Integration of Electrofacies Analysis and Seismic Inversion for Improved Reservoir Characterization of Early Cretaceous Reservoir Rock, NIM-TAY Block, Lower Indus Basin, Pakistan.

By

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CERTIFICATE

This dissertation submitted by CHAUDHARY UMER GHAFFAR S/O CHAUDHARY MUHAMMAD MUMTAZ is accepted in its present form by the Department of Earth Sciences, Quaid-i-Azam University Islamabad as satisfying the requirement for the award of M.Phil. degree in Geophysics.

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بسم الله الرحمن الرحيم

To start with the greatest name of Almighty Allah. The most gracious and merciful, with Him is the knowledge of the Hour, He sends down the rain, and knows that which is in the wombs. No person knows what he will earn tomorrow, and no person knows in what land he will die. The knower of the unseen is Allah these are the keys of the unseen, whose knowledge Allah alone has kept for himself and no one else knows them unless Allah tells him about them.

DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

Acknowledgement

In the name of **Allah,** the most merciful and most beneficent. All praises to Him who is Almighty, The One, The Everlasting, who begets none, is be gotten, by no one, and there is none His equal. Alhamdulillah. I bear witness that Holy Prophet **Muhammad (PBUH)** is the last messenger, whose life is perfect model for the whole mankind till the Day of Judgment. I am thankful to Allah for the strengths and His blessing in completing this thesis.

I am nothing without your help. Please keep me always in prostration before you and let me not leave before anyone except you.

Foremost, I would like to express my sincere gratitude to my supervisor **Dr. Tahir Azeem** for the continuous support of my M.Phil. study and research, for his patience, motivation, enthusiasm, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my study.

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ABSTRACT

Hydrocarbons are essential in the current industrialized society because they provide energy. To map and define a hydrocarbon reserve, better subsurface information is needed. This requires analyzing blocks for petroleum plays and structures. In several blocks, Cretaceous Lower Goru Formation has hydrocarbon reservoir proven potential. The NIM-TAY block, with its hydrocarbon-bearing structural traps, requires comprehensive research. To assess hydrocarbon potential and structural favorability, seismic data was analyzed and two horizons and four normal faults were delineated. The structural interpretation shows Graben structure limited by normal faults indicating the studied area's extensional tectonic regime. Petrophysical analysis indicate the presence of gas bearing zone within in the Lower Goru Formation. The value of effective porosity, shale volume and water saturation in this zone varies from 8.63-12.9%, 8.06-16.62%, and 36.84-53.57% respectively. Further four electrofacies i.e. sand, shaly sand, sandy shale, and shale were identified using unsupervised machine learning technique. The spatial distribution of these facies was analyzed with the help of Stochastic inversion. Results clearly indicate that the upper portion of Lower Goru Formation and northwest side of study area mainly contain sand facies. Whereas, the lower portion contain mixed facies. The proposed technique can be applied to delineate the reservoir facies in those areas having same depositional environments.

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Chapter 1
Introduction to the Study Area

1.1 Introduction

The most fundamental and often utilised geophysical survey method in the oil and gas exploration industry is seismic methods. Geological formations in the subsurface can be discovered through seismic data. Seismic signatures are used to identify oil and gas reservoirs. The most essential methods for identifying hydrocarbons are subsurface structure identification, petrophysical investigation, and estimation of rock properties (Link and Weimer, 1991).

The precise prediction of reservoir properties between wells is crucial for the effective planning of exploration and production wells. To create such predictions, conventional methods of quantitative analysis of seismic data, including such inversion, have been applied. The most often used inversion approach is stochastic inversion of seismic reflection data, which is entirely focused on a simple convolutional description of a seismic trace (Ampilov et al., 2009). High lateral resolution for the inverse issue is provided by stochastic inversion, which yields a single best solution (Bosch et al., 2010). However, it has a poor vertical resolution. When the reservoir thickness surpasses the threshold of seismic resolution, reservoir characterization will become challenging. To solve this issue, Stochastic inversion approaches are being investigated in order to successfully handle the resolution restrictions of typical inversion methods while producing output with little subsurface uncertainty (El-Behiry et al., 2019).

Geophysical methods are used to investigate the interior of the earth. These methods involve acquiring measurements at or near the earth's surface for analysis that can identify both vertical and lateral changes in the physical characteristics of the earth's subsurface.

Some fundamental petrophysical characteristics need to be analyzed in order to get an accurate estimate of the amount of hydrocarbon accumulation in the reservoir (sandstone, limestone, or dolomite). These include storage and flow qualities (porosity, permeability, fractional flow), fluid identification, fluid phase distribution within gross void space (saturation), interactions of surface forces existing between the rock and contained fluids (capillary pressure), measurement of pressure, stress conditions, electric conductivity of fluid-statured rocks, and so on. These characteristics and the interaction between them are used to identify and evaluate hydrocarbon reserves, as well as source rock, cap rock, and aquifers (Donaldson, 2011).

All of the measured, calculated, or implied quantities that may be obtained from seismic data are referred to as seismic attributes. Data that may be utilised for quantitative and qualitative interpretation is extracted from seismic reflection data using seismic attributes. (Chopra and Marfurt, 2005).

Electrofacies analysis is used to identify subsurface lithology. Since horizontal wells are seldom cored, there is a need for a technique that may indirectly deduce the facies distributions inside the formations that are penetrated by horizontal wells. Since contemporary logs are sensitive to variables that change with the make-up of those formations, there is a significant link between how well logs behave and the lithological and depositional facies of penetrated strata (Saggaf and Nebrija, 2000).The identification and investigation of lithofacies is becoming more important in terms of providing insights to the interpretation of sedimentary rock depositional settings. It is best to initially characterize a sequence of sedimentary sequence in terms of distinctive Lithofacies units that represent various deposition processes. Then, based on combinations of physical, chemical, and biological processes that have been discovered via examination of the facies, the facies may be categorized into the Lithofacies association, which can then be phrased in terms of depositional settings (Sahito et al., 2010).

1.2 Objectives

1. Interpretation of NIM-TAY 3D seismic to analyze and understand the subsurface geology and spatial extent of the lithologies of the area.
2. Identification of hydrocarbon bearing zones based on Petrophysical analysis.
3. Analyze the distribution of different facies based on unsupervised machine learning technique.
4. Integration of log facies through Stochastic inversion to analyze the spatial distribution of facies within the study area.

1.3 Introduction to Study Area

The study area is NIM-TAY block which is situated in Lower Indus basin (southern part of Indus basin).

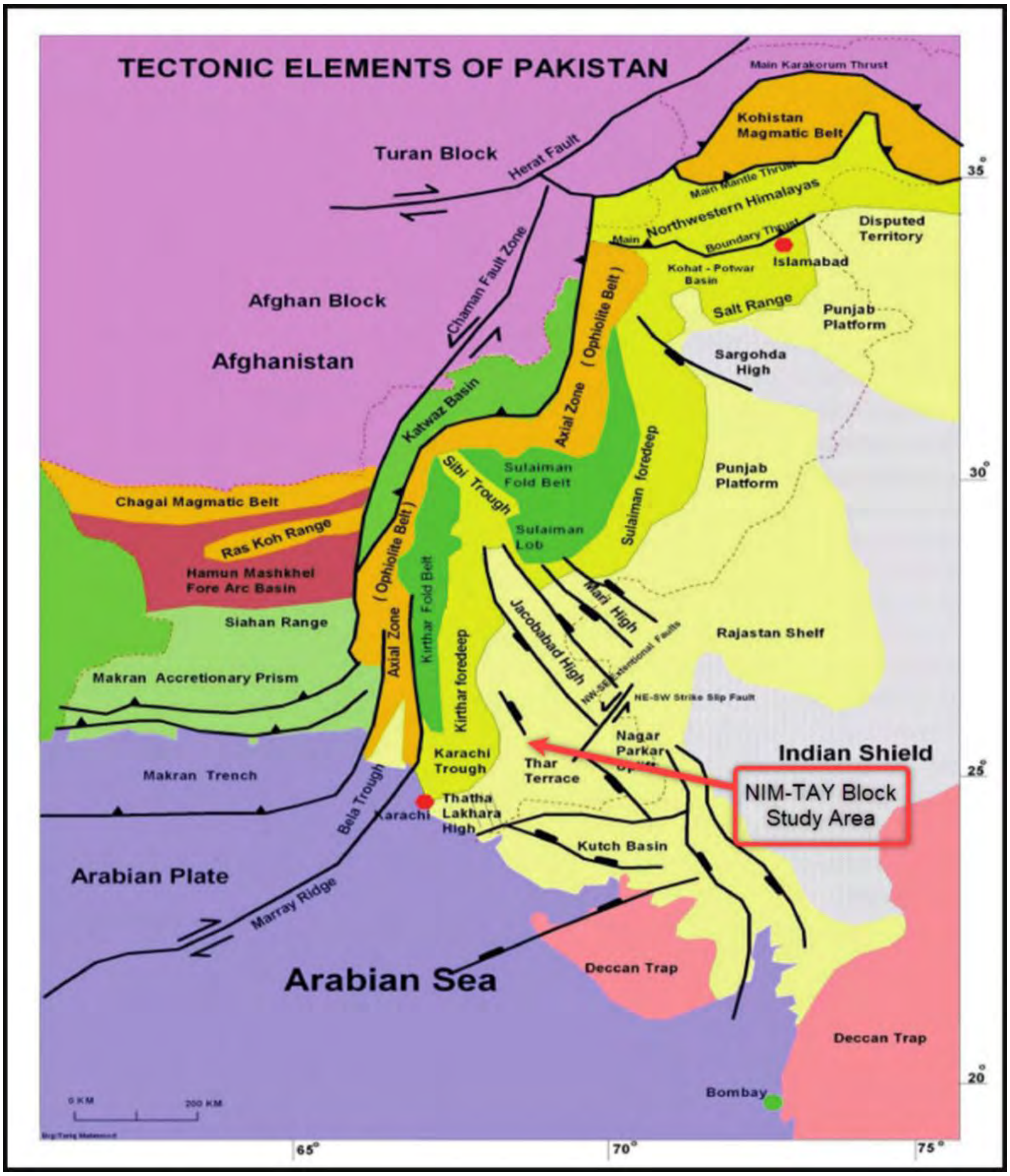

Figure1.1: Map showing the regional geological and tectonic setting of study area (Kazmi and Snee, 1989).

1.4 Data Sets

Seismic data in SEG-Y format

Well Log Data (LAS File, Tops)

1.4.1 Seismic Data

Table 1.1 contains the seismic dataset that was utilized for the study, and this research effort makes use of a 3D seismic cube that covers an area that is 10x10 km^2. This study makes use of a cube that has 164 inlines beginning at 229 and going all the way up to 393, as well as 121 crosslines that range from 176 to 297.

Lines	Start	End	Total no of lines
In-Line	229	393	164
Cross-Line	176	297	121

Table 1.1 Seismic data used for the research.

1.4.2 Base Map

Interpretation requires the base map, which shows seismic picket locations. Geophysicists use base maps to show seismic line alignments, seismic data locations, or the number of Inlines and Crosslines surveyed. A base map usually shows lease and license borders, wells, seismic survey sites, cultural information like buildings and roads, and geographic coordinates like latitude and longitude. Figure 1.2 displays map with well and seismic survey sites.

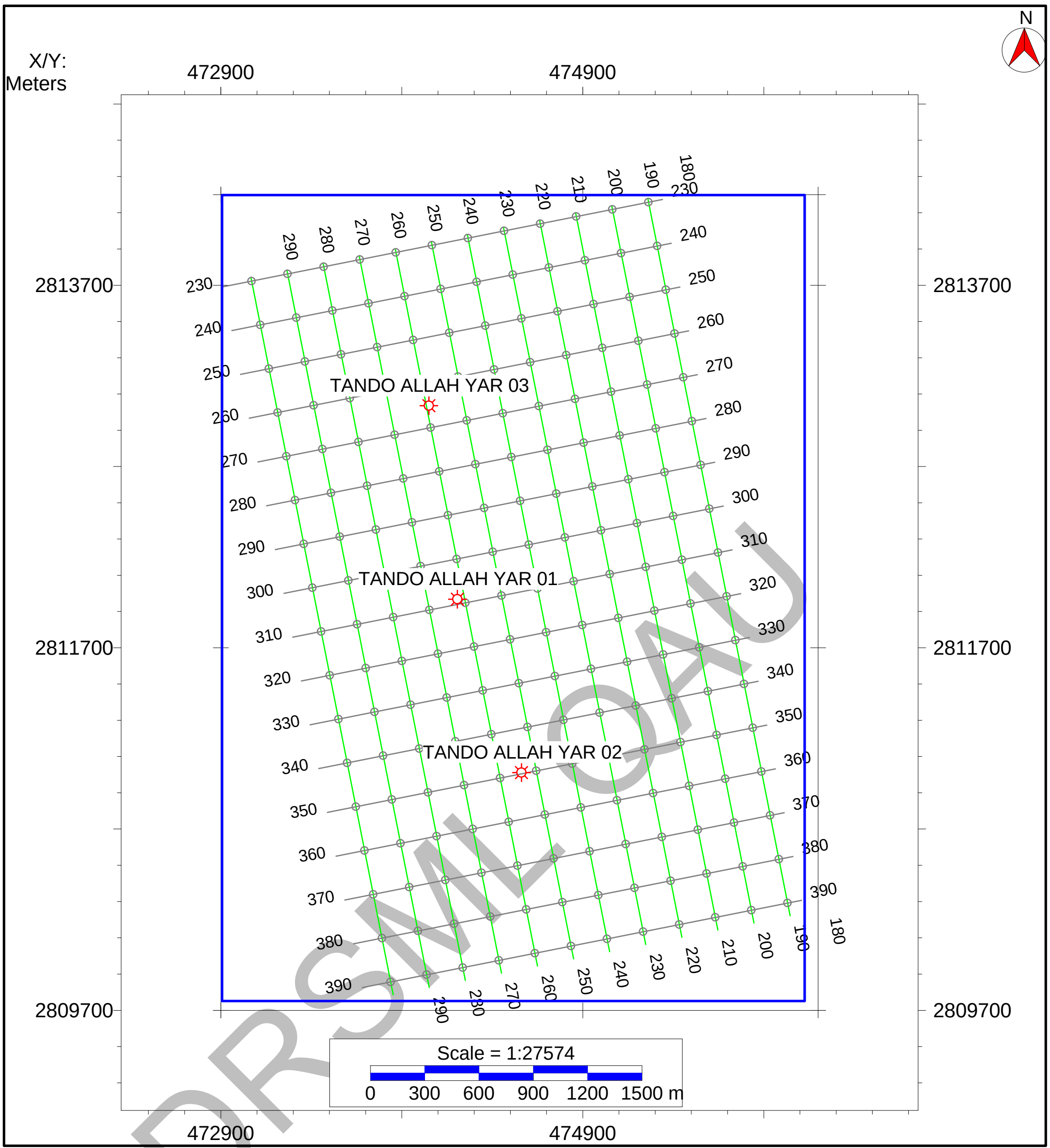

Figure 1.2: Base map of the study area depicting the inlines, crosslines and the well locations.

1.4.3 Well Data

Information of wells and technical well data, used in this research, is given in Table 1.2 and Table 1.3.

Sr.no.	Inline	Crossline	Wells
1	309	252	Tando Allahyar 01
2	350	244	Tando Allahyar 02
3	267	249	Tando Allahyar 03

Table 1.2: Well Data used for the research

Well Name	Tando Allahyar 01	Tando Allahyar 02	Tando Allahyar 03
Longitude	68.74355833° E	68.74710833° E	68.74196548° E
Latitude	25.42441944° N	25.41579166° N	25.41579166° N
K.B. Elevation	20.6 ft	21.37 ft	21.37 ft
Total Depth	1752m	1650m	1602m
Type	Development	Development	Development
Status	Gas	Gas	Gas
Company	OGDCL	OGDCL	OGDCL
Field	NIM-TAY, Sindh	NIM-TAY, Sindh	NIM-TAY, Sindh
Formation Tops	Depth(M)	Depth(M)	Depth(M)
ALLUVIUM	0	0	0
LAKI	165	165	163
RANIKOT	785	782	804
KHADRO	1022	1002	1047
PARH	1145	1136	1135
UPPER GORU	1150	1142	1147
LOWER GORU	1447	1536	1456

Table 1.3: Well information of Tando Allahyar 01, 02 and 03 wells

1.5 Research Methodology

Sands that are part of the Lower Goru formation will be characterized in great detail as the primary objective of this study. In order to accomplish this goal, a variety of methodologies have been used to the 3D seismic and well data. First and foremost, a structural interpretation has been carried out in order to make a prediction about the underlying structural geology. Confirming the horizons on seismic sections requires the generation of a synthetic seismogram. Well data is utilised to estimate the petrophysical parameters (shale volume, porosity, water saturation, and hydrocarbon saturation) of hydrocarbon bearing zones. The existence of thin sands in the Lower Goru Formation is shown through petrophysical research. The seismic inversion approach is used so that these thin beds may be identified. In order to execute seismic to well tie prior to running inversion, we first estimate wavelet and low frequency model then perform seismic to well tie. Estimates of the spatial distribution of facies were made for the zone of interest in within Lower Goru Formation. The lateral continuity of the sands of the Lower Goru Formation has been evaluated using stochastic inversion. Impedance measurements have been used to build inverted sections, which have been used to analyze the vertical resolution in the Lower Goru sands.

1.6 Workflow of Dissertation

Importing seismic data in the SEG-Y format allows the base map to be generated. In the seismic section, faults are located and marked in order to construct fault polygons and grids of designated horizons. The use of the well log data makes it possible to carry out petrophysical analysis as well as an estimate of the electrofacies analysis of the reservoir. where seismic data and well log data are combined to perform seismic inversion, as illustrated in Figure 1.3.

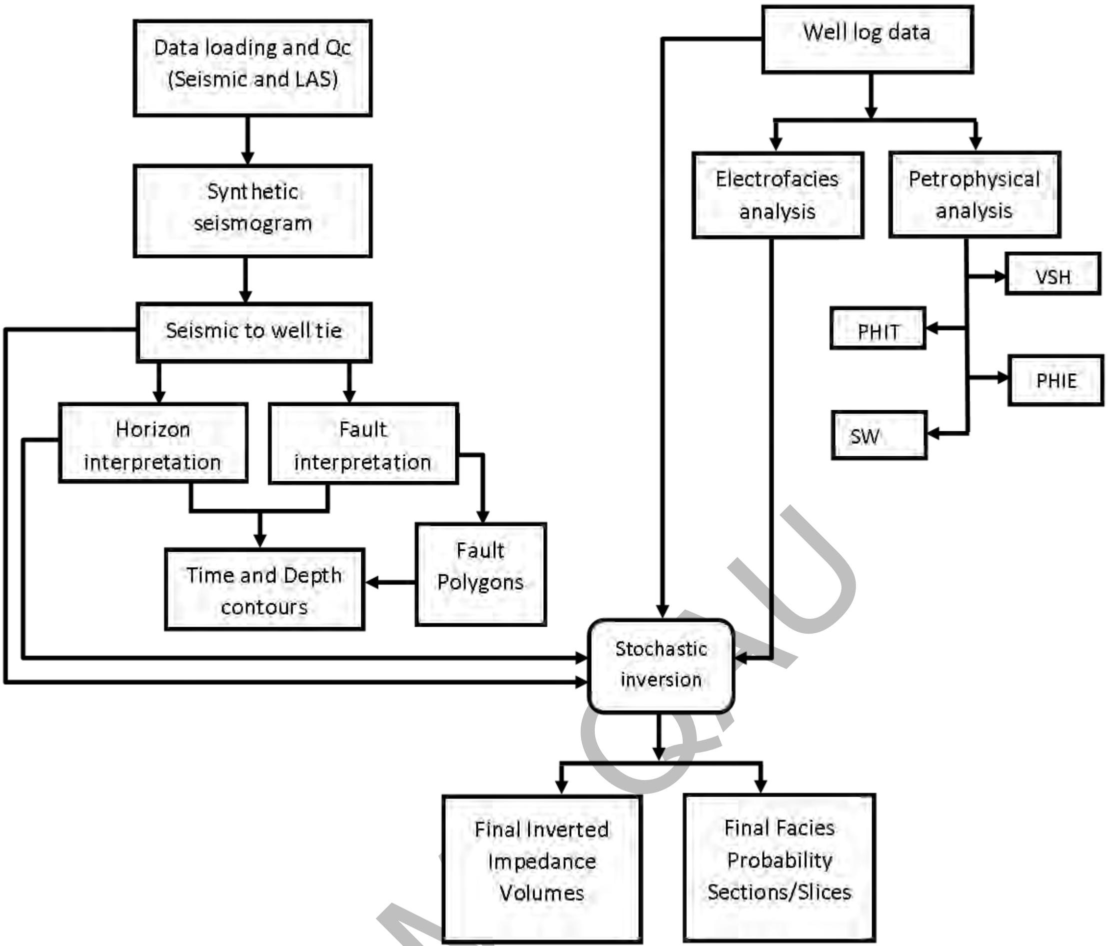

Figure 1.3: The workflow adopted to analyze the distribution of reservoir facies.

Chapter 2

General Geological and Stratigraphical setting of the Area

2.1 Introduction

The study of the solid Earth, the rocks that it is formed of, and the activities that are taking place inside the earth are referred to as "geology." Geology is the study of Earth's history, including topics such as the evolution of life and historical climates, as well as plate tectonics and the history of biological evolution. Geology is used in today's world for the investigation of minerals and hydrocarbons, as well as for the forecasting and comprehension of natural hazards.

Our prior understanding of the field area, including its geology and variations in velocity, assists us in providing an accurate analysis of the lithology and other factors. Variations in the area's velocity can provide us with information that will help us identify different reflectors. The identification of faults and the scope of their damage can also benefit from geologic information.

2.2 Geology and Tectonics

Being situated at the intersection of these two distinct regions makes Pakistan distinctive. The Indian sub Crustal Plate supports the southern half of Pakistan, which is continuation of the Gondwanian Domain. There is a lot of complexity in the geology of the Tethyan Domain, which includes the western and most northern parts of Pakistan. The Laurasian, Tethyan, and Gondwanaland geological domains are the three main geological divisions that may be found inside Pakistan (Kazmi and Jan, 1997). Their genesis dates back to the Late Paleozoic. Pangea was the name given to the supercontinent that formed when all of the continents merged together. Pangea broke apart as a consequence of Laurasia moving to the north and Gondwanaland moving to the south during the late Triassic period. These two landmasses were eventually divided by the Tethys seaway. Pakistan is situated at the crossroads of the Gondwanian and Tethyan domains. As was just said, the research site may be found in Pakistan's Southern Indus Basin. Horst and graben structures are frequent in this region, in contrast to the large thrusts that are more prevalent in the northern half of Pakistan. Normal faults predominate the landscape in this region. Numerous suggestions have been put forth in an attempt to explain where these crustal features came from; yet, these basements up warps continue to be baffling. The rifting that occurred on the Indian Plate during the late Jurassic and early Cretaceous period affected the structures and sedimentology of the Southern Indus Basin. Rifting that occurred throughout the Jurassic and early Cretaceous may have been responsible for the formation of northeast-southwest rift systems. During the middle to late Cretaceous time period, the Madagascar and Indian plates may have split apart, which may have resulted in strike-slip faulting, hotspot activity, and thermal doming in the region. In turn, this separation led to uplift, erosion, and the extrusion of the Deccan flood basalts, as well as potentially the NNW-striking normal faults. Carbonate deposited due to passive margin conditions during the Eocene. Sinistral floral and Left - lateral transpression with fold-thrust structures are produced in the west during the Oligocene to modern Himalayan collision. The sinistral floral structures overlay the fold-thrust structures.

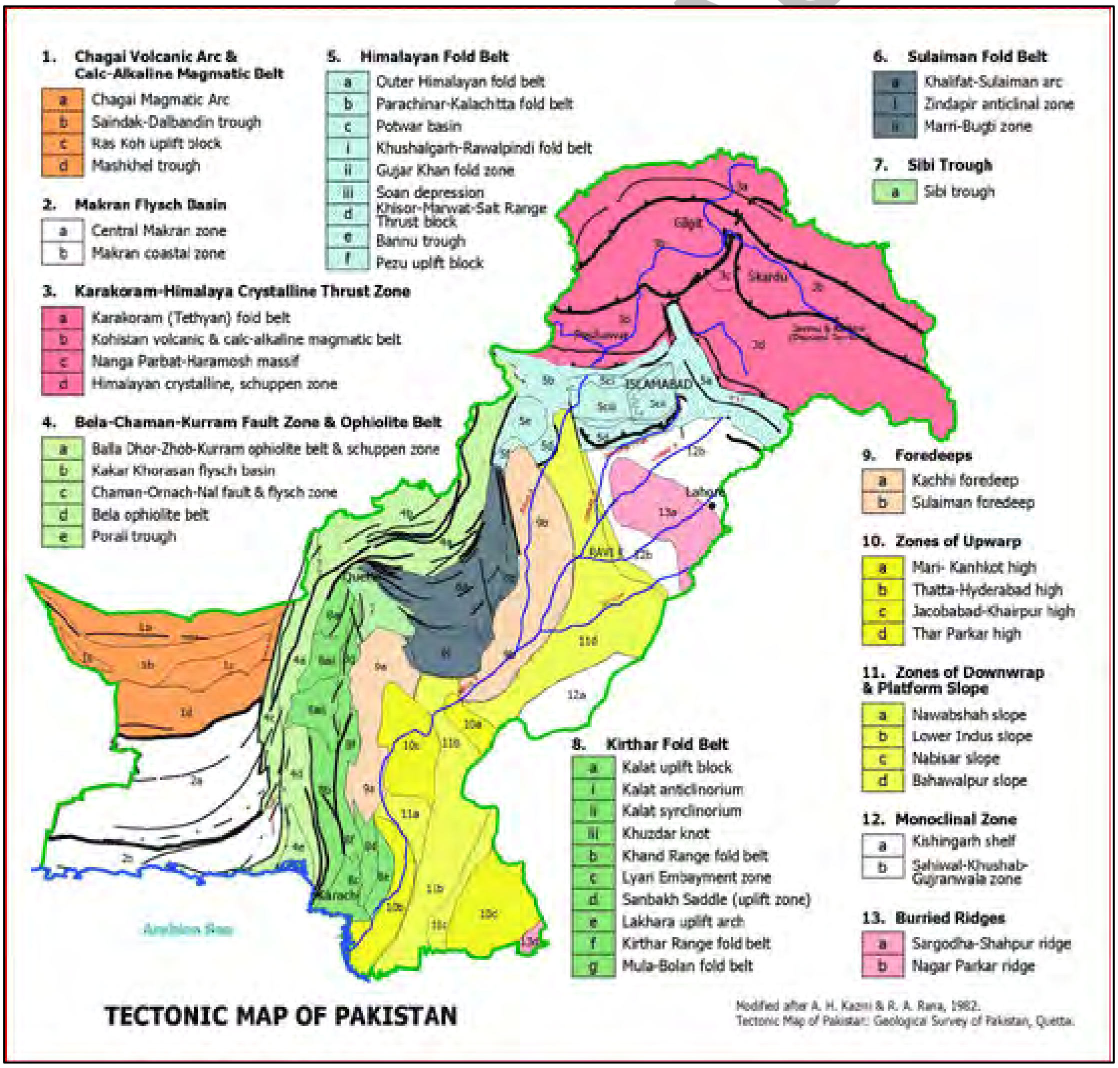

Figure 2.1: Tectonic map of Pakistan showing 13 tectonic subdivision of Pakistan including study area (Kazmi and Rana, 1982).

2.3 Introduction to Basins of Pakistan

Pakistan is consisting of two main sedimentary basins, each with their own unique origins and geological histories. Pakistan's Basinal Distribution is shown in the following Flow-diagram.

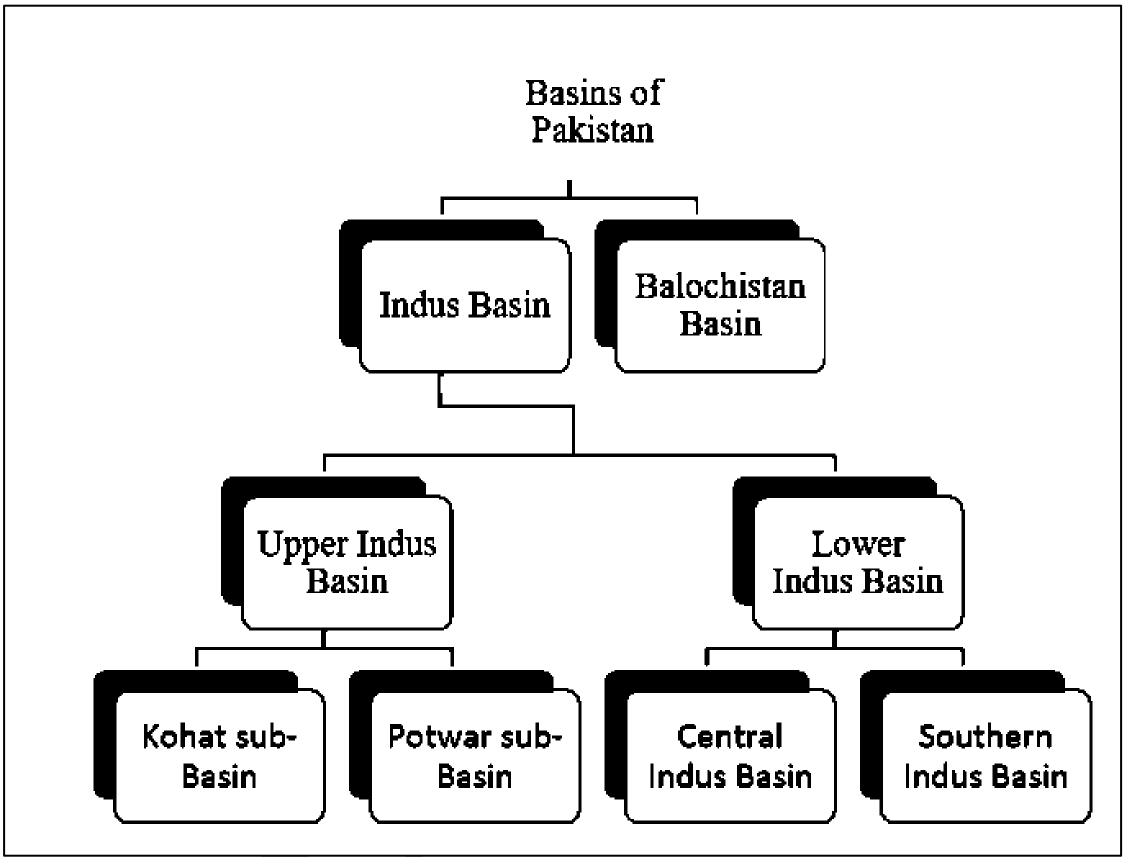

Figure 2.2: The classification of basins presents in Pakistan.

These basins were fused systematized during the Cretaceous and Paleocene epochs by Ornach Nal/Chaman Strike slip faults. There is so far another recently discovered smaller basin known as the Kakar-Khorasan Basin. This basin has its own unique geological history that contributed significantly to its development. The intersection of the Indian Plate and the Eurasian Plate resulted in the formation of this basin, which is stated to as the Median Basin (Kadri, 1995).

2.3.1 Balochistan Basin

The Makran accretionary wedge as well as the Makran offshore trench are both included in the Balochistan Basin. This is Pakistan's least explored area. In this enormous basin, just six wells have been sunk, and seismic surveying has been done to only a very limited extent. Despite the presence of various gas reservoirs along the Makran Coast, no commercial hydrocarbons have yet been discovered in the area.

(Kazmi and Jan., 1997). Dalbandin and Kharan trough are both located within this basin.

2.3.2 Indus Basin

This is the largest and most widely investigated basin in Pakistan. The sediments of the Indus Basin are more than 15,000 meters thick and range in age from the Precambrian to the Recent. The basin has a surface area of around 533,500 square kilometers. Partitioning of the Indus Basin, the Indus Basin is divided into the following basins:

- Upper Indus Basin: Potwar and Kohat sub basins
- Lower, Central, and Southern Indus Basins

2.3.2.1 Upper Indus Basin

The presence of the Sargodha High helps to differentiate this basin, which may be found in northern Pakistan, from the lower Indus basin. The northern and eastern borders overlap with the Main Boundary Thrust as the eastern side of the main Himalayan thrusts (MBT). The Margalla Hills, the Kohat Range, and the Kala Chitta Range are among regions that the MBT travels through. The western edge of the basin may be identified by an elevation of Pre-Eocene sediments as well as an eastward-oriented thrusting that is located to the west of Bannu. The Potwar basin is located to the east of the basin, while the Kohat basin is located to the west of the basin. Both of these basins are located on the opposing sides of the Indus River (Kadri, 1995).

2.3.2.2 Lower Indus Basin

Lower Indus basin refers to the section of the Indus basin that is located farthest to the south; this basin also includes Badin Block and the territories that are next to it. Exploration for petroleum began in the 1950s in the Lower Indus basin. Roughly speaking, its boundaries are located to the south of Khairpur High and stretch into the Arabian Sea. The first significant oil and gas discoveries were made in the early 1980s in Khaskheli, close to Badin, and the first gas discovery was made in district Dadu at Sari-Hundi in the Kirthar Range. Since then, several significant and smaller oil and gas fields have been found in this area. The Lower Indus basin can be divided into parts with rocks from both the Neogene to the Cretaceous eras exposed; the western part alongside Kirthar Range and into the regions with no surface geology exposure or modest to minor extent geological formations of the Neogene to the Pleistocene are planting out; the Badin Block were regions adjacent all of which do not have any surface and subsurface expression..

2.4 Stratigraphy of Lower Indus Basin

The South Indus Basin has stratigraphy that spans from the Cambrian to the Holocene, with non-deposition and erosion occurring at a number of different stratigraphic stages. Stratigraphic succession changes in the Punjab and southern Indus Basin region from east to west, exhibiting regional unconformities just at base Tertiary and basement Permian eras. However, the Tertiary series interacts directly with the Jurassic succession in the eastern part of the Lower Indus Platform, where the Mid Jurassic to Eocene strata of the Punjab Platform terminate under the Miocene-Pliocene unconformity. The strata's thickness increases westward. It is known that the Suleiman and Kirthar fold belt's strata dates from the Permian to the Holocene. The Cretaceous-Tertiary unconformity is more regional in nature, while intra-formational deposition breaks are more prominent in the Permian and Jurassic formations. In certain areas of the fold belt, erosion has been so severe that Jurassic rocks that were previously buried have been brought to the surface or very close to it (Ahmed et al., 2011).

From east to west, the geologic succession varies. In the south-eastern part of the basin, the Precambrian basement is exposed. The thickness of the sediments rises westward. in the basin's eastern rim, The Jurassic and Tertiary sequences are in constant communication with one another. The stratigraphic chart of the study area is given in Figure 2.3.

2.5 Stratigraphy of the Study Area.

The key tectonic event was the rifting of the Indian plate from Gondwanaland in the early Cretaceous, which governed the shape and stratigraphy of the southern Indus basin. The principal reservoir rock is Cretaceous sand from the Lower Goru area. The Sember Shale, which serves as the source rock, and the Upper Goru Shale, which serves as the cap rock, are both Cretaceous in age (Ahmad et al., 2009). The research region is in the Lower Indus Basin and exhibits extensional tectonics, with normal faults displaying horst and graben structures. The research area's lithological context and stratigraphic succession are shown below.

2.5.1 Goru Formation

The Goru formation, which dates back to the early Cretaceous, is mainly composed of interbedded layers of marl, sandstone, shale, and limestone. The deposition environment ranges from the shelf to shallow marine environments. The reflectivity indices in certain portions of this thick structure are high enough to give extremely vivid reflections. Goru formation is divided into two parts (Kadri., 1995).

2.5.1.1 Upper Goru

Marl calcareous clay-stone dominates, with intermittent interbeds of silt and limestone (Kadri, 1995).

2.5.1.2 Lower Goru

It is consisting of massive sand unit, lower shale, upper shale, Middle, sand unit lower shale and upper sand, Basal sand unit (Shah, 1977).

2.5.2Parh Limestone

This formation is mostly formed of hard, thin to medium-bedded limestone with additional calcareous shale and marl intercalations. The deposition environment is shallow sea (Shah, 1977).

2.5.3 Ranikot Formation

The Ranikot formation is thought to be an excellent source rock for the hydrocarbons in the surrounding region. Additionally, it also acts as a seal rock (Shah, 1977).

2.5.4 Khadro Formation

The Khadro Formation is a sedimentary rock formation found in the Lower Indus Basin, Pakistan. It is characterized by sandstones, shales, and siltstones and is believed to have been formed during the Late Cretaceous period. The Khadro Formation is of significant importance for petroleum exploration in the region, as it is known to contain hydrocarbon reservoirs (Tanveer and Qureshi 2009).

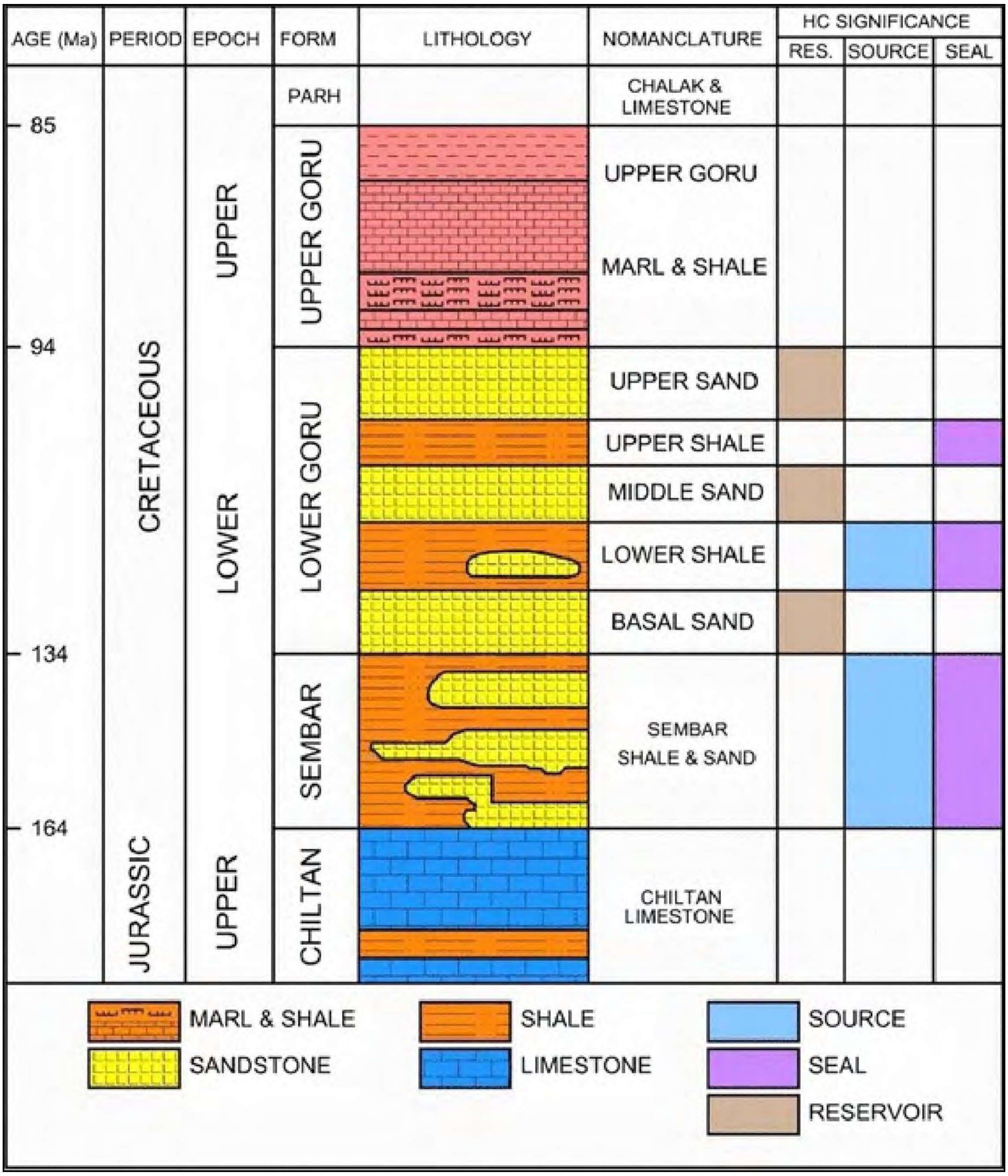

Figure 2.3: Generalized stratigraphic chart of the study area (Alam et al. 2002).

2.6 Petroleum Plays

A play is defined as "a set of geologically connected prospects with comparable source, reservoir, and trap characteristics." (Kadri., 1995)

2.6.1 Petroleum Play Elements

The existence of play components within a basin is critical for hydrocarbon formation. The seven play components are as follows:

- Source

- Seal or Cap
- Reservoir
- Trap
- Timing
- Maturation
- Migration

2.6.2 Petroleum Prospects of the Area

i. Source Rocks

The term "source rock" refers to any kind of rock that has the potential to produce hydrocarbons. In the region under investigation, the Sembar shale and shales of the Lower Goru Formation acts as the primary source rock. Sembar shale deposits are most likely in the Kirthar fold belt. Lower Cretaceous shale dominates the Sembar Formation, with minor mudstone and sandstone. Sandstone is more prevalent in the eastern half of the region than it is in the western section, which is dominated by shale and siltstone. The Sembar Formation was formed as a result of deposition in an aquatic environment, and its thickness may range anywhere from 10 to more than 260 meters (Shah, 1977).

ii. Reservoir Rocks

The lower Goru formations' hydrocarbon producing basal sands are the primay emphasis in this region. The basic goal is to find these sands. Massive sands, with their various sand sheets of varying thicknesses, are another remarkable generating reservoir. Although the possibility of a reservoir within Lower Goru are sand interbedded with basal sands cannot be ruled out, these sands have yet to demonstrate that they are such. The fluvial and shallow-marine sandstones that may be found in the lower half of the Goru in this region are the principal reservoirs. Westward expansion often results in thicker reservoirs but a decline in overall reservoir quality.

iii. Seal or Cap Rocks

Shale and evaporites are two examples of fine-grained rocks that have the potential to serve as excellent cap rocks. Faults and up-dip facies alterations are also exampling of potential additional seals that are effective. Shale with interbedded layers forms the known cap rocks in the region under investigation, and this shale layer overlays the reservoirs. The Lower Goru formation, which lies below the Upper Goru formation, is sealed by the thick layer of clay and marl that makes up the Upper Goru formation.

iv. Traps

In the region under investigation, all production comes from various structural traps. The construction of negative flower structures, in addition to the extension that was caused by rifting, is responsible for the tilted fault traps that can be observed in the Southern Indus Basin. Throughout the entirety of the Indus Basin, there is a wide variety in the temporal correlations that exist between the development of traps and the production, ejection, migration, and trapping of hydrocarbons. Along with inclined fault blocks and negative flower structures, this constitutes the primary trapping system.

CHAPTER 3
SEISMIC INTERPRETATION

3.1 Interpretation

A technique for transforming the whole of the seismic data into a structural or stratigraphically model of the subsurface is interpretation. Since the seismic section is a representation of the geological strata model of the earth, we use interpretation to attempt to identify the actual anomalous zone. The real geology is rarely known in a satisfactory way; therefore, it is unusual for the accuracy or incorrectness of an interpretation to be determined. The criteria for excellent interpretation are consistency instead of accuracy. An accurate interpretation requires knowledge of not just the seismic data but also the local gravitational and magnetic data, well parameters, surface geology, and geologic and physical concepts. (Telford et al., 1999) Conventional seismic interpretation entails picking and tracking seismic reflectors that are laterally consistent in order to map geologic formations, stratigraphy, and reservoir geometry. Identifying hydrocarbon accumulations, determining their extent, and estimating their amounts are the objectives. The conventional method of interpreting seismic data is an art that requires a high level of skill and extensive practical experience in geology and geophysics. In the last three decades, there have been enormous breakthroughs in data acquisition equipment, computer hardware, and seismic processing algorithms in order to meet the demands of investigating ever more complicated targets. Due to this development, seismic analysis is now a highly computational science. The fact that computer-based processing (processing and interpretation) is much more accurate, precise, efficient, and satisfying frees up more time for further data analysis. The whole of this task is accomplished by the use of many pieces of software, one of which is referred to as the Kingdom Suite. Our foremost goal is to consider the reflection as clear as possible so that we can simulate the structure and stratigraphic setting of the subsurface. When the acoustic impedance changes, the reflection indicates the boundaries to a geologist. We link the well characteristics to the seismic data in order to discern between the several horizons utilizing the seismic data. Seismic data has successfully analyzed using very good control and well log data has been used to connect the seismic data. Using the best seismic data in use, the structure and estimate of the sedimentary layers, seismic velocities, stratigraphy, and lithology are all calculated. (Dobrin and Savit, 1988). There are two main approaches for the interpretation of seismic sections:

- Structural Analysis
- Identification of structural features
- Stratigraphic Analysis
- Identification of stratigraphic boundaries

3.1.1 Structural Analysis

This type of research is particularly appropriate in Pakistan, since the great bulk of hydrocarbons are already recovered from structural traps. Reflector geometry is investigated using reflection times. The main application of seismic structural analysis is the search for structural traps which capture hydrocarbons. This is the primary use of structural analysis. Instead of time and depth structural maps, which are constructed to illustrate the geometry of multiple selected reflections, the mass majority of structural interpretation employ two-way reflection timings. Some seismic sections have visuals that can be understood with little to no trouble. Faults may be easily identified by discontinuous reflections, and folded beds can be uncovered by undulating reflections (Sheriff et al., 1990).

3.2 Seismic Interpretation Workflow

Figure 3.1 demonstrates the procedure used for seismic data interpretation. The base map is created by importing SEG-Y into the SMT Kingdom software. Horizons of concern are marked manually as well as automatically when the tracking mode is set to auto. Initially, horizons are identified using a synthetic seismogram created from well data. During this step, faults are spotted and then marked for further investigation. In order to determine the structural highs and lows, fault polygons and horizon contours are created. Following this step, time and depth contours are produced. Utilizing the well point velocity allows for the generation of depth contours.

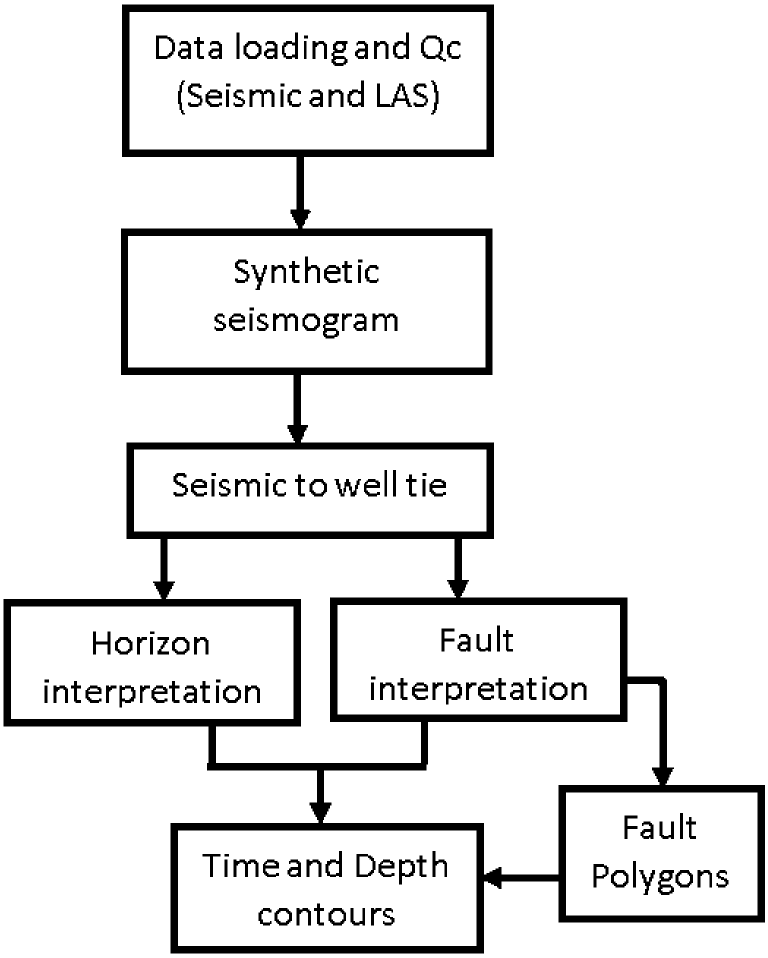

Figure 3.1: Workflow for seismic data interpretation.

3.3 Generation of Synthetic Seismogram

The creation of synthetic seismograms requires two-way time for each well top. Depth, sonic log data, and area replacement velocity generate two-way time for each well top or reflector. The preparation of the time depth chart involves employing two-way time in comparison to the top depth of each well. The recovered wavelet with a frequency of 25 Hz is convolved with the well data to produce the synthetic seismogram at the end. Tie this synthetic seismogram to the Seismic data. The synthetic seismogram of Tando Allahyar 01 is shown in Figure 3.2 respectively.

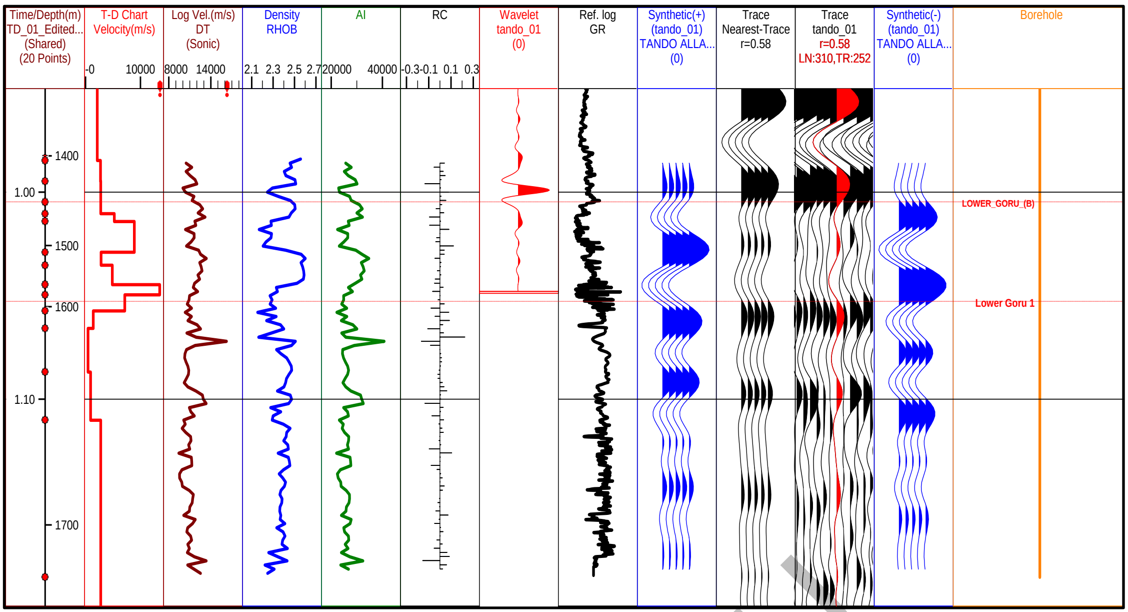

Figure 3.2: Synthetic Seismogram of Tando Allahyar 01.

3.4 Horizon Demarcation

High seismic amplitude generates powerful seismic reflectors, which are then labelled as "horizons" and geologically recognized. A previously created synthetic seismogram is superimposed over the seismic section, assisting in the accurate selection of horizons. On the basis of the synthetic seismogram and the promising reflection amplitude of each horizon, there are two horizons that have been marked. These horizons are referred to as Lower Goru (pink), Lower Goru 1 (yellow) Figure 3.3 and Figure 3.4 illustrates the horizons, and Lower Goru is the main reservoir for hydrocarbons in this location.

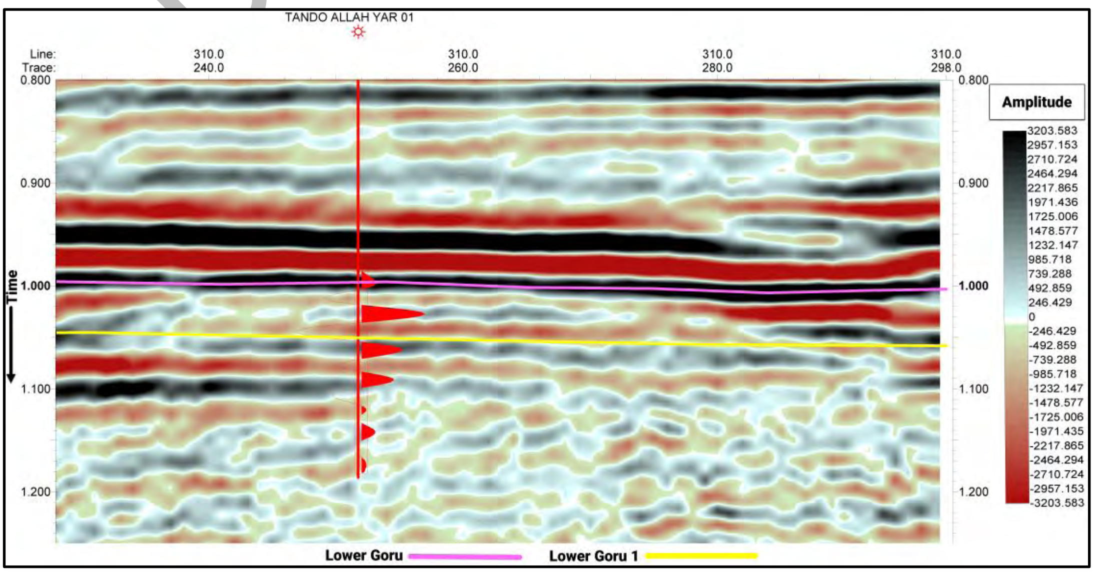

Fig 3.3: Interpreted inline 310, indicating two marked horizons.

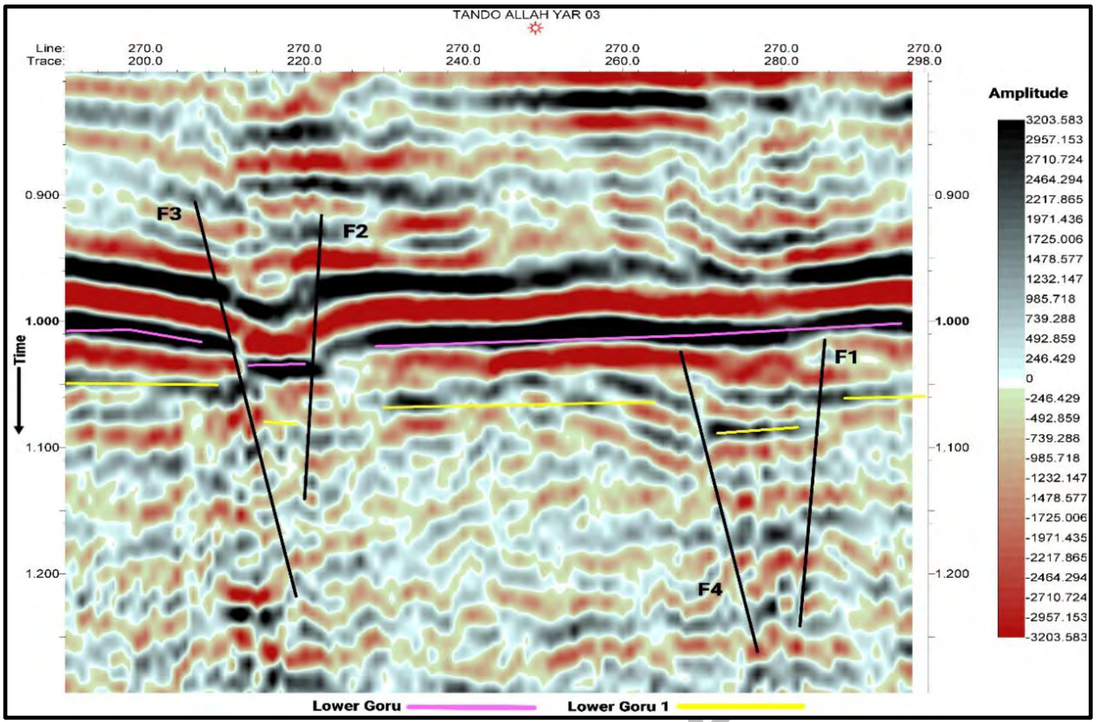

Fig 3.4: Interpretation of the inline 267 showing presence of normal faults forming horst and graben structure within the Lower Goru Formation

3.5 Time and Depth Contour Maps

A map that was created using seismic time horizons for each seismic line is supposed to depict the structure that is present in the subsurface. It is obvious that it does not display structure directly; nonetheless, it does provide us with an idea of the structure of the subsurface as well as the dispersion of horizons within the subsurface. The time and depth contour maps are subjected to a certain region; therefore, it is essentially a local analysis of the area. With the use of the SMT Kingdom software, time contour maps are produced for the purpose of this investigation. In order to determine the contours of time, the travel time of seismic waves in both directions is plotted against the northing and easting (X and Y coordinates), respectively. The information on these contour maps is presented as follows:

3.5.1 Time and Depth Contour Maps of Lower Goru Formation

Lower Goru is the main zone of interest of the study area from the hydrocarbon exploration point of view. Time and depth contour maps of Lower Goru formation are used to understand the structural trap present in the reservoir. Faults that are already present in the region are what identify the structural patterns. In order to effectively designate faults, a comprehensive understanding of the tectonic regime that is present in the region is required. In this specific region, an extensional regime prevails, which has resulted in the formation of a horst and graben structure, both of which may be seen on time and depth grids. Figure 3.5 and 3.6 illustrates the time and depth grids of lower goru.

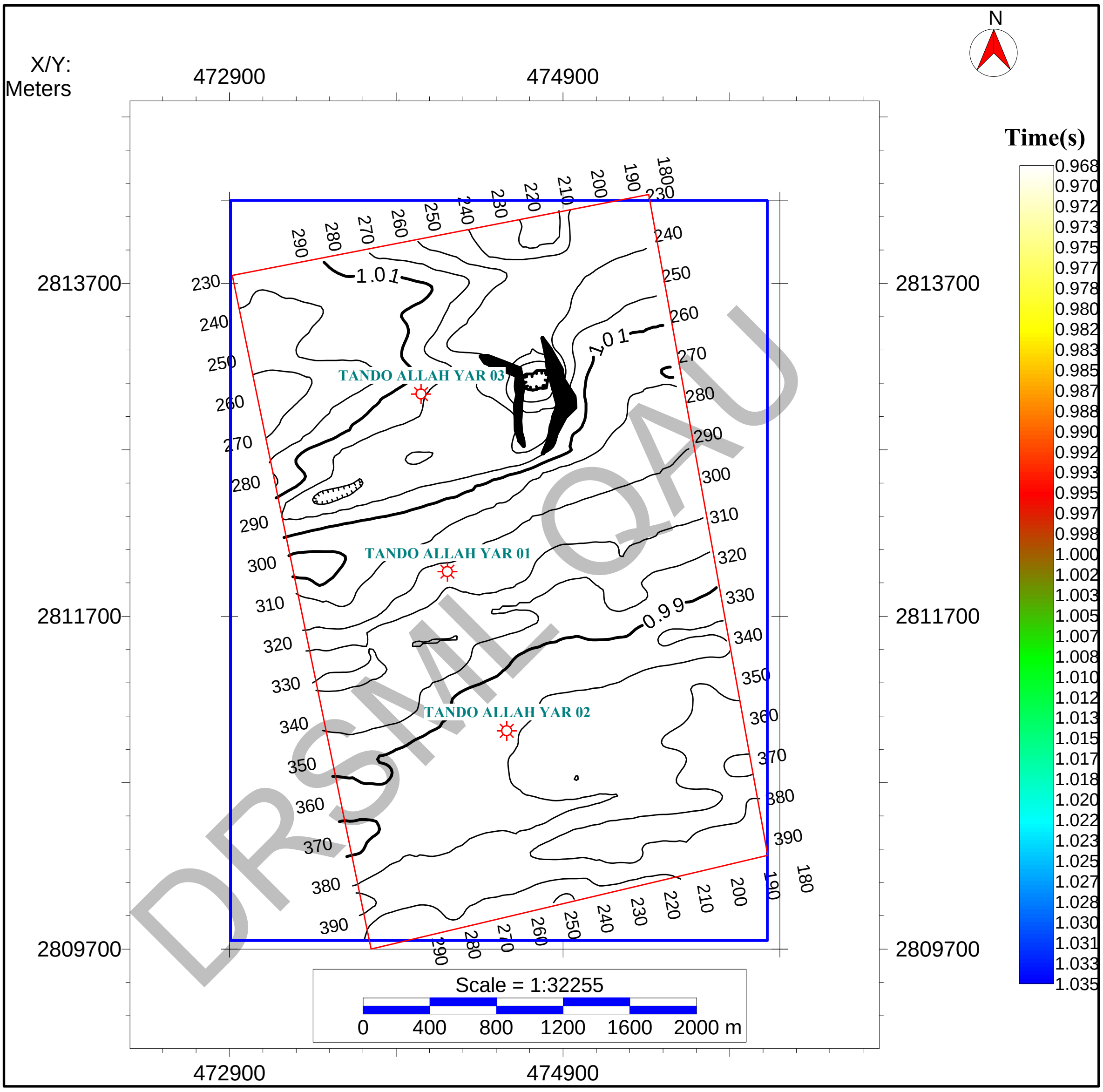

Figure 3.5: Time contour map of Lower Goru formation depicting that the formation is shallower towards south and deeper towards north.

Figures explaining the structure quite well as Lower Goru is main scope of Explorationists in the study area. Polygons are used to determine the type of fault and its orientation. Both of the prescribed polygons on the map, which are F1 and F2, display the strata's dip. The existence of relatively high values of time and depth in the center of fault polygons indicate the presence of graben between the faults F1 and F2.

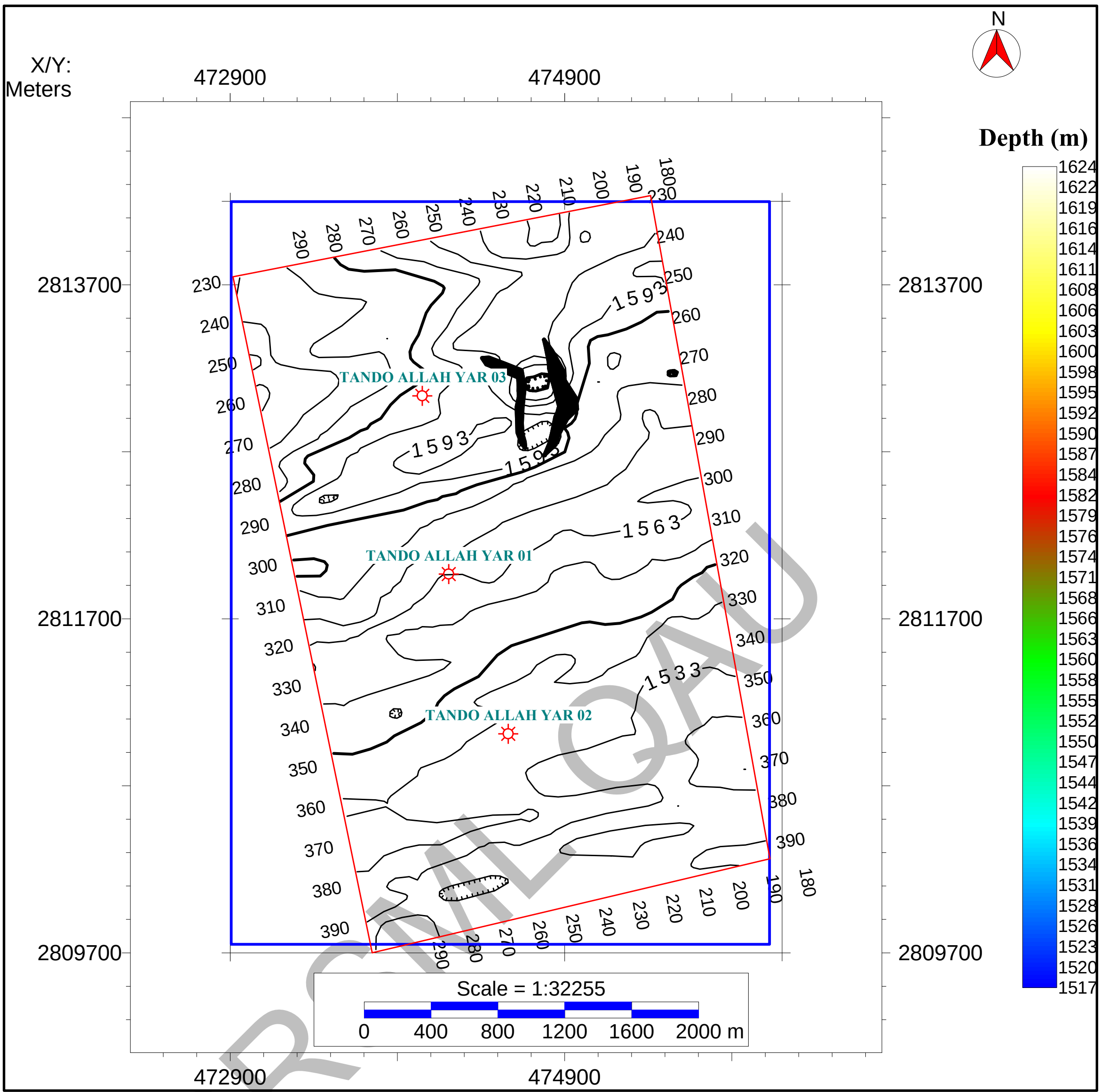

Figure 3.6: Depth contour map of Lower Goru formation depicting that the formation is deeper towards north.

3.5.2 Time and Depth Contour Maps of Lower Goru 1 Formation

Lower Goru is the main zone of interest of the study area from the hydrocarbon exploration point of view. Time and depth contour maps of Lower Goru 1 formation are used to understand the structural trap present in the reservoir. Faults that are already present in the region are what identify the structural patterns. In order to effectively designate faults, a comprehensive understanding of the tectonic regime that is present in the region is required. In this specific region, an extensional regime prevails, which has resulted in the formation of a horst and graben structure, both of which may be seen on time and depth grids. Figure 3.7 and 3.8 illustrates the time and depth grids of Lower Goru 1.

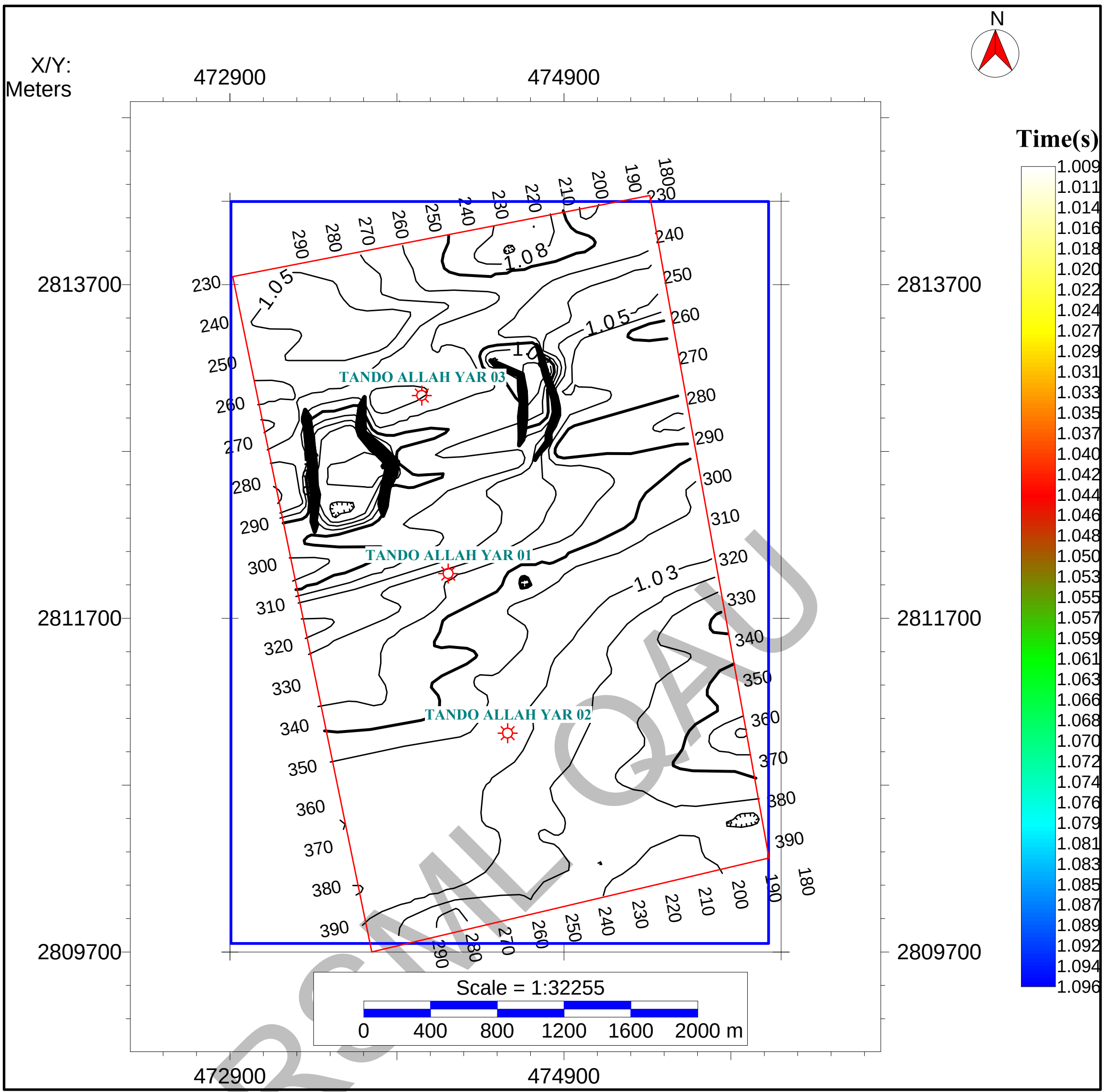

Figure 3.7: Time contour map of the marked, Lower Goru 1 horizon indicating that the horizon is deeper towards north and shallower towards south.

As Lower Goru is the main focus of Explorationists in the study area, the organization is well explained by the figures. Lower Goru 1 time and depth contours illustrating that the horizon becomes deeper moving northward and shallower moving southward. Using polygons, we may determine the kind of fault and its dip. The two specified horizon polygons on the base map each indicate the strata's dip, which can be seen to run from F1 to F2 and F3 to F4, respectively. Because there are relatively high values in the center and at the lower edge of fault polygons F1 and F2 as well as F3 and F4, a graben structure is created in the space in between Fault polygons F1 and F2.

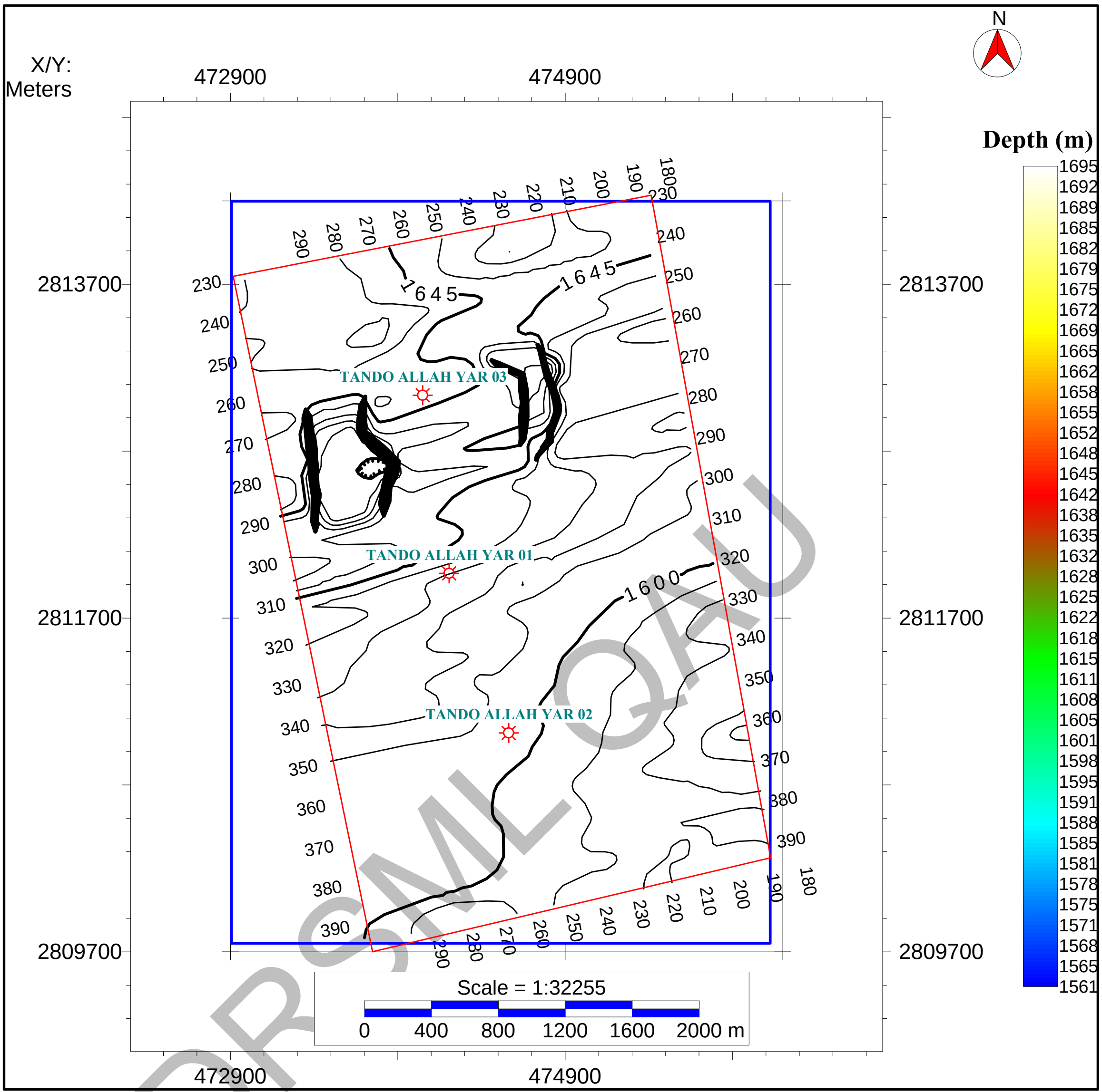

Figure 3.8: Depth contour map of the marked Lower Goru 1 horizon visualizing the shallower depth of the horizon towards south.

Chapter 4
Well Log Analysis

4.1 Introduction

Petrophysics may aid in the determination of the physical characteristics of rocks, particularly reservoir rocks. The process of identifying reservoir zones that contain potentially extractable hydrocarbons is known as "reservoir characterization. This process is a key step in the oil and gas industry because it assists in the location of wells and the evaluation of the potential of fields.

Petrophysical analysis is an essential step in the process of locating, quantifying, and dividing up hydrocarbon-containing formations. The interpretation of porous medium petrophysical parameters includes resistivity, permeability, porosity, shale volumes, and fluid properties (Kumar et al., 2018). Well log data creates a bridge between seismic and core data required to characterize reservoirs. (Rider, 1986).

Locating the reservoirs and identifying the zones of interest as well as the transition zones is an essential part of doing well log analysis. This may be accomplished by performing a quick investigation of gamma ray behavior, resistivity log separation, and including neutron and density log crossover. Following log analysis, basic petrophysical properties such shale volume, average effective porosity, and water saturation are computed (Poupon and Leveaux., 1971). Archie's equation was used to provide an estimate of the level of Water saturation.

The hydrocarbon reservoir was identified by a petrophysical analysis of the NIM-TAY Block. Estimating reservoir attributes requires the use of three wells, which are designated as Tando Allahyar 01, Tando Allahyar 02, and Tando Allahyar 03. For the purpose of this investigation, the following log curves were employed: spontaneous potential log (SP), gamma-ray log (GR), sonic log (DT), lateral log deep (LLD), lateral log shallow (LLS), neutron log, and density log (RHOB). Estimates have been made for the following parameters:

- Volume of Shale (V_{sh}- by Gamma-ray log)
- Porosities (PHIE and PHIT - by Density, and Neutron log)
- Water saturation (S_w- calculated by LLD, LLS, and SP log)
- Hydrocarbon saturation (1- S_w)

4.2 Workflow of petrophysical analysis

Complete workflow adopted for petrophysical analysis is stated below

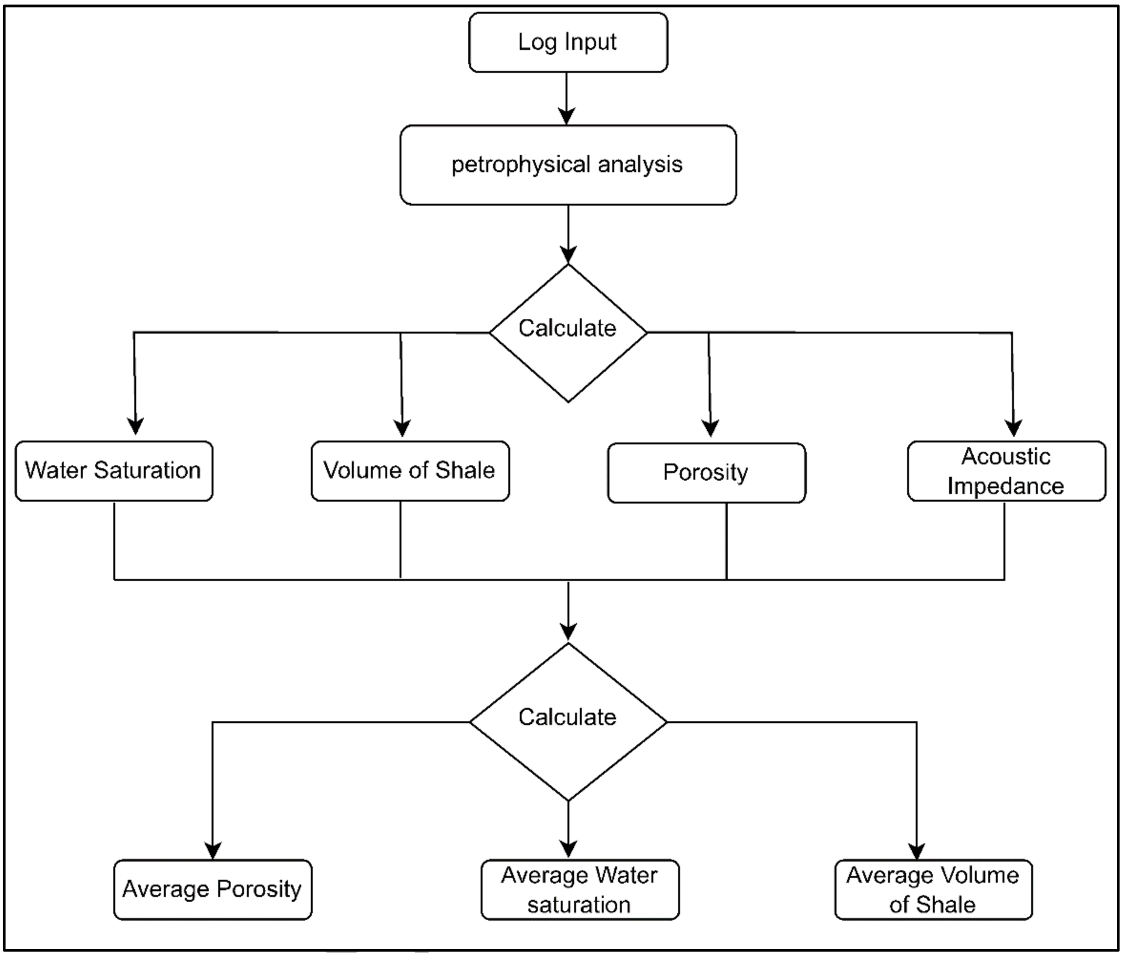

Figure 4.1: Generalized workflow for the petrophysical analysis of the well log data.

4.3 User defined equations

Following equations are used for evaluation of Petrophysical properties of reservoir.

4.3.1 Estimation of Volume of Shale

Shale volume (VSH), commonly known as shale percentage, is the amount of mud or shale in a rock body. It is possible for the Volume of Shale, which is represented by the symbol (Vsh), to exist in any reservoir rock and assume any shape. It was also possible to laminate it, disperse it, or spread it architecturally. The evaluation of shale in the lithology is essential for the characterization of the reservoir since Vsh is used to evaluate the porosity of the reservoir.

The best lithology indicator, the Gamma-ray log, is used to calculate the amount of shale. The GR log is founded on the idea that it monitors the radiological concentration of the formations; radioactive elements like thorium, uranium, and potassium are abundant within a certain range for particular types of rocks (Tiab and Donaldson., 2015).

There are several ways, both linear and non-linear, for determining the volume of shale, and some of these are included here. These are dependent on the gamma ray index, and their mathematical representation is as follows (Rider, 1986):

$$I_{gr} = \frac{GR_{log} - GR_{min}}{GR_{max} + GR_{min}} \tag{4.1}$$

Where I_{gr} represents gamma ray index. GR_{log} is the value of gamma ray at a certain depth, while GR_{max} and GR_{min} are the maximum and minimum value of GR_{log} value respectively?

4.3.2 Estimation of Porosity

A rock body with pores can accumulate hydrocarbons and has adequate permeability to enable fluid flow is called a reservoir. The porosity of a material can be determined using the density log, the neutron log, the sonic log, or any combination of these three logs. The combination of these logs is helpful for accurate identification of the lithology and exact assessment of the porosity, both of which are very critical for controlling the fluid saturation level in a reservoir.

The porosity was determined by utilizing the logs that are shown below:

4.3.2.1 Density log

The result of a density log is the measurement of the rock's bulk density. This measurement takes into account the fluid and solid matrix that is present in the pores of the rock by using the following equation, which was provided by (Rider, 1986) as:

$$\phi_d = \frac{\rho_m - \rho_b}{\rho_m - \rho_f} \tag{4.2}$$

where, $\boldsymbol{\rho_m}$ is density of matrix (g/cm^3), $\boldsymbol{\rho_f}$ is fluid density. (g/cm^3), and $\boldsymbol{\rho_b}$ is density log Response. (g/cm^3).

4.3.2.2 Neutron log

The hydrogen index within the reservoir, which is directly connected to porosity, may be measured with the use of a neutron log by examining the neutron count rate. When a neutron collides with the nuclei of a formation, energy is emitted in the process. Neutron log values identify this kind of porosity. Lower neutron porosity is seen in gas-bearing sands due to their low hydrogen ion concentration. (Tiab and Donaldson, 2015).

4.3.2.3 Average Porosity (PHIT)

The total porosity takes into account all of the void space, regardless of whether the pores are linked or separated. Neutron and sonic logs, or density log and neutron log, are used to calculate the total porosity. The fact that the density log and the neutron log crossover indicate the presence of hydrocarbons that can be predicted from the data. The formula for calculating average porosity is given as (Rider, 1986)

$$\phi_{avg}=\frac{\phi_d+\phi_n}{2} \tag{4.3}$$

Where ϕ_{avg} is the average porosity, ϕ_d is the porosity calculated from density log, and ϕ_n is the porosity calculated from, neutron log.

4.3.2.4 Effective Porosity (PHIE)

The interconnected pores that are present in a rock volume and that provide flow to fluids or permeability in a reservoir are referred to as having an "effective porosity." In reality, the total porosity of a material is almost never higher than its effective porosity. Porosity is calculated by subtracting shale from rock volume. Formulas are used in its computation (Rider, 1986)

$$\phi_e= \phi_{avg}\times (1-V_{sh}) \tag{4.4}$$

Where ϕ_e is the effective porosity, ϕ_{avg} is the average porosity, and V_{sh} is the volume of shale.

4.3.3 Water Saturation

Water saturation is the quantity that describes the proportion of pore volume to water volume. Calculating the amount of water and hydrocarbons that are saturated in a well is the main objective of well logging. The effective porosity and resistivity log are used for the purpose of achieving this objective. Archie's Equation has been used in order to do calculations on the saturation of water. The model may be illustrated in its mathematical form by using

Calculate water saturation using Archie's Equation (Rider, 1986):

$$S_w^n = \frac{aR_w}{\phi^m R_t}, \tag{4.5}$$

Whereas

$\mathbf{S_w}$ = calculated water saturation.

$\mathbf{R_w}$ = water resistivity (formation).

$\boldsymbol{\phi}$ = porosity, m is (cementation factor) = 2.15, a (tortuosity factor) = 0.62

$\mathbf{R_t}$ = LLD log response.

$\mathbf{R_w}$ = has been calculated with help of the SP log.

$\mathbf{R_w} = \phi^2 \times R$

The petrophysical analysis of wells Tando Allahyar 01 Tando Allahyar 02 and Tando Allahyar 03 is shown in Figures that are given below.

4.3.4 Hydrocarbon Saturation

The term "hydrocarbon saturation" refers to the volume of pores that are filled with hydrocarbon. The formula for its calculation is as follows:

$$\boldsymbol{S_h = 1 - S_w} \qquad (4.6)$$

Where as S_h is the saturation of hydrocarbon while S_w is the saturation of water.

4.4 Petrophysical Evaluation

Formation identification refers to the act of examining and making sense of the information included in well logs. In general, all of the logs acquired from wells and the evaluation results of those logs are merged into a single display that is known as a "composite log." The following discussion will focus on the petrophysical findings obtained from wells Tando Allahyar 01, Tando Allahyar 02, and Tando Allahyar 03.

4.4.1 Results of Tando Allahyar 01, Tando Allahyar 02 and Tando Allahyar 03

Petrophysical analysis of Tando Allahyar 01 indicates that Lower Goru Formation (sands) has good effective porosity, satisfactory reservoir quality and hydrocarbon potential. Figure 4.2 show complete petrophysical result of Lower Goru Formation of Tando Allahyar 01. The zone of interest in Tando Allahyar 01 ranges from1450 m to 1518 m which shows Gr log decreasing trend is clearly depicting a reservoir zone, a clear separation between resistivity logs (LLD-LLS) and The cross over between bulk volume of density and neutron porosity logs gives the clear indication of hydrocarbon accumulation in sands of lower goru represented by sky-blue color. it is evident from results that shale volume is not constant throughout the log display of Lower Goru Formation. The results indicate that average shale volume of Lower Goru is 16.62%, Average effective porosity of Lower Goru reservoir is 8.63%, water saturation of Lower Goru reservoir is calculated using Archie's Equation model. Average saturation of water in reservoir zone is 53.57% whereas hydrocarbon saturation is 46.63% Detailed petrophysics results of Tando Allahyar 01 in Lower Goru reservoir (sands) are displayed in Table 4.1

Similarly, Lower Goru Formation (sands) have acceptable effective porosity, adequate reservoir quality, and hydrocarbon potential, according to petrophysical investigation of Tando Allahyar 02. Zone ranges from 1538m to 1542 m, as shown in Figure 4.3. A decrease in the gamma ray log and a clear separation between resistivity logs (LLD-LLS) indicate a clearly defined reservoir zone. It is evident from the results that shale volume is not constant throughout the log display of the Lower Goru Formation. The crossover between density and neutron logs indicates the average reservoir zone. The average shale volume for the zone is 15.17%. The average effective porosity of the zone is 12.90%. The water saturation of each zone was calculated using Archie's equation model. The average saturation of water for the zone is 56.95%. The average hydrocarbon saturation for the zone is 43.41%. Detailed petrophysical results of Tando Allahyar 02 in the Lower Goru reservoir (sands) are displayed in Table 4.1.

Zone of interest in Tando Allahyar 03 ranges from 1467m to 1522 m as shown in Figure 4.4. Decrease in Gamma ray log, separation between LLD-LLS logs and Crossover between density and neutron logs indicates good reservoir zone. Average shale volume of Lower Goru is 8.06% Overall, the presence of shale is high above and below the marked zone. Average effective porosity of Lower Goru reservoir is 10.22%. Water saturation of Lower Goru reservoir is calculated using Archie's Equation model. Average saturation of water in reservoir zone is 36.84%. The hydrocarbon saturation for reservoir zone is 63.16%. Detailed petrophysics results of Tando Allahyar 03 in Lower Goru reservoir (sands) are displayed in Table 4.3

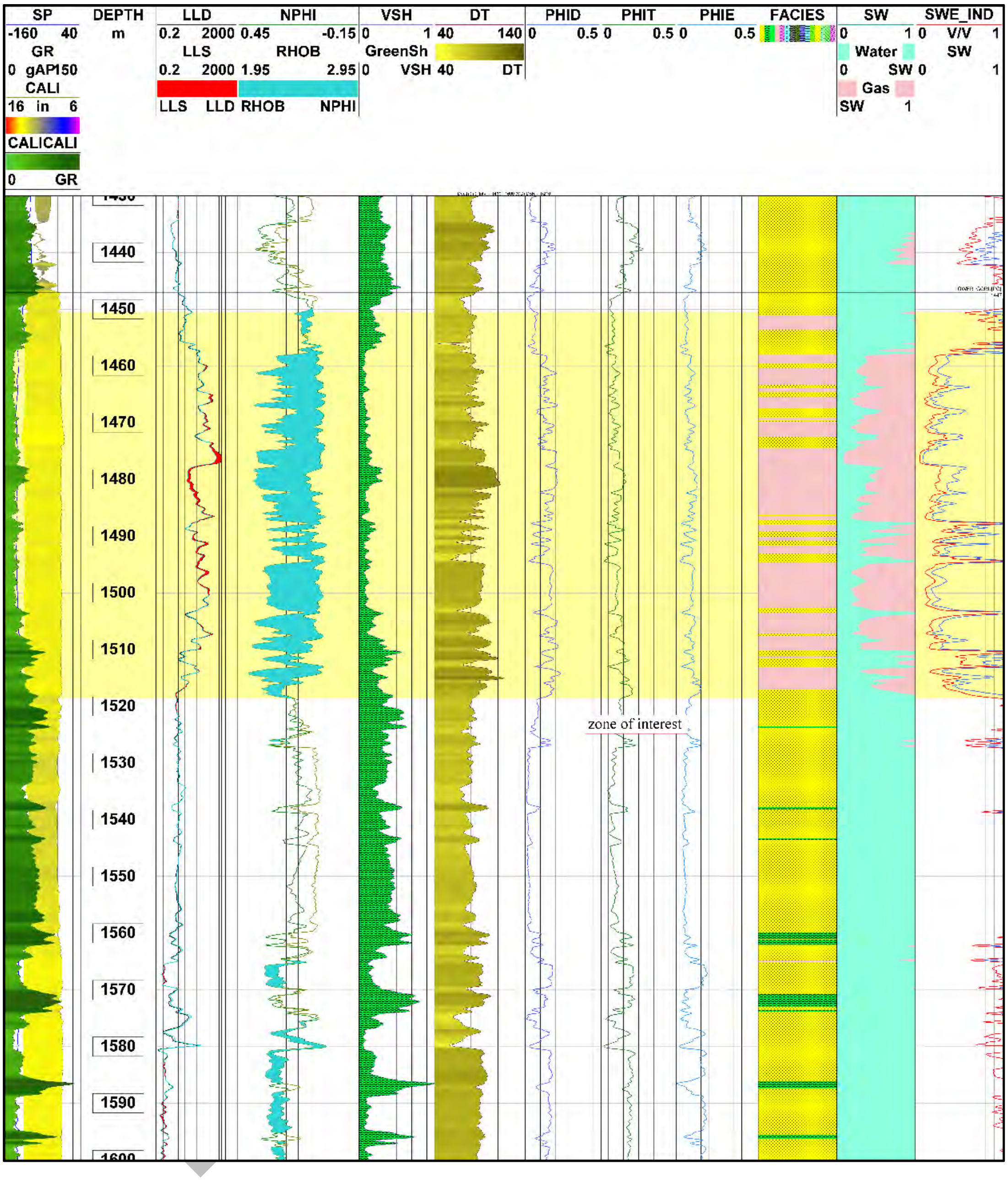

Figure 4.2: Zone of interest marked on the basis of composite log response of well Tando Allahyar 01.

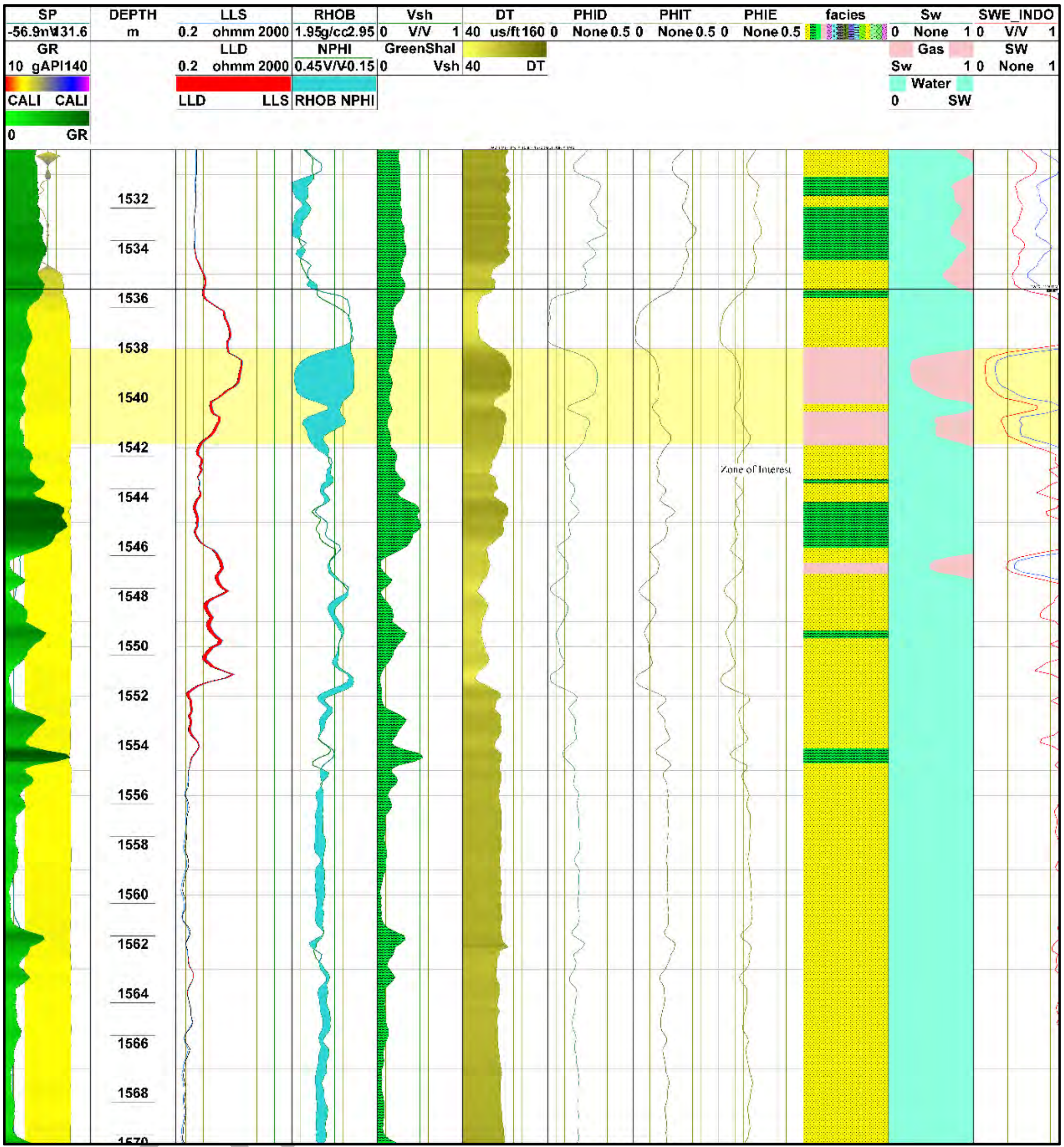

Figure 4.3: Zone of interest marked on the basis of composite log response of well Tando Allahyar 02.

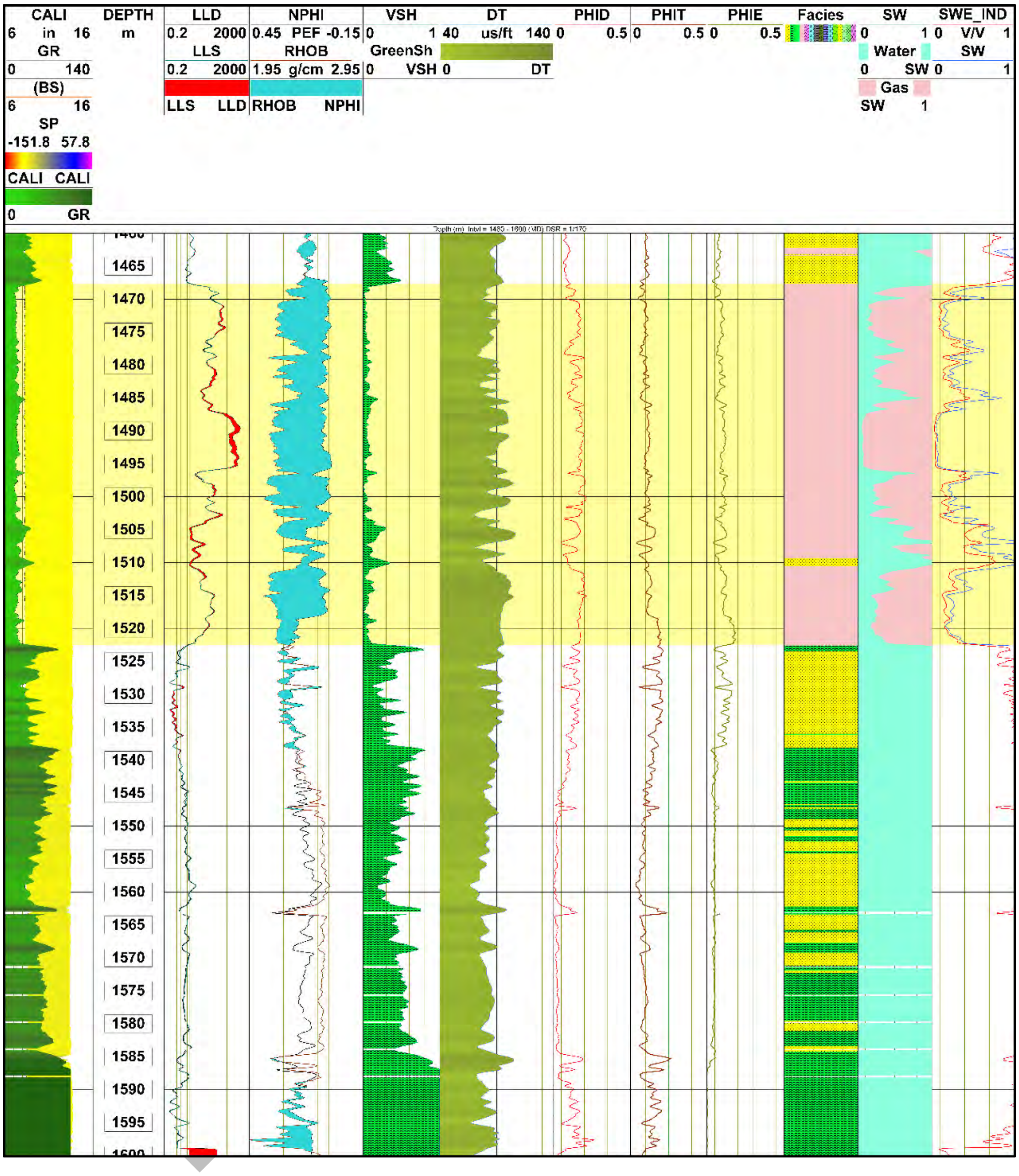

Figure 4.4: Zone of interest marked on the basis of composite log response of well Tando Allahyar 03

Serial no	Calculation parameters	Tando Allahyar 01	Tando Allahyar 02	Tando Allahyar 03
1	Average Volume of Shale=$\boldsymbol{V_{sh}}$	**16.62%**	**15.17%**	**8.06%**
2	Average Porosity Obtained from Density log= $\boldsymbol{\phi_{davg}}$	**14.03%**	**22.64%**	**15.48%**
3	Average Total Porosity in (PHIT) Percentage=$\boldsymbol{\phi_{avg}}$	**10.55%**	**15.17%**	**11.15%**
4	Average Effective Porosity in Percentage= $\boldsymbol{\phi_{eavg}}$	**8.63%**	**12.9%**	**10.22%**
5	Average water Saturation in Percentage=$\mathbf{S_w}$	**53.57%**	**56.95%**	**36.84%**
6	Average Hydrocarbon in Percentage= $\boldsymbol{S_h}$	**46.43%**	**43.05%**	**63.16%**

Table 4.1: The average values of the petrophysical parameters estimated for the well Tando Allah Yar 01.

Chapter 5
Electrofacies Analysis

5.1 Introduction

Electrofacies is a term that was first introduced by Serra and Abbott in 1980. Its meaning may be described as "the set of log responses that define a bed and enable this to be distinguished from others." Whereas log responses are measurements of the physical properties of rocks, electrofacies are usually assigned to one or more lithofacies. The process of identifying the different types of rock that make up a reservoir is an essential part of petroleum exploration. Facies were manually discovered by cross-plotting wire-line recordings and correlating their behavior to cores. Recent years have seen the development of a number of mathematical approaches that can automate the process of face recognition. Principal Component Analysis, Multivariate Analysis, Nonparametric Regression, Classification Trees, Artificial Intelligence (AI)-based Approaches, and Clustering are all examples of such multivariate statistics and regression-based methodologies.

5.2 Methodology

A comprehensive suite of wireline logs for three wells was available for this study. These well logs were run into boreholes which were drilled at three different sites and a sequence was developed to identify electrofacies.

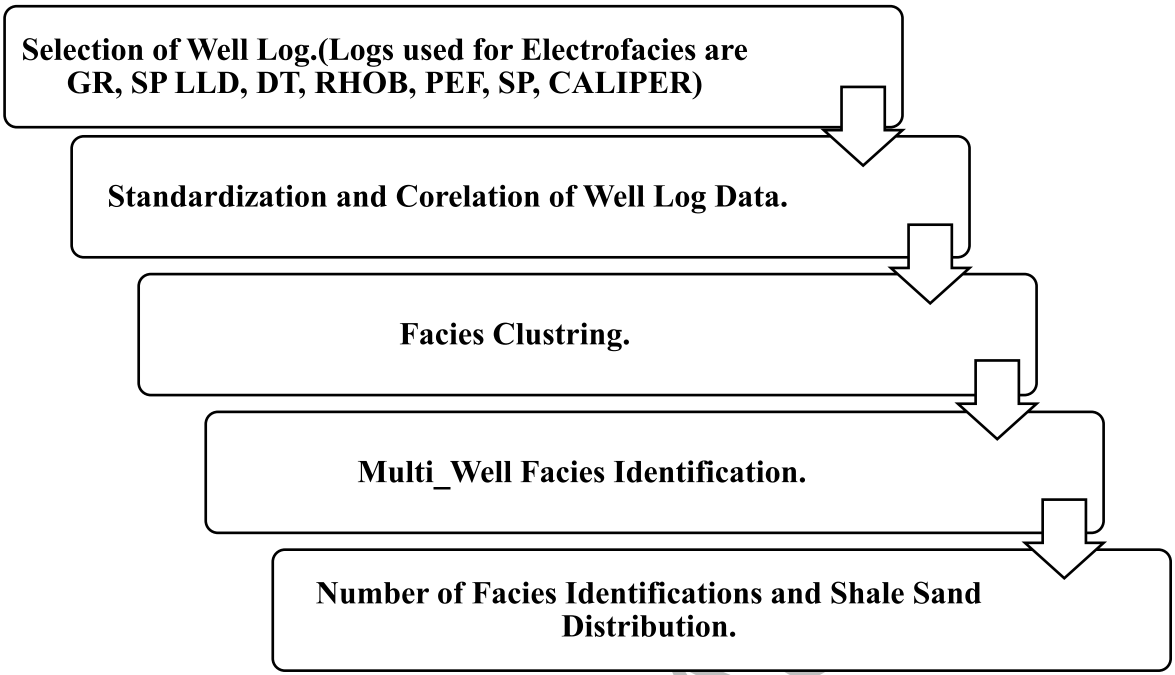

Figure 5.1: Flowchart showing the steps of electrofacies classification.

Techlog software is mostly used for well log interpretations. Provided well log las. files were loaded in the software for its better understanding. In the next step, selection of suitable logs was done. In this study gamma ray, resistivity, caliper, bulk density, photoelectric factor, spontaneous potential and sonic logs are used. These logs were used in collaboration as they give the best results. In this regard, geology module to generate IPSOM was used to demarcate the electrofacies zones. For identifying the electrofacies, unsupervised method was considered and for this fuzzy classification method was used. After this with the help of electrofacies sand and shale distribution zone marked.

Geoscience data integration and inference using machine learning have greatly increased in recent years (Bérubé et al., 2018) and artificial neural networks (ANN), support vector machines (SVM), random forests, genetic algorithms, recurrent neural networks, fuzzy logic, etc. have all been used regularly to predict permeability, and there is a wealth of literature giving the same results. (Mishra et al., 2022) Unsupervised machine learning looks for underlying patterns, structures and lithology in the data without the use of a connected response variable. Data patterns in geoscience frequently reflect lithology, alteration, and mineralization. The R programming language for statistical computing is used to apply unsupervised learning techniques including hierarchical cluster analysis, K-means clustering, and principal component analysis (PCA) (Ordóñez-Calderón and Gelcich, 2018).

5.3 Electrofacies Classification

Gamma ray and resistivity logs were run for electrofacies classification. After selecting the logs, process of standardization was done for the removal of any alteration triggered by difference in measurement from all well data. For this, same scale for logs was set in all wells to check the differences in wells due to their unlike borehole conditions. Further, facies clustering was done, and consistency of logs was rechecked.

A set of observations of potentially correlated variables are transformed via an orthogonal transformation in the statistical process known as principal component analysis (PCA) into a set of values of linearly uncorrelated variables known as principal components (Mahesh, 2020).

This classification was done with the help of PCA, clustering, and self-organizing maps. PCA was loaded with well logs in the form of matrix X_{nxp} which has n objects (log curves) and p variables. In the next step correlation and summarization of these variables and matrix was done along the uncorrelated axes.

Each well log curve's variance is the mean squared variation of all its n values and may be computed as follows:

$$Vi = \frac{1}{n-1}\sum_{m=1}^{n}(x_{im} - \bar{x}_i)^2 \quad (5.1)$$

Here,

x_{im} represents the value of ith variable in the object m

x_i is the mean value of i

The degree to which one variable affects the value of another is known as covariance. The following equation is used to compute it:

$$Cij = \frac{1}{n-1}\sum_{m=1}^{n}(x_{im} - \bar{x}_i)(x_{jm} - \bar{x}_j) \quad (5.2)$$

Here,

- Cij is the covariance of i and j variables

  x_{im} and x_{jm} are the values of i and j variable in object m

- $\bar{x}_i$ and $\bar{x}_j$ are the means of i and j

Both the covariance and the variance are helpful metrics to utilize when doing an analysis of the differences in the dataset. Logs of gamma rays and resistivity are chosen for the PCA analysis. Following that, the Techlog programme is updated with these logs. PCAs may be generated by this piece of software using the 'techstat module' in accordance with predetermined procedures.

Following the creation of PCAs, cross-plots were created for each specific log curve to explain the link of PCA with the combinations of distinct log curves. Additionally, PCA was cross-plotted in the Techlog IPSOM module to carry out self-organizing maps and cluster analysis for the purpose of discovering electrofacies.

5.4 Electrofacies classification

Well logs from three drilled wells were utilised to correlate and identify the electrofacies analysis. Electrofacies analysis showing four different facies on this basis of eight different well logs (gamma ray, resistivity, caliper, bulk density, photoelectric factor, spontaneous potential and sonic logs) responses are sand, sandy shale, shaly sand and shale. Illustrate in Figure 5.3 given below.

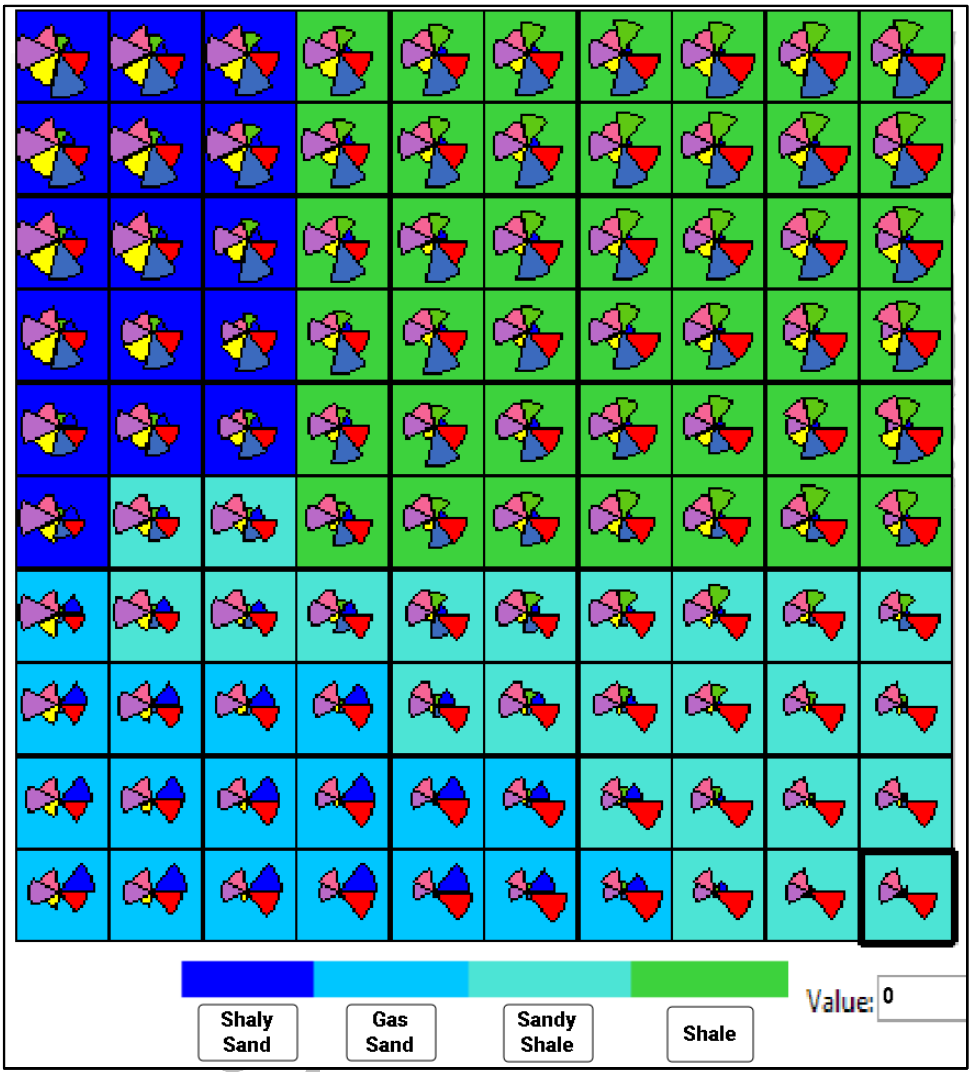

Figure 5.2: IPSOM electrofacies classification and self-organizing map of wells based on gamma ray, resistivity, caliper, bulk density, photoelectric factor, spontaneous potential and sonic logs. Each log's contributions are indicated by a color index

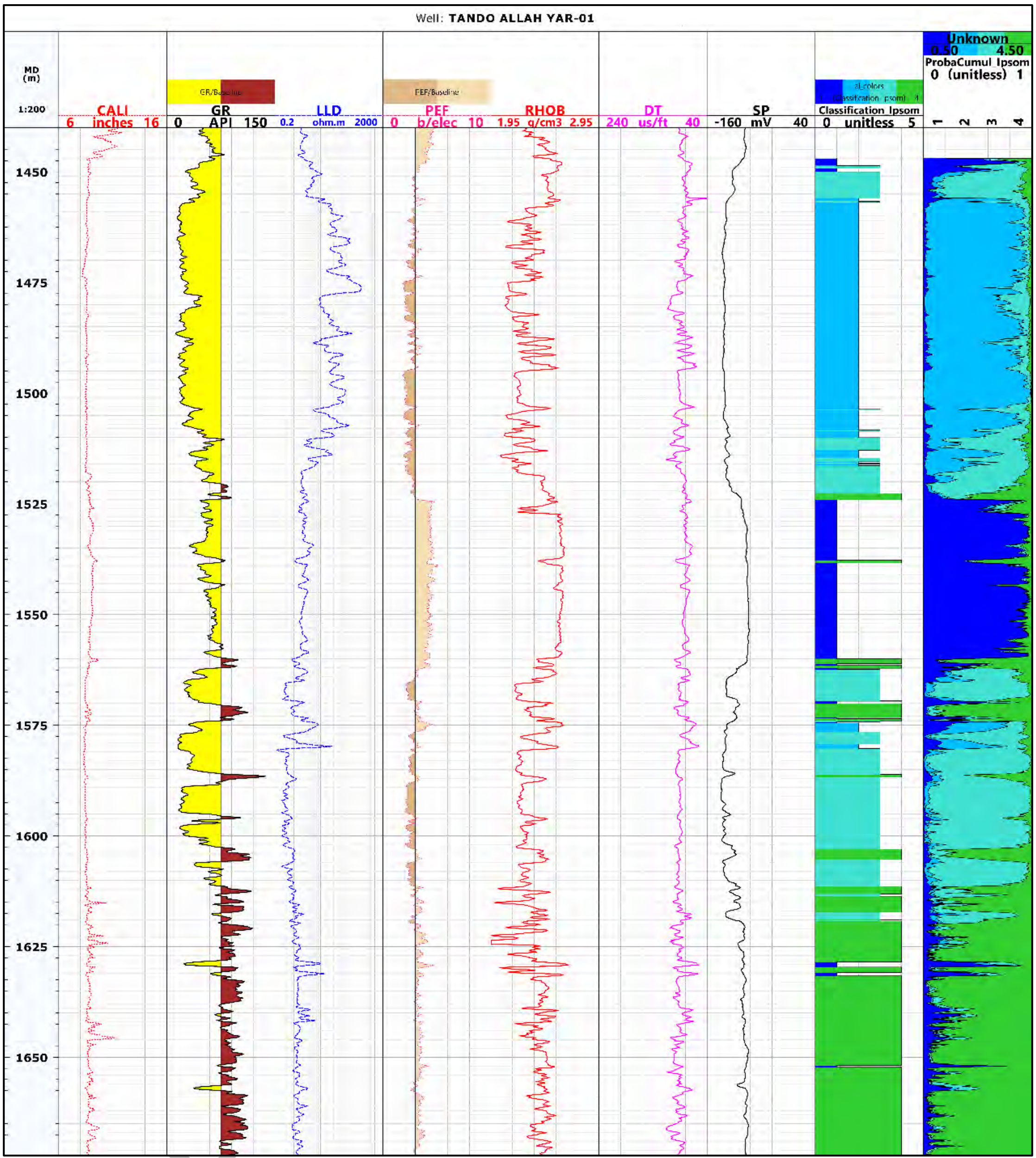

Figure 5.3: Electrofacies classification in Tando ALLAH Yar 01 on the basis of composite log responses

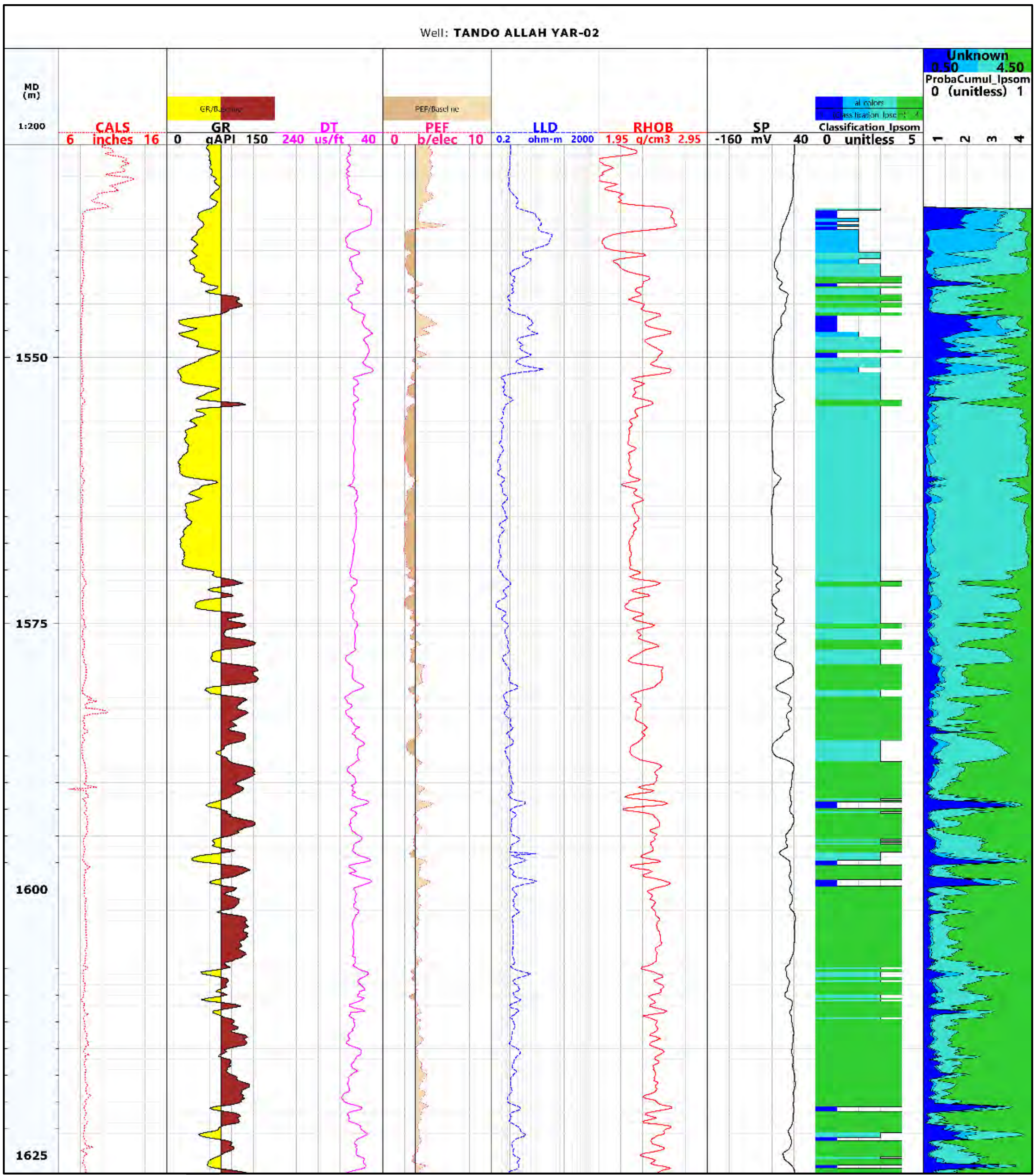

Figure 5.4: Electrofacies classification in Tando ALLAH Yar 02 on the basis of composite log responses

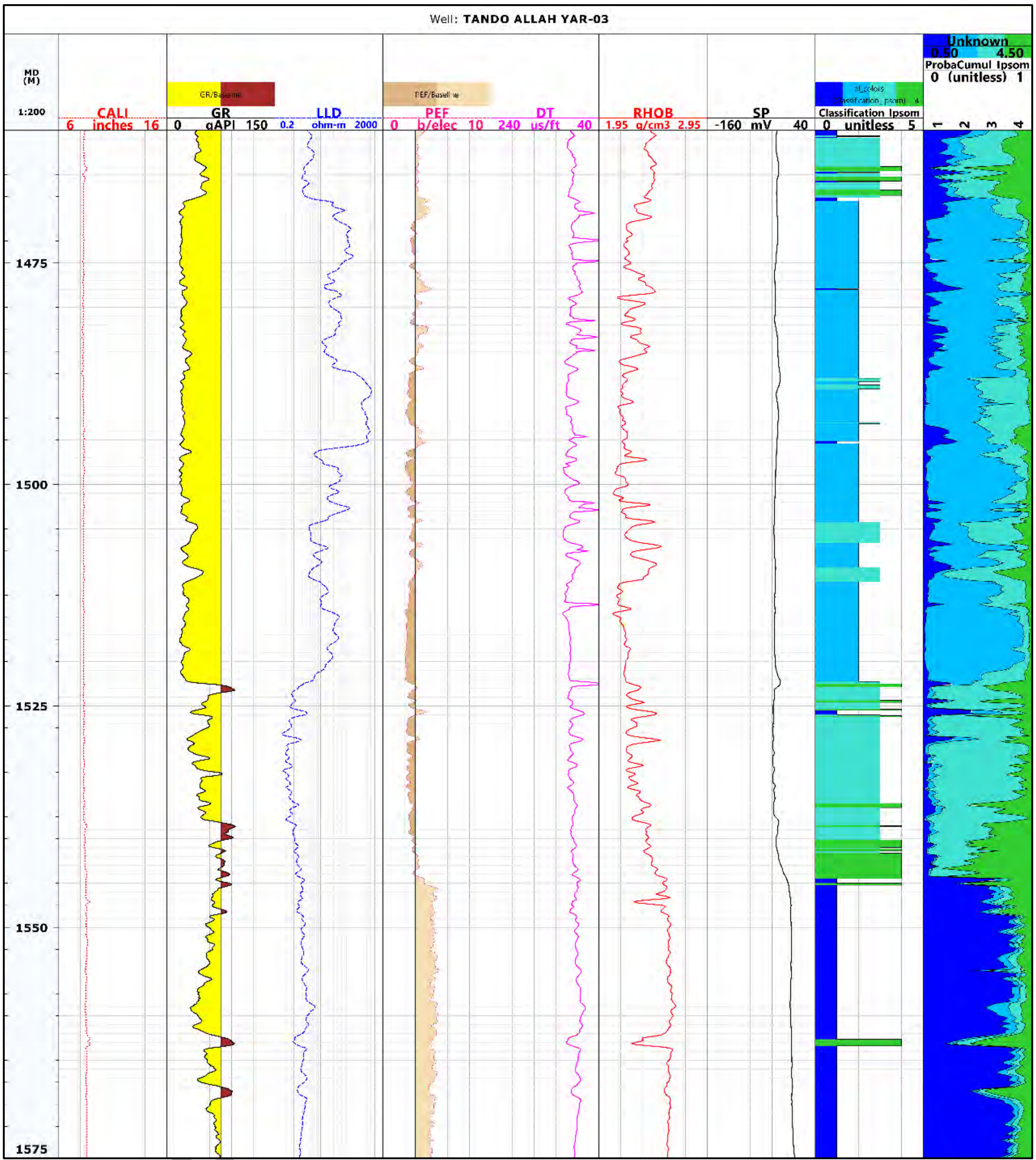

Figure 5.5: Electrofacies classification in Tando ALLAH Yar 03 on the basis of composite log responses

5.5 Zone of Interest

The reservoir potential zones of three wells shown in giving table:

Well name	Formation	Zone of interest(m)
Tando ALLAH Yar well-01	LOWER GORU	1450-1518
Tando ALLAH Yar well-02	LOWER GORU	1537-1542
Tando ALLAH Yar well-03	LOWER GORU	1467-1522

Table 5.1: Zone of interest

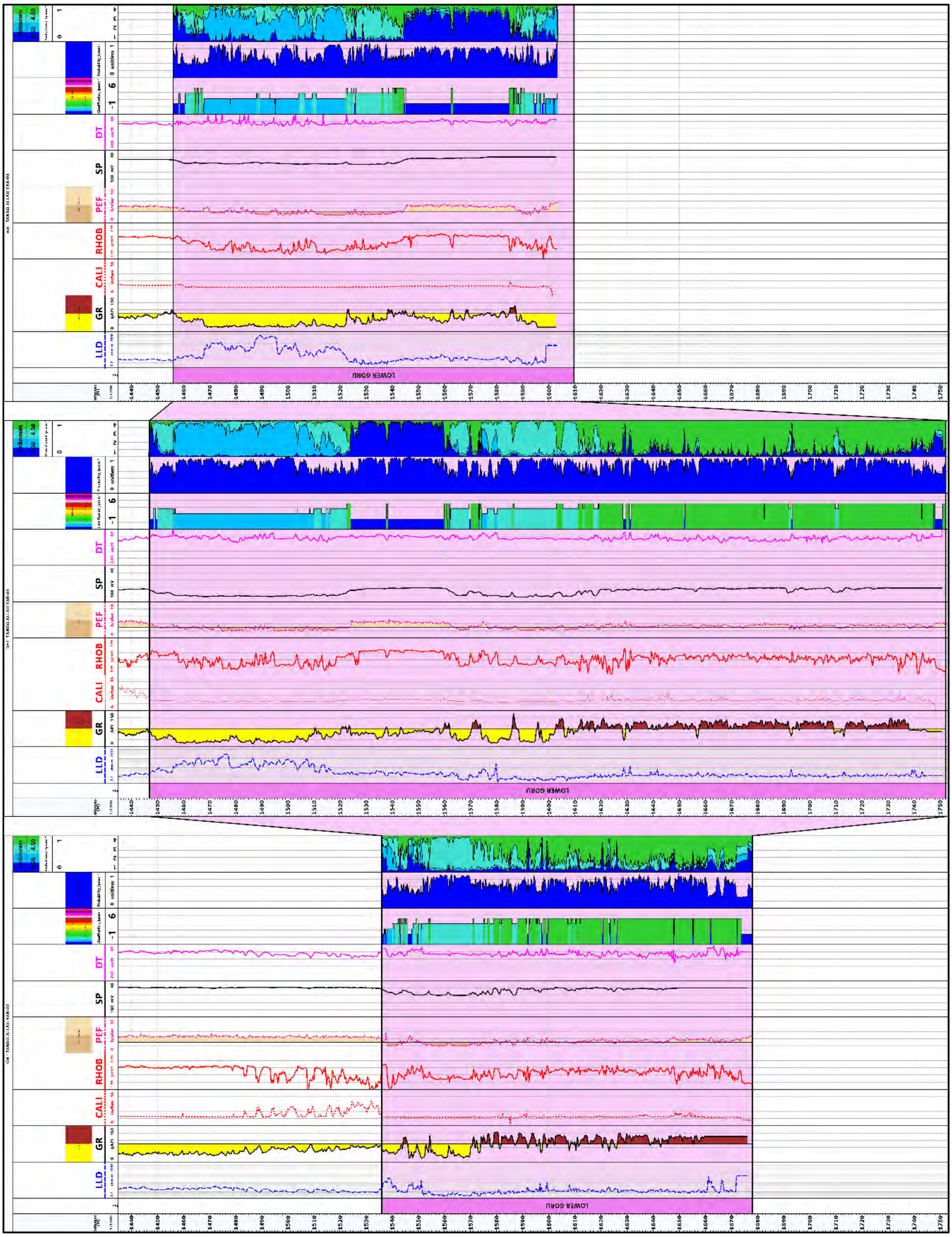

Figure 5.6: Well Coorelation using electrofacies on the basis of composite log responses

The primary goal of PCA is to decrease the dimensionality of the data. After identifying the main principle components, cluster analysis and self-organizing maps were generated using the Techlog program's IPSOM module to identify distinct facies. This categorization is based on the idea that the wireline log attributes refer to a rock with a distinct set of physical features. More specifically, each rock has a unique lithology, composition, compaction, and pore fluid concentration. Because a rock's electrofacies are categorized analytically, the number of different electrofacies is unexpected; nonetheless, the number of correct electrofacies is somewhat reliant on the number of decent log characteristics employed in their computation.

Data of three wells were utilized for electrofacies classification of lower Goru zonation using self-organizing maps in IPSOM module of Techlog software. When the given values were placed in the software a self-organizing IPSOM map was generated. Studying the map with the help of GR and LLD shows four types of electrofacies, namely: sand, shale, oi and gas zones respectively. This self-organizing map provides easiness in identifying and marking the reservoir zones.

The analysis tells four distinct types of electrofacies representing to clean porous sandstone, fine-grained shaly sandstone, sandy shale, shale, oil, and gas. Firstly. Light-blue color represents to clean and porous sandstone. Secondly, green color shows to fine-grained shale. Thirdly, sky blue color indicates gas body sandy shale. Fourthly, blue color highlights oil reservoir in shaly sand (Figure 5.4,5.5,5.6). Further, electrofacies analysis all three were stratigraphically and structurally corelated as in Figure 5.7.

Chapter 6
Geostochastic Inversion

6.1 Introduction

For reservoir characterization, the construction of precise three-dimensional models of petrophysical properties is necessary, and these models must be placed within a geological setting. The structural seismic analysis is the foundation upon which the reservoir model is constructed, yet its use in the generation of the 3-dimensionally populated petrophysical properties is not very frequent. This is due to a number of factors, some of which include a deficiency in the availability of a 3D dataset, the inability to quantitatively connect seismic data to reservoir characteristics, an insufficiency in the amount of vertical resolution required to develop accurate property models, as well as other factors (Rowbotham et al., 2003). The availability of 3D seismic may solve the second problem by offering seismically determined impedance volumes as a seismic parameter that can be specifically linked to a reservoir feature (for example, phi). The lack of vertical resolution in classification applications has proved more difficult to rectify. Stochastic seismic inversion with higher vertical resolution is one method for developing exact 3D reservoir property models (Gunning and Glinsky, 2003).

Geostatistical techniques are widely used to estimate different geophysical features from seismic and well-log data. Geostatistical methods make use of the sample points, also known as the petrophysical characteristics of the well, and interpolate the data by constructing a surface for each site based on the observed locations (Haas and Dubrule, 1994). Deterministic and geostatistical interpolation are the two main types of approaches used in the field of geostatistics (Russell, 1999). Deterministic interpolation methods rely on mathematical functions, while geostatistics uses both mathematical and statistical methods (Hampson et al., 2001). There are many methodologies available for determining reservoir parameters using interpolation techniques. Among these techniques, the most often utilised is Geostochastic inversion (GeoSI), which transforms bandlimited seismic data to high frequency seismic data. GeoSl employs the notion of decreasing the sample interval to 1 ms, enabling inversion results to enhance reservoir models with minimal mistakes (Rowbotham et al., 2003).

Since the middle of the 1990s, there have been significant breakthroughs in the approach that is taken to geostatistical inversion. These developments may be seen most prominently in the integration of data and the conditioning of reservoir models with seismic data and earlier rock physics information. In a sequential process, the stochastic impedance realizations are converted using various statistical techniques, including collocated co-kriging (Doyen et al. 1989), Bayesian classification, and linear regression functions, to fill reservoir modeling with seismic conditioned reservoir properties (Cole'ou et al., 2005). Co-simulation of lithofacies and impedance, for example (Torres-Verdin and Sen, 2004), was a fairly early development. The rationale of using seismic directly to condition reservoir properties in a 3D model that use the facies concept is credible (Sams and Saussus, 2012). For example, unless saturation is incorporated in the inversion model, it is difficult to verify that elastic features are consistent with a saturation height function (Sams et al., 2011). Theoretically, applying all restrictions simultaneously results in deeper integration and a more robust and consistent reservoir models.

Recent research has concentrated on developing stochastic algorithms that expand beyond acoustic inversion and into simultaneous elastic inversion. The use of position stochastic inversion in a stricter Bayesian framework has also received some attention. In this situation, the answer to a seismic inverse issue and the degree of uncertainty associated with it are described using a posterior distribution function.

Reservoir models created only from log data have excellent vertical resolution, but poor areal (horizontal) resolution. This is because the resolution qualities of the log data provide a high vertically resolution but a low spatial resolution. The reason for this is due to the fact that the log data has both of these features. The areal resolution of seismic data (the bin size of 3D surveys) is rather good, while the vertical resolution is quite poor (function of the seismic frequency content and velocity of the reservoir). Stochastic seismic inversion offers a unique framework for integrating the benefits of seismic and well log data (Rowbotham et al., 2000). The seismic data are responsible for providing the stochastic impedance volumes with the areal resolution, whereas the log data that are used in the inversion approach provide the technique with the vertical resolution. The created high-quality 3D volumes are ideal for detailed property development. The usual stochastic inversion has a vertical resolution of about 1-2 meters on average. It is often on this scale that models of petrophysical reservoir properties are constructed. Impedance data, together with well log data, may be utilised to build reservoir property models like as porosity (Rowbotham et al., 2003). On the basis of sequential Gaussian simulation, (Haas and Dubrule., 1994) established the first practical use of geo-statistics in seismic inversion. During each and every trace of the seismic survey, and the well log data (both density and sonic) are employed to create pseudo-logs. A synthetic seismogram is created with the help of the pseudo-impedance log, and then it is compared to the real seismic trace recorded at that point. At any given time, the inversion solution is the simulation that yields a synthetic seismogram that most closely resembles the observed seismic trace. The vertically cell size, not seismic data frequency, determines the simulated log data's vertical resolution. The GeoSl software generates a three-dimensional volume that takes into consideration both the log data and the seismic data and has an aerial resolution comparable to that of seismic data and a vertical resolution comparable to that of log data.

6.2 Methodology

The seismic inversion approach is used so that these thin beds may be identified. In order to execute seismic to well tie prior to running inversion, we first estimate wavelet and low frequency model then perform seismic to well tie, which is used to extract wavelet and to generate low frequency model. Well log data is used to estimate facies to performed stochastic inversion. Spatial distribution of facies were made for the zone of interest in within Lower Goru Formation. The lateral continuity of the sands of the Lower Goru Formation has been evaluated using stochastic inversion. Impedance measurements have been used to build inverted sections, which have been used to analyze the vertical resolution in the Lower Goru sands. The workflow used in the study is as in Figure 6.1.

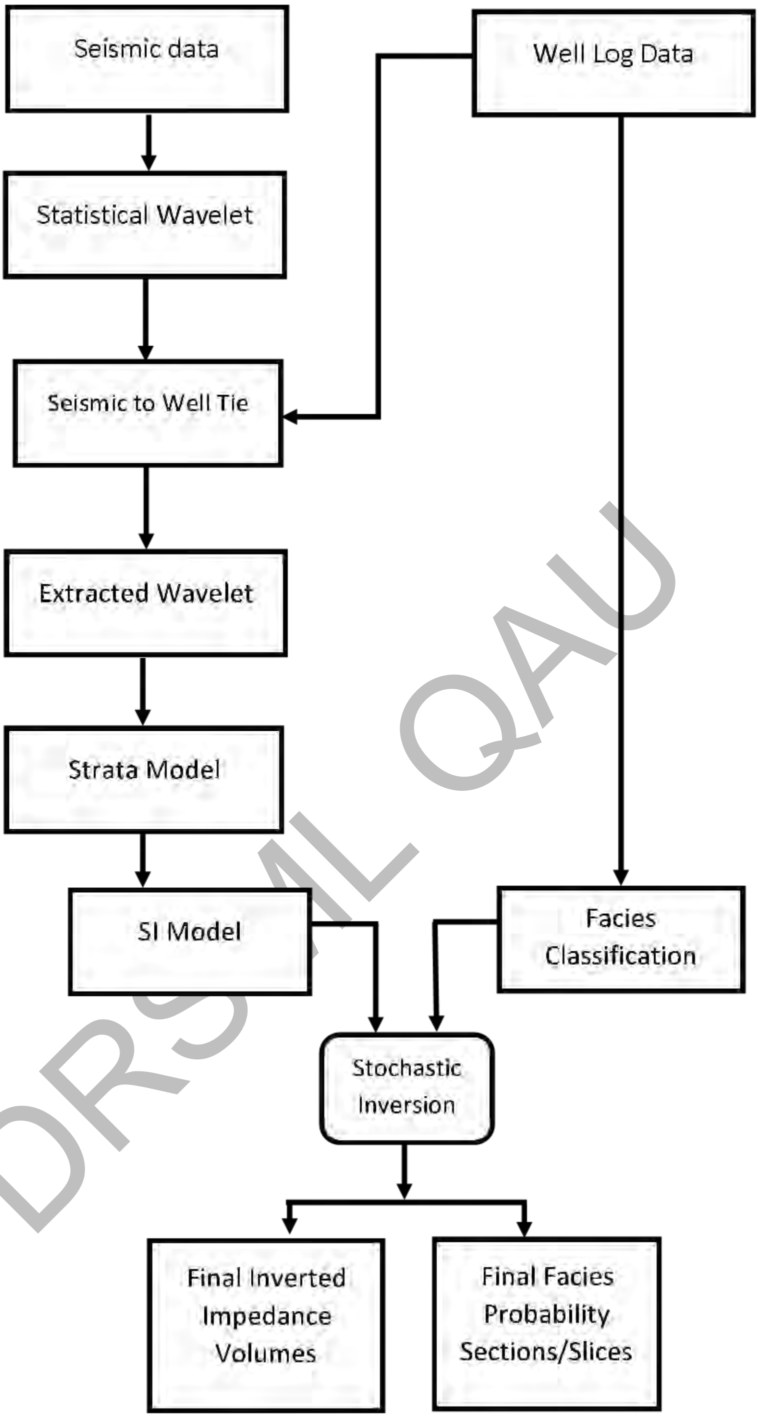

Figure 6.1: Adopted workflow to perform stochastic inversion.

6.3 Seismic to well tie and Wavelet Extraction

The obtained wavelet in Figure 6.2 must be scaled to fit the strata model. Wavelet were zero phase for post stack data, and separate wavelets were recovered from seismic data for each one. Following that, the wavelets were scaled in order to be employed in the stratum (GeoSI previous) model

The inversion was performed only on the selected time window 960-1100ms in which the horizons of interest lie as in Figure 6.3. The inversion results show colored layers displaying different values of acoustic impedance for each layer. The stochastic inversion results show a good lateral variation in acoustic impedance which can be used for depicting shelling out sequence. Similarly, each inversion approach, including GeoSI, begins with a connection between well and seismic. Maximum correlation was obtained using the well-to-seismic tie done in PSSI.

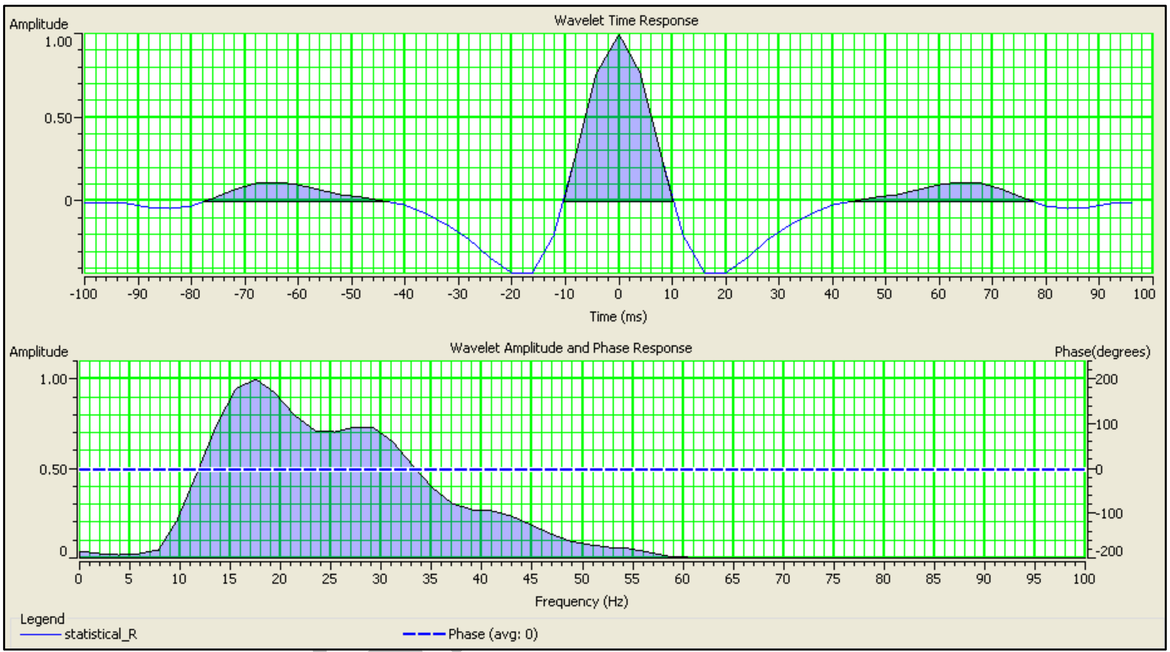

Figure 6.2: Extracted statistical wavelet for seismic

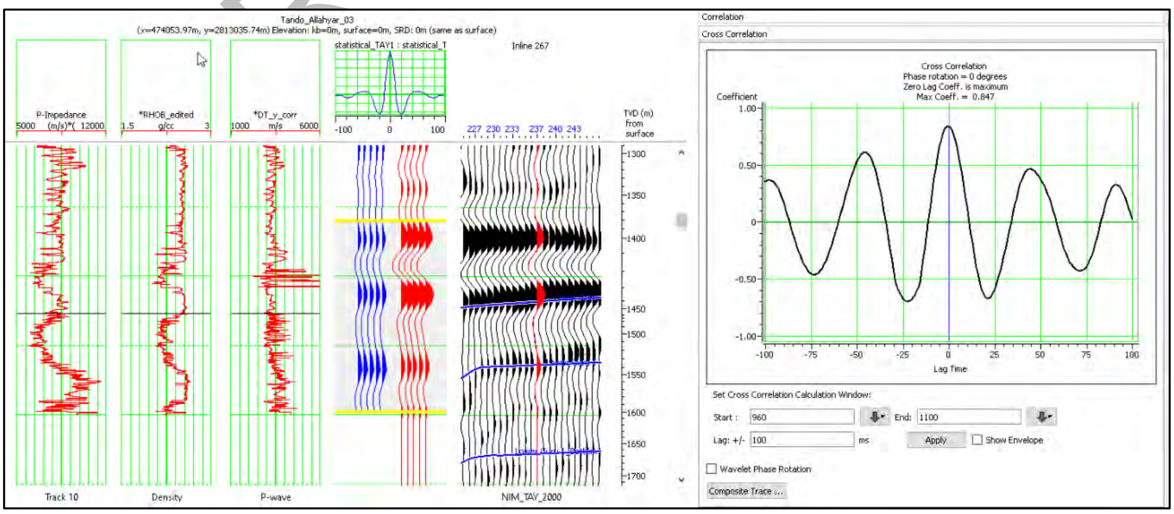

Figure 6.3: Seismic to well tie and wavelet extraction for post stack inversion using well Tando Allahyar 03

6.4 Low Frequency Model

In traditional inversion, the initial model (LFM) is often generated by combining well logs throughout the full seismic volume, the LFM, also known as the Strata Model in GeoSI, is derived from a previously completed inversion approach, and a subsequent model is constructed. This was done while ensuring that the structural tendencies were maintained. LFM incorporate well data and seismic data to incorporate low and high frequencies, simply add up the missing frequencies from data and gives us impedance values. Lateral extend indicates continuity and vertical extent depicts changes inn lithologies. As a result, in order to effectively conduct the stochastic inversion, these LFMs are employed as previous models as in Figure 6.4 and 6.5

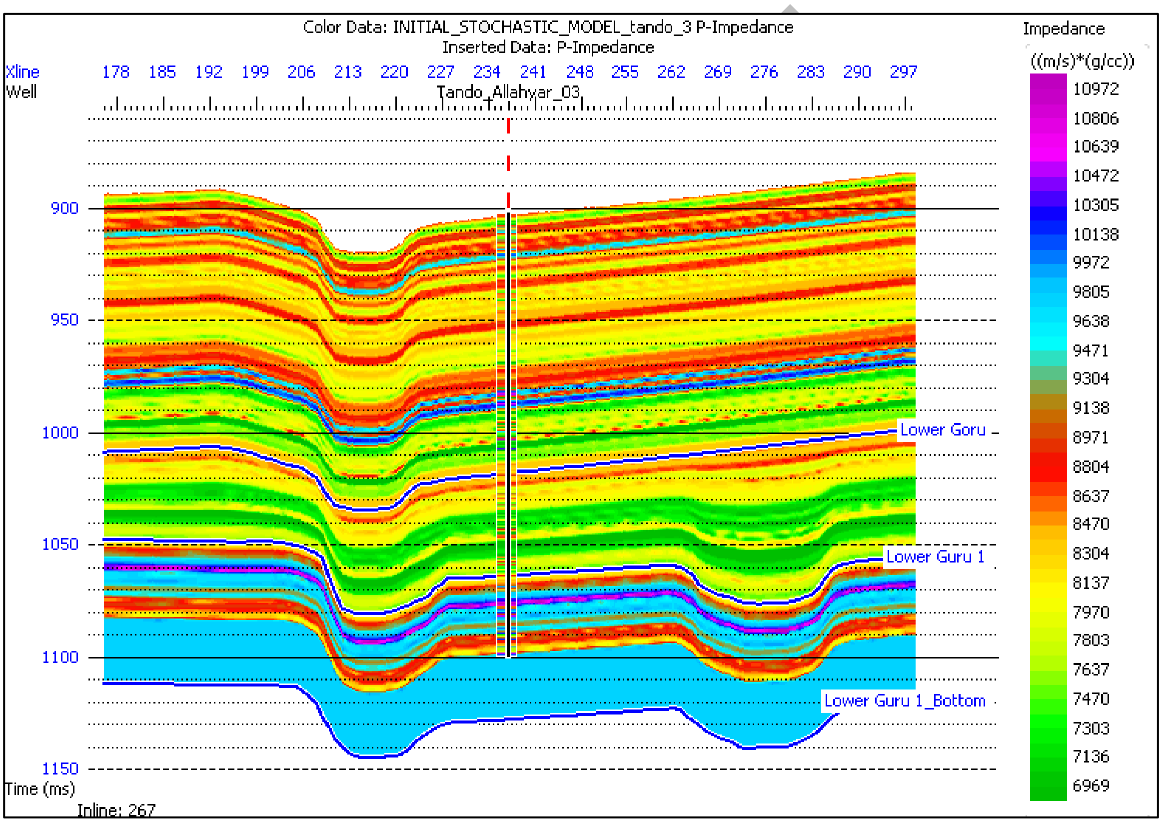

Figure 6.4**:** A low impedance model for In-line 267 built by applying lower and upper impedance limit.

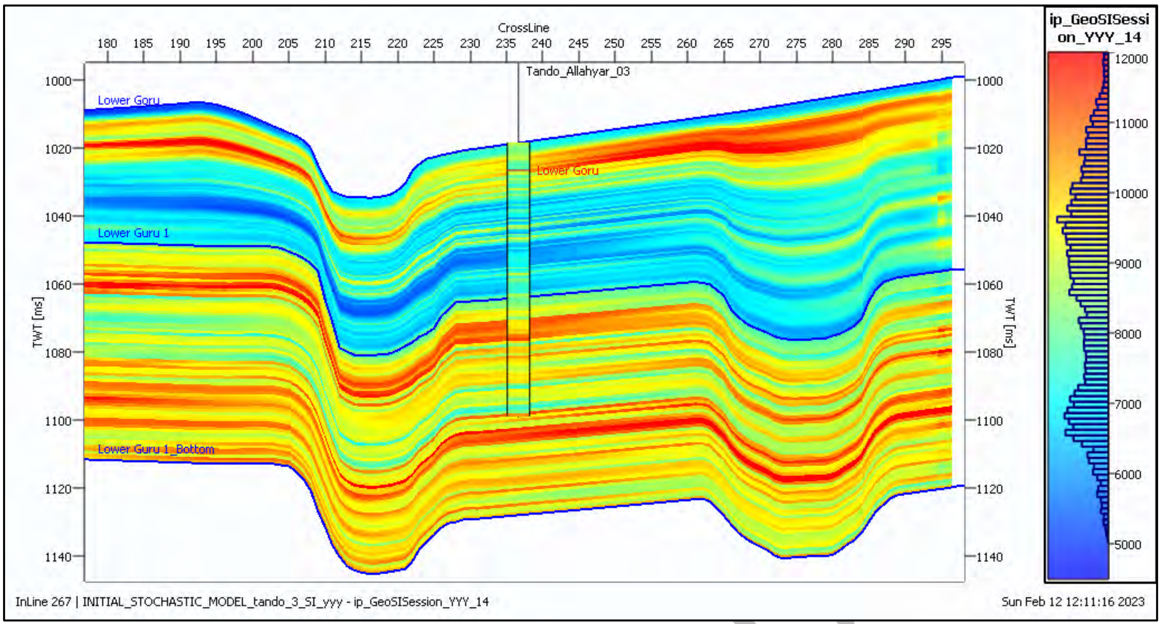

Figure 6.5: The SI Model depicting the generated impedance values.

6.5 Stochastic inversion

Stochastic inversion is widely used in geophysics to estimate subsurface properties from measurements of various physical properties. The main advantage of stochastic inversion is that it can provide a range of possible subsurface models that are consistent with the observed data, along with their associated probabilities. stochastic inversion performed by using the following Variograms, Facies classification. These variograms and Facies classification used to create PDF's.

6.5.1 Variograms

For both sparse (well) and rich (seismic) data, a variogram may be used as a measurement of geographical variances (spatial consistency or changes in space). Variograms are used to calculate stratigraphic grid spatial variations using a statistical technique and Kriging/Co-kriging processes. Due to the fact that the values of these "regionalized variables" have a geographical (posterior) distribution, these variograms deal with a kind of variable that is neither completely random nor deterministic. The presence or absence of a specific component or structure in a sample therefore depends heavily on its position on the depositional surface as represented by the grid (Saussus and Sams, 2012). Three points are used to evaluate a theoretical variogram: range, nugget, and sill. The range is the potential outcomes between the minimum value and the largest value. The variogram readings will eventually cease changing and hit a "plateau" at some point. This is referred to as the range. All of the data points that fall within the "range" will be given weight and included in the computations, but any data points that fall outside of the range will not be considered (Zhang et al., 2018). The number that corresponds to "Sill" in the variogram is the point at which the change in that graph ceases. Because the sill has no geographical link to the reference point, offset is irrelevant. The data points in this case are not utilised to compute the unknown value. "Nugget" depicts the origin's discontinuity. Although it should be zero, sampling error and data point small scale variability lead it to be non-zero (Bosch et al., 2012).

6.5.1.1 Vertical and horizontal variograms

Variogram models in stochastic inversion (GeoSI) encompass vertical and horizontal modelling. Vertical variograms were created using high-quality log data, and horizontal ranges were approximated using seismic data while taking structural and stratigraphic changes into account. Vertical study was carried out over three layers: "layer 1" (from Upper Goru to Lower Goru 1), "layer 2" (from Lower Goru 1 to lower Goru 1 basement). Figure 6.6 displays the vertical variograms that were generated for the two layers that had variance.

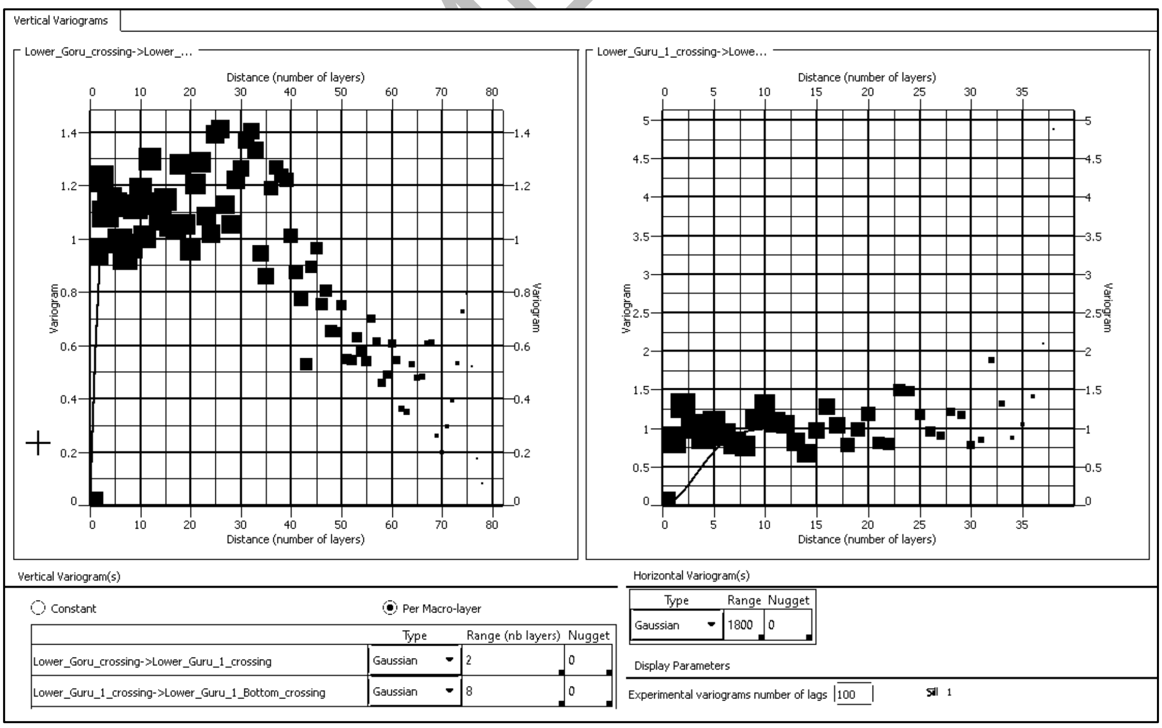

Figure 6.6-Variogram Correlation plot "layer 1" (from the horizons Lower Goru to Lower Goru 1), "layer 2" (from horizons Lower Goru 1 to Lower Goru Bottom).

6.5.2 Facies Classification

Facies classification using stochastic inversion is a technique used in geology and geophysics to predict subsurface rock properties and identify different geological formations. The process involves generating multiple realizations of possible subsurface models based on statistical analysis of available data, such as well logs, seismic data, and core samples.

Stochastic inversion involves creating a set of models with varying properties and assigning probabilities to each model based on how well it fits the available data. The process can help to identify the most likely geological formations present in the subsurface, as well as provide information on the uncertainty associated with those predictions.

Once the models have been generated and probabilities assigned, facies classification can be performed. This involves identifying the different rock types present in the subsurface, such as sandstone, shale, and limestone. Facies classification is important because different rock types have different properties that can affect drilling and production operations.

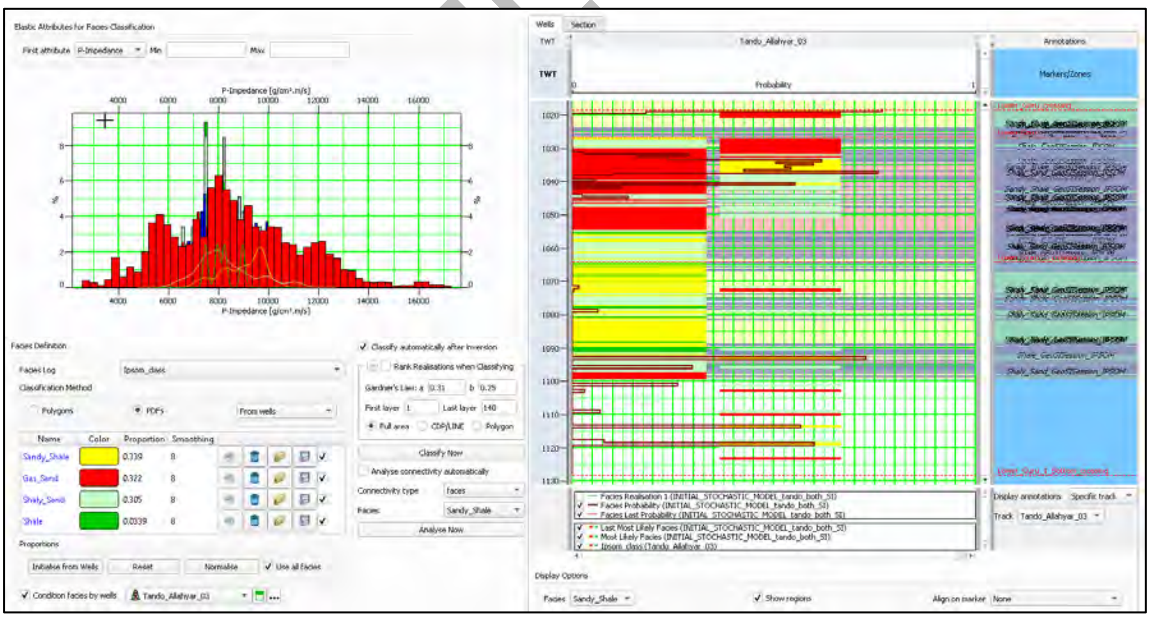

Figure 6.7-The defined probability density function generated using the electrofacies log of well Tando Allahyar 03, used in spatial distribution of the gas sand, shaly sand, sandy shale, and shale facies.

6.5.3 Probability Density Functions (PDF's)

Noise in the data, as well as mistakes in the modelling procedures, induce variances in the inversion findings. As a consequence, GeoSI gives a superior solution by providing various outcomes iteratively in realizing subsurface features. This not only produces better resolution data than the input, but also allows for the quantification of uncertainty within the reservoir model's probable scenarios. As a result, Monte Carlo simulation (MCS) based on Bayesian categorization offers a reliable method for predicting probability distributions for hydrocarbon facies.

6.6 Inverted impedance section

The layered strata model, scaled wavelet, and facies classification were used to run 50 realizations. to generate 50 different distribution scenarios for the gas sand, shaly sand, sandy shale and shale facies, together with volume realizations for the geobodies and connectivity analyses. Due to the fact that stochastic inversion is founded on geostatistical techniques, a variogram analysis is essential in order to replicate the spatial variation in each of the directions. The inversion variogram matched the well-matched data cloud with a consistent trend, as shown in Shown in Figure 6.8. As shown in Figure 6.8, 14 number realization of the facies volumes and geo-bodies were retrieved, and give us better co-relation with impedance

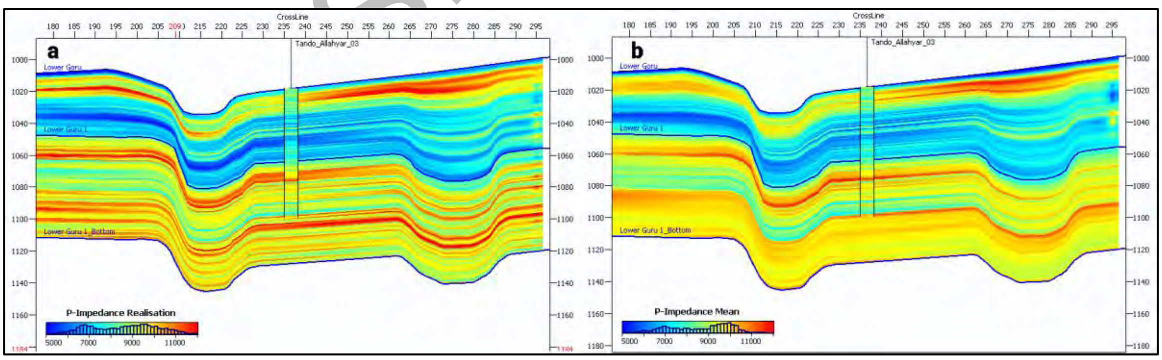

Figure 6.8: (a) A realization section for stochastic based inverted impedance of the inline 267 (b) the mean impedance section of the inline 267.

6.7 Inverted facies sections (time window 960-1100ms)

Four sections of facies are extracted from the inverted impedance volume. Gas Sand section indicate the presence of gas sands in the subsurface. Gas sand probability section as in Figure 6.9 (a) specify that gas sands are present in two zones. The upper portion or shallower reservoir zone has high amount of gas sands. Upper gas sand zone is present throughout the section with high gas sand probability while the lower zone has less amount of gas sand. Figure 6.9 (b) indicate the presence of sandy shale in the area. reservoir while shallower reservoir zone has less amount of it as in Figure 6.9 (c) Upper zone has less amount of shaly sand while deeper portion of reservoir has high amount of shaly sand. Lower reservoir zone has high probability of sandy shale which is why it is not a good quality. Shale probability section in Figure 6.9 (d) specify that shale is not present in high amount in both reservoir zones.

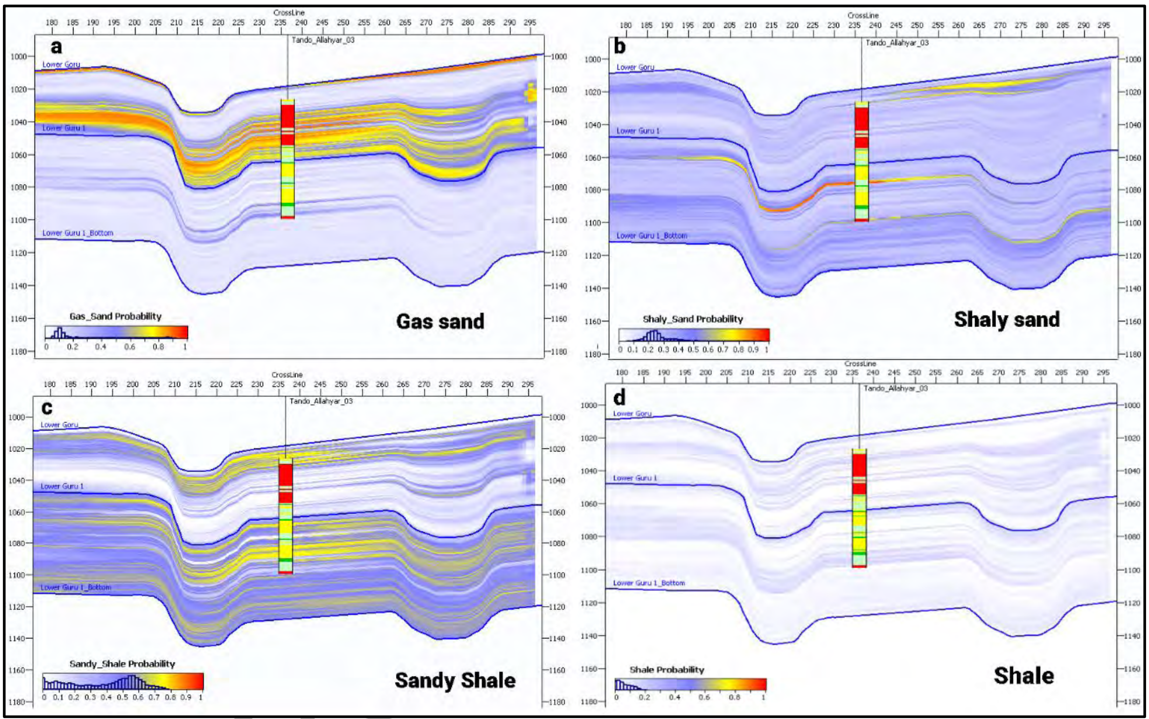

Figure 6.9-Inverted facies section (a) gas sand section depicting high values in the upper portion of the formation (b) shaly sand section indicting high values in lower portion (c) sandy shale section indicating distributing throughout the formation, particularly in lower portion (d) shale facies section depicting low shale presence.

6.8 Inverted facies slices (time window 960-1100ms)

From the reservoir perspective, Lower Goru can be divided into two portions. One is upper part or shallower reservoir and second is lower or deeper reservoir. On the basis of facies defined, slices have been taken for both the intervals. Four facies are defined as gas sand, shaly sand, sandy shale and shale. These slices express the facies spatial distribution in the area.

In the shallower reservoir zone, the probability of getting gas sands is high. Gas sands are present throughout the area particularly in the north. Towards north the shaly content is low and high content of gas sands is observed (6.10) In Figure 6.10 (a) Gas sands are present in the area that is indicated by blue and light blue color with high probability towards north and south-west. Sandy shale is also in low amount particularly in this region as it is clear from the green color in the slice however the major concentration of the sandy shale is high towards east (Figure 6.10b). Shaly sand is overall low but a bit higher towards the north (Figure 6.10c). Furthermore, the presence of shale content is low in this particular portion (Figure 6.10d). The facies distribution along with the inverted impedance values confirm that is the upper portion of the Lower Goru Formation is a good quality reservoir.

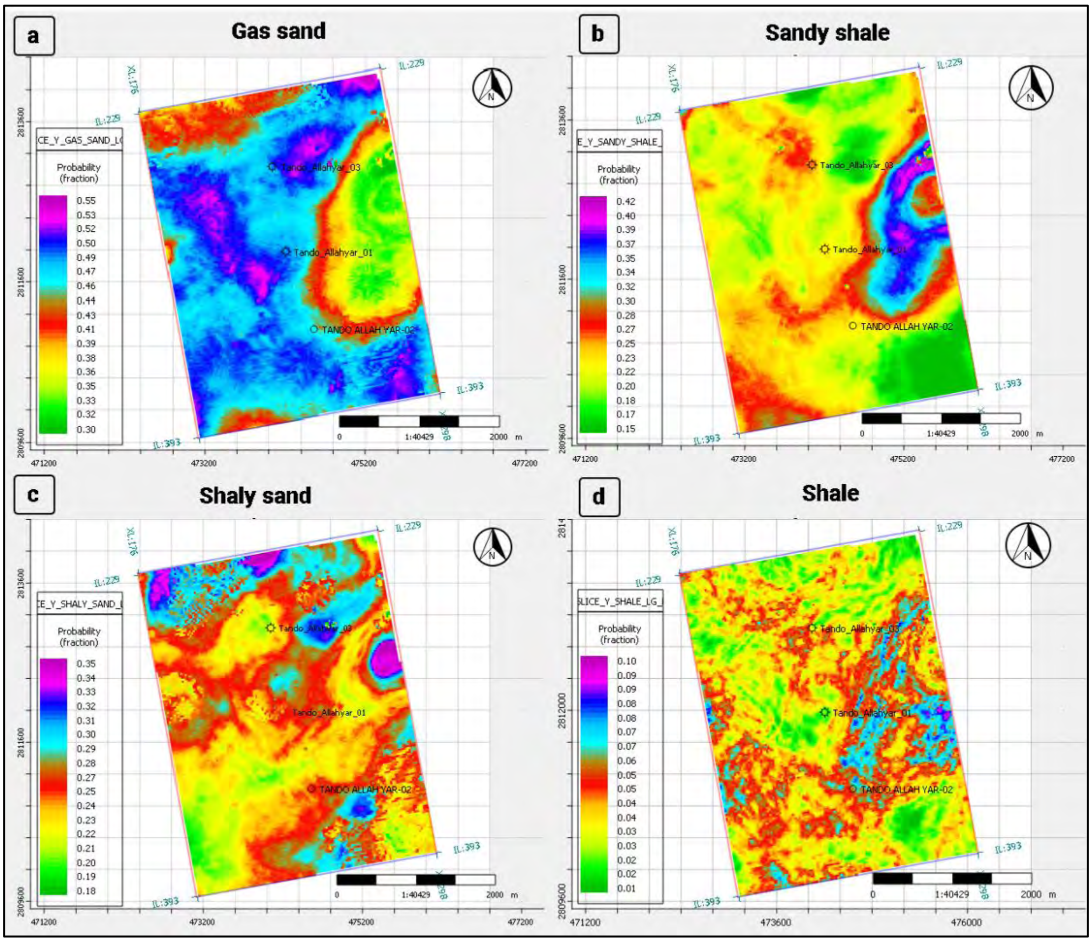

Figure 6.10: Inverted facies slices of the upper portion of Lower Goru Formation (a) gas sand showing high values throughout the formation (b) sandy shale slice depicting overall low values but relatively high values towards east(c) shaly sand slice indicating relatively high values towards north and low values towards south (d) shale slice depicting low values throughout the upper portion.

Four slices of facies have been extracted for the deeper portion of the reservoir (Figure 6.11). The gas sand presence is overall low but relatively high towards southwest in this portion of the formation (Figure 6.11a). The shaly sand content is relatively higher than gas sands and is more towards the southwest side (Figure 6.11b). High amount of sandy shale can be observed in this portion, particularly towards north (Figure 6.11c). The shale content is overall low (Figure 6.11d). Lower region of reservoir has less gas sands and shaly content is higher in the area.

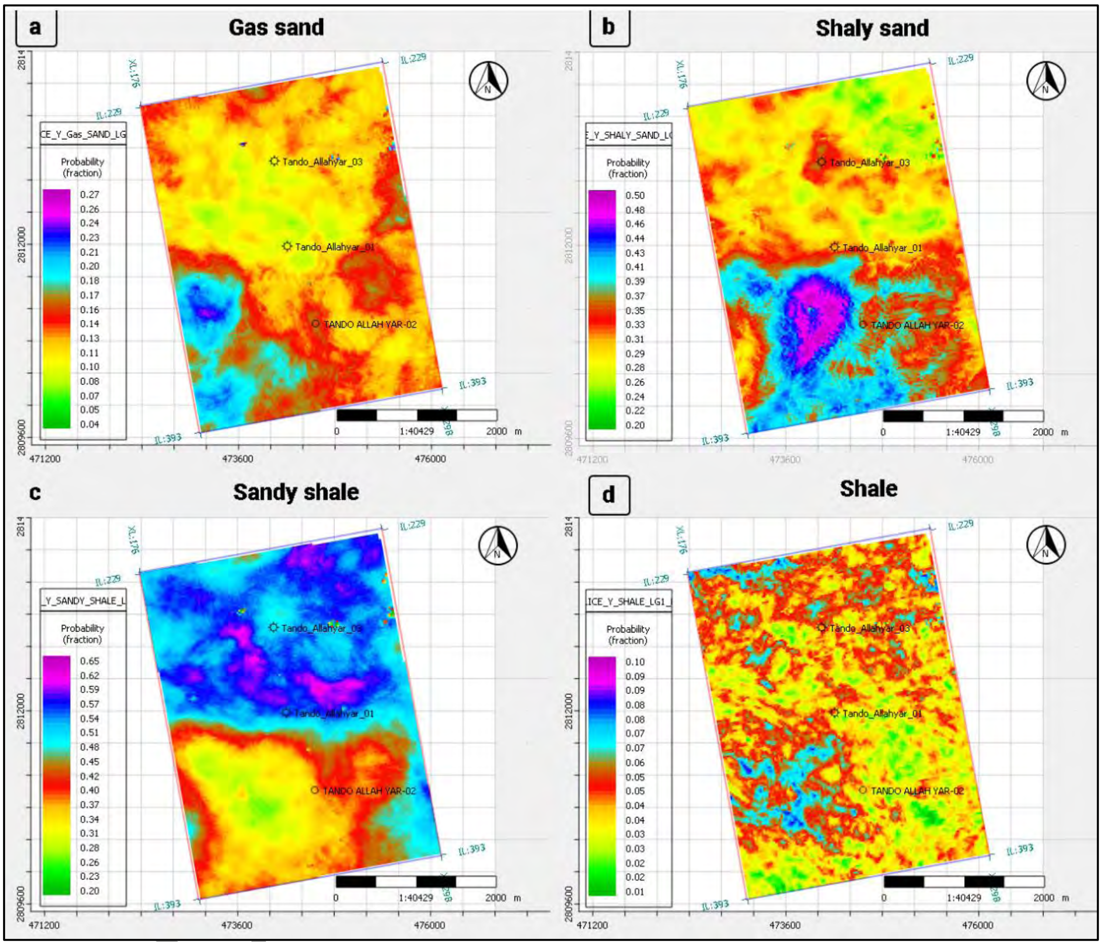

Figure 6.11: Inverted facies slices in the lower portion of the Lower Goru formation (a) gas sand slice depicting overall low values but relatively higher values towards south (b) the shaly sand facies showing high values towards south (c) sandy shale facies slice depicting relatively high quantity compared to other facies particularly concentrated in the north(d) shale facies slice indicating relatively low values.

Shallower reservoir has high gas sands in the area while the deeper zone has shaly content which effect the reservoir quality. From the analysis of the regions the upper zone (Lower goru to Lower Goru 1) of reservoir is a good quality reservoir as compared to lower zone (Lower goru1 to Lower Goru 1_bottom).

Chapter 7
Discussion and Conclusions

Discussion

Adopting an efficient methodology for the prospect evaluation of a heterogeneous reservoir using inversion techniques is challenging (Shakir et al, 2021). The inversion technique started with a bandlimited recursive inversion (Lavergne, 1975; Lindseth, 1979) and was later modified as an objective function based deterministic inversion (namely, model-based inversion), which introduces a low frequency model to compensate for the loss of low and high frequencies (Russell, 1991). The deterministic inversion gives an averaged effect of the impedance values and is therefore not suitable for reservoir model constraint which is useful in volumetric property estimation, fluid simulation, or connectivity analysis (Francis, 2006). This necessitates the use of geostatistical modeling which generates multiple impedance realizations, reflecting the subsurface heterogeneity embedded in the seismic data (Francis, 2006).

The geostatistical inversion technique deals with delineating the reservoir properties firstly by inverting the volume to obtain spatially distributed impedance, followed by the volumetric facies' classification using probability distribution function (Avseth et al., 2001; Mukerji et al., 2001; Grana et al., 2012). This study therefore made use of the stochastic (geostatistical) inversion in order to study the properties and facies distribution of the heterogeneous Lower Goru Formation in Tando Allahyar, Pakistan. The research was initiated through the seismic data interpretation which indicates that the Lower Goru Formation is relatively deeper towards north-west and shallow towards south-east and the area is under the influence of an extensional regime confirmed by the presence of normal faults and the subsequent graben structure (Figure 3.4). The petrophysical analyses suggest a suitable environment for the presence of gas in the formation (Table 4.1,4.2,4.3). These properties along with the interpreted seismic data are used as priori information for application of the stochastic inversion technique while focusing on the potential zone of interest. The stochastic inversion results suggest the presence of a hydrocarbon bearing zone in the upper portion of the Lower Goru Formation and a relatively low potential for hydrocarbons in the lower portion (Figure 6.8).

The inverted impedance volume, although sufficient for reservoir analysis on its own, can be used to estimate the spatial distribution of other reservoir parameters, such as lithofacies, for prospect confirmation. Accurate prediction of the facies requires the core sample analysis (Cuddy, 2000; Hambalek and Gonzalez, 2003) and might not be reliable using simple regression relations. This problem was resolved to a great extent by introducing a machine learning based facies prediction named as the electrofacies analysis (Wolff and Pelissier-Combescure, 1982; Doveton and Prensky, 1992; Bucheb and Evans, 1994; Lim et al., 1997; Mathisen et al., 2003). The electrofacies is an artificial intelligence-based facies prediction technique which uses the information from individual logs (Nashawi, 2009) and can be subsequently correlated with petrophysical properties such as porosity and permeability, allowing for a more accurate interpretation of reservoir properties (Teh et al., 2012). In this study, the electrofacies calculated from the well log data using unsupervised machine learning technique perfectly correlates with the petrophysical results, indicating the presence of four facies, namely gas sand, shaly sand, sandy shale, and shale (Figure 6.9).

The integration of electrofacies analysis and stochastic inversion is a well-established technique for improving the facies distribution prediction in terms of reservoir characterization (Fink et al., 2002). Electrofacies analysis involves the statistical clustering of well log data into discrete rock types (Nashawi and Malallah, 2009) while the stochastic inversion involves the transformation of seismic data into quantitative estimates of rock properties such as, acoustic impedance and density (Rajput, 2014). The integration of these two techniques can significantly improve reservoir characterization by providing a more comprehensive understanding of the subsurface geology. The spatial distribution of electrofacies using stochastic inversion confirms that the gas sand probability is relatively high in the upper portion of the formation, particularly towards the west, making it a good reservoir (Figure 6.10). In contrast, the probability is low in the lower portion of the formation but relatively high towards the south-west (Figure 6.11).

Overall, the study provides an insightful analysis of the potential of the Lower Goru Formation as a gas reservoir. The interpretation, petrophysical analysis, electrofacies, stochastic inversion, and spatial distribution of electrofacies together provide a comprehensive understanding of the formation's potential. The comparison of these results suggest that the applied approach turned out to be useful for characterization of the early Cretaceous reservoir rock in the NIM-TAY block of the Lower Indus Basin in Pakistan and can be applied to the rocks of same era in various localities.

Conclusions

1. The Aim of this study is to analyze subsurface structure and reservoir properties. Based on this interpretation, two horizons and normal faults were delineated to understand the subsurface structure. Time and depth contours were constructed, which indicate that the Lower Goru Formation is thick in the north-west and thin in the south-east. The occurrence of normal faults provides more evidence that the extensional regime is present.
2. Petrophysical findings show a favorable environment for the presence of gas. Petrophysical analysis indicate the presence of gas bearing zone within in the Lower Goru Formation. The value of effective porosity, shale volume and water saturation in this zone varies from 8.63-12.9%, 8.06-16.62%, and 36.84-53.57% respectively.
3. The presence of sand, shaly sand, sandy shale, and shale is indicated by electrofacies, which were calculated from the well log data using an unsupervised machine learning technique. The results of the electrofacies have a perfect correlation with the results of the petrophysical experiments.
4. The results of the stochastic inversion show low impedance values in the upper part of the Lower Goru Formation, which points to the presence of a prospective hydrocarbon zone. The lower part of the formation has impedance values that are relatively high, which indicates that the potential for the reservoir is not very good.
5. The stochastic inversion of the spatial distribution of the electrofacies reveals that the sand probability is relatively high in the upper portion of the formation, particularly towards the west, which confirms that it is a good reservoir. This finding comes from the upper portion of the formation. In the lower part of the formation, the probability of sand is low, but it increases significantly as one moves towards the south-west.

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