indurated.

b. Basal Sands

Sandstone is light brown to white in color. It is friable and in terms of grain size coarse grained. Sandstone is moderately sorted with visual porosity of 10-12 %. Grains of sandstone are angular to sub rounded in shape. Sandstone is transparent to translucent.

c. Talhar shale

Shale is of grey, greenish grey to blackish grey color. Shale has pyritic, silty, micaceous and slightly calcareous chemical composition. Shale has indurated blocky appearance. Siltstone is of grey color. In terms of grain size siltstone is medium to fine grained. In terms of chemical composition it is glauconitic to calcareous in nature.

d. Massive sandstone

Sandstone is fine to medium grained in terms of grain size and grains are sub angular to sub rounded in shape. Sandstone is of off white to light grey color. In terms of cementation it is moderately cemented with poor to fair visual porosity. Sandstone is argillaceous, pyritic and calcareous to non-calcareous in terms of chemical composition.

Upper Goru Formation: It is also a subdivision of Goru Formation. This Formation is of early Cretaceous age. This formation has lithology consisting of limestone, shale and siltstone. Limestone is fine grained in terms of grain size and has gray to olive gray color. Limestone is thin bedded. Shale and siltstone are interbedded. Shale and siltstone are of gray to greenish gray in color.

Ranikot Formation: It is of Paleocene age. In terms of lithology, Ranikot formation has sandstone and shale. This formation is subdivided into Khadro, Bara and Lakhra formations. Bara formation is has light brown sandstone and shale with limestone as well. Bara formation has diversified sandstone, shale and limestone and shale is also in Lakhra formation as well.

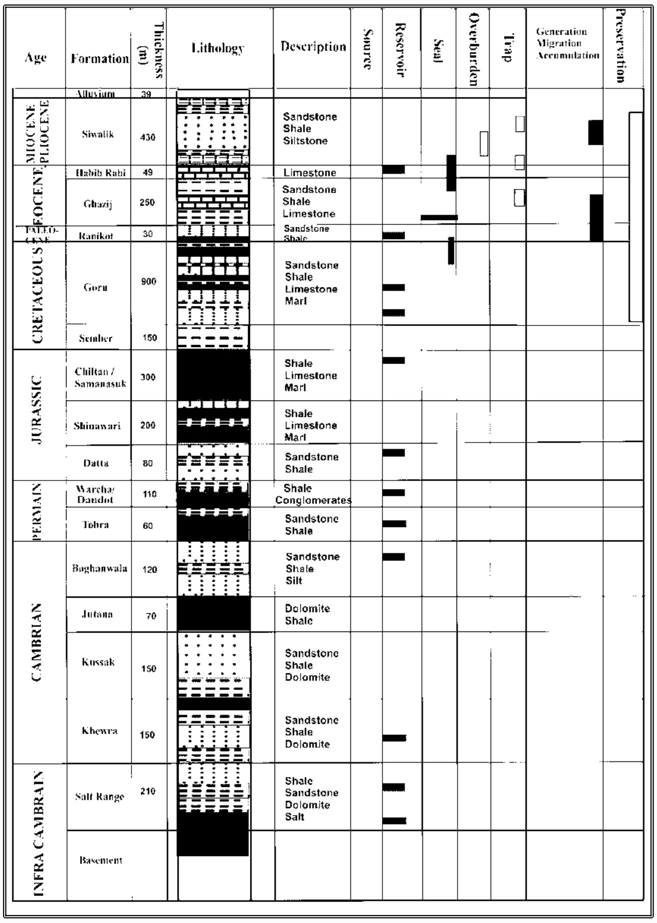


Figure 2.3: General stratigraphy of Middle Indus Basin

2.6. Petroleum system

KADANWARI FIELD mostly has structural traps. In these traps, petroleum system is formed by Sembar formation as source rock and Lower Goru formation has reservoir potential meanwhile Upper Goru Formation act as seal rock.

2.7. Basin type

Middle Indus basin has significant hydrocarbon. Many exploration companies are exploring prominent hydrocarbon fields mainly gas fields in Middle Indus basin such as OMV. Miano well, Sawan well, Latif well, Tajjal well and KADANWARI wells are explored. KADANWARI FIELD has increased gas reserves as compared to other fields of Middle Indus basin. The reason of high reserves is up-dip migration of hydrocarbons. This up-dip migration is caused by structural high known as KADANWARI HIGH.

Since Middle Indus basin is in extensional regime and extensional regimes develop normal faults alongside tilted fault blocks. These tilting blocks are dipping in South-West. Normal faulting can form a larger number of half grabens. Tilting blocks become shallow as moving towards West forming potential prospects by up-dip migration of hydrocarbons. Middle Indus basin has transition from “foreland” to “piggyback” basin.

Chapter 3

Electrofacies and Machine Learning

Electrofacies are defined as combinations of curves obtained from petrophysical logs. These numerical combinations characterize a bed on basis of physical and chemical components. Electrofacies are determined by many procedures for example by principal components analysis or cluster analysis. Log responses are measurement of physical properties of a bed/rock. Electrofacies can be designated to lithofacies as well.

Term electrofacies was given by Serra and Abbot in 1980. Serra and Abbot considered electrofacies to be related to lithofacies.

3.1. Importance of electrofacies

Facies identification plays a vital role in petroleum prospect and reservoir estimation. Reservoir modeling is mainly done by petroleum engineers but geologist with mathematical and computer skills can perform geological modeling, petrophysical modeling and geological reservoir modeling. Skills for modeling include statistical analysis of properties of well logs. Electrofacies play an important role in enhanced oil recovery, well completion design and development strategies in petroleum prospect.

3.2. Working principle

Electrofacies are determined from log responses. Then intervals having same responses are divided into subsets. Meanwhile difference of each set from other is given as mathematical function. Since electrofacies are enormous amount of data hence these are calculated by programmable algorithm.

Principle component analysis is used for electrofacies identification. Principle components analysis is of two types; cluster analysis and classification tree analysis. These analyses are used to identify and characterize electrofacies. Fuzzy-logic model can determine permeability of formation.

3.3. Cluster analysis

Cluster analysis is unsupervised machine learning. This is trial and error method. Cluster analysis basically classifies data sets into groups. These groups are formed on basis of similarities or differences. In this method no external model or training set is involved. In clusters analysis logs sensitive to lithology are used as lithological differences are required in this method. First of all a data base is constructed for the object. After construction of data base a matrix of similarities or differences is applied between objects. After this in Iterative process, clustering algorithm is applied to similarity matrix. Objects with highest similarities are merged. After merging of similar objects, matrix is recomputed and process is repeated again and again until objects are linked in a hierarchy. This hierarchy is represented in form of dendogram. After formation of dendogram, objects are in clusters and then these clusters are cut into branches coinciding with specific groups.

3.4. Classification tree analysis

Classification tree analysis is used to predict membership of objects in classes. These objects are dependant variable of one or more than one predictor variables. This method provides effective procedure for set up of rules for prediction or interpretation of categorical variables such as electrofacies or for continous variables such as permeability.

3.5. Artificial neural networking

Conventional method for facies identification is done manually with cross plotting from wire line log or by correlating behavior to cores. Now a day, Artificial intelligence is playing a very crucial role in research and advancement of science; several methods other than conventional methods are being used. These methods include techniques based on artificial intelligence and clustering; for example multivariate analysis, nonparametric regression and principal component analysis.

Artificial neural networking can generalize linear regression as no relationship between variable is required. It is arranged in multiple layers. Each of these layers contains a number of nodes connecting each layer by simple weighed layers. Each node except that from input layer multiplies to respective weight and then all weighted inputs are summed. A constant can also be a part of this process. Final input is calculated by application of activation function to the sum of weighted inputs.

Neural networking is used for production of a particular output from a specified input. For multi layered neural network, a supervised learning logarithm known as back propagation is used. Back propagation adjust connection weights to minimize the difference between predicted and observed output. Another model is also used with working principle of trial and error method.

3.6. Machine learning

Machine learning is a method of data analysis mainly aiming at use of data and algorithms for enabling learning and improving of system without being explicitly programmed. It is an application of artificial intelligence.

Working of machine learning basically depends upon given input. This input can be in different form for example in form of graphs or training data. More the input will be clear, more will be learning. These inputs are used in decision making by making algorithms. These algorithms give an estimation of pattern in given data. After decision making error function is evaluated. Error function is used to increase accuracy of model. After error function, model optimization process is used for adjustment of data points for optimization between the known example and model.

3.7. Importance of machine learning

Machine learning is used for construction of algorithms for making predictions about data therefore this technique is useful for complexity of earth. As most of times data about parts of earth is not accessible. Machines can identify pattern and relationship between given data sets hence this technique reduces time cost. It is a consistent technique totally based upon data analysis. This method is used in geology in different types of mapping including landslide susceptibility mapping and hazard mapping, feature identification including discontinuity analysis and quantification of water inflow, for classification such as soil classification or geological structure classification and for electrofacies detection and classification.

3.8. Types of machine learning

This data analysis is of three types as supervised learning, unsupervised learning and reinforcement learning. In supervised machine learning labelled data sets are used to predict outcomes accurately. Hence, process of cross validation is used to solve a variety of real world problems.

In unsupervised machine learning algorithms are used to analyze and cluster unlabelled data. In this technique hidden patterns or data groupings are discovered without any given data set. This method is ideal for exploratory data analysis. Neural networks, K-mean clustering and probabilistic clustering methods are some of the examples of algorithms used in unsupervised learning.

Reinforcement machine learning method has similarity with supervised learning method but in this method algorithm is trained by trial and error method. In this method a sequence of successful outcomes will be formed by trial and error method and this sequence provides best recommendation for given problems.

Chapter 4

Petrophysical Analysis

Most useful tool for the characterization of reservoir rock is petrophysical analysis of well logs. Different logs such as gamma ray log, caliper log, resistivity log, neutron log and density log are included in geophysical well logs. Petrophysical properties are main factor in productivity of reservoir. Petrophysical properties are lithology, porosity, water saturation, hydrocarbon saturation and permeability etc. Borehole measurements are used to evaluate and characterize subsurface formations, this process is called petrophysical framework.

4.1.Significance

Well logging analysis and interpretation as shown in table 4.1, are used to compute and analyze petrophysical properties. Petrophysical analysis is mainly used for identification and evaluation of reservoir. This analysis is used for hydrocarbon potential measurement.

4.2.Well log

Direct measurement of petrophysical properties is done by using coring and special core analysis. From subsurface, samples are obtained. These samples are later on measured by core labs. This process is expensive and consumed a greater extent of time. Hence well log analysis is not used for all drilled wells.

Table 4.1: Curves of well log analysis by wireline logging

Track	Scale	Curves
Track 1 (lithology)	Linear	GR, SP,CALI,BS
Track 2 (resistivity)	Logarithmic	MSFL,LLS,LLD
Track 3 (porosity(	Linear	RHOB,NPHI,PEF,DT

Well Logging is relatively inexpensive method. Electrical well logging, Nuclear well logging and Acoustic/Sonic well logging are three main types of well logging. Wireline or LWD methods are used to convey measurement tools.

First track indicates gamma radiation level of any rock. If gamma radiation level is low then the rock will be coarse grained with more pore space and if rock will be fine grained with less pore spaces if there will be higher amount of gamma radiation level. The next track represents the depth below main/reference point. After depth track the next track is of electrical resistivity of rock. Decrease in hydrocarbon saturation and increase in water saturation cause low resistivity.

Next to resistivity track there is track for water saturation. Fifth track represents the fraction of total rock filled with fluids. Sixth or last track indicates solid portion of rock.

4.2.1. Correlation track:

Wireline logs indicate lithology of borehole location. Structure and stratigraphic trends of study area are used for collection of logs. Well logs can be correlated across a large area by identification of patterns in logs. These correlations can help infer information about the depositional environment.

This track represents the gamma ray log, spontaneous potential log and caliper log and most frequently it is initial track of log table. Caliper log indicates abnormality and fluctuation in diameter of borehole. Gamma ray log differentiate the lithologies encountered in the bore hole meanwhile computed gamma ray log includes the behavior of Potassium and Thorium. Spontaneous Potential (SP) log contributes guidelines towards authentication of permeable and impermeable zone and estimation of resistivity of water.

4.2.2. Resistivity track

Resistivity is measurement of resistance of a material to electrical conduction. It is measured in ohm-m. Resistivity can be defined as the division of electrical field by current density. It is mainly affected by factor of frequency of applied signals of electrical conduction

Resistivity logs are electrical well logs. There are three depths of resistivity that can be logged. These depths include shallow, medium, and deep depth. These are the record of resistivity of the formation when current applied. Resistivity log is displayed on track 4. Resistivity has a direct relationship with distance from bore hole. It increase as distance form bore hole increase and vice versa. Resistivity logs interpret porosity, water saturation and hydrocarbon saturation of a formation.

Significance of resistivity logging

Resistivity logs interpret porosity, water saturation and hydrocarbon saturation of a formation. These logs are used for mineral as well as geological exploration. This log is used for formation evaluation during drilling. Values of resistivity logs are used to differentiate between clay and sand.

4.2.2.1. Laterolog deep (LLD)

Laterolog is an electrical method which is used to describe better recording of formation resistivity. Current of constant intensity is forced along wall of hole. Current is forced by special electrode arrangement and automatic control system. Later on potential drop is recorded along open hole. These tools are reliable in boreholes drilled with water-based muds.

Significance: LLD is used for drilling of holes with drilling muds which are conductive in nature. LLD is conductivity sensitive log, hence can mark low to medium resistivity of formations accurately.

4.2.2.2. Laterolog shallow (LLS)

When main concern is the shallow investigation of uninvaded zone then LLS log is used to measure resistivity of mud cake. LLD and LLS are collectively termed as "micro resistivity logs". Separation between LLD and LLS indicates existence of permeable zone and sandstone. The pores of sand filled with water have low resistivity values (Javid, 2013).

4.2.3. Porosity track

Ratio of volume of voids to total volume of rocks is known as porosity (Tiab and Donaldson, 2004). It is one of the important elements of the reservoir (Mavko et al, 2009). On basis of sorting, cementation and size of grain in the reservoir rocks, porosities range from 5-50 %. Effective porosity is main factor for hydrocarbon accumulation. If pores are sealed by cementation or re-crystallization then these pores are of no use in hydrocarbon accumulation. Neutron effective porosity is calculated by using formula given by Poupon, A. and Leveaux in 1971, as given in equation 4.1.

$$\Phi e = \Phi (1 - Vsh) \qquad (4.1)$$

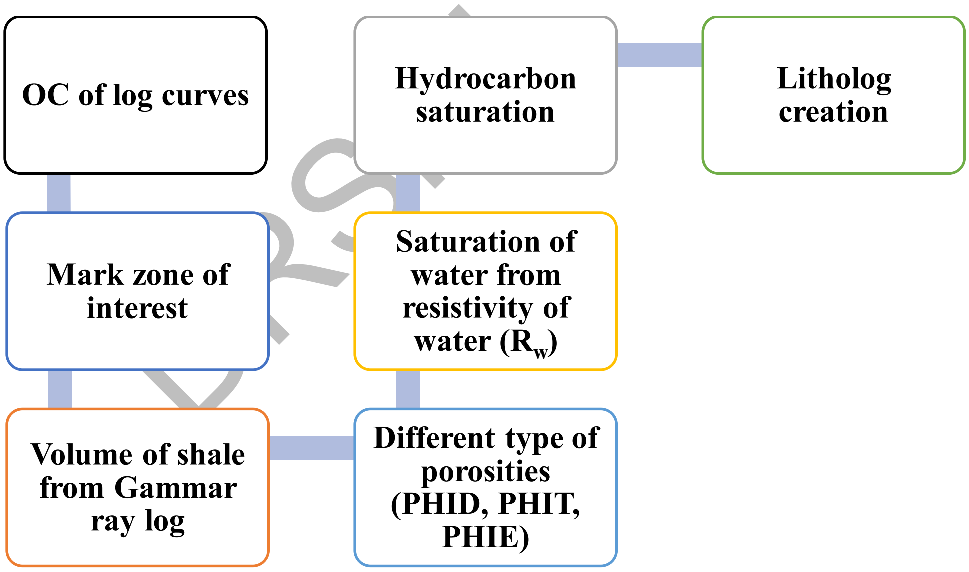
Sonic, density and neutron log or combination of these logs is used to calculate total porosity. Effective porosity is estimated for reservoir evaluation. It is estimated by subtracting the effect of shale (Rider, 1995). Sonic log, Density log and Neutron log are types of porosity log.

4.2.4. Calliper log

Caliper log measure size and shape of bore hole along diameter. This log is used in hydrocarbon exploration. Measurements of size and shape indicate wash out or shale swelling in bore hole. These factors affect results of other logs. In short, this log provides knowledge about cavities, washouts, breakouts and mud cakes. These events cause disturbance in the conditions of borehole effecting response of other logs such as values of porosity and resistivity. This log plays a critical role for the quality check of other logs.

4.2.5. Objectives of petrophysics

Petrophysical analysis is performed in a sequence as represented in flowchart 4.1 to investigate the reservoir nature of study area. The logs defined are used to calculate the reservoir parameters. These parameters include Volume of shale (Vsh), Porosities (PHID, PHIT, PHIE) and Water saturation (Sw).



Flowchart 4.1: Petrophysical analysis flow chart

4.2.6. Gamma Ray log

Gamma ray log is calculated by baseline separating clean sand and dirty sand. When gamma ray log passes the baseline, respective formation will be indicated as shale formation.

Volume of shale (V_{sh})

Volume of shale indicates shale in formation. Volume is shale is calculated to understand zone of interest for reservoir. In quantitative evaluation of shale content radioactive minerals other than shale are assumed to be absent. Volume of shale indirectly indicates volume of sand. In case of sandstone the values of GR are lower. Presence of shale and clay effects porosity. For calculation of volume of shale GR_{max} AND GR_{min} are calculated.

Volume of shale can be estimated through Neutron and density log and through SP log. There are two methods for calculation of volume of shale. It is estimated through GR log by using a linear formula given as (Tiab and Donaldson, 2004). According to Linear method volume of shale is calculated by equation 4.2:

$$V_{sh} = (GR_{log} - GR_{min}) / (GR_{max} - GR_{min}) \qquad (4.2),$$

where, V_{sh} is volume of shale, GR_{min} is minimum gamma ray log (measured in API units) and GR_{max} is maximum gamma ray log (measured in API units). GR_{max} and GR_{min} range from 100API to 10API. Zones of shales can be marked on basis of volume of shale as shown in table 4.1.

Table 4.2: Zones of shale

Volume of shale (%)	**Zone of shale**
Less than 10 %	Clean zone (with no or very less shale)
10% to 35%	Shaly zone (intermediate amount of shale)
Greater than 35%	Shale zone (greater amount of shale)

In non-linear method various formulas like Stabier, Larinov and Clavier are used to compute minimum volume of shale. Stabier formula is used mostly because it gives minimum volume of shale.

- **Stabier formula:**

Most commonly used formula for calculation of minimum volume of shale was given by Stabier as in equation 4.3.

$$V_{sh} = IGR / 3\text{-}2\ IGR \qquad (4.3),$$

where ,**IGR** is the index Gamma Ray

- **Larinov formula**

This formula given by Larinov is used for determining volume of shale in older rocks as in equation 4.4.

$$V_{sh} = 0.33(2^{2\,IGR} - 1) \qquad (4.4)$$

- **Clavier formula**

Another formula used for calculating volume of shale is given by Clavier as in equation 4.5.

$$V_{sh} = 1.7-(3.38-(IGR+0.7)^2)^{0.5} \qquad (4.5)$$

4.2.7. Porosity measurements

Following parameters are calculated to estimate the porosity in a rock are neutron log, density log, sonic tool, average total porosity and average effective porosity.

4.2.7.1.Neutron log

Hydrogen atoms in formation are measured. Working principle of neutron log is to record count of collision between neutron and hydrogen atoms within borehole wall. Energy loss is caused by collision. Energy loss will be greater if greater concentration of hydrogen atoms.

Hydrogen is present in pores of a formation filled by fluid. Neutron energy loose is related to porosity of a formation. Oil and water have higher concentration of hydrogen as compared to gas hence oil and gas would have higher porosity. Older neutron logs required conversion to porosity units within logged sections meanwhile new logs require no conversion as these are directly scaled in units of porosity. Shale has high porosities than effective porosity on the neutron log due to bound water.

4.2.7.2.Density log

Density log is measurement of density of a rock. Density is calculated from absorption of gamma rays. These gamma rays are emitted from radioactive source by the formation. Density log calculates bulk density of reservoir (Scholes and Johnston, 1993) as given in equation 4.6. Denser rocks would absorb more gamma rays and as a result less rays would be transmitted to the ray count detector. Density log is used to measure porosity of reservoir. In current density logs photoelectric curve is detected. This curve is beneficial for formation mineralogy.

$$\mathbf{RHOB\phi = (RHOB_{mat}-RHOB_{log})/(RHOB_{mat}-RHOB_{fluid})} \qquad \mathbf{(4.6),}$$

where, **RHOB ϕ** is the density, $\mathbf{RHOB_{mat}}$ is the value of matrix density and $\mathbf{RHOB_{fluid}}$ is the density of fluid

4.2.7.3.Sonic tool

In sonic logging, speed of ultrasonic sounds through the formation is calculated. For radiating ultrasonic sounds a mechanical source is used in bore hole. Acoustic velocity of rocks is recorded with respect to depth. This log is measured as transit time. Units of transit time are microseconds per foot. This tool is used for porosity estimation. Sound will travel lower in formations with higher amount of fluids and vice versa. Porosity can be calculated by interpolating measured value between expected value of quartz and of water. Formula used for consolidated rocks is as given in equation 4.7;

$$\mathbf{\phi_S = (\Delta T\ log - \Delta T\ mat) / (\Delta T\ log\ fluid - \Delta T\ mat)} \qquad \mathbf{(4.7),}$$

where, **Φs** is the sonic porosity, **ΔT log** is sonic log, $\mathbf{\Delta T_{mat}}$ is value of travel time in matrix and $\mathbf{\Delta T_{fluid}}$ **is v**alue of travel time in fluid
Delay time of Formation increases due to hydrocarbon is known as hydrocarbon effect. This influence affects the values of calculated porosities.

Total porosity

Underground water is present in fractures of rocks and in pore spaces. Total porosity (n) is the ratio of void spaces to the total volume of the rock. Total volume includes solid and void spaces of rock. Porosity is also described as total porosity. It is represented as a fraction or as percentage.

Generally consolidated sediments and igneous and metamorphic rocks have lower porosities as compared to unconsolidated materials (20 to 55%). Some weathered or fractured sedimentary, igneous or metamorphic rocks have high porosities meanwhile porosity of vesicular basalt is dependent upon degree of void creation. Total porosity can be estimated by using formula as given in equation 4.8.

$$ØT = (Ød + Øn + Øs)/3 \qquad (4.8),$$

where, **ØT** is average porosity, **ØD** is density porosity, **ØN** is neutron porosity and **ØS** is sonic porosity

4.2.7.4.Effective porosity

During assessment of underground fluids, interconnected pore volume is of great interest. All pores are not connected. Some pores are filled by cementation, some are small, and some pores have dead ends. These pores are not useful for exchange of fluids. Interconnected pores form effective porosity. Effective porosity is ratio of volume of interconnected pores to total volume. It can be calculated by using formula as given in equation 4.9.

$$\Phi_e = (1 - V_{sh}) * \Phi_{avg} \qquad (4.9),$$

where, Φ_e is effective porosity, Φ_{avg} is average porosity ansd V_{sh} is volume of shale.

Effective porosity is different for each soil. It can be or cannot be relevant to total porosity. In most cases total porosity for soils can be used as effective porosity as well.

4.2.8. Water saturation

Water saturation is ratio of volume of water in pore space to volume of total pore space. It is estimation of volume of water by fraction between volume of water in pore space to total pore space. It is estimated by logging (empirical modeling) and estimation of core analysis. Resistivity of water is used as a parameter for calculating water saturation. Parameters for example bottom hole temperature, surface temperature, water salinity (ppm) and SP are used to determine resistivity of water. Resistivity of water can be calculated either by Pickett cross-plot method or by SP method.

4.2.9. Pickett Cross-plot Method

It is a simple and effective method for measuring the resistivity of water. This method can also provide estimation of other factors. Formation water resistivity, Cementation factor and Matrix parameters for porosity logs can also be estimated by Pickett cross-plot method. True resistivity is used in this technique. General flowchart for Pickett cross-plot is given in figure 4.2.

Pickett cross plot is created on 2/3 cycle log-log paper. A plot of porosity versus deep resistivity (LLD) data is created. This cross plot has number of water saturation lines. Lowest or left-most line of water saturation shows water bearing line with 100% saturation. Data points above straight line (Ro) represent water saturation less than 100%. Slope of straight line represent cementation factor (m) water-bearing line.

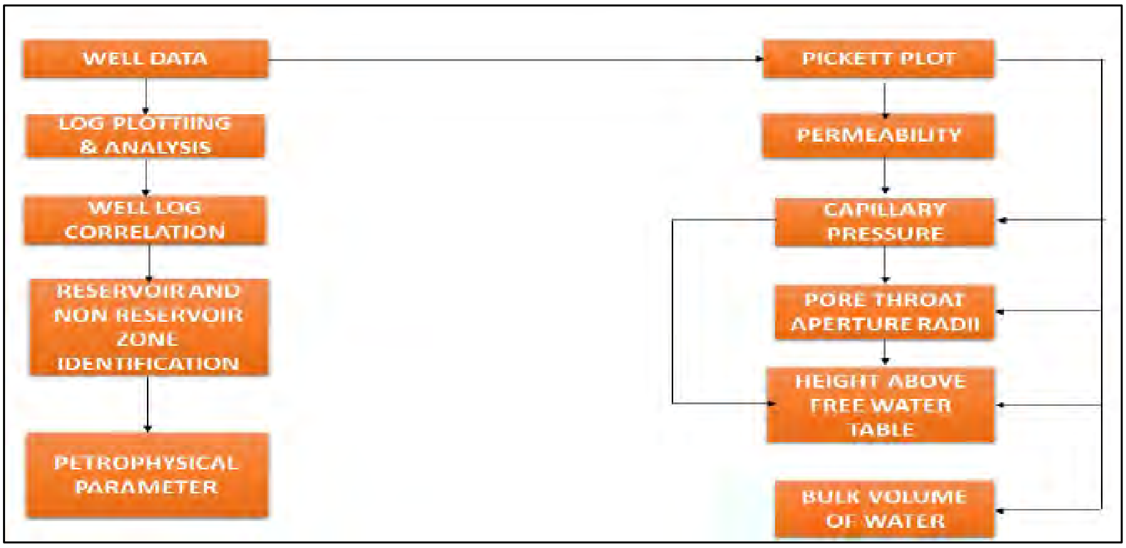


Figure 4.2: Work flow chart for Pickett cross-plot modeling

4.2.10. Hydrocarbon saturation

Fraction of pore spaces containing hydrocarbon is known as hydrocarbon saturation. Hydrocarbon saturation is used for reserve estimation and characterization. Equation 4.10 is used for determining hydrocarbon saturation.

$$S_W + S_H = 1 \qquad \textbf{(4.10)},$$

Where S_H is hydrocarbon saturation and S_W is water saturation. The saturation of hydrocarbons is percentage of pore volume occupied by hydrocarbon.

4.2.11. Petrophysical interpretation

The main reservoir of KADANWARI GAS FIELD is Lower Goru Formation. Lithology, porosity, resistivity, effective porosity and water saturation are inspected. There is a separation between LLD and LLS and this separation is measured. Cross plot between Neutron and density log show crossover. This cross plot is used as evidence. Effective porosity can provide good amount of hydrocarbons. Zones are marked on basis of observed logs and calculations. The petrophysical interpretation of KADANWARI-01, zone B (Figure 4.3), KADANWARI-01, zone E (Figure 4.4), KADANWARI-03, zone B (Figure 4.5), KADANWARI-03, zone E (Figure 4.6), KADANWARI-10, zone B (Figure 4.7), KADANWARI-10, zone E (Figure 4.8), KADANWARI-11, zone B (Figure 4.9) and KADANWARI-11, zone E (Figure 4.10) is shown.

Table 4.3: Table indicating values of petrophysical parameters in each well

	K-01 Zone B	**K-01 Zone E**	**K-03 Zone B**	**K-03 Zone E**	**K-10 Zone B**	**K-10 Zone E**	**K-11 Zone B**	**K-11 Zone E**
V_{sh} (%)	12-14	8-10	13-16	13-15	8-10	25-30	65-70	40-50
PHIE (%)	6-8	14-16	9-11	11-13	4-6	16-18	1-2	2-4
S_W (%)	22-25	28-30	35-40	15-20	30-35	22-24	85-90	80
S_G (%)	78-75	72-70	65-60	85-80	70-65	78-76	15-10	20

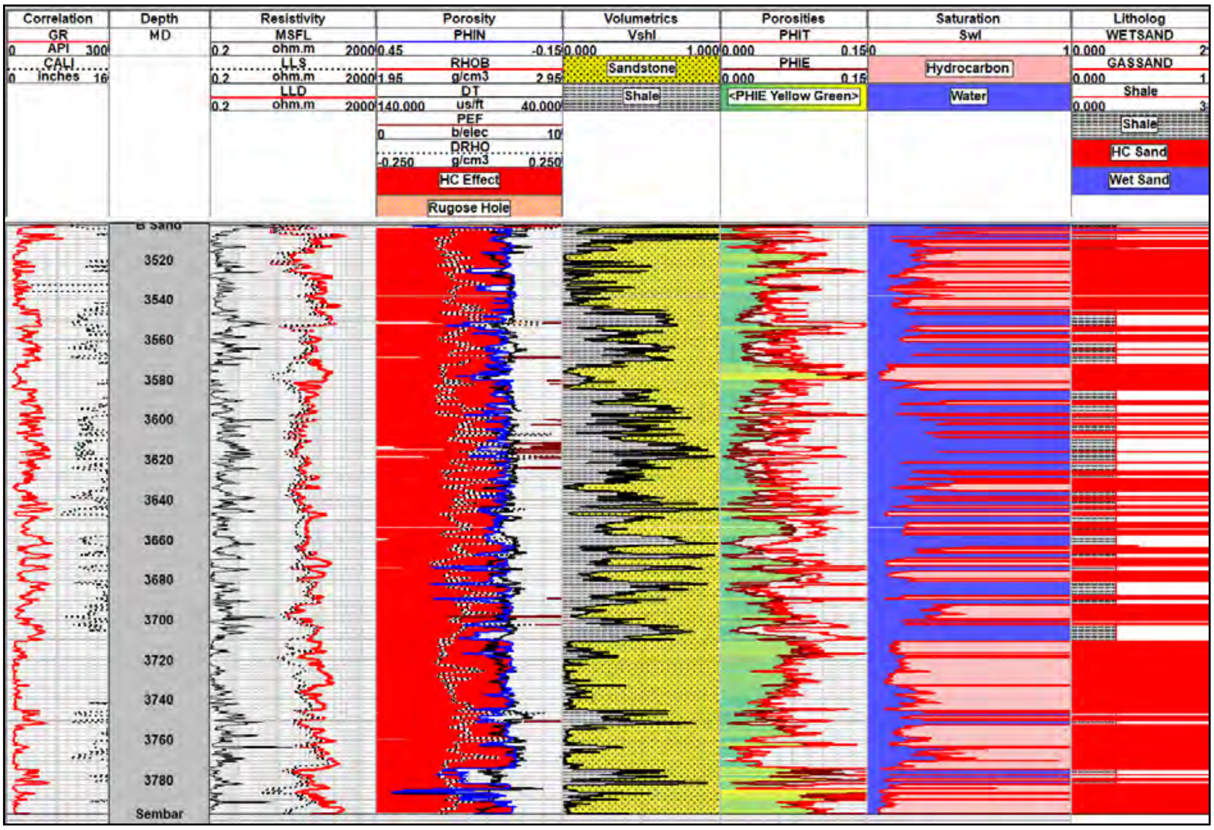


Figure 4.3: Petrophysical analysis of Kadanwari well 1 – B zone

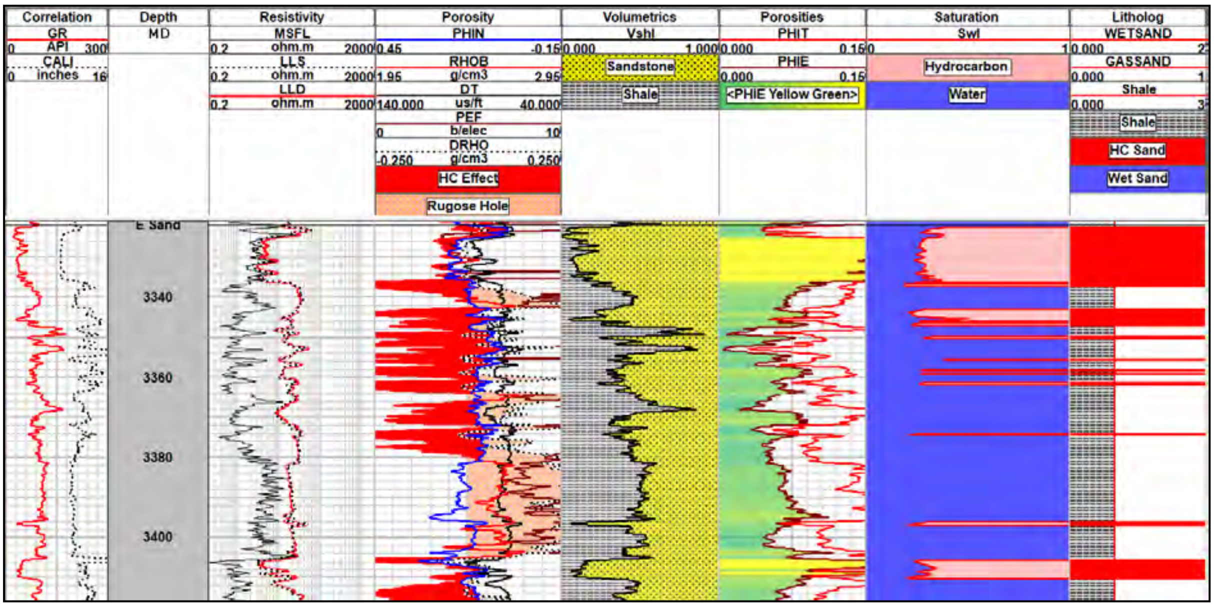


Figure 4.4: Petrophysical analysis of Kadanwari well 1 – E zone

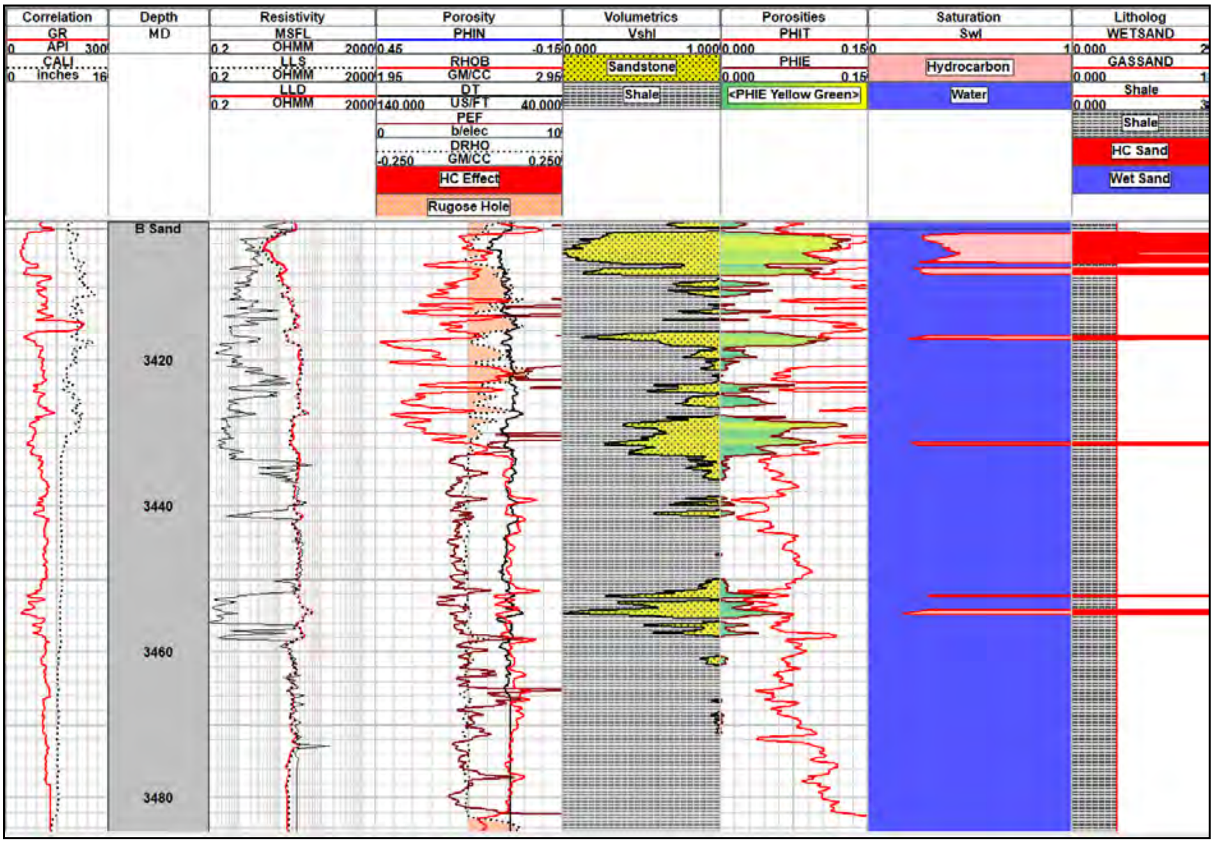


Figure 4.5: Petrophysical analysis of Kadanwari well 3 – B zone

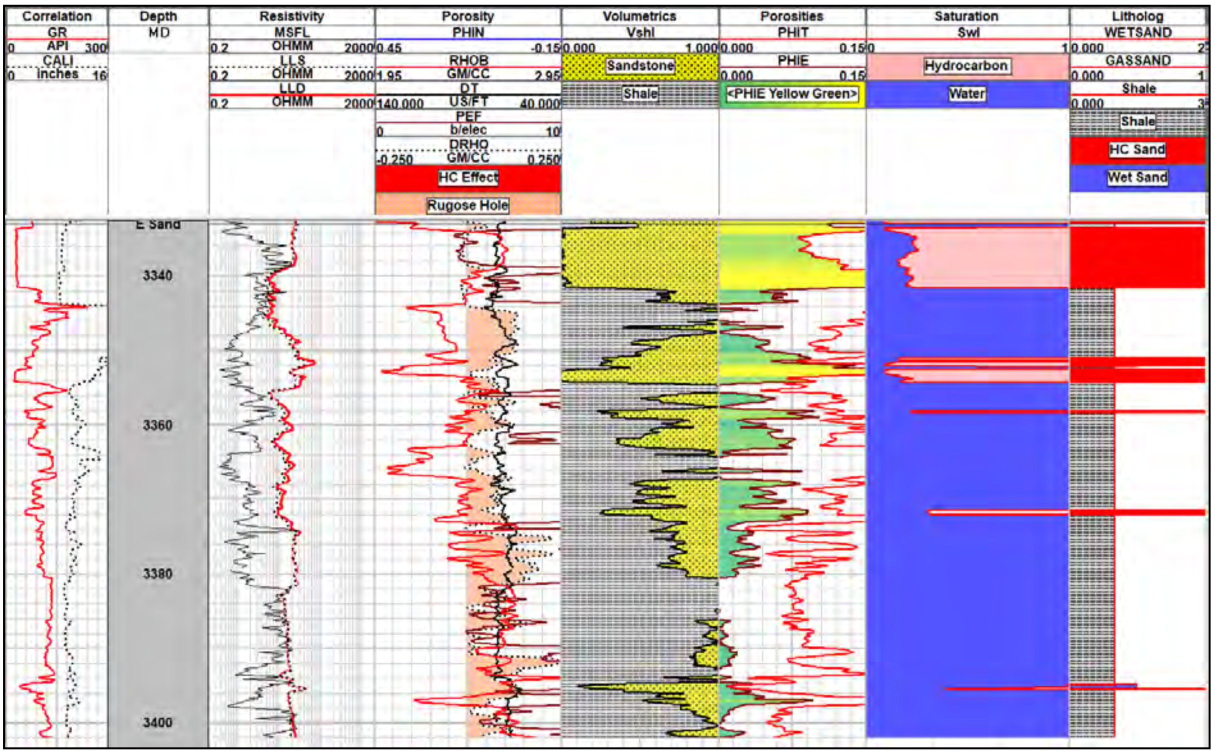


Figure 4.6: Petrophysical analysis of Kadanwari well 3 – E zone

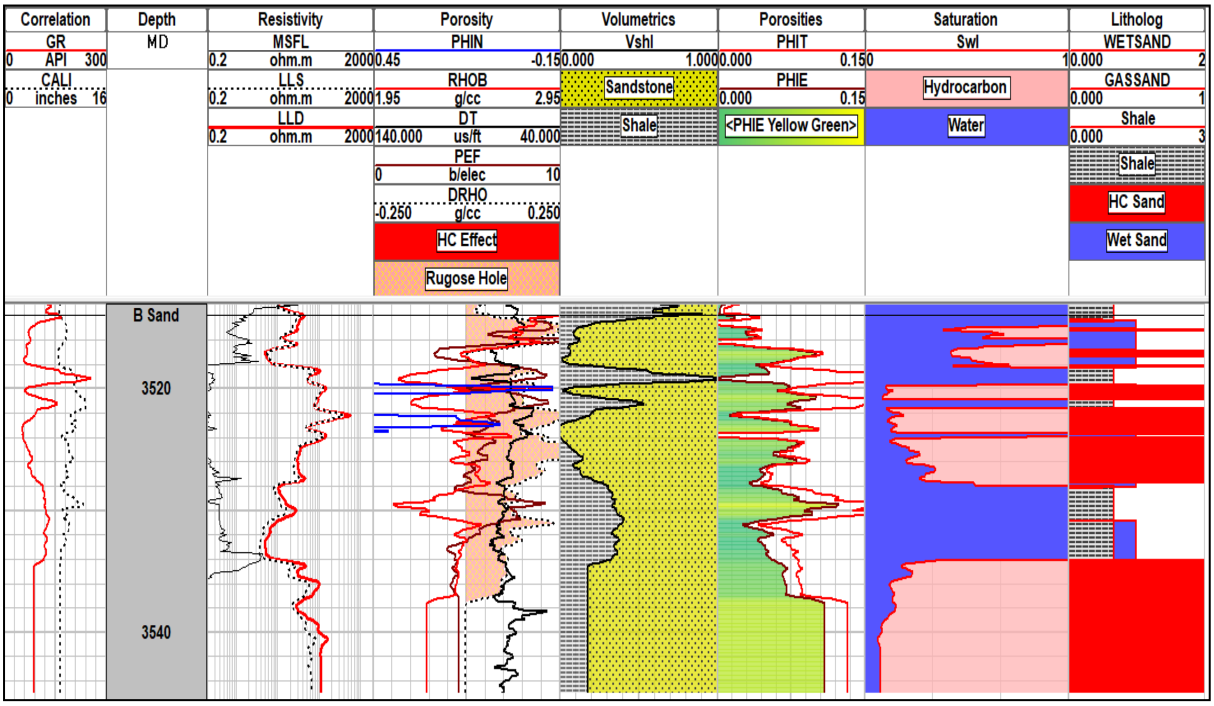


Figure 4.7: Petrophysical analysis of Kadanwari well 10 – B zone

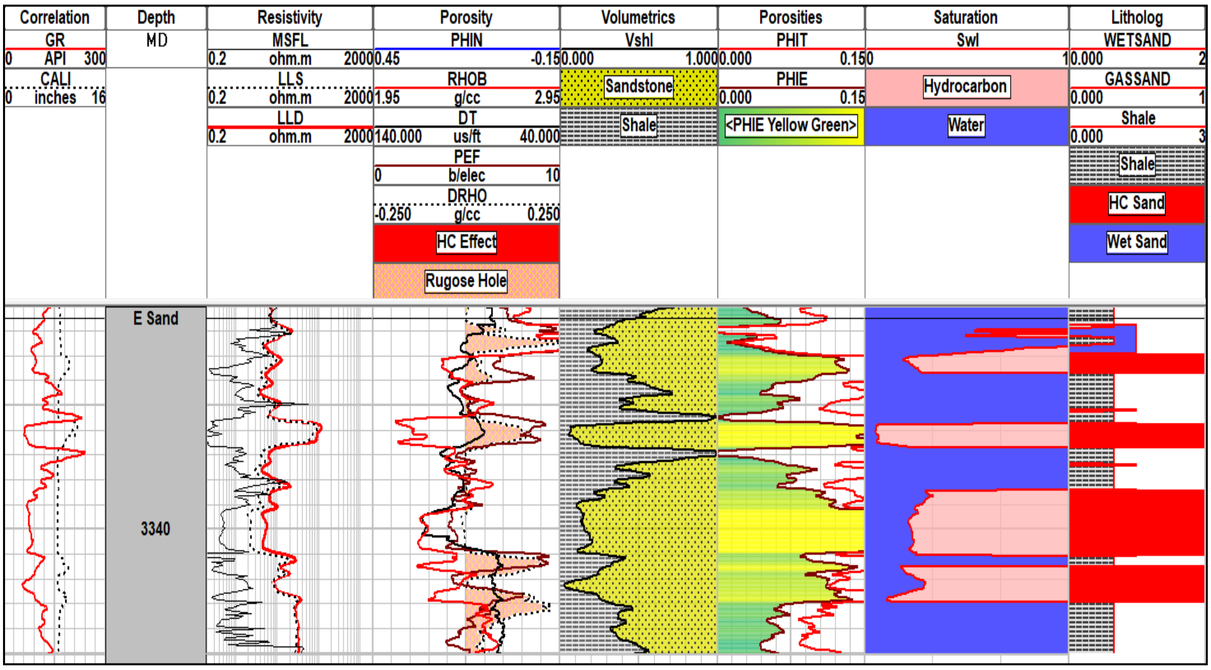


Figure 4.8: Petrophysical analysis of Kadanwari well 10 – E zone

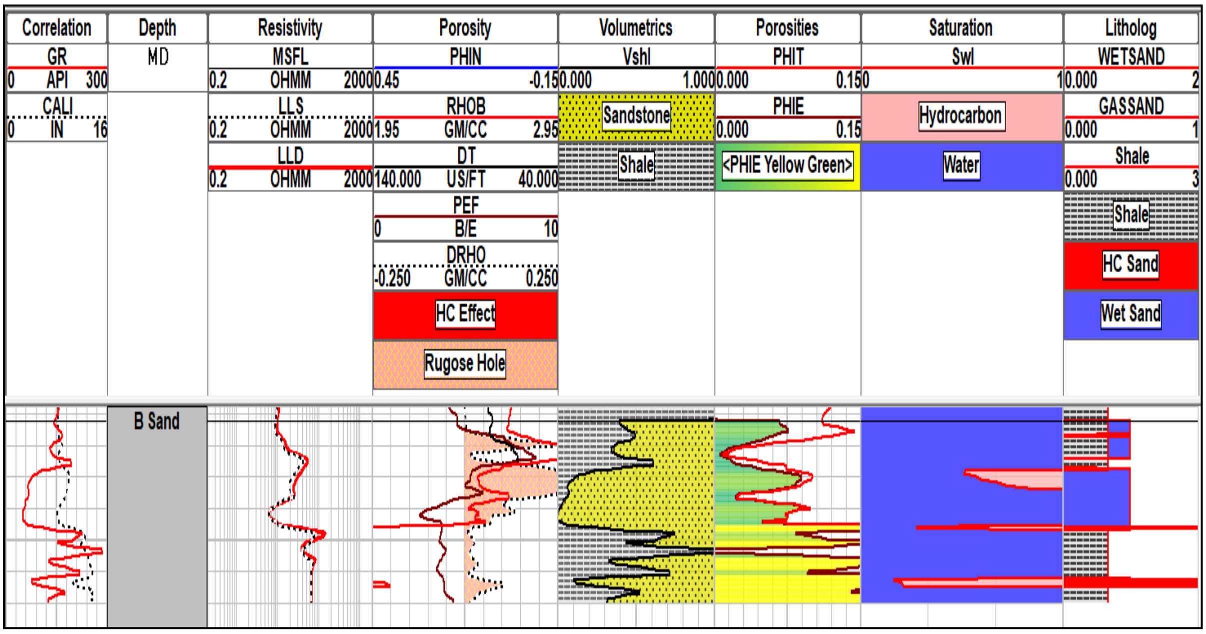


Figure 4.9: Petrophysical analysis of Kadanwari well 11 – B zone

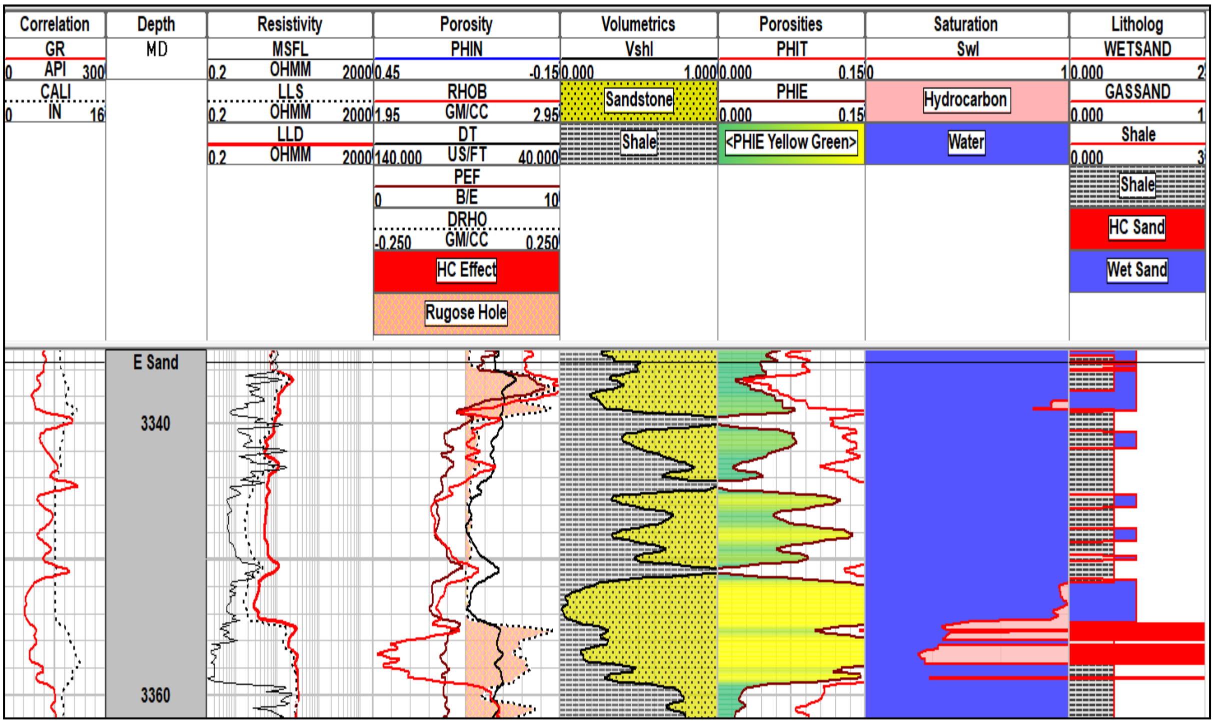


Figure 4.10: Petrophysical analysis of Kadanwari well 11 – E zone

Chapter 5

Self organizing map

Well logs are sophisticated source of information about numerous rock property measurements, like the reservoir conditions of pressure, temperature, and fluid content. These properties play an important role in petroleum industry. Well log's quality can vary significantly from one well to the other. Well logging tools provides high dimensional data. Number of variables owned by a data point is known as the dimension of data (Qian et al., 2019).

5.1. Self organizing map/SOM

Self organizing maps are used to reduce dimensionality of data; basically representing high dimensional data in form of low dimensional data. Self organizing map is a major branch of artificial intelligence. It does not include error correction learning. In this method after input data is displayed in form of map (map can be in form of square, hexagon or sphere). Topological structure is kept constant during input of data by using neighborhood function (Kohonen, 2012). This is a useful tool for clustering data. This technique is applied in various aspects such as psychology, economic, medical and technical fields like mechanical, construction and geology. In geology, these maps are used for classification of electrofacies of complex geological formations for example Lower Goru Formation. This formation when encountered in study area is classified into elctrofacies by using self organizing maps.

5.2. Functioning of self organizing map

Kohonen's self-organizing maps (Kohonen, 1995) is based on neurobiological establishments. These establishments are used for spatial mapping to model complex data structures internally. For this purpose different sensory inputs (motor, visual, auditory, etc.) are mapped onto corresponding areas in an ordered form. This ordered form is known as topographic map.

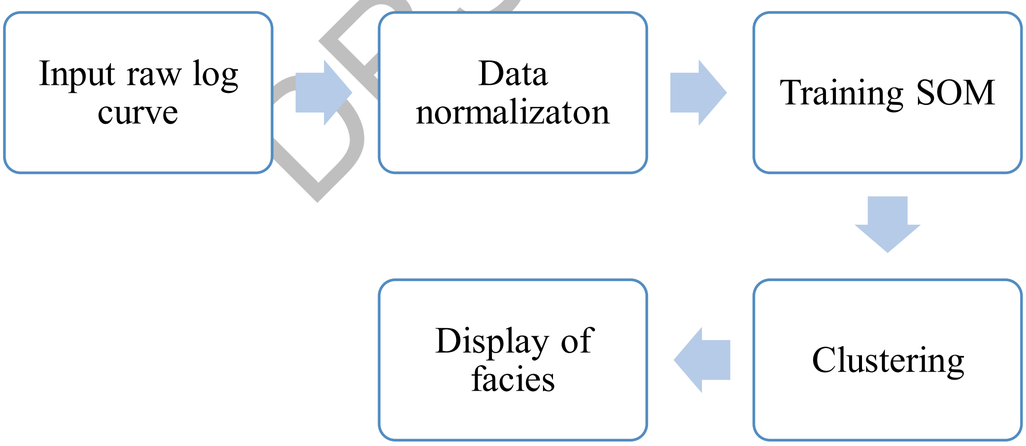
The self organizing map network architecture consists of nodes/neurons arranged on 1D/ 2D lattices. Higher dimensional maps are not common. The neurons are connected to adjacent neurons and this connection dictates the topology, or structure, of the map. In each training step, Euclidean distance measure is used measuring distance between any sample vector x and all weight vectors of self organizing map. The neuron with the weight vector, closest to the input vector x is called the Best Matching Unit (BMU). The best matching unit is moved close to the vector input in input space.

A Gaussian function is the decreasing function of the distance between nodes on the map grid. This regression is usually reiterated over the available samples. These connections are initialized with small random values.

5.3. Self organizing map for electrofacies

This technology can predict missing log data over the SOM grid. For prediction trends of input data are used. These input trends are used for electrofacies identification. The SOM has low cost and more accuracy as compared to other facies identification method (Chang, et al., 2002). For electrofacies classification of Lower Goru, SOM is used in KADANWARI-01, KADANWARI-03, KADANWARI-10 and KADANWARI-11. Sequence-wise steps for finding out electrofacies using SOM technique are given in flow chart 5.1.

The workflow begins with the input and normalization of raw log curves. Log curves of GR, RHOB and NPHI are used for electrofacies modeling of the Lower Goru Formation. SOM model is trained by log data of input curve and later on calibrated by using hierarchical clustering. Trained SOM model is displayed in the form of two-dimensional facies map.



Flow chart 5.1: Flow chart for finding out electrofacies using SOM technique

5.4. Electrofacies analysis of Lower Goru Formation

Lower Goru formation act as an important reservoir rock in Lower Indus Basin of Pakistan. This formation has great variation in lithological composition. This formation has alternating layers of shale and sandstone. On basis of this alteration in lithology this formation is classified into further smaller units by OMV and OGDCL (Ahmad et al., 2004).

For this research OMV classification is used. OMV classification divides the sandstone layers of Lower Goru formation as A, B, C and D interval (Dar et al., 2021). Identification of facies plays a very important role in reservoir characterization. Traditionally facies in study area are identified by previous studies and field work (outcrop and core data). Now, modern computing techniques have taken over the world. These techniques are not only cost-efficient but are also least time consuming as compared to field work. Electrofacies are classified by SOM on basis of well log responses of respective formation encountered in wellbore. The raw log curves including GR, RHOB and NPHI were used while performing electrofacies analysis of the Lower Goru Formation.

5.4.1. Electrofacies analysis of E sand zone in Lower Goru Formation

5.4.1.1. Training the SOM model

The data obtained from input log curves of E sand zone of KADANWARI-01, KADANWARI-03, KADANWARI-10 and KADANWARI-11 is plotted on the two-dimensional square map. The map was initiated with 20 nodes. Parameters for map are given in figure 5.1. Relation of the width of map and total nodes can represented by equation 5.1.

$$\textit{Total nodes} = \textit{Map width}^2 \qquad \textbf{(5.1)}$$

Random value is given to the nodes of map in starting. After assigning these values, value of each node in map is determined by weight value of each input curve. In the case of respective formation nodes are indicating the weight of GR, NPHI and RHOB.

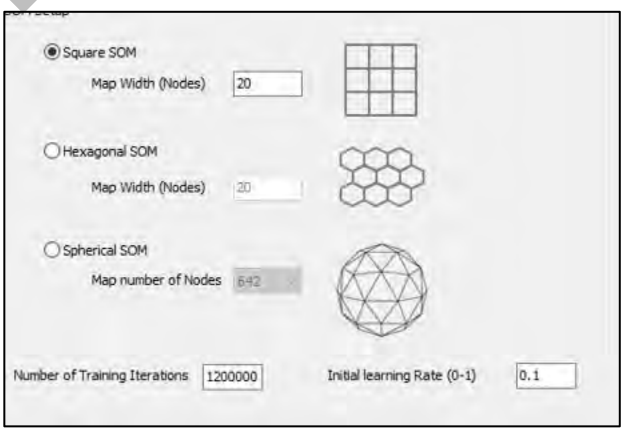


Figure 5.1: Parameters for map using SOM technique

After initialization, calculation of best matching unit (BMU) was done for each input data level. BMU is basically the node which is quite similar to the given input data.

Calculation of BMU

The calculation of BMU is accomplished by the calculation of Euclidean distance. Euclidean distance is calculated among the specific input vector and the weight vector of each node. Map is given in figure 5.2. The lowest value of Euclidean distance marks the BMU. Equation of Euclidean distance given by Kohonen (2012) is given as equation 5.2.

$$Euclidean\ Distance = \sqrt{\sum_{i=0}^{i=n}(V^i - W^i)^2} \quad \textbf{(5.2),}$$

Where, V is the input vector and W is the vector weight of node.

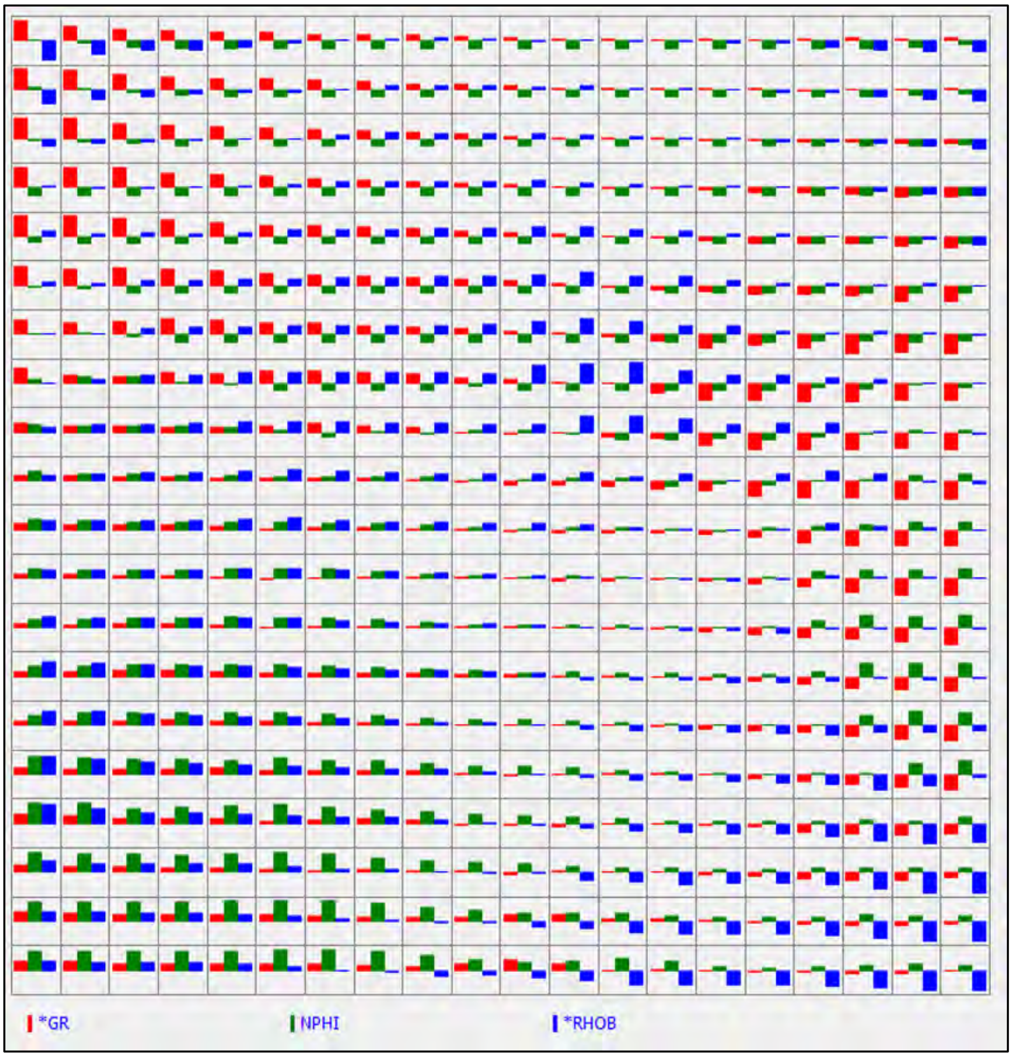


Figure 5.2: Map of well curves for E sand zone of Lower Goru Formation using SOM techniques whereas legends are given at bottom

The weight of nodes is readjusted after finding out BMU. Weights of nodes are readjusted to develop similarity among nodes and input vector. Mathematical equation for weight readjustment is givenin equation 5.3.

$$\mathbf{W_{t+1} = W_t + L_t (V_t - W_t)} \qquad \textbf{(5.3),}$$

Where, W is the weight, t is for time step, V is input vector and L is learning rate.

For each iteration, decrease in initial rate is given by equaton given Kohonen (2012) given in equation 5.4.

$$\boldsymbol{Lt = Lo\ exp\ (-1/\lambda)} \qquad \textbf{(5.4),}$$

where, Lo is the initial learning rate, t is for training pass iteration and λ is indicating time constant. The learning rate used for SOM was 0.1 and the numbers of iterations were 60,000. Data distribution on basis of color-palate is given in figure 5.3.

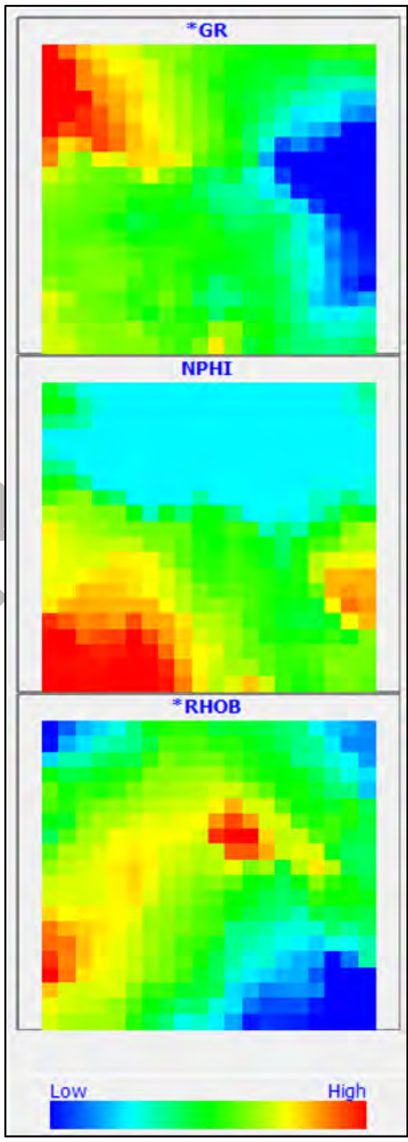


Figure 5.3: Data distribution for E sand zone of Lower Goru Formation on basis of color-palate using SOM technique

Adjustment of weight vectors of BMU leads to the adjustment of neighboring nodes of BMU. Pythagoras theorem is used to identify neighboring radius of BMU. Initialization of radius as a half mapping grid is done after estimation of neighborhood radius. Neighborhood radius reaches to single node after reduction of radius with each iteration. Equation 5.4 is for decrease of neighborhood radius. This equation show decrease in learning rate.

Weights of neighboring nodes are adjusted by executing predefined numbers of iterations. SOM map is ready for clustering upon completion of iteration. Information about the measure of resemblance of trained SOM with the training data is provided by distortion of SOM. The estimated distortion value of SOM is 1.8 which shows that map is suitable for clustering.

5.4.1.2. Clustering of data

clustering of data is done after training of SOM model. Hierarchical model is used for clustering. Average distance between merged clusters as shown in figure 5.4, is used to indicate classification of data points into four facies.

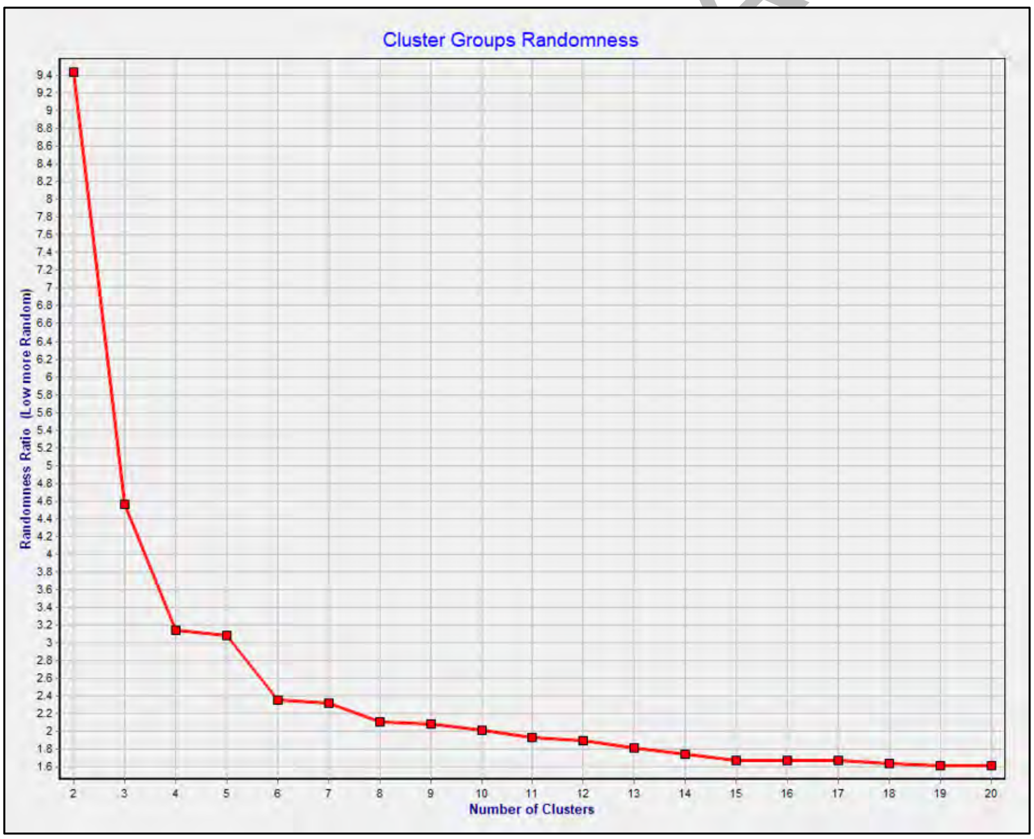


Figure 5.4: Number of clusters and randomness among cluster data for E sand zone of Lower Goru Formation using SOM technique

According to Randomness ratio shown in figure 5.4, four clusters are suitable for data, due clear visibility of inflection plot at cluster number four. Dendogram represents hierarchical clustering from 20 clusters to four clusters as shown in figure 5.4.Since it is difficult to show all data points, only relationship among the clusters is represented.

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5.4.1.3. Facies classification

On basis of SOM results, there are four classifications including; Facies 1, Facies 2, Facies 3 and Facies 4. The color pallet indicates facies on basis of assigned colors.

Facies 1 (yellow)

This is high quality reservoir facies with low GR values and low saturation of water. This log has medium to high porosity log values. Facies 1 shows gas sand facies.

Facies 2 (gray)

This is a medium to good quality reservoir with low to medium GR values and medium to high values for saturation of water. Porosity log has medium values.

Facies 3 (pink)

This facies has mixed lithology; sandstone and shale. It has medium values of porosity and medium to high values of density log. GR values range from medium to high.

Facies 4 (green)

This facies has shale in lithology with high GR values. It has high density log values and high neutron porosity values as well. Color palate for facies is given in figure 5.4.

Facies	Value	Text Value	Color
1	1	Facies 1	
2	2	Facies 2	
3	3	Facies 3	
4	4	Facies 4	

Figure 5.4: Color palate for consolidated clustered facies

Classified electrofacies are related on basis of SOM averages. Relationship among facies is illustrated by using star plot shown in figure 5.5.

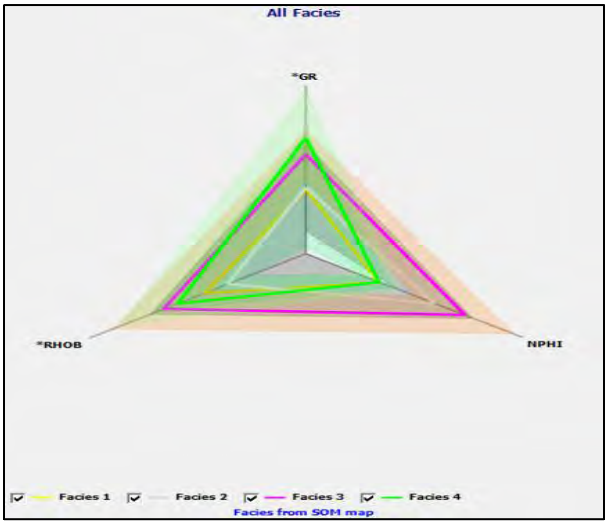

Figure 5.5: Relationship of classified facies of E sand zone; solid lines indicating average value of specific facies and shaded portion indicating standard deviation within specific facies cluster

Facies are clustered on basis of input of log curves of SOM model. SOM averages are used to relate electrofacies to each other. Clusters are formed on basis of SOM model. Input data has three raw curves; volume of shale, porosity and saturation of water. This classification is followed by display of facies on 2D SOM. Average values of specific facies are indicated in arms of star plot as shown in figure 5.6.

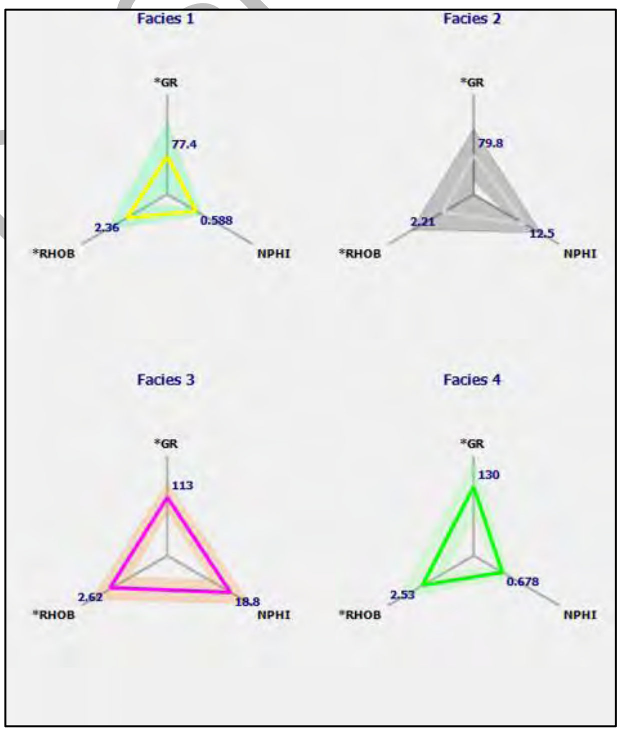

Figure 5.6: Mean log curve value for facies of E sand zone

Mean value of each curve for specific facies is shown in table 5.1. Mean value is shown with data points and standard deviation.

Table 5.1: values for clustered facies of E zone of Lower Goru Formation

	Number of Data Values	*GR Mean Value	*GR Std Deviation	NPHI Mean Value	NPHI Std Deviation	*RHOB Mean Value	*RHOB Std Deviation
Facies 1	60	77.35	28.62	0.5884	1.605	2.363	0.1515
Facies 2	94	79.84	21.8	12.5	4.007	2.212	0.2458
Facies 3	77	112.6	12.12	18.82	5.197	2.621	0.1588
Facies 4	78	129.5	23.55	0.6777	2.122	2.53	0.1839
All Facies	309	100.1	30.97	8.776	8.499	2.423	0.2535

Classification of facies is later on displayed on 2D SOM. Results of clustering are displayed over SOM. Calibrated map is shown in figure 5.7.

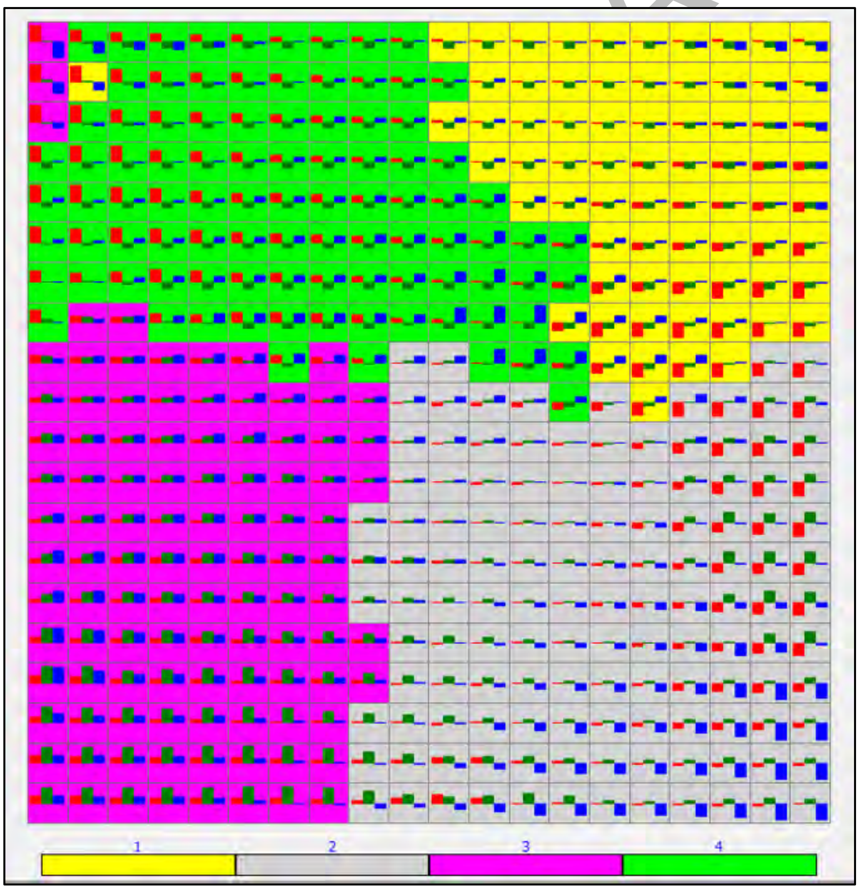

Figure5.7: Facies calibrated SOM indicating major portion of facies for E zone

5.4.2. Electrofacies analysis of B sand zone in Lower Goru Formation

5.4.2.1. Training the SOM model

Data for B sand zone of Lower Goru Formation is obtained from KADANWARI-01, KADANWARI-03, KADANWARI-10 and KADANWARI-11. This data is later on plotted on two dimensional square map. Parameters for map are given in figure 5.1. Relationship of total nodes and width of map can be given in equation 5.1. at start random value is given to nodes of map later on, value of each node is determined by weight value of each input curve. Three curves used for this are GR, NPHI and volume of shale.

After that calculation of best matching unit (BMU) was done for input data.

Calculation of BMU

BMU is calculated by using Euclidean distance. This distance is calculated among specific input vector and weight vector of each node. Map is given in figure 5.8. BMU is marked by lowest value of Euclidean distance. Equation of Euclidean distance is given by equation 5.2. After that calculation of BMU from input data was done.

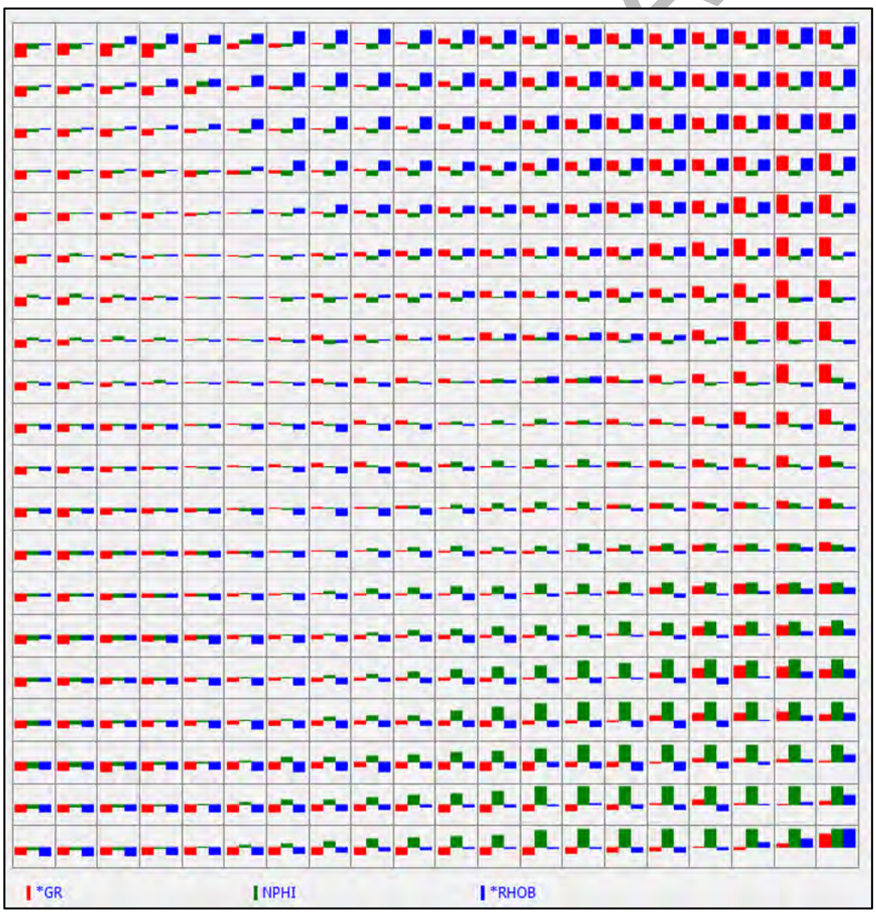

Figure 5.8: Map of well curves for B sand zone of Lower Goru Formation using SOM techniques whereas legends are given at bottom

Once, value of BMU is analyzed, weight of nodes is readjusted to create similarity among nodes and input vector. Mathematical equation for weight readjustment is given in equation

5.3. Decrease in initial rate, for every iteration is given in equation 5.4. Data distribution on basis of color-palate is given in figure 5.9.

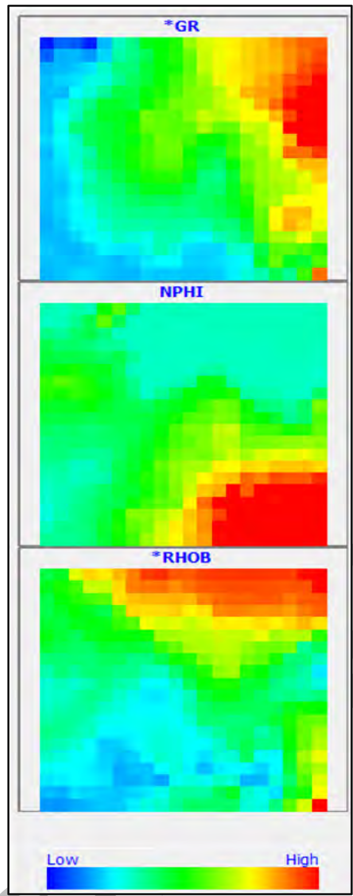

Figure 5.9: Data distribution for B sand zone of Lower Goru Formation on basis of color-palate using SOM technique

Neighboring nodes of BMU are adjusted by adjustment of weight vector of BMU. Pythagoras theorem is used to detect neighboring radius of BMU. Radius is initialized as half grid map is done after analyzing neighborhood units. Neighborhood radius decrease with each iteration. Equation 5.4 is used for marking decrease of radius.

Weights of nodes are adjusted. After adjusting weight of nodes by using number of iterations, SOM map is later on clustered. Distortion of SOM provides information about measure of resemblance of trained SOM with training data. Estimated distortion value of SOM is 1.8. Hence, this map is suitable for clustering

5.4.2.2. Clustering of data

Hierarchical model is used for clustering of data after training SOM model. Average distance between merged clusters is used to represent classification of data points. According to figure 5.10, data points are classified into four facies.

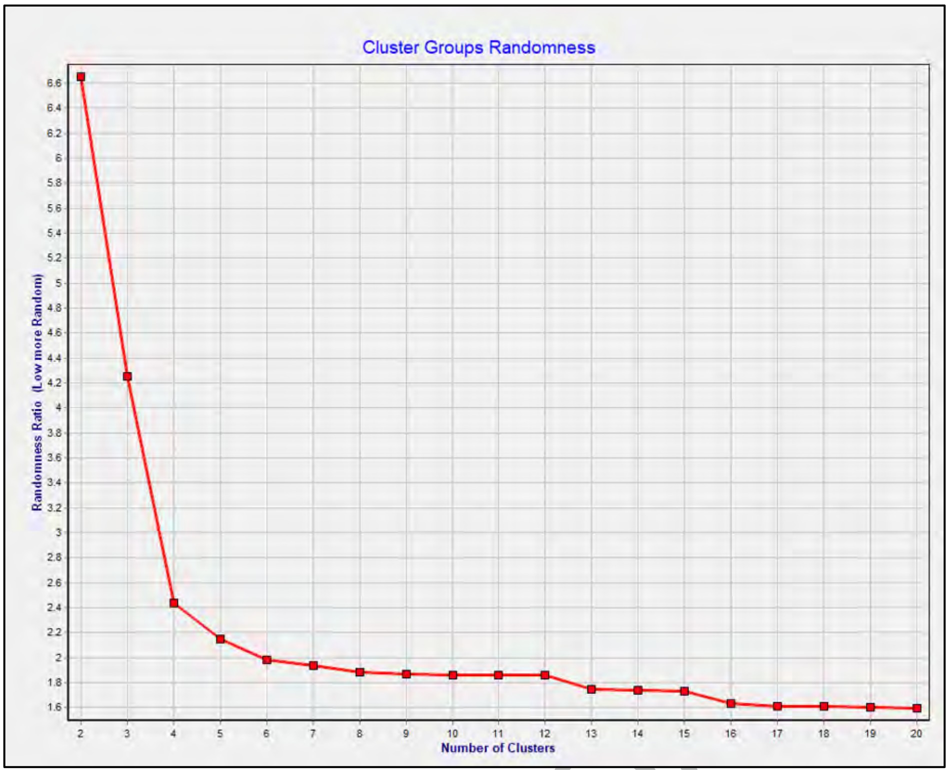

Figure 5.10: Number of clusters and randomness among cluster data for E sand zone of Lower Goru Formation using SOM technique

5.4.1.3. Facies classification

Figure 5.11, represents randomness of data. According to randomness of data four clusters are suitable for data. Inflection point is clearly visible at cluster number four. Hierarchical clustering form 60 clusters to four clusters is shown in figure 5.11. Since all data points cannot be shown, only relationship among clusters is represented.

5.4.2.3. Facies classification

There are four classifications on basis of SOM results. These classifications are Facies 1, Facies 2, Facies 3and Facies 4. Facies are indicated on basis of assigned colors.

Facies 1 (yellow)

This is high quality reservoir facies with low GR values and low saturation of water. This log has medium to high porosity log values.

Facies 2 (gray)

This is a medium to good quality reservoir with low to medium GR values and medium to high values for saturation of water. Porosity log has medium values.

Facies 3 (pink)

This facies has mixed lithology; sandstone and shale. It has medium values of porosity and medium to high values of density log. GR values range from medium to high.

Facies 4 (green)

This facies has shale in lithology with high GR values. It has high density log values and high neutron porosity values as well. Color palate is given in figure 5.11.

Facies	Value	Text Value	Color
1	1	Facies 1	
2	2	Facies 2	
3	3	Facies 3	
4	4	Facies 4	

Figure 5.11: Color palate for consolidated clustered facies of B sand zone

Classified electrofacies are related on basis of SOM averages. Relationship among facies is illustrated by using star plot shown in figure 5.12.

Figure 5.12: Relationship of classified facies of B sand zone; solid lines indicating average value of specific facies and shaded portion indicating standard deviation within specific facies cluster

Facies are clustered on basis of input of log curves of SOM model. SOM averages are used to relate electrofacies to each other. Clusters are formed on basis of SOM model. Input data has three raw curves; volume of shale, porosity and saturation of water. This classification is followed by display of facies on 2D SOM. Average value of specific facies are indicated in arms of star plot as indicated in figure 5.13.

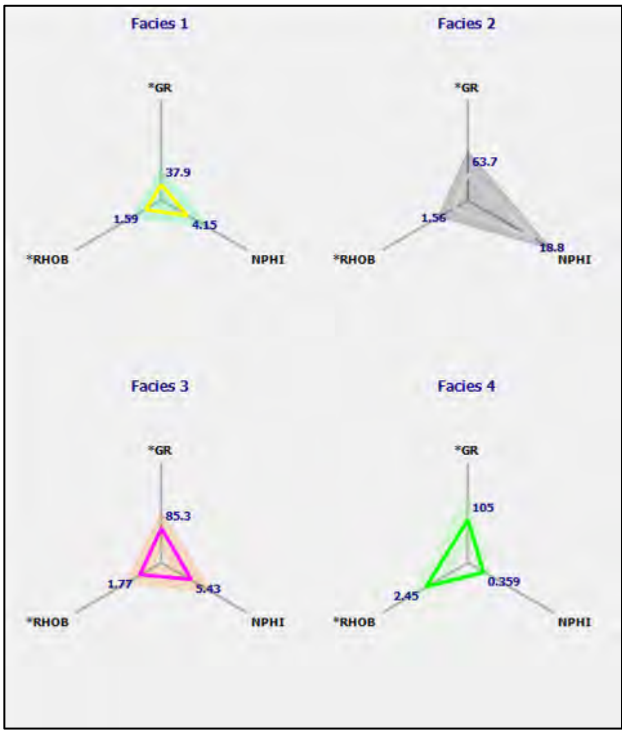

Figure5.13: Mean log curve value for facies of B sand zone

Mean value of each curve for specific facies is shown in table . Mean value is shown with data points and standard deviation.

Table : values for clustered facies of B zone of Lower Goru Formation

	Number of	*GR	*GR	NPHI	NPHI	*RHOB	*RHOB
	Data Values	Mean Value	Std Deviation	Mean Value	Std Deviation	Mean Value	Std Deviation
Facies 1	180	37.94	18.54	4.153	4.074	1.591	0.2261
Facies 2	18	63.73	27.16	18.85	3.2	1.564	0.246
Facies 3	94	85.26	18.7	5.432	4.026	1.769	0.24
Facies 4	144	105	31.12	0.3592	1.054	2.453	0.2647
All Facies	436	71.36	38.01	3.783	4.998	1.913	0.4556

Classification of facies is later on displayed on 2D SOM. Results of clustering are displayed over SOM. Calibrated map is shown in figure 5.14.

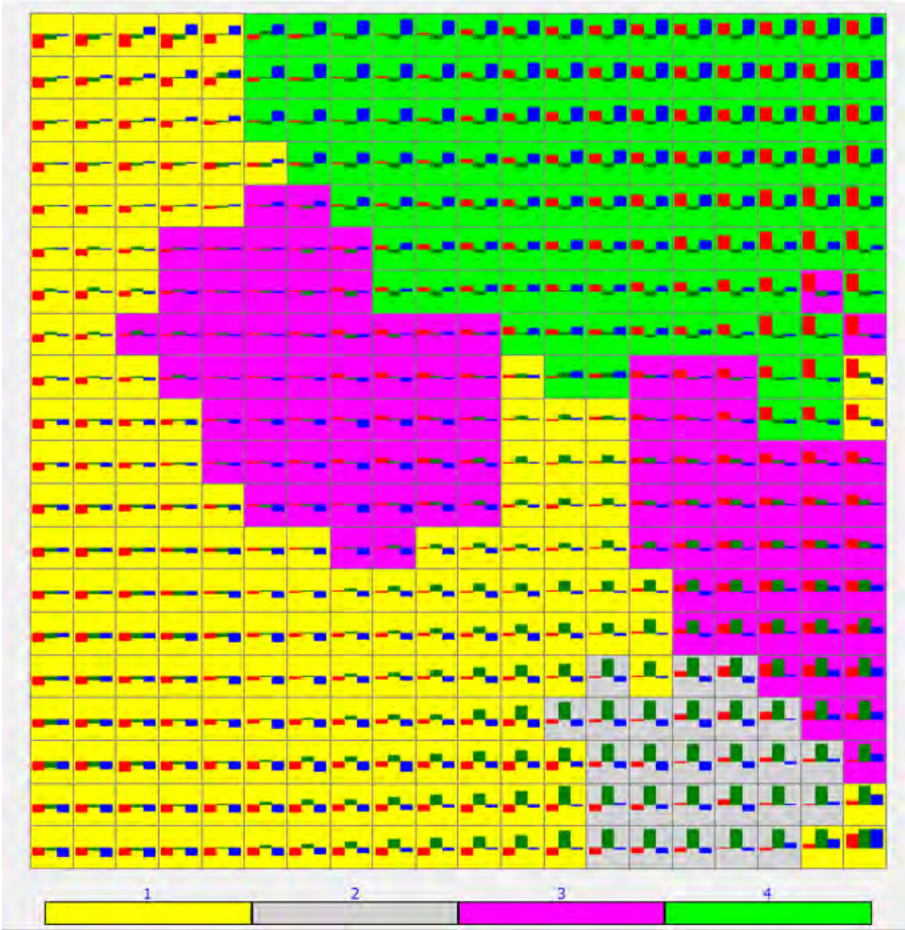

Figure5.14: Facies calibrated SOM indicating major portion of facies for B zone

Chapter 6

Discussion

Main aim of this research was petrophysical analysis of E and B zone of Lower Goru Formation followed by analysis by using SOM technique. Well logs data, formation tops and well header information of KADANWARI-01, KADANWARI-03, KADANWARI-10 and KADANWARI-11 are used for this research. Lithological heterogeneity of respective formation is modeled by using SOM technique.

First of all reservoir zones were identified within Lower Goru Formation of KADANWARI-01, KADANWARI-03, KADANWARI-10 and KADANWARI-11 by using well log responses. Suitable zones were identified in all four wells. Later on, petrophysical analysis of reservoir formation was completed.

By petrophysical analysis it is estimated that E and B sand zones are main reservoirs. For E zone shale volume is 15-20 %, effective porosity 10-12 % and water saturation 25-30 %. For B zone shale volume is 8-10%, effective porosity6-8% and water saturation is 30-35%. Lower Goru Formation has alternating layers of sand and shale.

Petrophysical analysis of respective formation is followed by identification of electrofacies using SOM technique. Electrofacies can be described as subclasses of lithofacies. By electrofacies analysis strategy can be prepared for heterogeneity of respective formation. For reservoir identification and characterization; efficient lithological identification is essential. Log data containing three logs gamma ray log, porosity log and density log is classified into twenty clusters and later on into four main clusters that were clearly visible. These four clusters were marked as electrofacies named as facies 1, facies 2, facies 3 and facies 4. Correlation of KADANWARI-01, KADANWARI-03, KADANWARI-10 and KADANWARI-11 can be shown by using SOM technique.

Self organizing maps (SOM) technique is a method of machine learning by artificial neural networking. Data obtained from log curves of respective wells is used to train the model of SOM. With the help of SOM, multidimensional map is plotted on 2D map.

Data obtained from SOM is consolidated into four clusters using hierarchical cluster method. Marked electrofacies are Facies 1, Facies 2, Facies 3 and Facies 4. Electrofacies marked by using SOM technique in KADANWARI-01, KADANWARI-03, KADANWARI-10 and

KADANWARI-11 are depicted in figure 6.1 and 6.2**.** Quality reservoirs of all the four wells lay in E and B sand zones of Lower Goru Formation.

By comparative analysis of petrophysical analysis and SOM technique method it is clear that machine learning can provide acute results for small scale as well. It can be inferred that machine learning has enhanced accuracy with very less time consumption.

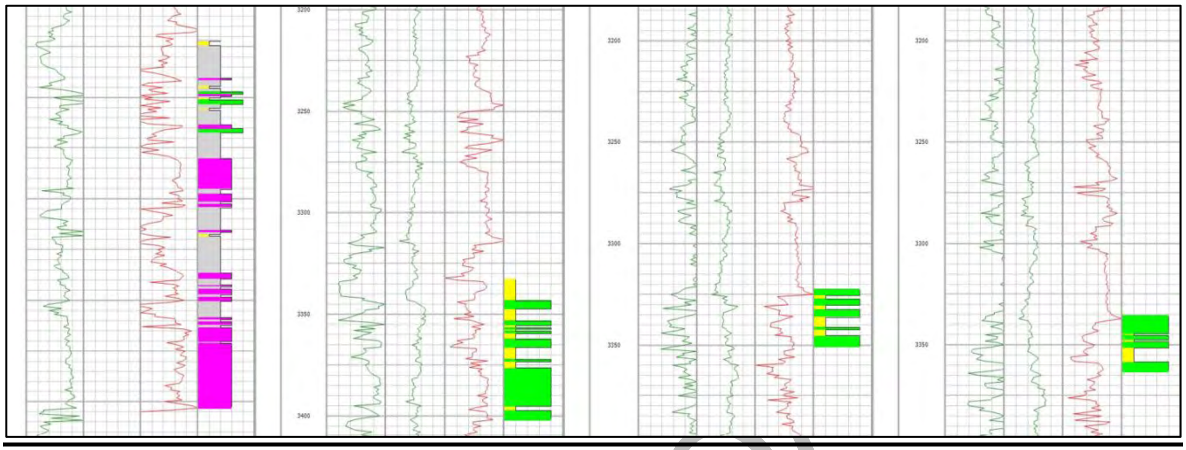

Figure 6.1: Well correlation of E sand zone of Lower Goru Formation using SOM technique

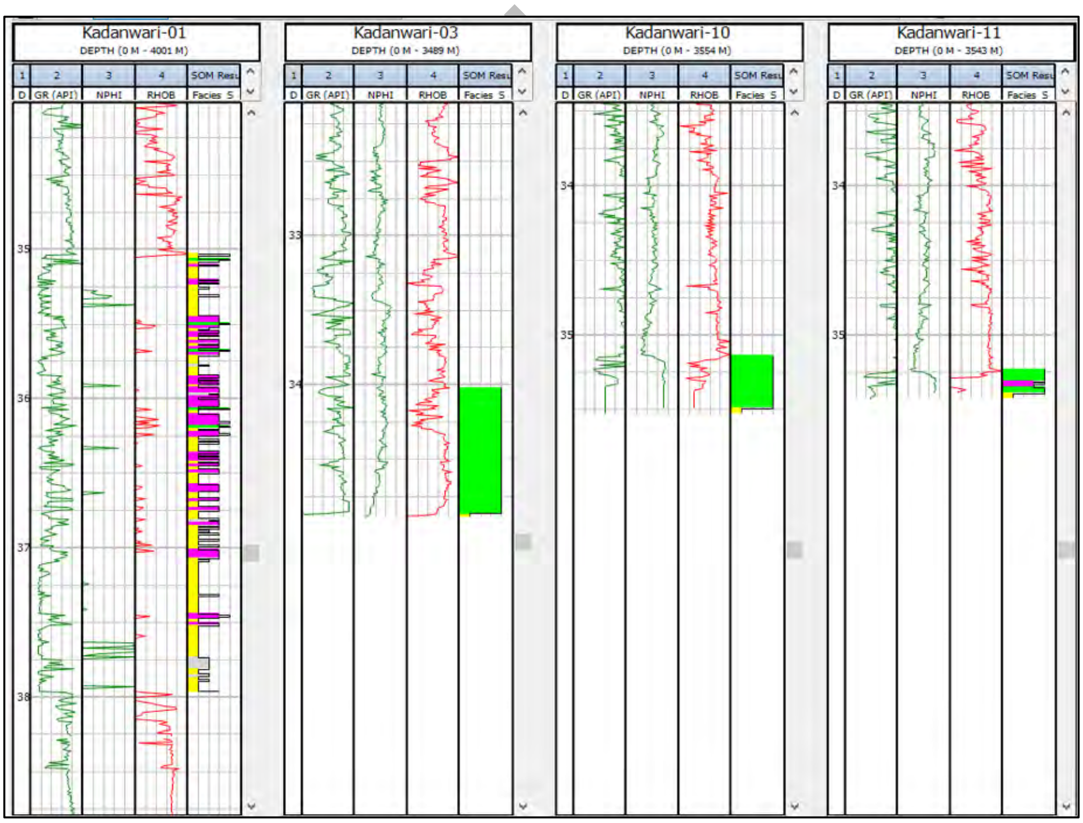

Figure 6.2: Well correlation of B sand zone of Lower Goru Formation by using SOM technique

Conclusions

As per research work following are the conclusions:

- Formation evaluation of Lower Goru formation indicates that this formation has a potential to be the prominent reservoir of Middle Indus Basin. Lithological analysis confirmed the alternating layers of shale, sandstone and sometimes marls indicating lithological heterogeneity within the formation.
- Petrophysical analysis recommends that E and B sand zones of Lower Goru Formation are prominent reservoirs. For E zone shale volume is 15-20 %, effective porosity 10-12 % and water saturation 25-30 %. For B zone shale volume is 8-10%, effective porosity6-8% and water saturation is 30-35%. Lower Goru Formation has alternating layers of sand and shale.
- SOM technique is used to mark four facies within E and B sand zones of Lower Goru Formation. SOM technique displayed multidimensional data into 2D facies map.
- By analyzing results of petrophysical analysis and SOM technique it is evident that machine learning has ability to mark facies at very small scale with better accuracy. So this technique can be used for reservoir estimation and hydrocarbon exploration analysis.

Recommendations

For improving efficiency of research in future following are the recommendations from conducted research;

- For avoiding flaws is interpretation, lithological identification should be done efficiently.
- Lithological identification could be cross checked by other method to reduce errors.
- Machine learning should be adopted for exploration analysis to reduce errors and increase efficiency.
- SOM technique should be used to visualize multidimensional data sets in 2D maps.
- Comparative analysis of conventional workflow with machine learning should be considered for better understanding of subsurface.

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