GEO-STATISTICS BASED RESERVOIR MODELLING FOR HYDROCARBON RESOURCE POTENTIAL IN ZAMZAMA BLOCK, SOUTHERN INDUS BASIN, PAKISTAN

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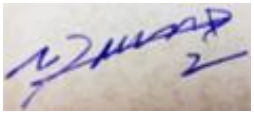

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ABSTRACT

The research area for the Zamzama gas field is located in Sindh's Dadu district, within the Zamzama block. The investigation region lies in Pakistan's Southern Indus basin's Kirthar foredeep. The geologic succession ranges from Jurassic to modern times. The Zamzama structure is a massive north-south thrusting anticline with an eastward trending. To interpret its structure and tectonic regime, seismic and borehole data are presented. The general geology, stratigraphy, and tectonics of the area is thoroughly investigated in order to better comprehend the tectonic evolution since Pangea's formation. Two horizons of interest are marked, and no fault is encountered in the given 3D seismic cube, then interpreted to determine the depth, extension, and orientation of subsurface structure. The petrophysical analysis is run to investigate reservoir formation in order to determine rock type and hydrocarbon potential. Different logs, such as LLS and LLD form various cross overs, indicating the presence of fluid in porous and permeable rocks. Porosities, shale volume, water saturation, and hydrocarbon saturation are estimated, indicating that the reservoir rock has sufficient conventional reservoir rock potential for oil and gas production. Seismic post stack inversion is applied on a seismic line integrated with well data to understand the reservoir response on large scale. Model-based inversion is used which shows the low impedance at the depth of reservoir indicating presence of porous and permeable rock.

Rock physics modeling is performed to distinguish the facies by plotting different cross plots between various rock parameters. Hence, Zamzama is a potential gas-producing field in the lower Indus basin, where the Pab sandstone in Zamzama -03 is a producing field. Bayesian classification is run on 3D seismic data cube to predict the lithologies and fluid present in the reservoir. For Bayesian classification different cross plots are used for the prediction of lithology and fluid, with density plotted on Z axis. The cross-plots clearly separated and delineated the Litho-fluid classes (hydrocarbon sand, gas sand, and brine sand) with specific orientation/patterns.

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CHAPTER 1

INTRODUCTION

Zamzama field is an important resource, which spreads over an area of about 120 square kilometers based on the gas reserves discovered in Pakistan. The Zamzama field adds nearly 15% to Pakistan's daily gas production, thereby minimizing the need for oil and gas imports. Sindh is located in the south of Pakistan; it is also known as "Energy Basket" of Pakistan. The Zamzama gas field was discovered in the mid-1990s by BHP Billiton in Sindh province and represented its first commercial production in Pakistan. Several other gas fields include the Bhit gas field, which is located in the southwest of Zamzama and the Sawan, Kadanwari and Miano fields to the northeast (Kadri, 1995).

Zamzama Gas Field in Zamzama Block is in Dadu District, Sindh (Figure 1.1). The research area is located at the bottom of the Kirthar of the Lower Indus Basin, which in addition to the ZGF has several oil and gas fields. The area is bounded by 26° 30'N to 27 ° N and 67 ° E to 67 ° 50'E and is located approximately 200 km north of Karachi and 10 km west of Dadu (Yilmaz.,2001).

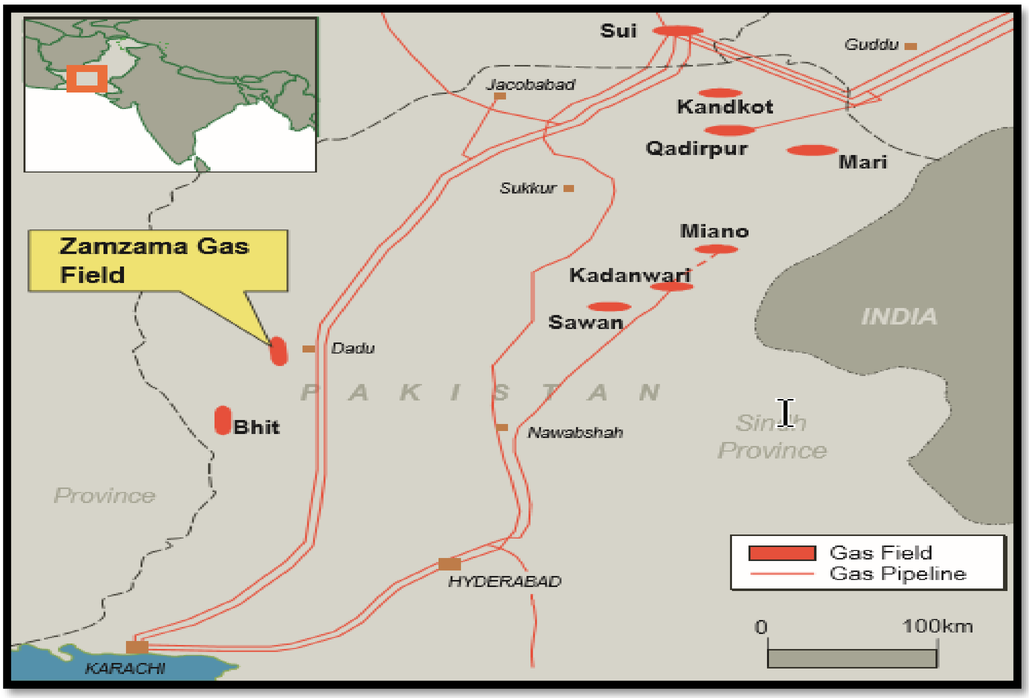

Figure 1.1 Locality of Zamzama gas field along with other fields (Abbasi et. al., 2016)

1.1. Exploration History of Zamzama Block

In 1993-1994, petroleum potential of Pakistan was assessed by BHP Billiton and emphasized the Indus Basin as a prospective zone. In February,1995 BHP was awarded Dadu Concession (Block 2667-1) and the very next year BHP acquired 196 kilometers of 2D seismic data which discovered the Zamzama structure.

Zamzama-1/ST1 was the very first exploratory well that was spudded in block in January 1998, up to the depth of 3,938 meters and proved the hydrocarbons presence in Khadro formation and Pab Sandstone. Wireline logs consequently discovered a gas column more than 300 meters.

For the appraisal phase of Zamzama field 3D seismic data was acquired that involved drilling of Zamzama-2 appraisal well. Zamzama-2 was drilled up to the total depth of 3933 meters that also identified the presence of hydrocarbons in Khadro and Pab formations and wireline log data confirmed 350 meters gas columns.

1.2. Hydrocarbon Potential of Zamzama Gas Field

Reserves of Zamzama gas field that was proved plus the probable recoverable reserves was proclaimed up to 1.7 trillion cubic feet of gas (gross) and from this total equity shares of BHP Billiton's are nearly 650Bcf. Plateau production rate of Zamzama field would be nearly 320MMcf/d of gas along with 2,000 (STB/d) of condensates for the time period of 10 to 12 years. It is expected, almost 15 to 25 years, economic life of this field.

Pab sandstone formation is the target reservoir in this field which is highly productive reservoir that exist at 3.500 meters depth. The gas explored from Zamzama is sweet and dry, with 6.5 barrels/mmcf, low condensate to gas ratio.

1.3. Locality of Study Area

Zamzama field lie within the Indus valley southern Pakistan having surface elevation of 30 to 40 meters. Primary structure consists of single anticline thrust against an NS trending fault (Jackson et al, 2004).

The field area is located within the Zamzama block, which lies in Dadu district, Sindh (Province of Pakistan). It lies almost 200 kilometers towards North Karachi and 10 km from the west of Dadu. The area under study is situated in Kirthar Foredeep in Lower-Indus Basin. Geographically, the area is bounded by 26º30´N to 27ºN and 67º E to 67º 50´E.

From the Upstream Petroleum Activities Map published by Directorate General Petroleum Concessions (DGPC) cooperated with Landmark Resources (LMKR) in October 2014, the Zamzama is furthermore divided into 3 more blocks named as Zamzama, Zamzama-North and Zamzama-South showed in figure 1.2. BHP Billiton was granted the production and development lease for the Zamzama. Hycarbex held the exploration license for Zamzama-North and Zamzama-South with rests with the PPL (Pakistan Petroleum Limited).

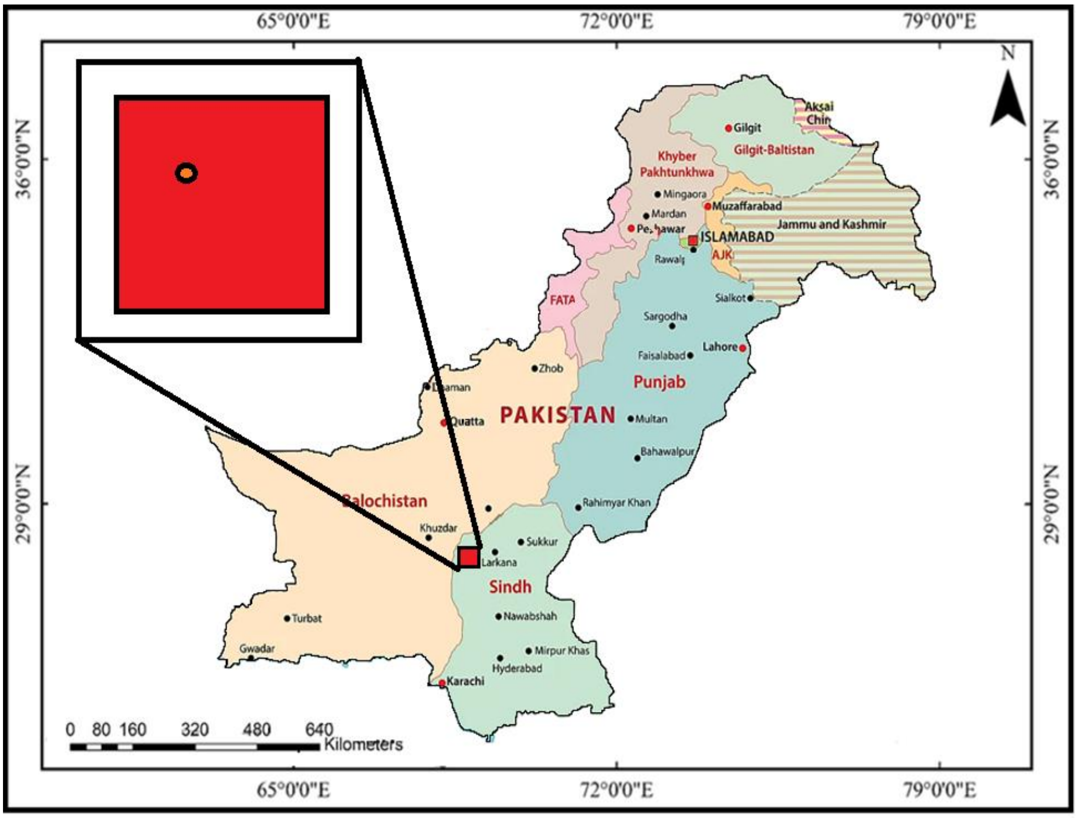

Figure 1.2 Locality of Zamzama Gas Field showing division of Zamzama blocks (DGPC& LMKR)

1.4. Literature Review

There is no seismic study and research have been done in Mehar block because it is a newly development gas field. however small amount of research has been carried by employees of PETRONAS, although these studies are private and not published and these repost are not offered for open source. As the Mehar block is lies near the Kirthar Fold Belt to obtain a sense of the area's surroundings regarding to Kirthar Fold Belt, look at few latest research completed in the neighboring region of Mehar area.

Research investigation of the Miano area used petrophysical analysis, seismic characteristics, facies modelling, and seismic inversion techniques. It presents a structure with horst and negative floral structure that illustrates a sloping crack and an irregular graben block located in the southwest and northeast orientation. The B interval of lower Goru shows prominent light spots that tend to offer instantaneous amplitude while still offering the potential of a reservoir. The assessment and modelling of the facies also support the presence of a considerable amount of lithology shale and sand in the Goru B sand interval, which was also identified as the primary reservoir. The results of the selected well's petrophysical examination revealed at least one prospective reservoir in the sandy range of the lower Goru zone, as well as at the Miano well. A model-based inversion was used to assess acoustic impedance, with the results revealing small to large variations in impedance values. The correlation is analyzed using porosity and petrophysical analysis, and then extracted from the seismic inversion, which is then examined for the results' credibility (Zaheer et al., 2018).

There is different type of work done in surrounding field of Mehar block like Zamzama field. Structural interpretation with the help of seismic data discloses that the Zamzama geometry is a one, irregular, thrusted anticline along double separate culmination in hanging wall and a well solved, pronounced thrust and an original common gas water contact across these two culminations. Even the main crustal thrust in the Zamzama East-1 well region is broken up by a significant lateral ramp that connects the footwall with hanging wall. These lateral ramps, which function as relay ramps, run among all crustal thrust, and allow approaches to widespread aquifer across the hanging wall. As a result, there are no discrete pressure-isolated structural compartments in the hanging wall. The new structural interpretation was able to describe unequal water penetration into the crust of the structure, therefore the lack of zones is main effect of newly structural interpretation (Zaigham and Mallick, 2000).

Research is based on, combined study created on result of Seismic Interpretation, Well-logging, seismic inversion, Neural Network, and Bayesian classification will be carried out for the Mehar block. Neural Network and Bayesian classification has not yet been using such techniques, and the consequences and comparison will be used to assess the correctness of these methodologies for study purposes.

1.5. Data Used

3D Seismic data of Zamzama gas field covering an area of 12 squares kilometers in format of SEG-Y was provided by LMKR, after the approval of Department of Earth & Environmental Sciences (BUIC) and DGPC.

Table 1.1 Inlines and crosslines in Zamzama 3D survey

Lines	Start	End
In Lines	420	510
Cross Lines	1320	1440

1.6. Objectives

1. To identify the faults associated with subsurface structures to examine the hydrocarbon zones through seismic interpretation.
2. Petrophysical analysis to identify the hydrocarbon bearing zones.
3. To analyses reservoir properties by using seismic model-based inversion techniques.
4. Characterization of fluid by the application of rock physics modelling at Pab sandstone level.

1.7. Methodology

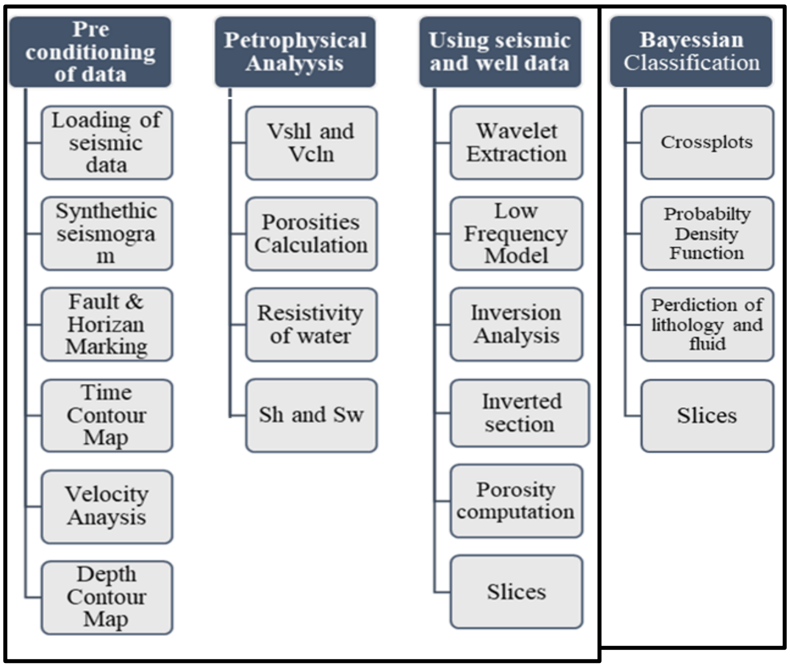

Figure 1.3 Flow chart showing the methodology followed throughout the research

CHAPTER 2

REGIONAL TECTONICS AND STRATIGRAPHIC FRAMEWORK

Currently, the tectonic configuration of Pakistan (found in the North-Western fringe of the Indian plate) is illustrated by the tertiary convergence between the two plates i.e., Indian and. Eurasian plates. The structures that range from north to south according to the structural position and decreasing age are the main central overlap (TCM), the Indo-Tsango (TS) suture and the main border overlap (Gansser,1981;Seeber et al,.1981). The collision zone originating from the north side of Pakistan is separated as Main Karakoram Thrust (MKT), Main Mantle Thrust (MMT), Main Boundary Thrust (MBT) and Thrust Salt Range (SRT) (Farah et al,.1984, Yeats and Lawrence, 1984).

2.1. Generalized Description of Indus Basin

The basin area, of nearly 5,33,500 km^2, has sediments 15,000 m thicker that nearly ages from the Precambrian to the recent age. The oil and gas potential of Indus Basin lies in the inner folded areas of the Kirthar Ranges.

In addition, the Indus basin is parted into three divisions.

1. Upper Indus Basin
2. Central Indus Basin
3. Lower Indus Basin

In this research work, lower Indus basin will be focused as the study area is Zamzama block located in Kirthar Fold Belt.

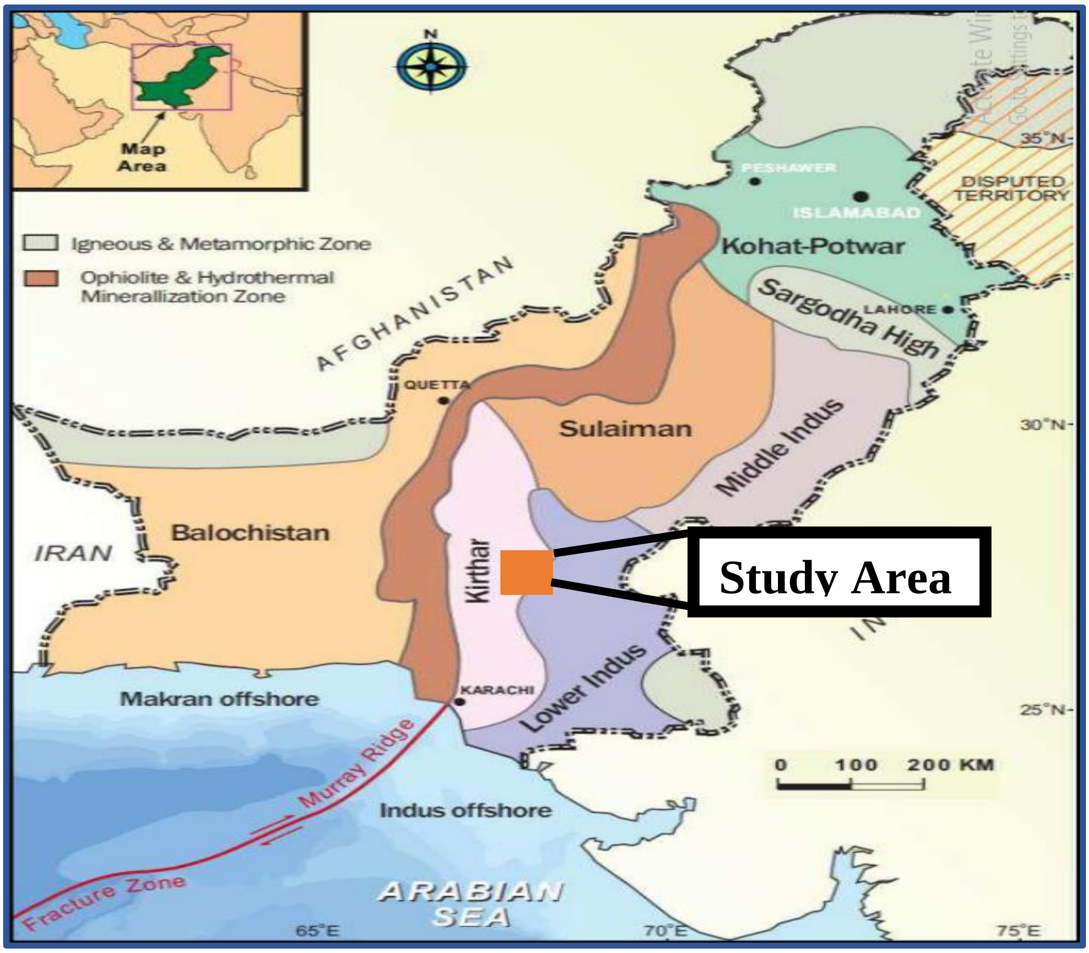

Figure 2.1 Generalized map illustrating the division of Indus Basin. (Courtesy: PPL)

2.1.1. Lower Indus Basin

The Southern /Lower Indus Basin comprises of the following.

1. Thar Platform
2. Karachi trough
3. Kirthar foredeep
4. Kirthar fold belt
5. Offshore Indus

2.1.1.1. Thar Platform

The subsoil topography controls the Thar platform and the Punjab platform that exist in the Central Indus basin. The sediment cover on the Indian Shield is exposed at Nagar Parkar High which pinches out. Thar platform shows the buried structures, this is how it differs from the Punjab platform, where there is extension tectonics due to the rotation of the Indian plate counterclockwise. of a watch (Kadri.,1995).

2.1.1.2. Karachi Trough

According to geological history, it is a trough. Karachi trough contains thick strata of Cretaceous sediments of late marine. There are narrow chains of anticlinal structure which contains oil and gas fields like; Hundi, Sari and Kothar. Interestingly, some of the Cretaceous rocks, which had been deposited continuously along the Cretaceous-Tertiary (K-T) boundary, are very well preserved (Kadri, 1995).

2.1.1.3. Kirthar Foredeep

Kirthar Foredeep contains 15,000 m thick sediments trending from north-south. In addition, it contains a faulty boundary (on the east side) with the Thar platform. At this region, a well-developed Paleocene stratum can be seen whereas,

The Upper Cretaceous strata is missing. Kirthar Foredeep was discovered with an excessive potential for source rock maturation (Kadri,.1995).

2.1.1.4. Kirthar Fold Belt

Tectonically trending north-south, the Kirthar Fold belt resembles the Sulaiman belt. It is bordered on the west by the Bela-Zhob ophiolites and the thrust belt, on the north by the Sibi trough, and on the west by the Kirthar foredeep and the Indus Platform. Triassic to modern rocks have been deposited here (Kadri,.1995).

2.1.1.5. Offshore Indus

It is part of the passive continental margin. Sedimentation on the Indus coast occurred in two different phases of geological time, i.e., the Cretaceous-Eocene phase and the Oligocene-Recent phase.

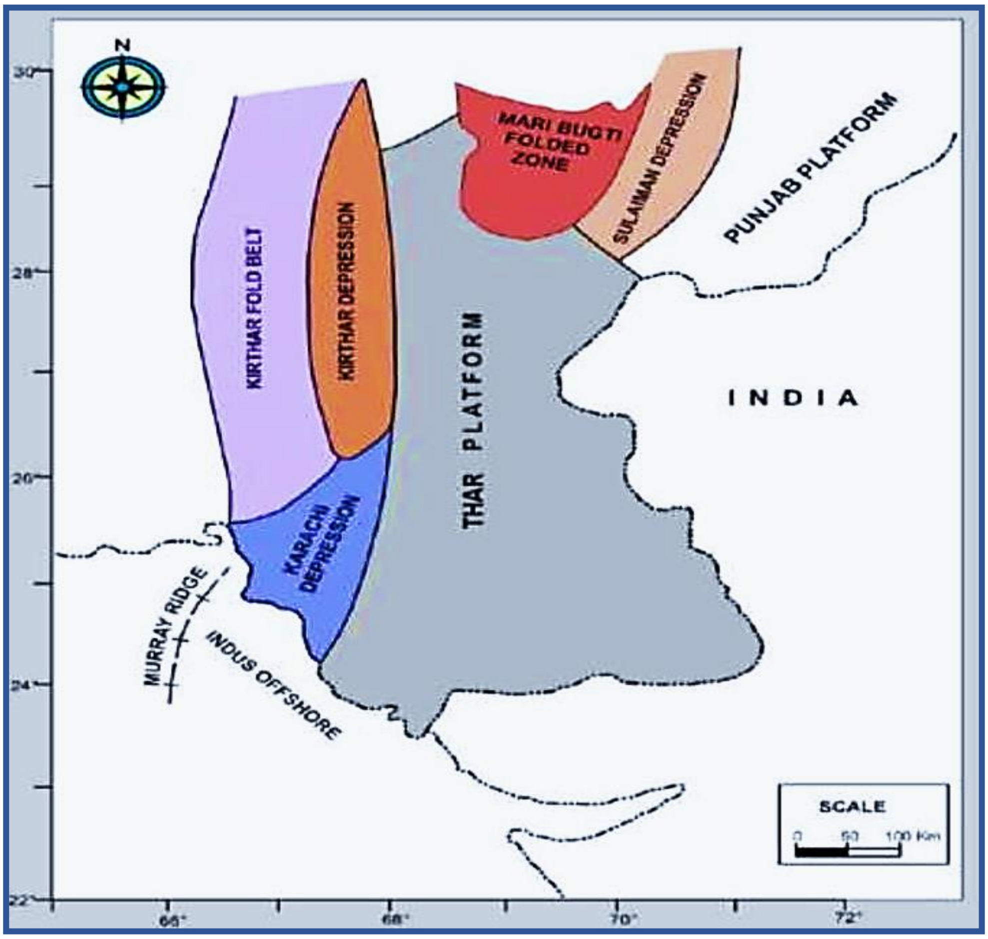

Figure 2.2 Main components of Southern Indus Basin (after Kadri, 1995)

2.2. Geological and Tectonic Setting of Zamzama Area

Zamzama is basically a thrusted anticlinal structure, with a north-south orientation. The Pab sandstone in the Kirthar Fold belt serves as the primary reservoir, along with Zamzama and neighboring gas Bhit field.

Sandstone analysis bordering the Khadro formation shows a gas reservoir in the Zamzama area. The Khadro formation and Pab sandstone formation displays the uniform thickness across the Zamzama structure (Jackson et.al,2004).

The Khadro formation is 54 meters thick on average, while the Pab sandstone is about 300 meters thick. The Pab sandstone formation overlies the Fort Munro formation and forms a conformable stratigraphic contact.

Girdo formation acts as a top seal for Pab sandstone and Khadro Formation containing marine shales. Khadro reservoir is a heterogenous formation with poor quality due to the presence of volcanic clasts (Wandrey et. al., 2004).

2.3. Generalized Stratigraphy of Zamzama

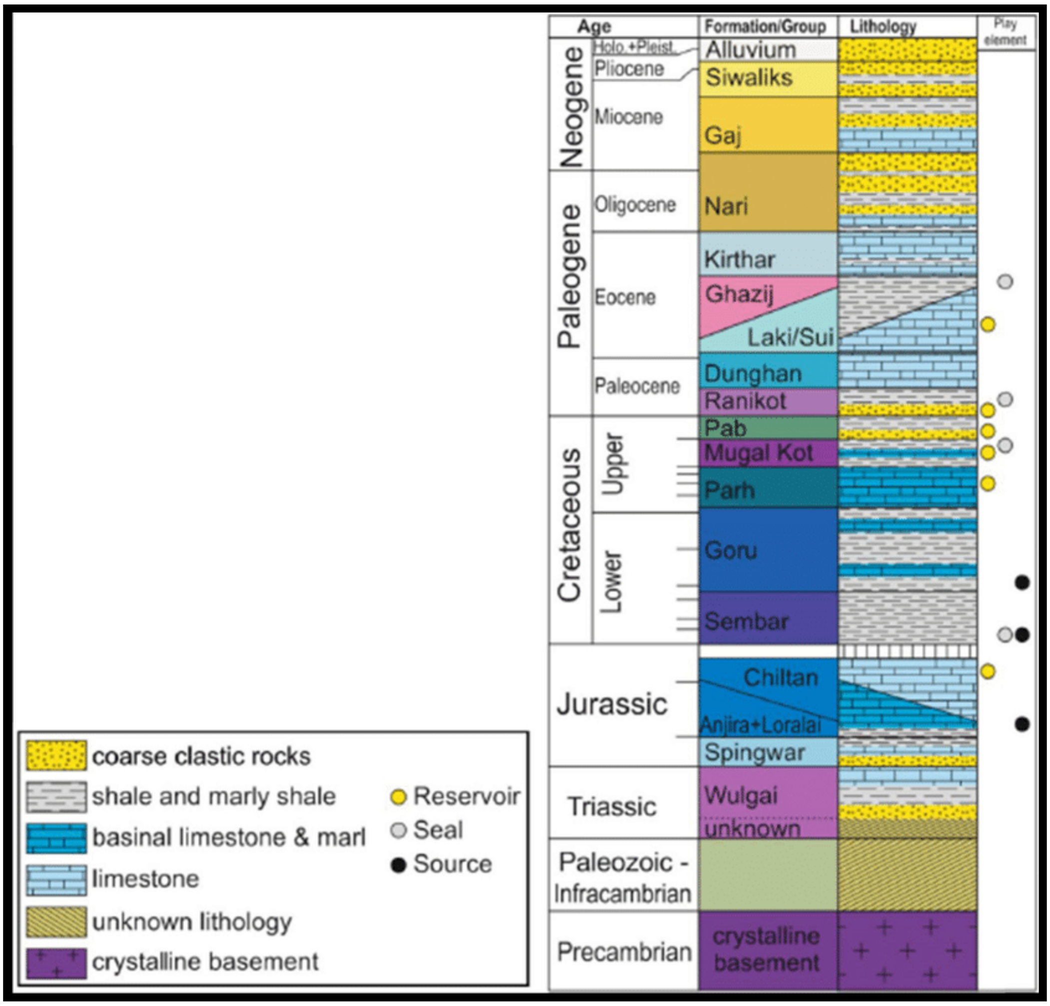

Figure 2.3 Stratigraphy of Lower Indus Basin (Majid et al, 2016)

2.4. Petroleum Play of Zamzama Area

The factors that make up a hydrocarbon trap are source rock maturation, paths for hydrocarbon migration (secondary), reservoir capabilities and seal. Petroleum play is made up of all these elements.

2.4.1. Source Rock

The main source rock in Zamzama area is Sember shales, which were deposited on the broad shelf, while evidence fauna (Goru) indicates a pelagic habitat. The Sember is mostly type-III Kerogen, and the TOC (total organic content) values of Sember source rock in the Lower Indus Basin range from 0.5 to 3.5 percent, with an average of about 1.4 percent, indicating a considerable potential for gas production (Wandrey et. al, 2004).

2.4.2. Reservoir Rock

It is a necessary component in the formation of a complete petroleum play of an area. The Pab Sandstone from the late Cretaceous, is the primary reservoir for the Zamzama gas field having Fluvial-tidal depositional environments. It also includes a changeable deposited system, such as the sand-rich delta coastal plain system (Jackson et. al 2004).

2.4.3. Cap/Seal Rock

It's a type of rock that prevents fluid or hydrocarbon movement by acting as a barrier in its path. It usually acts as a barrier around and above the reservoir rock carrying hydrocarbons, trapping hydrocarbons, and limiting their movement to reservoir rock. Mudstones and shale normally act as a seal or cap such as, the Lower Ranikot group, which has Paleocene-aged shales (Bara-Lakhra and Girdo formations) acting as a seal/cap in this petroleum play (Jackson et. al 2004).

2.4.4. Trap

Trap is an essential part; without it the hydrocarbon petroleum play would be incomplete. The movement of hydrocarbons is stifled and sealed by impervious rocks. The Zamzama structure, which is north-south trending, is a massive structure (thrusted anticline) that leans east, making it a big trap (Jackson et. al 2004).

2.4.5. Migration

Oil and gas migrate from source rock to reservoir rock during the migration process. Buoyancy, chemical potential, topography, compression, thermal expansion, maturation (volume increase over time), and gravitational separation of water, hydrocarbon and water are all key factors in migration (Magoon., 1995).

Table 2.1 Petroleum play of study area

Play elements	Formations	Age
Seal	Lower Ranikot	Paleocene
Reservoir	Pab Sandstone	Late Cretaceous
Source	Sembar Shales	Early Cretaceous

CHAPTER 3

SEISMIC INTERPRETATION

In the Petroleum exploration, reflection seismology is the most famous and vital indirect geophysical method because of its very good resolution. Moreover, classical methods i.e., gravity and magnetism that are indirect methods, are practical in the early stages of petroleum exploration for the identification of regional subsurface structures. Furthermore, all of the geophysical methods used in exploration are dependent on the fundament law of physics based on it that kind of physical property is determined, and experts interpret the data measured so that to look for anomalous zone what we are interested in, one tries to deduce the geology after applying some cosmetics from the indirect observations. As there is no immediate relation between the physical property measured at the surface and in subsurface (Robert J.Lillie., 1999).

The purpose of interpretation of seismic 3D reflection data is to find out the hydrocarbon bearing zones that are discovered in the sedimentary rocks. As there is no direct controlled method for finding promising zones for hydrocarbons or estimating the reserves of hydrocarbon for a given site.

There are several steps involved for the interpretation of 3D seismic reflection data. These steps are applied in order to mark the seismic section based on all geosciences knowledge and to extract the hidden information from the data preserved in subsurface.

The main objective of reflection seismology analysis, in oil and gas sector, is to recommend and spot the promising location of hydrocarbons trapped in potential structure.

3.1. Seismic Interpretation types

Basically, seismic data is analyzed based on two main approaches which are concisely discoursed.

3.1.1. Structural Interpretation

For the understanding of structural behavior, structural interpretation of seismic reflection data was done for determining the structures that are able to accumulation and trap hydrocarbons. In structural interpretation of seismic data, two-way reflection time technique was used rather than depth (Kearey.,1988).

3.1.2. Stratigraphic Interpretation

For the Stratigraphic analysis, seismic section involves the stratigraphic analysis, seismic sections are interpreted depending on the seismic signature of stratigraphic surfaces and expressions of genetically related sedimentary sequences such as onlaps, toplaps, pinchouts and several types of sequences surface concerning with the sedimentary deposition cycles (Kearey et al., 2002).

3.2. Basic flowchart for Seismic Data Interpretation

There are major interpretation steps taken in order to interpret the 3D seismic data:

1. Base map generation
2. 1D forward modeling and well tie with seismic
3. Horizons and Fault marking
4. Creation of fault polygon
5. Generation of horizon time/depth grid
6. Time and Depth contours

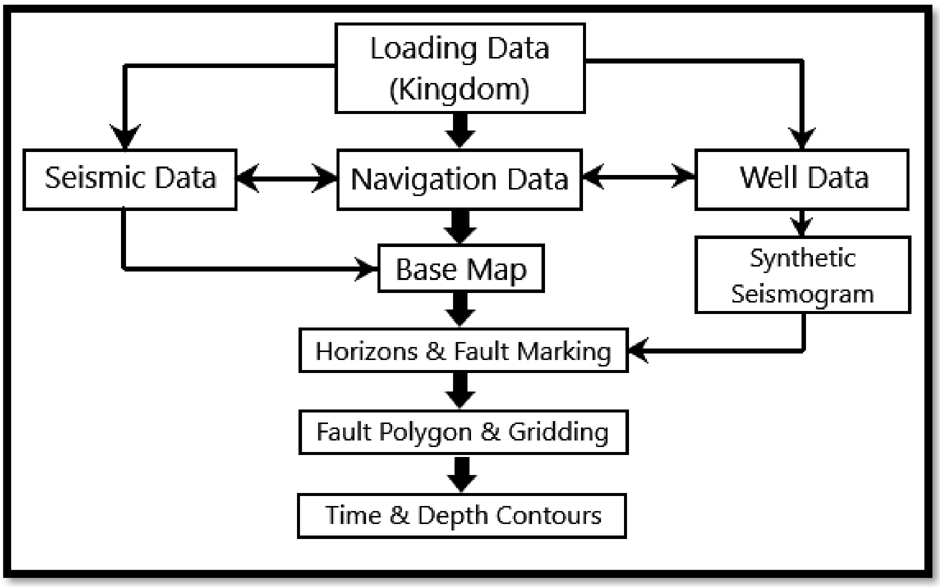

Figure 3.1 Workflow of seismic interpretation.

3.3. Base Map of Zamzama

Base map typically includes the locality of concession or lease boundaries, survey points of seismic well locations, Inlines and crosslines and other cultural data, with a geographic reference such as Universal Transverse Mercator (UTM) grid longitude and latitude with other information. Base map is used to plot interpretation data.

3D base map consists of crosslines and inlines parallel to vertical and horizontal directions. In the grid of base map of gas field Zamzama, inlines are oriented (East-west) and crosslines are oriented (North-South), base map shows ZAMZAMA-03 well in grid i.e., Zamzama-03 (inline:474, crossline 1372) as shown in the (figure 3.2).

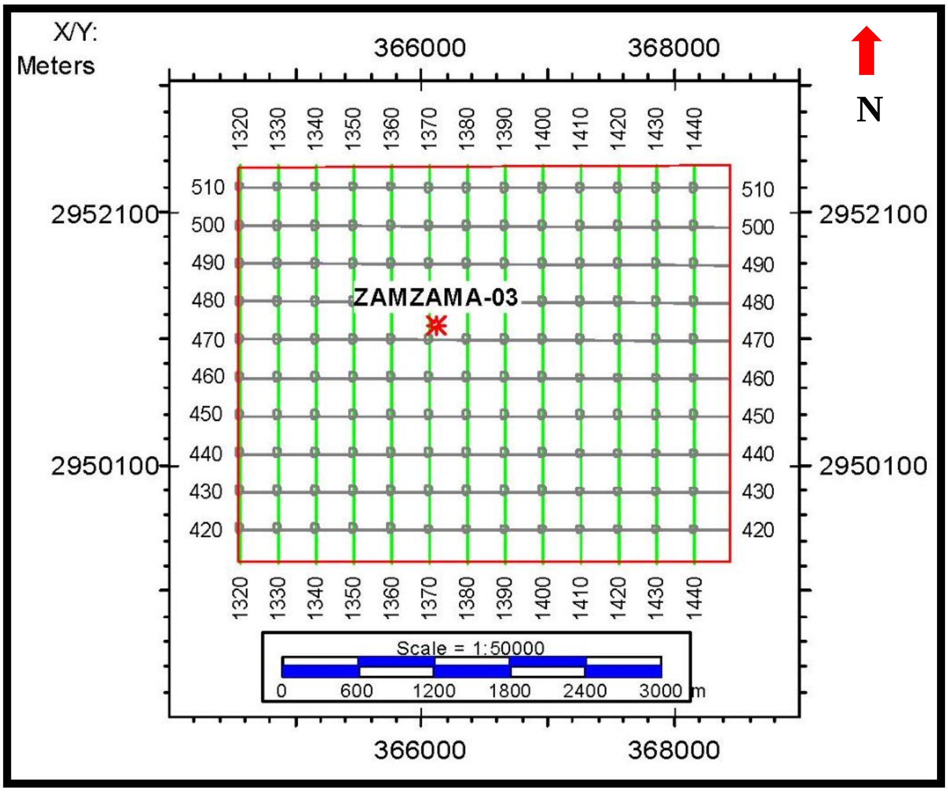

Figure 3.2 3D cube base map of Zamzama area

3.4. Generating Synthetic Seismogram

Synthetic seismogram is a 1D forward model of acoustic energy that traveled through the earth horizons having acoustic impedance contrast. This synthetic was generated by the convolution of earth reflectivity series that was derived from the sonic and density logs, and the wavelet extracted from the provided seismic data. The degree of the correspondence between a seismic section and synthetic seismogram is dependent on the quality of well log data. To produce a synthetic seismogram, sonic (DT) and density (RHOB/ROHZ) are required. Before marking the horizons, synthetic seismogram of given wells are generated (Chopra and Marfurt., 2005).

Following steps were taken for generating the synthetic seismogram in the IHS Kingdom software.

1. Loading of given Las file of well into software.
2. Open the 1D modeling projects and select the well-logs
3. Calculate density from density log.
4. Calculate velocity from sonic log for P and S waves.
5. Using sonic log create TD chart.
6. Acoustic impedance is calculated using density and velocity log.
7. Reflection coefficient is calculated from the impedance of layers.
8. Extraction of wavelet is done from seismic data being used.
9. Amplitude of synthetic seismogram is generated by convolving the reflection coefficient with the extracted source wavelet from seismic data.

Basic equation for 1D-modeling is shown.

$$St = Rc * Sw \quad (3.1)$$

Synthetic seismogram of Zamzama-03 is shown in (figure 3.3).

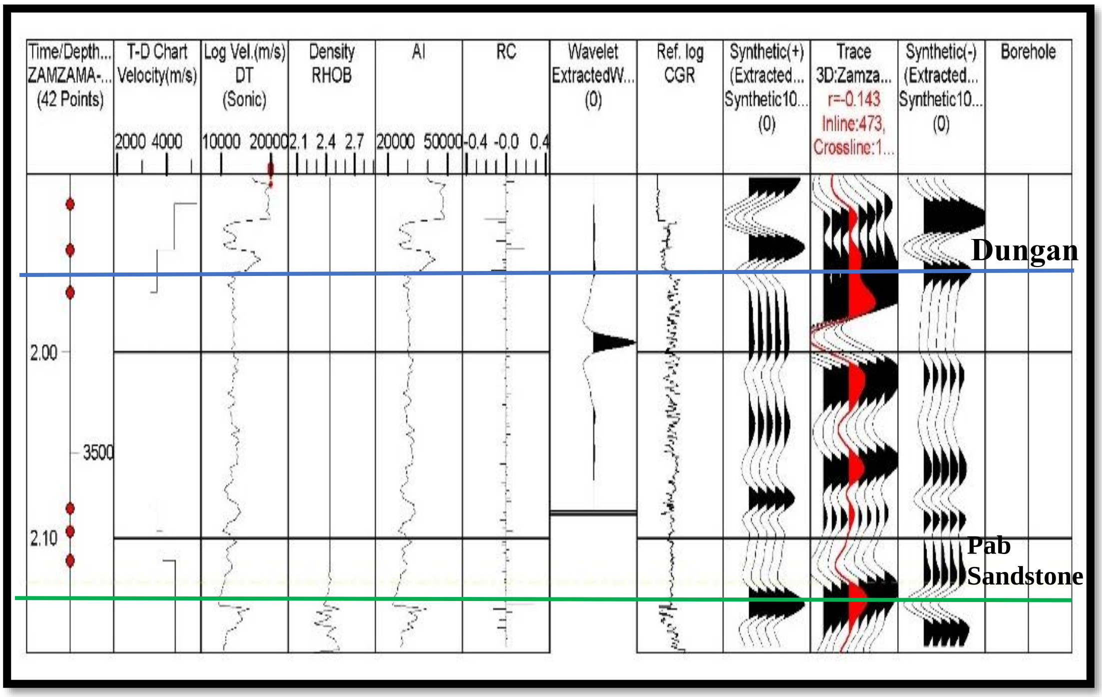

Figure 3.3 Synthetic seismogram of Zamzama-03 well (IHS Kingdom)

In synthetic we have TD chart in the first column, in the second column we have sonic log values which gives us velocity values and from density log we obtain density. Their product gives us acoustic impedance which helps us create reflection coefficient series. By convolving reflection coefficient series with the wavelet that we have extracted from the seismic data provided, gives us synthetic seismogram.

Synthetic seismogram is tied with the seismic reflection data in the time domain so that to mark the horizon of interested. The horizons that were picked during interpretation are:

Table 3.1 Formations marked on seismic section

Formation	Lithology	Age	Depth(m)	Time(s)
Dunghan	Limestone	Paleocene	2696	1.765
Pab Sandstone	Sandstone	Late Cretaceous	3528	2.116

For the interpretation Inlines are marked because they are oriented in the dip direction of structure. Based on literature, previous work and through the attributes of discontinuity it is confirmed that 3D data of Zamzama structure has a reverse faulting.

3.5. Seismic to well tie

After generation of synthetic seismogram, next step is seismic to well tie. The reason behind this tie is to mark the exact reflector of horizon on the seismic section. In 22 the figure, shows the exact location of formation along the synthetic traces of Zamzama-03. Interested formation are marked corresponding to their time.

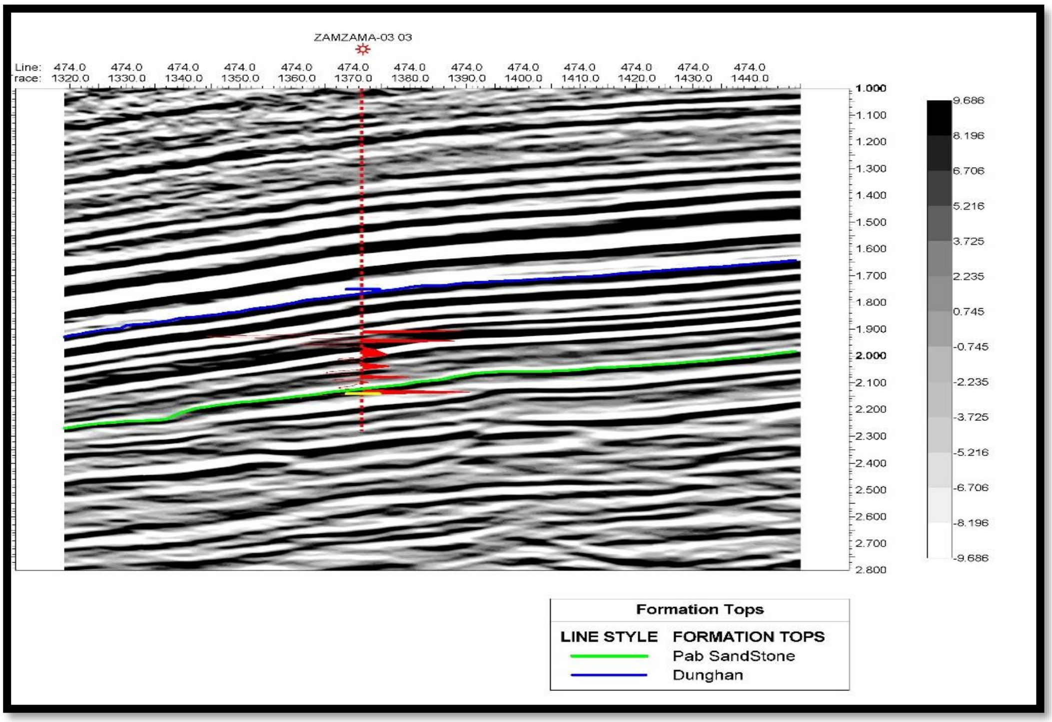

Figure 3.4 Interpreted seismic inline 474 with synthetic seismogram of Zamzama-03

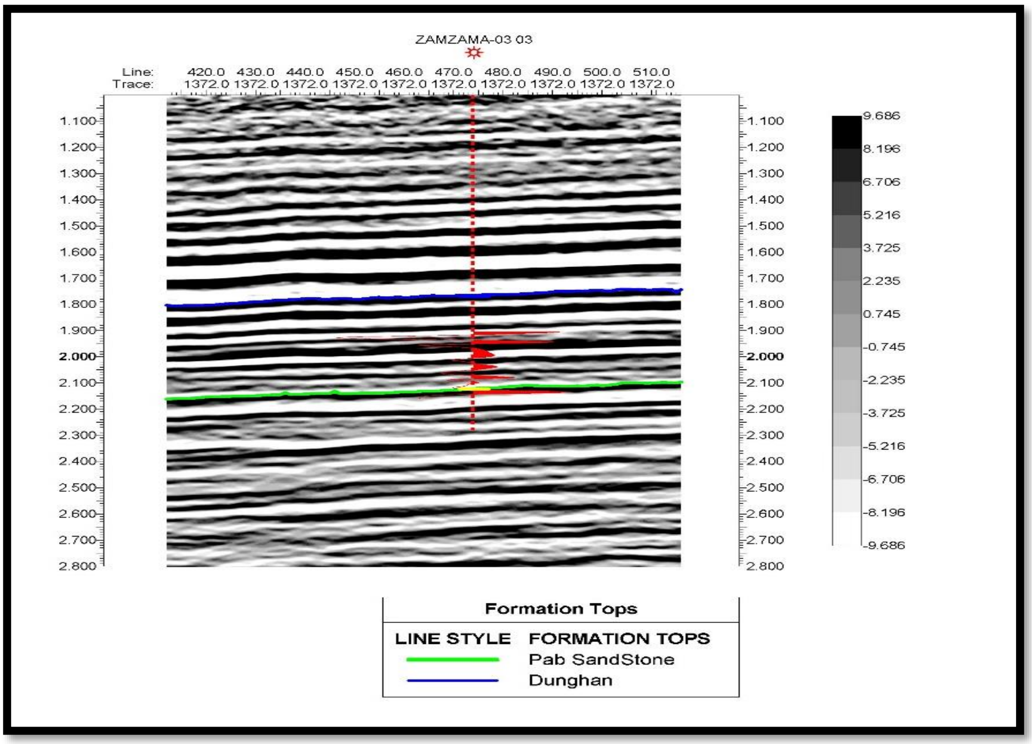

Figure 3.5 Interpreted seismic cross line 1372 with synthetic seismogram of Zamzama-03

3.6. Horizon Marking

It is the primary task of a seismic interpreter to mark the horizons with the help of generated synthetic seismogram on the seismic section using logs. This synthetic is correlated or tied with seismic to confirm the horizons. Kingdom SMT suite was used for marking the horizons. Well tops were correlated with seismic for marking the exact position of reflector. For the prospect generation, interpreter should be well aware of stratigraphy also the geological structure. Synthetic seismogram of Zamzama-03 well also its formation tops were used for the demarcation of structure and interpretation of horizons on the time section.

3.7. Interpretation of Inlines and Crossline

By using the synthetic correlated with the seismic section, main horizons on the Inlines were marked to better understand the Zamzama Structure and its trend.

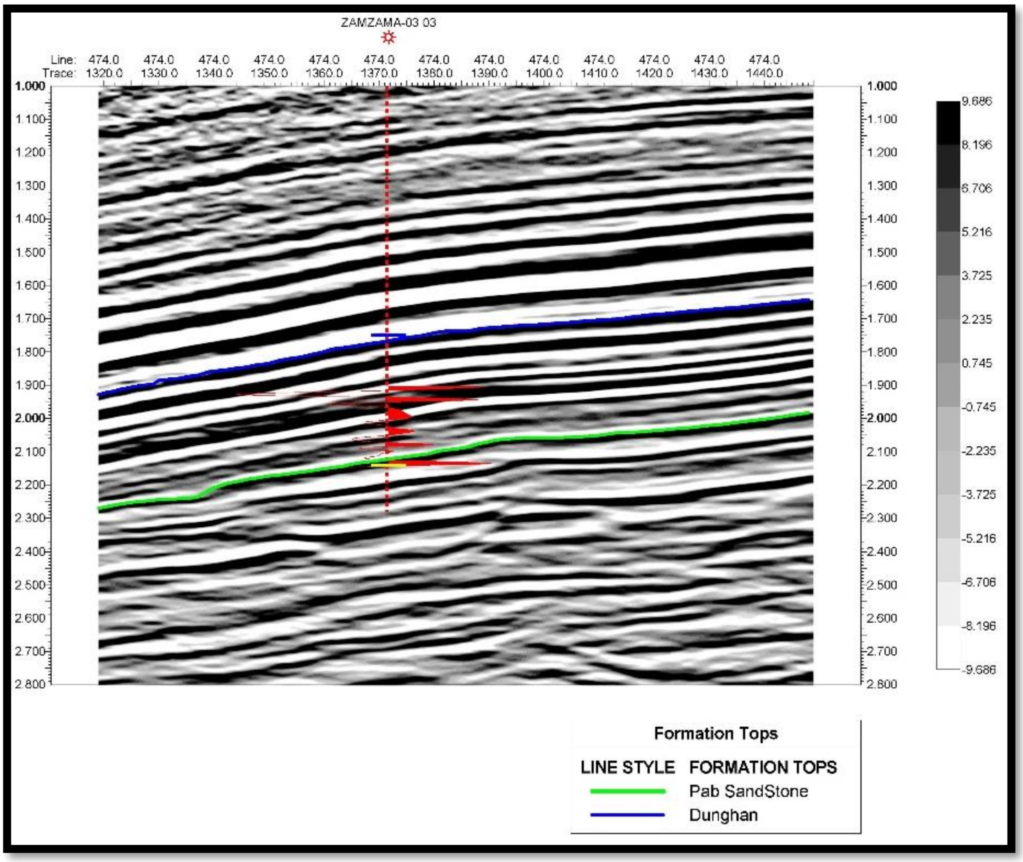

Figure 3.6 Marked horizons of inline 474

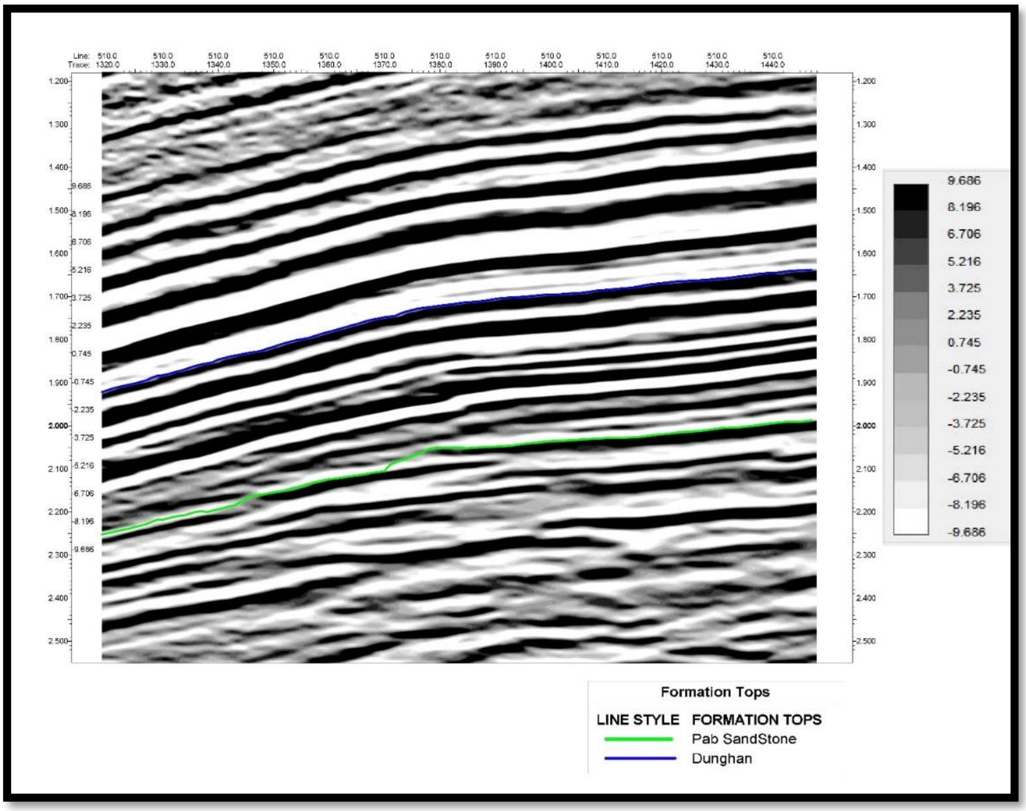

Figure 3.7 Marked horizon of inline 510

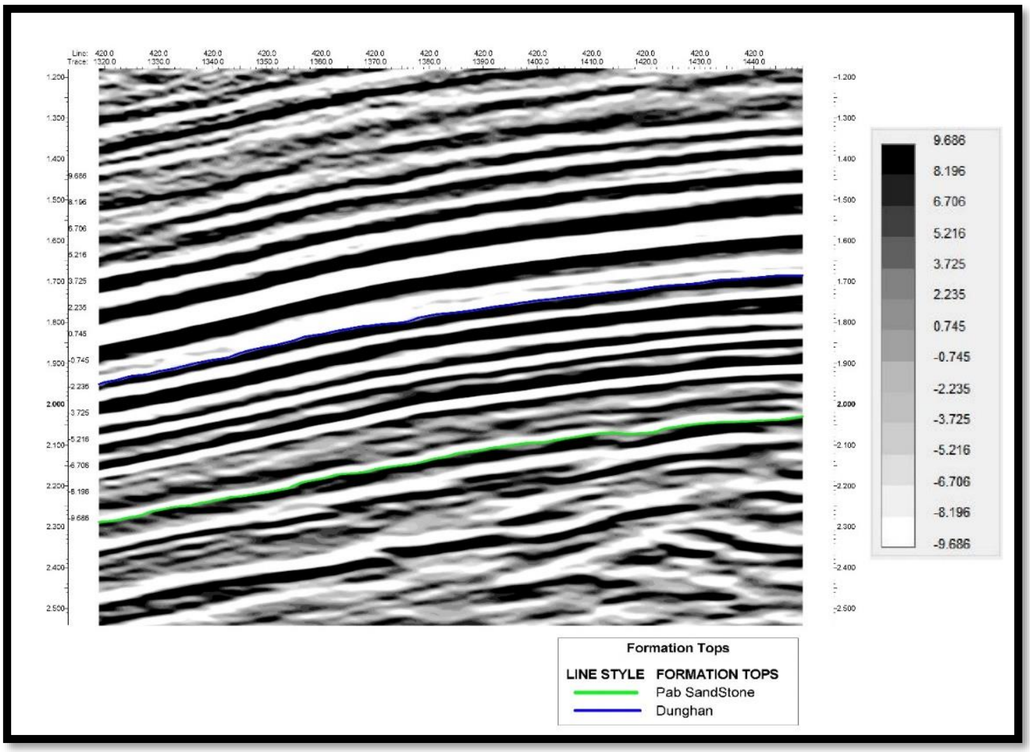

Figure 3.8 Marked horizon of inline 420

As it is much clear from the marked seismic section that there is no reverse fault, as the Zamzama structure actually consist of reverse faulting studied in previous work and literature review, it is because provided 3D-seismic provided contains no fault.

3.8. Computation of Time and Depth Contour Maps

After the marking of horizons in which we were interested, in this step we computed the contour maps. Basically, fault polygons are usually digitized after plotting our interpretation on the base map and then time contour maps are prepared as seismic data is usually in the time domain. Later on, depth contour maps are constructed with the help of depth grid of any given horizon, by using the average velocity, seismic data is converted in depth from time domain.

As it is obvious from the interpretation, data provided and interpreted lines contain no fault because 3D cube is away from faulted extension so, no fault polygons could be digitized, that shows the extension of fault in the study area. Time contour and depth map of Pab sandstone and the Dunghan formation were computed, that are discussed below.

3.9. Pab Sandstone

Pab sandstone is a chief reservoir of the Zamzama area, of late cretaceous age having lithology of mainly sandstone. In the figure 3.9 and 3.10 showing the time and depth-contour maps of Pab sandstone, red color in the figure denotes the elevated part, lesser time, and shallow area, indicating crest of anticlinal structure however blackish blue color in the contour map representing the deeper part and greater values of time, showing the verge of anticline. As it can be seen, color bar has the time range of 1992 to 2264 milliseconds.

Red color in depth-contour shows the deeper part of given cube and black-blue color showing the shallower area of cube and equivalent depth range is 3450 to 3900 meters. As Pab sandstone formation is a main reservoir having the thickness of approximately 220 meters.

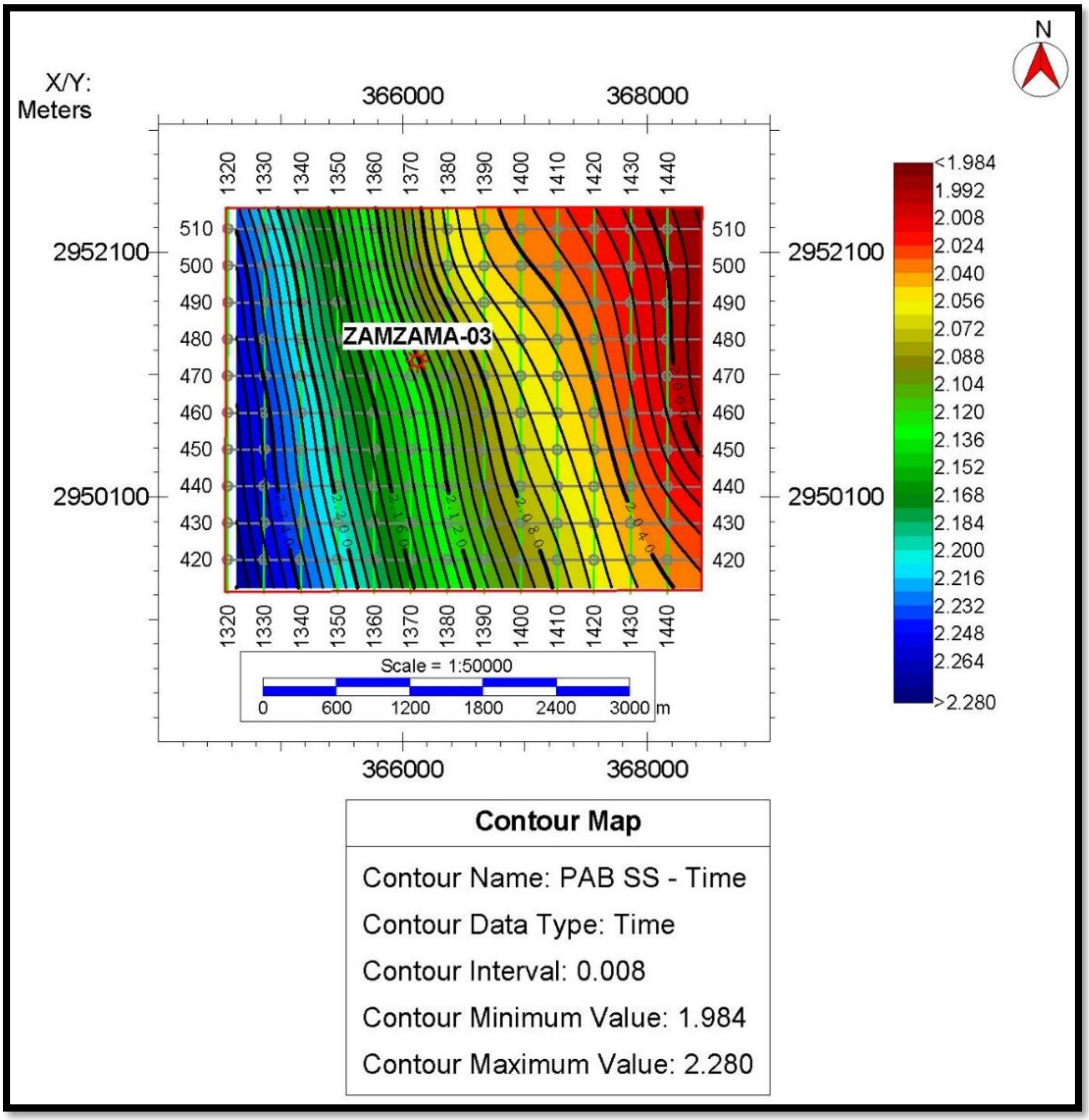

Figure 3.9 Time contour map of Pab Sandstone

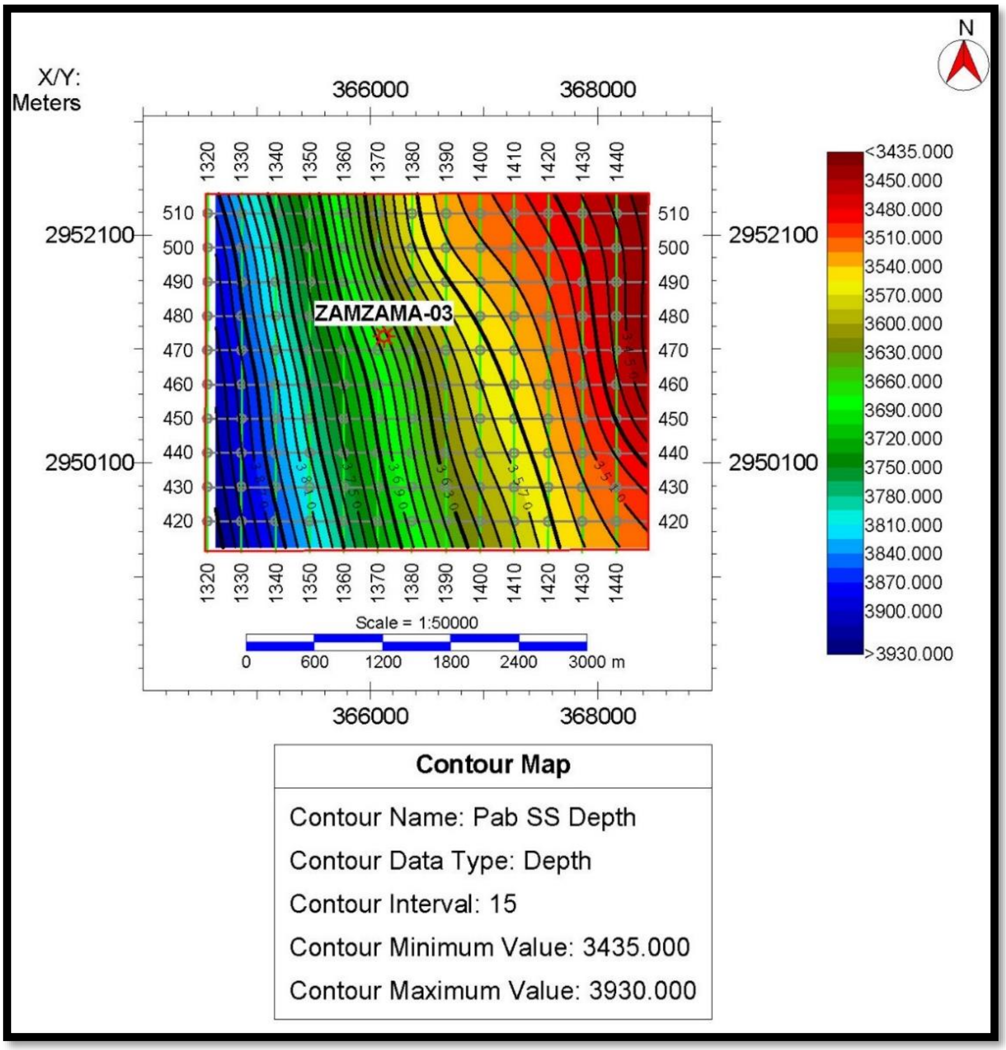

Figure 3.10 Depth contour map of Pab Sandstone

3.10. Dunghan Formation

The Dungan Formation is mainly well-developed in the Sulaiman and Kirthar provinces. The Dungan Formation in the study area dominantly consists of thin-thick bedded and massive limestone. At places, subordinate shale, conglomerates, and limestone are also seen the thickness of the formation varies from place to place and ranges from 100 m to 600 m (Cheema 1977).

Dungan Formation has been assigned to Late Paleocene to Early Eocene age (Latif 1964)

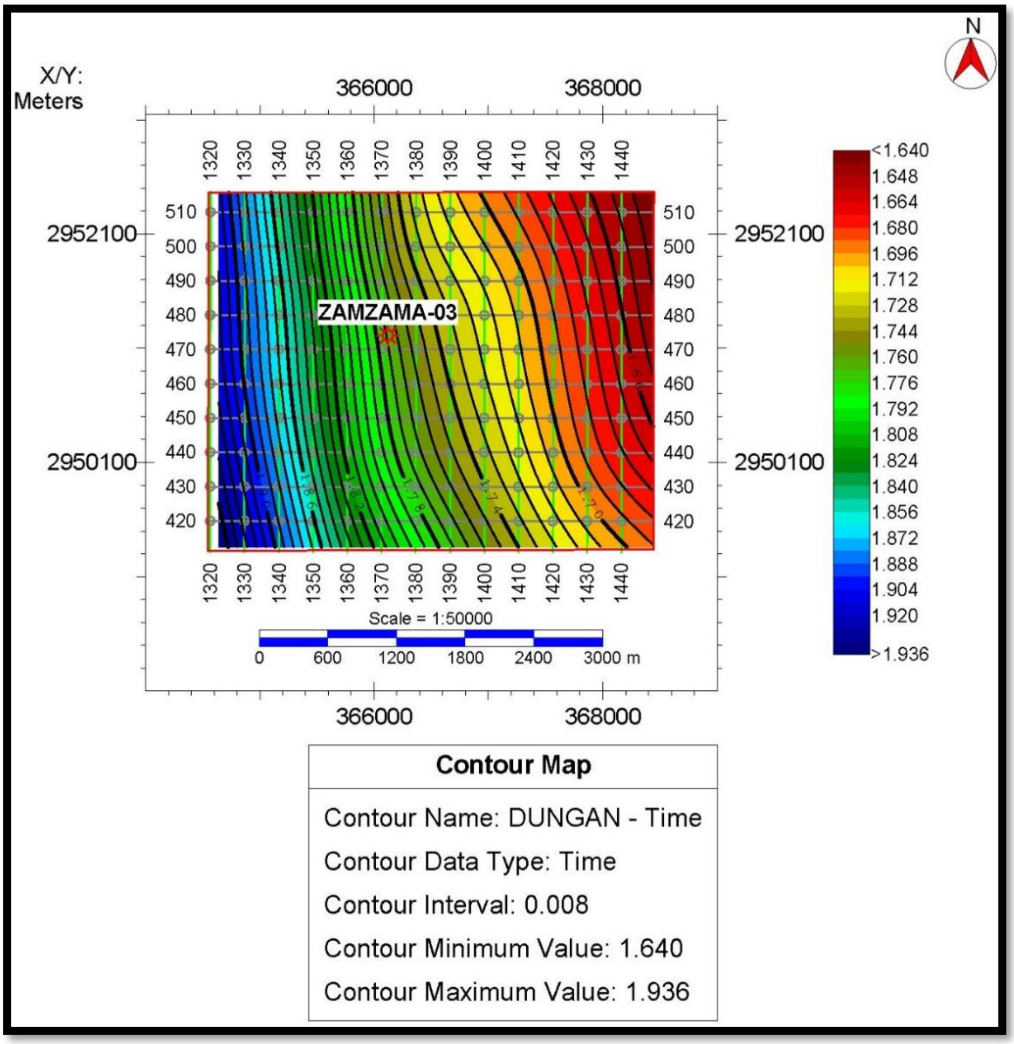

Figure 3.11 Time contour map of Dunghan formation

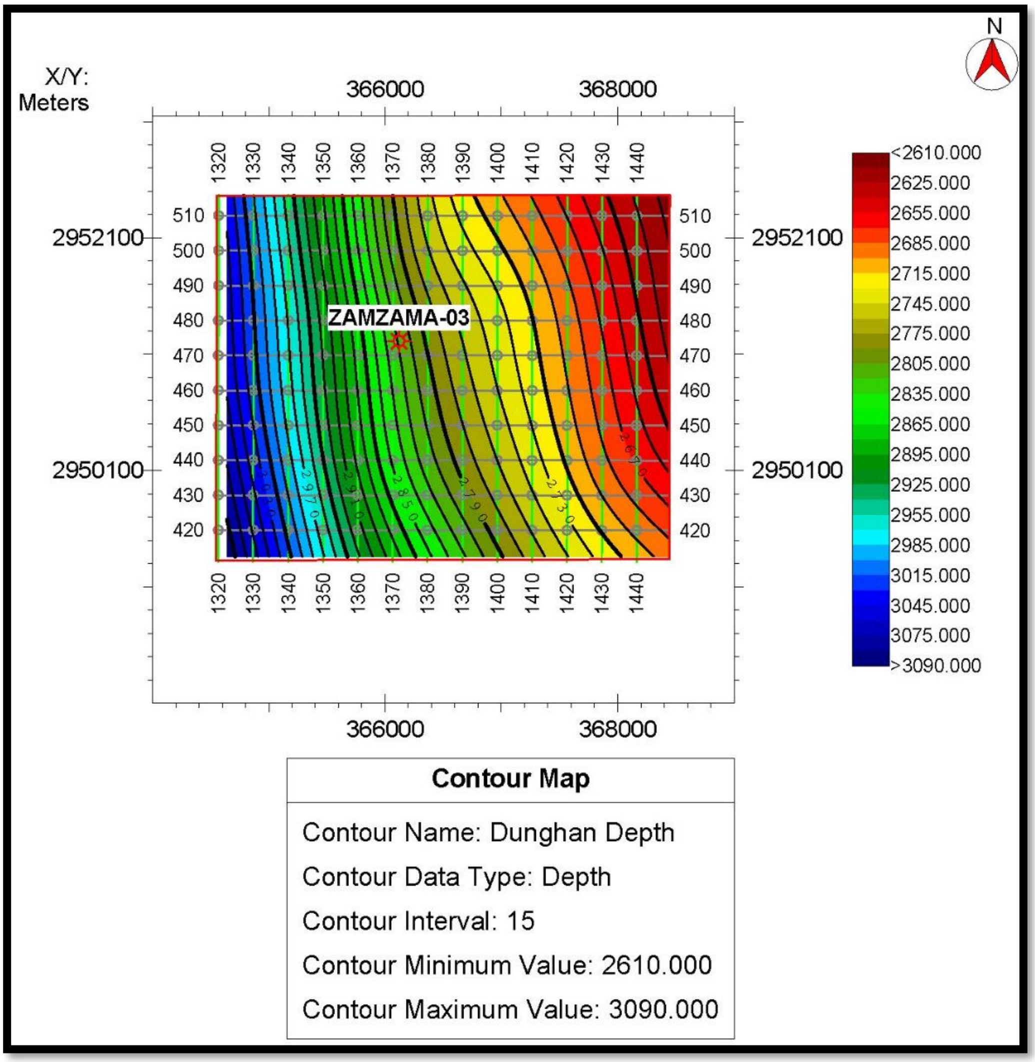

Figure 3.12 Depth contour map of Dunghan Formation

CHAPTER 4

PETROPHYSICAL ANALYSIS

Petrophysics is also known as the sub-branch of geology that is the study of reservoir characterization, identification, and quantification of hydrocarbon present in the reservoir moreover their interaction with the gases and aqueous solution. To quantify and identify the fluid properties and the rock properties, that aid reservoir characterization, petrophysical interpretation was carried out by evaluation of well log data. For the determination and quantification of key geological and geophysical parameters, well logging is being done, along the well's depth. Sonde, the instrument that is utilized for well logging, that identify some of physical, chemical rock properties and their contact with the fluids, (Rider., 1960).

4.1. Wireline Logging

Traditionally, well log is the plot of the various measurements of physical properties of rock versus depth. To evaluate formation and to acquire a continuous curve of the properties of rock, wireline log is used in oil and gas sector. Wireline log is concisely defined as, "the acquisition and the investigation of geophysical properties, performed as a function of well log depth, also with the aid of other related services". Wireline log is available in diversified variety categorized by its individual dedicated measurement or function. Before the oil and gas well is lined or cased 'open hole logs' are run and after the well is lined with casing or production pipe 'cased hole logs' are run (Cannon, 2016).

4.2. Well Data Used

Data was provided by the LMKR with well Zamzama-03 after approving from DGPC. LMKR provided the well data in the digital form i.e., Las (Log ASCII Standard) file format, following well was present in the file.

1. Gamma Ray Log
2. Caliper Log
3. Sonic Log
4. SP Log
5. Resistivity Log
6. Density Log
7. Neutron Log

Well tops and their headers were also given by LMKR. Petrophysical analysis of Zamzama-03 was carried out only. Below is the concise introduction of well and tops given. This well lie at the Inline 474 and Crossline 1372 With the help well tops seismic data was correlated with the seismic.

Table 4.1 Well Header Information of Zamzama-03 Provided by LMKR

Well Name	Latitude	Longitude	KB(m)	Total Depth(m)
Zamzama-03	26°40’ 32.15N	67 ° 39’16.25 E	40.00	3380

Table 4.2 Borehole stratigraphy of Zamzama-03

Sr. No	Formation Top	Formation age	Depth (m)	Thickness (m)
1	Siwalik	Miocene Pleistocene Pliocene	0	1452
2	Gaj	Miocene	1452	84
3	Nari	Oligocene	1536	631
4	Kirthar	Eocene	2167	159

5	Ghazij		2327	144
6	Laki		2471	390
7	Dunghan	Paleocene	2861	421
8	Girdo		3282	362
9	Khadro		3645	63
10	Pab Sandstone	Late Cretaceous	3708	220
11	Fort Munro	Late Cret/Early Cret	3928	104

4.3. Flowchart of Petrophysical Analysis

Different log curves were used for petrophysical analysis of Zamzama-03 well. This process is followed by the steps given below.

1. Vsh (Volume of Shale)
2. PHID (Density Porosity)
3. PHIT (Total Porosity/ Average Porosity)
4. Sw (Water Saturation)
5. Sh (Hydrocarbon Saturation)

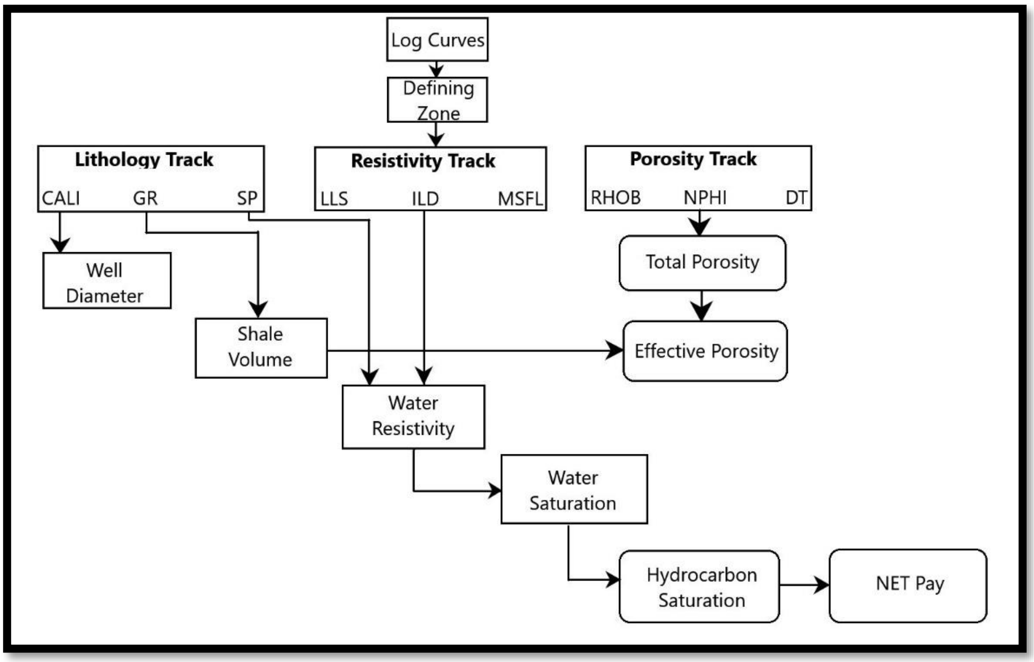

Figure 4.1 Schematic workflow followed in petrophysical analysis

4.3.1. Calculation of Vsh (Volume of Shale)

Some of the sedimentary rocks are radioactive depending on the available organic content. Shale generally shows the strong radioactive behavior, in alluvial rocks, due to this gamma ray (GR) recording also known as the shale recording. GR log is typically used to quantify and identify VSH, as well as potential SP logs. The sand base is the lowest average GR record value, which is exhibited when no shale is present, and the shale base is the highest average GR record value, which is shown by the shale baseline. The shale volume (Vsh) can be derived from log GR using a linear scale (Doll, 1948).

$$\mathrm{VSH} = \frac{\mathrm{GR}-\mathrm{GR_{min}}}{\mathrm{GR_{max}} - \mathrm{GR_{min}}} \text{ ---------------- } (4.1)$$

Where,

Vsh = Volume of shale

GR = GR values of Formation

GR(max) = Maximum value in GR

GR(min) = Minimum value in GR

4.3.2. Calculation of Porosities

Porosity is directly related to the quantification of the reservoir, since the oil and gas are contained in the reservoir in the small voids present in the rocks. The number of voids per unit volume of rock is called rock porosity and permeability is defined as the rock's ability to transfer fluid through these voids predicted by their interconnection (Wyllie’s et al, 1958).

4.3.2.1. Density Porosity Calculation

Calculate the density - porosity using the density log data. The porosity may be properly determined using the density log if the densities of the discovered rock matrix are known (Asquith and Gibson., 2004). The primary focus in the research was Sandstone. The following equation was used to calculate the porosity density: (Rider., 1986).

$$\mathrm{PHID} = \frac{\rho_m - \rho_b}{\rho_m - \rho_{fl}} \text{-------------(4.2)}$$

Where,

PHID = Density, Porosity

ρ_b = Bulk density

ρ_m = Density of matrix

ρ_f = Fluid density

4.3.2.2. Average Porosity Calculation

To calculate the average porosity, the neutron porosity and the log porosity density calculated previously were used. PHIA was calculated by using the equation mentioned below.

$$\mathrm{PHIA} = \frac{\mathrm{PHID}+\mathrm{PHIN}}{2} \text{ -------------- (4.3)}$$

Where,

PHIA = Average Porosity

PHID = Density Porosity

PHIN = Neutron Porosity

Average porosity log was used to calculate the effective porosity.

4.3.2.3. Effective Porosity Calculation

The ratio of the volume of rock that has interconnected pore spaces to the total volume of that rock, known as the effective porosity, after removal of the shale that affects that rock. For the shale-rich parts of any formation, the effective porosity will be zero. PHIE was calculated by using following equation.

PHIE = PHIA * (1-Vsh) --------------(4.44)

Where,

PHIE = Effective Porosity

PHIA = Average Porosity

Vsh = Volume of Shale

4.3.3. Measurement of Resistivity of Water

For Rw calculation of Zamzama-03 well, Pickett plot method was used to determine the reservoir resistivity using the Archie equation with factors a= 1, m= 2, and n = 2. Water saturation Sw and resistivity index I are determined using this approach, which uses a log-log plot of deep resistivity (LLD) vs porosity (eff). True resistivity is a function of porosity, water saturation, and cementation factor, according to the Pickett plot approach (Ali et al., 2019). The Rw for the Zamzama-03 well is 0.0247. Rw is calculated by Pickett Plot method.

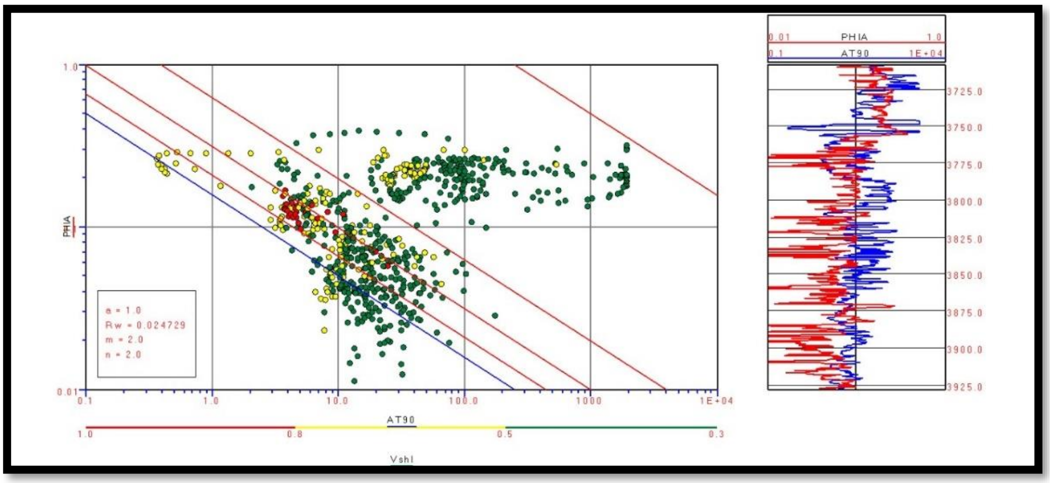

Figure 4.2 Pickett plot for estimation of Rw in Zamzama

4.3.4. Water Saturation (Sw) Calculation

Water saturation is defined as the ratio of water volume to pore volume, or the percentage of effective pores filled with water in a particular formation. Using the following equation, water saturation (Sw), also called Archie's equation (Asquith and Gibson., 2004).

$$Sw = \sqrt[n]{\frac{a \times R_w}{R_t * PHIA^\wedge m}} \text{ ------------- } (4.5)$$

Where,

Sw = Saturation of Water

a = Tortuosity factor

m = Cementation factor

n = Saturation exponent

Rw = Resistivity of formation and water

PHIA = Average porosity

4.3.5. Calculation of Hydrocarbon Saturation

The amount of pore spaces in a formation that contain hydrocarbons is known as hydrocarbon saturation, and it may be computed using the equation below.

Sh = 1- Sw --------------- (4.6)

Where,

Sh = Hydrocarbon Saturation

Sw = Water Saturation

4.4. Petrophysical Analysis of Pab Sandstone

The petrophysical analysis Pab Sandstone was carried out with the availability of three basic tracks, also known as triple combo which is listed below.

1. Lithology Track
2. Resistivity Track (LLD/LLS)
3. Porosity Track

4.5. Zone of Interest Marked

Two zones of interest were marked fulfilling all the criteria for being a good reservoir. First zone starts from 3713 to 3720 m with a thickness of only 7 meters. Average porosity for this zone is 14% while, the effective porosity is calculated as 10%. The calculated water saturation is 67.5% and hydrocarbon saturation 32.46% is estimated as. After these good results, this zone turns out to be a good pay zone for this well.

Table 4.3 Calculated petrophysical parameters of Pab Sandstone (Zone 1)

Depth (m)	Vsh (%)	PHIA (%)	PHIE (%)	Sw (%)	Sh(%)
3713-3720	14	14	10	67.54	32.46

Second Zone starts from 3785 to 3800m with a thickness of only 15 meters. Average porosity for this zone is 9% while, the effective porosity is calculated as 8%. The calculated water saturation is 74.03% and hydrocarbon saturation 25.97% is estimated as. After these good results, this zone turns out to be a good pay zone for this well.

Table 4.4 Calculated petrophysical parameters of Pab Sandstone (Zone 2)

Depth (m)	Vsh (%)	PHIA (%)	PHIE (%)	Sw (%)	Sh(%)
3785-3800	11	9	8	74.03	25.97

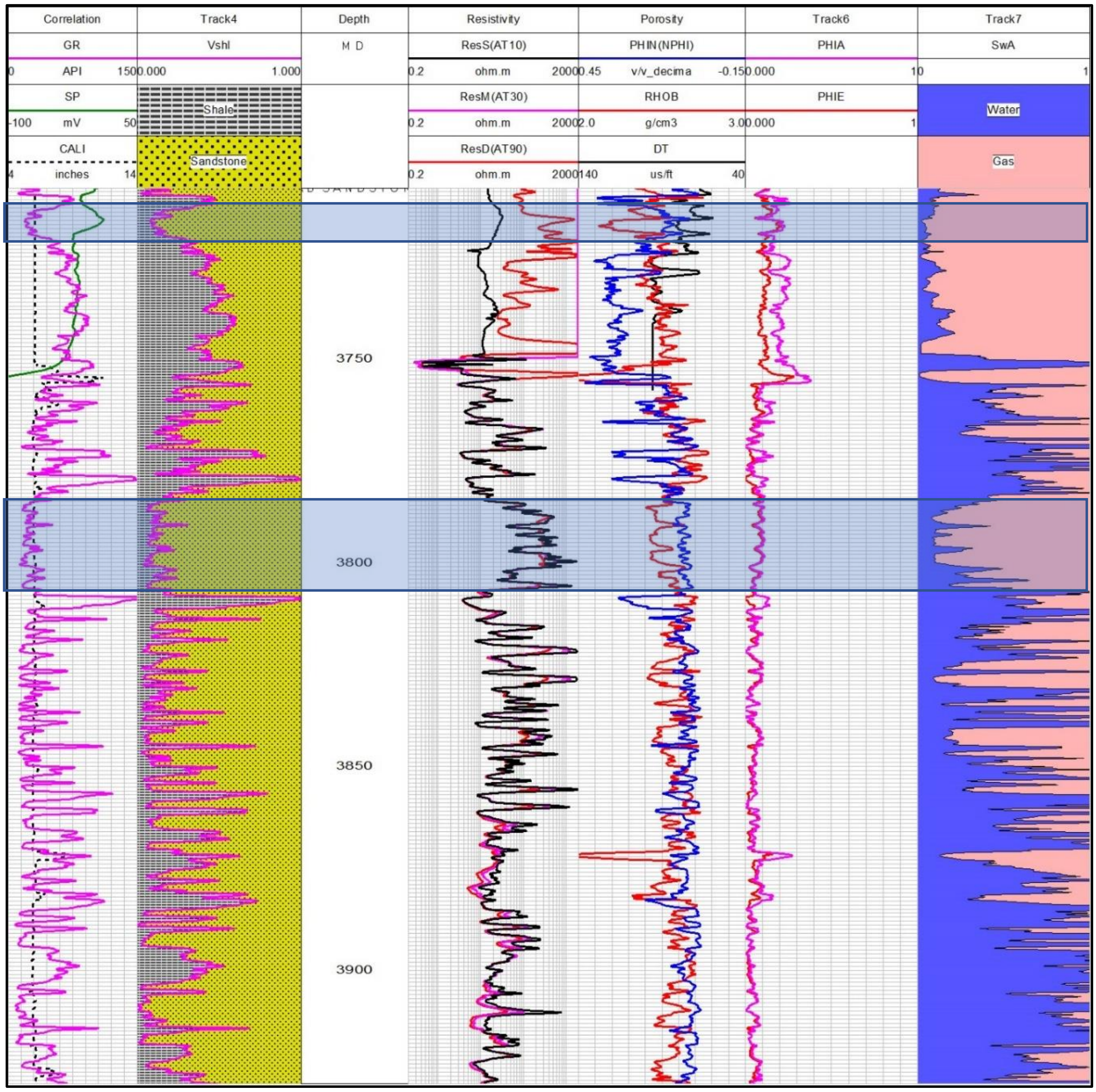

Figure 4.3 Petrophysical analysis of Pab Sandstone

CHAPTER 5

INVERSION ANALYSIS

Seismic inversion is a reverse modelling tool which characterizes the reservoir by deriving the impedance seismically and correlating it with the log data to gain other rock properties and it also helps to extend the well information all over the reservoir. By eliminating the wavelet introduced into the data during the capture or processing processes, seismic inversion is a way of calculating the rock's property, i.e., the seismic data's acoustic impedance. Seismic inversion employs a variety of techniques, including model-based inversion, stochastic inversion, genetic inversion, sparse peak inversion, and geostatistical inversion (Francis, 2014)

Generally, inversion begins by the creation of an initial geological model that fits and depicts genuine seismic data. This model is updated by increasing its parameters until the estimated data best matches the seismic data observed. The matched model aids in the extraction of hidden information and the prediction of physical features of the reservoir under investigation. Inverted P impedance, that is a result of layer velocity and density multiplication, is seen in seismic inversion. The goal of inversion is conversion of seismic data into rock properties such as acoustic impedance, elastic impedance, shear impedance, density, velocity, and other well logging parameters such as porosity, saturation of water, and shale volume by establishing a good relationship between impedance and these properties in order to extract petrophysical properties for the entire seismic volume (Veeken and Da Silva, 2004). The interpreter can further constrain the most likely zone for hydrocarbon accumulation by obtaining fine information on such criteria. Seismic inversion will eventually aid in reducing the risk of well failure and assisting in decision-making in the exploration industry for well planning (Veeken and Da Silva, 2004).

Furthermore, this process is also used in optimal development of field along with the reservoir characterization(Barclay et. al, 2008).

Moreover, this process is used in the optimal development of the field as well as the characterization of the reservoir (Barclay. Et. Al, 2008).

To monitor the observed changes in rock properties, reservoir characterization, and well planning resulting from injection or fluid production, the reverse or seismic inversion modeling technique is a very useful attribute (Gavoti et. al., 2014).

In order to monitor the changes observed in properties of rocks, characterization of reservoir and well planning that resulted from injection of fluids or production, Seismic inversion / reverse modeling technique is very useful attribute (Gavoti et.al., 2014).

Seismic post stack is basically divided in to three of its types (Hampson, and Russell, 1991).

1. BLI (Band limited inversion)
2. SSI (Spark Spike inversion)
3. MBI (Model Based Inversion)

In this research work, Model-Based technique was applied on the given data of Zamzama area, and it provided good results with better lateral resolution.

5.1. Basic Theory

Inversion is created on the basis of convolutional model which defines that the generation of traces of seismic ST with help of convolving a wavelet WT including the earth reflectivity function RT along with the added noise NT.

$$ST = RT * WT + NT \text{ ------(6.1)}$$

Whereas the “*” sign represents the convolution of wavelet operator. If the noise is considered as zero or negligible, then above equation 6.1 becomes.

$$ST = RT * WT \text{ -------(6.2)}$$

The reflection coefficient of earth is calculated with help of equation given below,

$$R_c = \frac{\rho_{i+1}V_{i+1} - \rho_i V_i}{\rho_{i+1}V_{i+1} + \rho_i V_i} ----(6.3)$$

Where, vi is p-wave velocity and ρi is density and layer i+1 is overlain by layer i. The basic equation 6.1 is used to invert data in seismic inversion. After removing the noise, the residual seismic trace is deconvolved using equation 6.1 and the inversion of the source wavelet. It generates the earth's unique reflectivity, from which impedance can be determined by rearranging equation 6.1, which provides the impedance of each layer, converting surface property into layer property. Throughout the operation, the goal is to retrieve the true amplitude. (Russell, 1988). For inversion extraction of inverse wavelet is a basic process which is later convolved with data that is comes from seismic to extract the coefficient furthermore reordering equation 6.3 give value of each layer in term of inversion as calculated by equation which transform reflection coefficient (produced by interface) into layer property (Russel, 1988).

$$\rho_{i+1}V_{i+1} = \rho_i V_i \frac{1+R_i}{1-R_i} ------ (6.4)$$

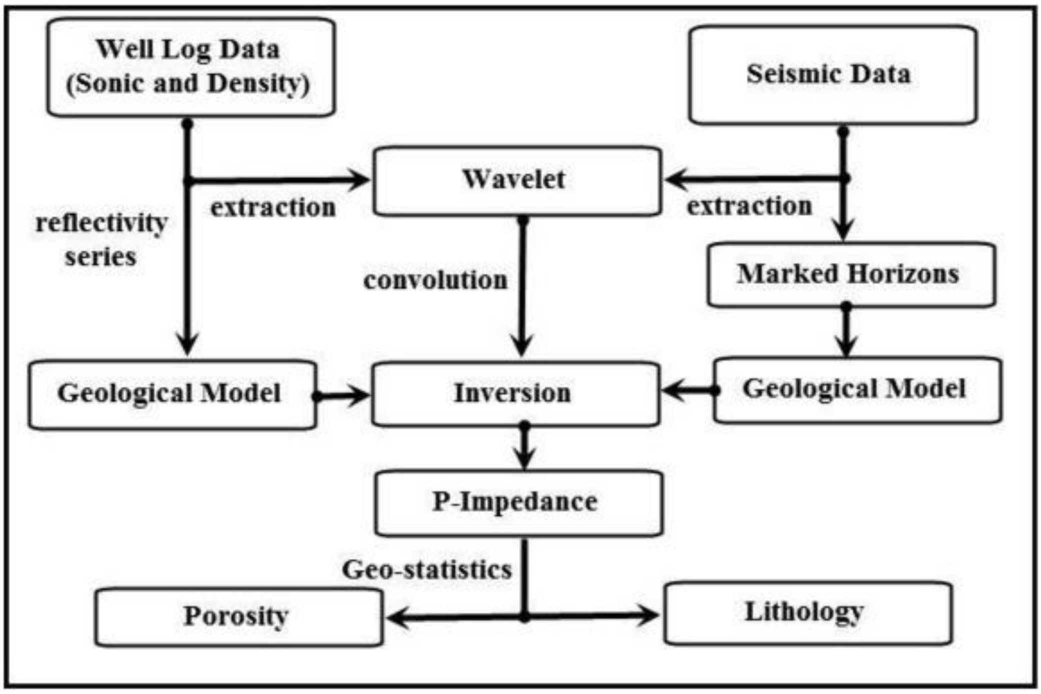

Figure 5.1 Basic workflow of inversion

5.2. Post Stack Inversion

Stacked Seismic data is given as input for post stack inversion. Stacking reduces the noise effect from the signal by keeping true amplitude preserved (Da Silva et al., 2004). Traces from common-mid-point (CMP) are picked and stacked at zero incidence angle. Resulting seismogram represent reflectivity at normal incidence. So, inversion performed on such seismic data is called post-stack seismic inversion. Seismic post stack inversion is robust technique with its simpler assumptions. It has two approaches broad band inversion and band limited methods respectively (Mallick, 1995). Furthermore, broad band inversion classified into sparse spike and model-based inversion.

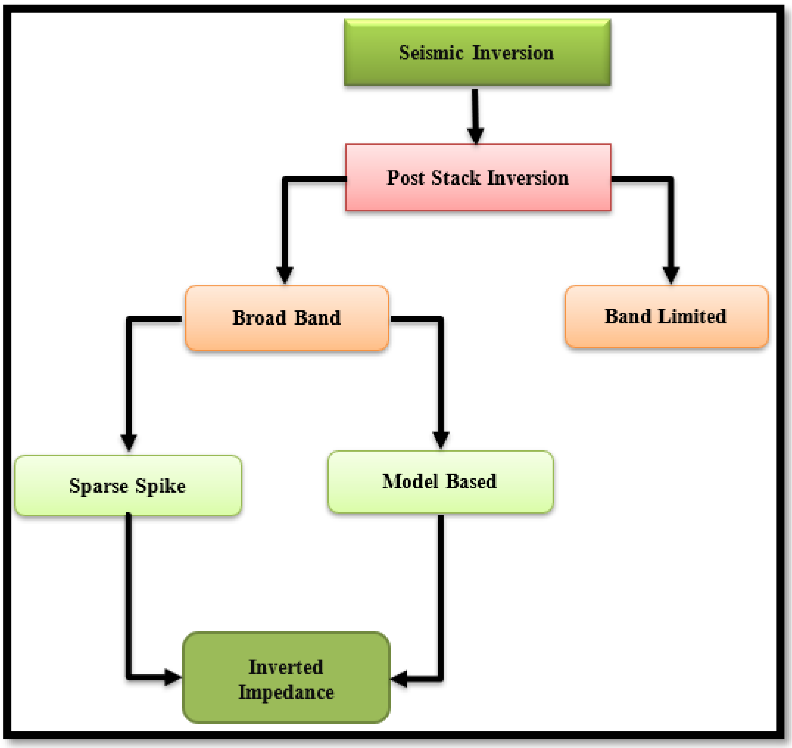

Figure 5.2 Workflow of seismic post stack inversion for impedance estimation.

5.3. Model Based Inversion

Convolution theory is the bedrock of model-based investing. According to convolution technique, the seismic traces with normal incidence can be represented as the convolution of the source wavelet with terrestrial reflectivity plus the addition of noise.

The post stack model-based inversion begins with the original model acquired by geology and interrupts the problem of synthetic seismogram and seismic trace have a high correlation. It's an intriguing strategy because it doesn't allow you to flip seismic data directly (Mallick, 1995). Model based inversion is affective for thin reservoir because seismic data is band limited, the resolution and accuracy of directly inversion approaches may not fulfills requirement of production companies. Model based inversion contains mutually low and high elements of frequency so comprehensive information about stratigraphic and natural properties is obtained (Karim et al., 2016). For Model-Based inversion method, a linearly generalized algorithm of inversion is operated. The algorithm utilized is totally based on the matching of initial model constructed, as it is an iterative process model is updated and improved until and unless matching of synthetic trace and actual trace is done unless optimal level achieved (Gavottiet al., 2014). To minimize the matching error that lie between synthetic and original seismic trace, added initial geological model is altered in an iterative way.

If we have enough background of geology of particular area then an effective and optimal model can be created as this approach is consistent (Kneller et.al., 2013).The basic postulation in seismic post stacked inversion is to remove and measure degree of misfit that is present between real and synthetic data, basically the approach used in the algorithm is given in equation below.

$$J = \text{weight}_a \times (S - W * R) + \text{weight}_b \times (M - H * R) \text{------------} (1)$$

In the equation mentioned, seismic trace mentioned by S, W for wavelet extracted form seismic data, reflectivity series by R data, initial created model denoted by M and integration operator. As it is obvious that in the initial part of equation is modelled with seismic trace and other part actually modelled the initial model estimated (Gavotti et. al., 2014).

A schematic workflow for illustration of Model-based inversion can be visualized for better understanding of the model-based technique in (figure 5.3).

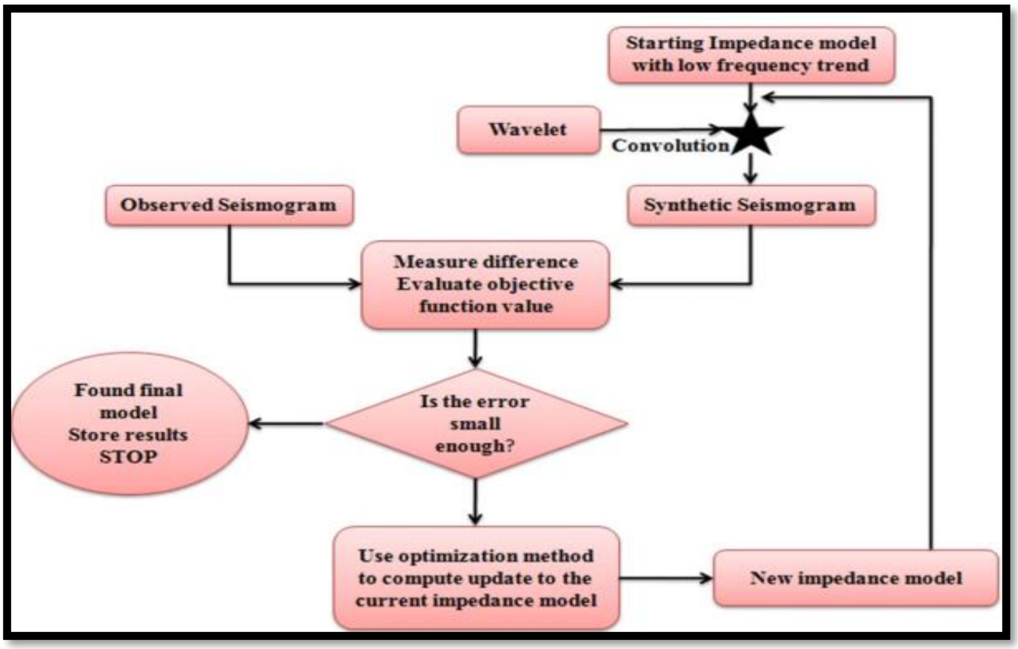

Figure 5.3 Workflow describing Model-based seismic inversion algorithm.

5.4. Methodology

Inversion techniques consist of following steps shown in (figure 5.4). Discussion about seismic data and picking of horizons is done in chapter three. So, in this section rest of the steps are discussed briefly. Hampson and Russell Software is used to perform the model-based algorithm of post stack inversion

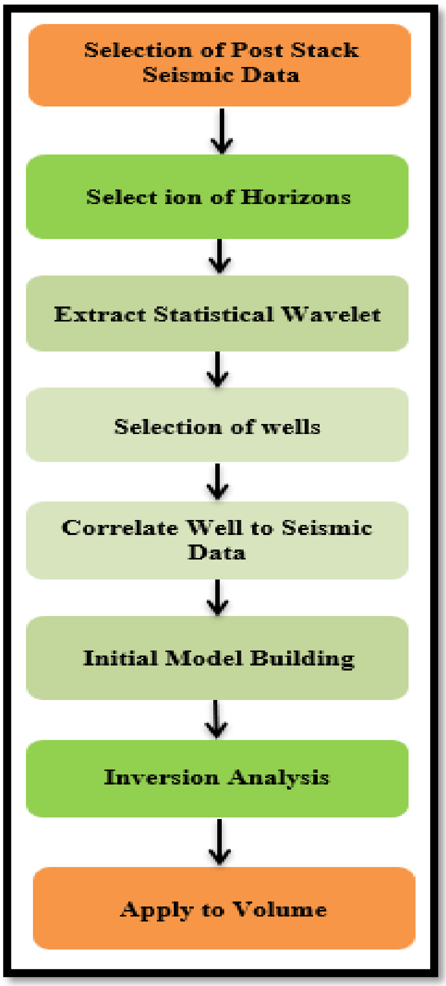

Figure 5.4 Steps followed for seismic inversion.

5.4.1. Wavelet Extraction

Estimation of seismic wavelet form the seismic data or of particular source used, very crucial and for various techniques of inversion that is required to be very accurate for generating the synthetic trace by convolution of wavelet with the reflectivity series, we are interested in (Hampson-Russel, 2007).

Wavelet is altered with time and depth depending on different effects happening in subsurface and making it more complicated (Barclay et al., 2008**).** This extracted, statistical wavelet was picked from the time window range of 1000-3000 ms with the wavelength of 200ms along with the tapper length of 25ms.

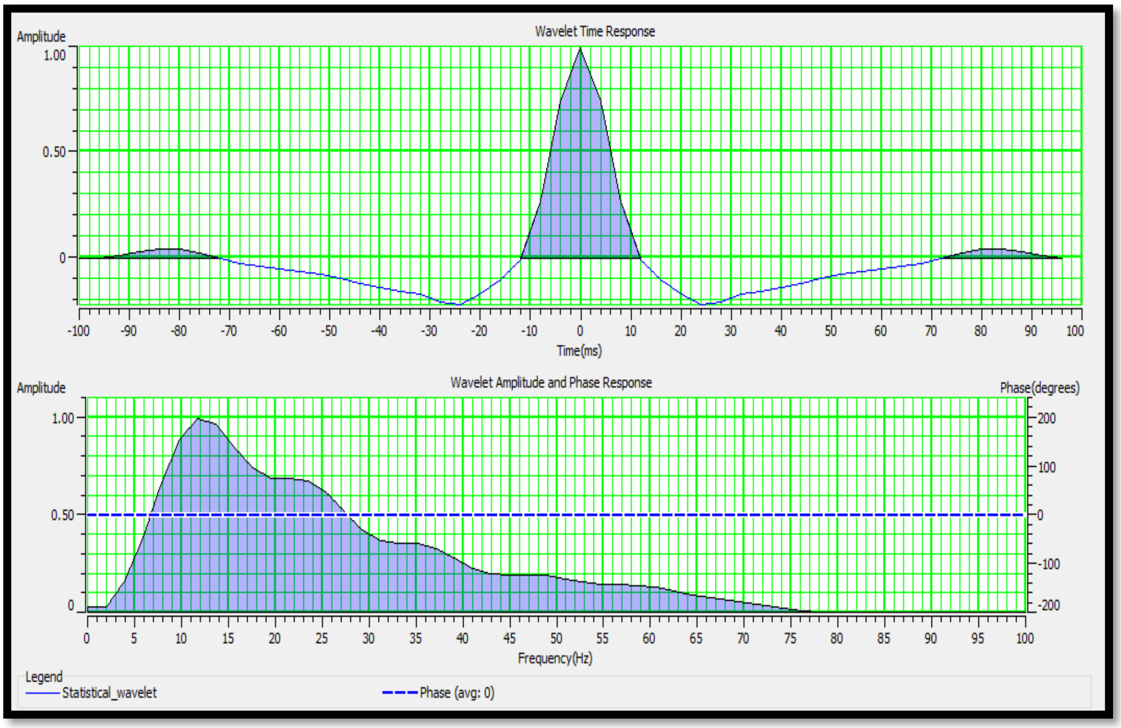

Figure 5.5 Extracted seismic statistical wavelet for seismic inversion

Phase is very much important in seismic interpretation and inversion method, for getting desired results wave phase should be minimum or zero phase. As inversion results are greatly affected by the phase shift in the input. In the figure below dotted line denoting the average phase of statistical wavelet extracted. In the resultant impedance results, if the phase shifter is greater than error will be higher (Jain,. 2013).

5.4.2. Initial low frequency model

Estimation of initial model of low frequency is based on acoustic impedance, as acoustic impedance can be divided in to two types as listed.

1. Relative Acoustic Impedance
2. Absolute Acoustic Impedance

Generation of low frequency model is not required by relative acoustic impedance for its calculation. Because of relative properties of layers, it is useful for the qualitative interpretation of seismic sections.

For both quantitative and qualitative interpretation of seismic data absolute acoustic impedance is used because it is an absolute property of layers (Cooke and Cant, 2010**).** Initial lower frequency model was required for inverting the given seismic amplitude data, in inversion algorithms, addition of required lower frequency model for inversion guarantee results to be more significant in interpretation (Lindseth , 1979).

In the inversion algorithm of Model-based inversion it is a requirement to add an initial low frequency model rather than generating an isolated model of low frequency as it is done in Sparse Spike method of inversion (Cooke and Schneider, 1983).

Initial obtained low frequency model is generated by using density and sonic log in vicinity of well. Estimated initial model of low frequency can be visualized in (figure 5.6).

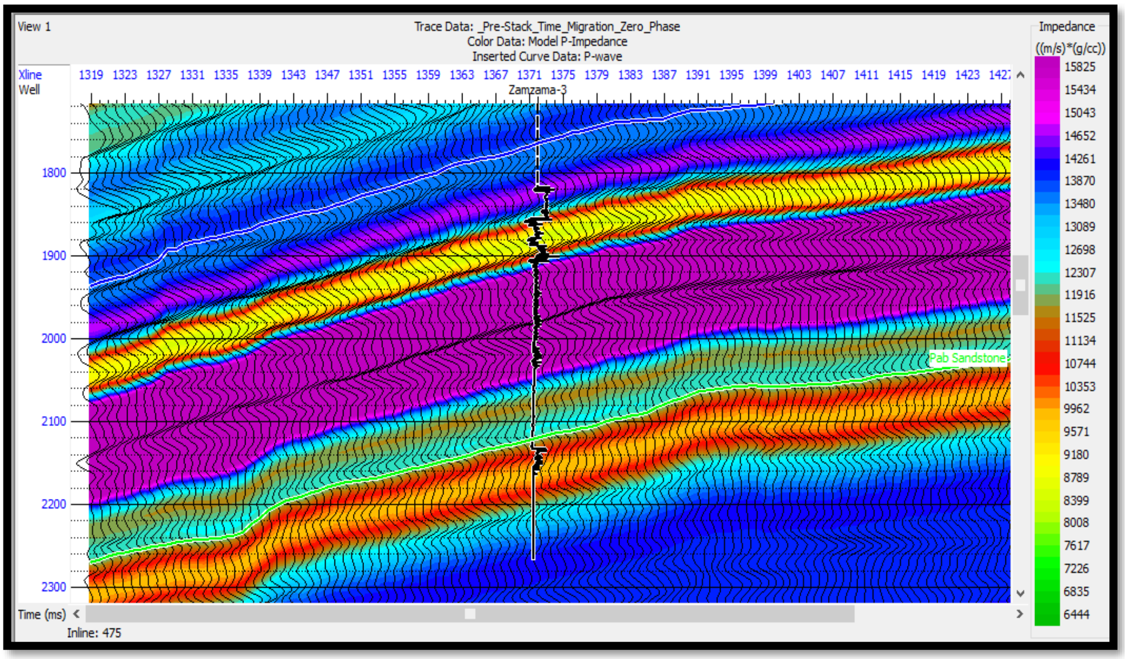

Figure 5.6 Initial frequency model of seismic section at well location.

5.4.3. Inversion Analysis

The provided seismic cube data was analyzed for MBI at the well site, Zamzama-03. The wavelet extracted from the time window of 1000 to 3000ms. Wavelet extracted seismically, was adjusted by the comparison of synthetic trace and inverted trace at the well location. From the figures 5.4 shown, it can be seen that correlation between seismic trace (black) synthetic (red) is good having the correlation coefficients of (0.09978) with the root means square error between the seismic trace and synthetic is 0.0654.

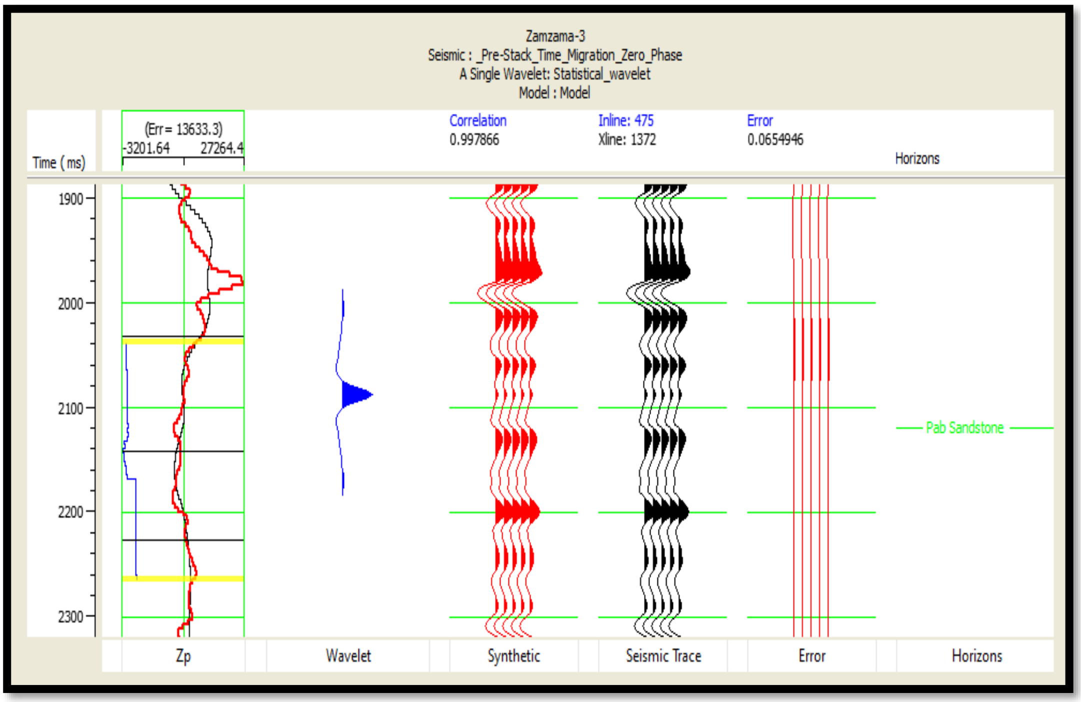

Figure 5.7 Model Based Inversion analysis of Zamzama-03

Inverted impedance estimated by using MBI algorithm of seismic post stack inversion resolved the impedance zone of Pab Sandstone Formation with Impedance of range 10553 to 11525(m/s)*(g/cc), as show in (figure 5.9). For the QC of this inverted section P-impedance curved is inserted with its matching color data which shows well computed impedance agrees well with the MBI inverted impedance. Impedance value of formation gives the indication of hydrocarbon bearing zone. To confirm the availability of hydrocarbon, porosity is also estimated.

5.4.4. Results of Model Based Inversion

From the analysis of model-based inversion it can be observed that seismically derived inverted impedance better match and picks the trend of well log impedance furthermore, it is concluded that the coefficient of correlation between derived synthetic (black) and seismic trace(red) is almost 99.7% for zamzama03 (figure 5.7). Pab Sandstone interval picked at 2116 ms having low impedance of 10500 (m/s) *(g/cc) as shown figure 5.9. Model based inversion easily resolves the layer and it follow the trend of initial geological model. MBI resolves the impedance laterally as well as vertically with in reservoir because the generated wavelet for inversion is extracted from time window of reservoir.

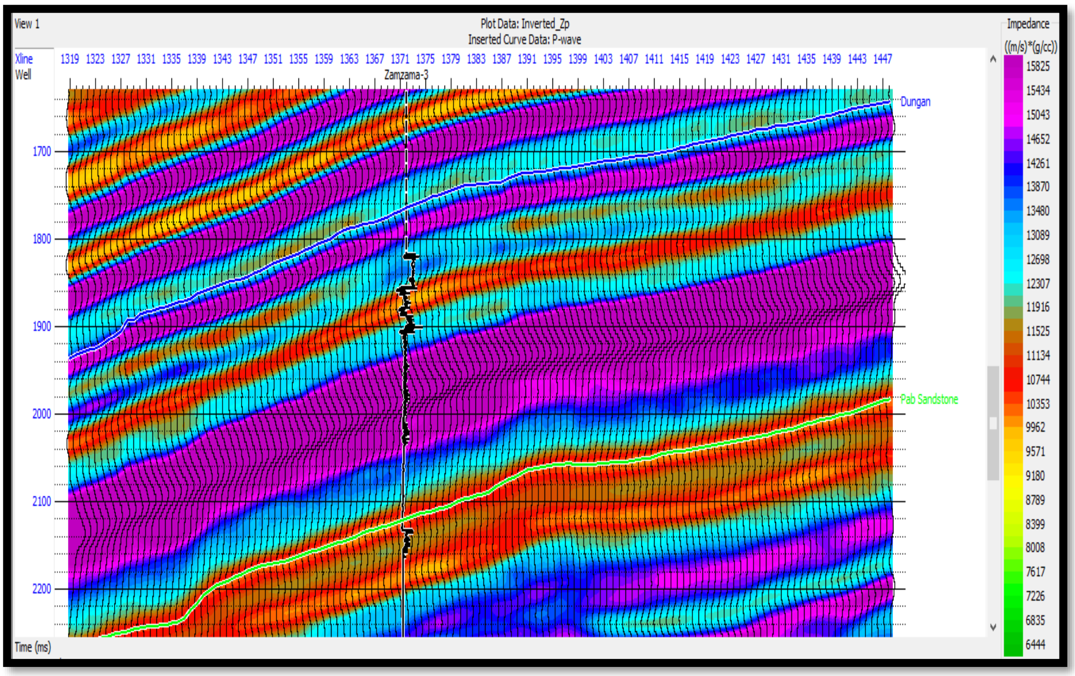

Figure 5.8 Inverted Zp (final computed model of Zamzama

5.5. Impedance Slices

5.5.1. Pab Sandstone

The whole cube of seismic data of Zamzama area showing the variation in impedance along the Pab Formation horizon is shown in the (figure 5.10). Less impedance is shown with green and yellow colors whereas high impedance is shown with blue and violet colors. The impedance of Pab Sandstone is 10317 (m/s)*(g/cc) indicated with green color

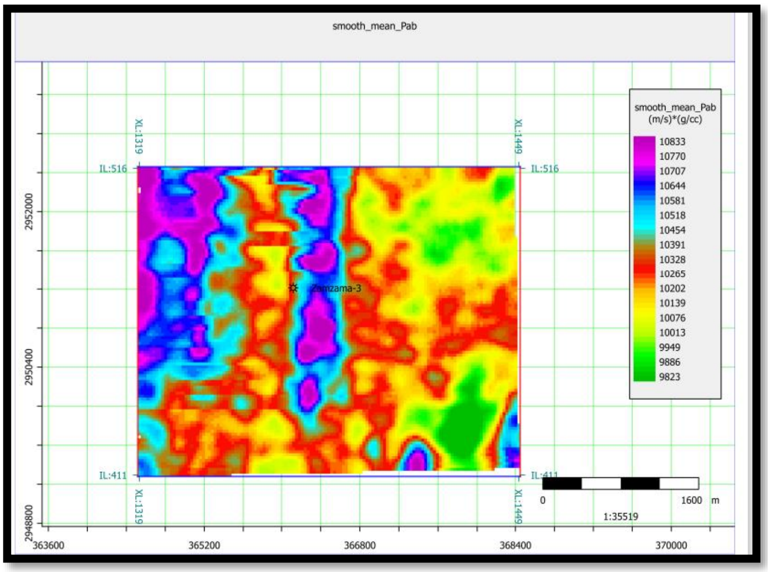

Figure 5.9 Seismic data cube slice for Pab Sandstone showing impedance variation

CHAPTER 6

ROCK PHYSICS MODELING

The task of extracting the maximum amount of hydrocarbon from a well is always difficult. One of the most common causes of well failure is rising water saturation. Seismic data can only tell you how likely it is that hydrocarbons are present in the structure. The fluid substitution, which is an important aspect of rock physics modelling, provides data on the fluid and quantity in the reservoir (Akhter et al., 2014; Kumar, 2006). The effects of various fluid saturation levels on seismic velocities and densities are examined in this research. For a successful well, the reservoir properties must be understood completely. So, up to the extent of available data, good quality seismic data aids in understanding such features.

For the exploration of hydrocarbon, it is important to characterize reservoir in term of fluid and lithology. LMR (Lambda-Mu-Rho) cross plot are generated for inversion feasibility and to discriminate fluid and lithology within reservoir. Reservoir properties and its fluid heterogeneities are not sufficiently observed by only seismic data but with integrated well log data. Reservoir properties are estimated by petro physical analysis. It shows Pab Sandstone has sufficient hydrocarbon bearing zone in study area. The data used in this study include seismic and well data of Zamzama – 03 that was provided by DGPC. These cross plots are generated using Hampson Russel Software (HRS).

In exploration and petroleum industry application of seismic inversion techniques have become effective tool for the detection of hydrocarbon and detailed reservoir characterization, Seismic data carry information about interface and applied inversion transforms this property into layer property which can directly correlate with well log data, in this way inversion help for enhanced characterization of reservoir (Ming Li, 2014).

Feasibility analysis is carried out, to predict the sensitivity of reservoir rock properties, to determine the best inversion algorithm applied for the characterization of reservoir.

6.1. Significance of LMR Cross Plotting

1. For Pre stacked and Post stacked Seismic inversion feasibility.
2. Lambda-Rho inversion slices better server for delineating gas sands and to validate seismic attributes response of sand bodies.
3. Lambda-Rho and Mu-Rho is effective as lithology and fluid discriminator.
4. To map hydrocarbon bearing sands.
5. To check the well logs data quality condition.

6.2. Cross Plot Analysis

Cross plots are well log attribute, in which two or more variables that are visually represented. In order to identify or discriminate anomalies that could be interpreted as indication of lithology and occurrence of hydrocarbon or other fluids. Well log attributes are used to determine rock properties accompanied with better identification of fluids and lithology within reservoir (Omudu *et al*, 2007).

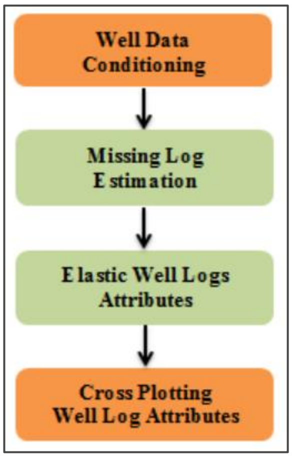

Figure 6.1 Workflow adopted for cross plotting LMR parameters.

These attributes usually include shear wave velocity log but if it is not present, it is recommended to establish an equation developed from regression analysis from surrounding well. As Vp and Vs are both present on Zamzama-03 well of same field, to establish a relation by making cross plot of P-wave and S-wave, the regression analysis is done for estimating shear wave for other well in which shear wave log is absent. So, an equation is developed for this study as given in equation 6.1.

$$Vs = -0.996091153 + 0.835122793 * Vp \qquad (6.1)$$

6.3. Cross Plot Vp/Vs against Acoustic Impedance

In order to discriminate gas sands from brine saturated and shale intervals, P-impedance is plotted on x-axis and Vp/Vs ratio on y-axis and color coded with density in z-axis. Cross plot is generated in the depth ranges of Pab Sands reservoir. Reservoir zone is distinguished mainly into three zones by generating this cross plot namely, gas sand zone, brine saturated zone and by shale zone. Theoretical limit of Vp/vs for the presence of gas sand is varied between 1.6-1.88 (Omudu *et al*, 2007).

It shows better identification of lithology along P-impedance axis showing that p-impedance shall better discriminate reservoir condition in term of fluid content and lithology than Vp/Vs. Cross plot response of Vp/Vs and P-impedance is shown in figure 6.2

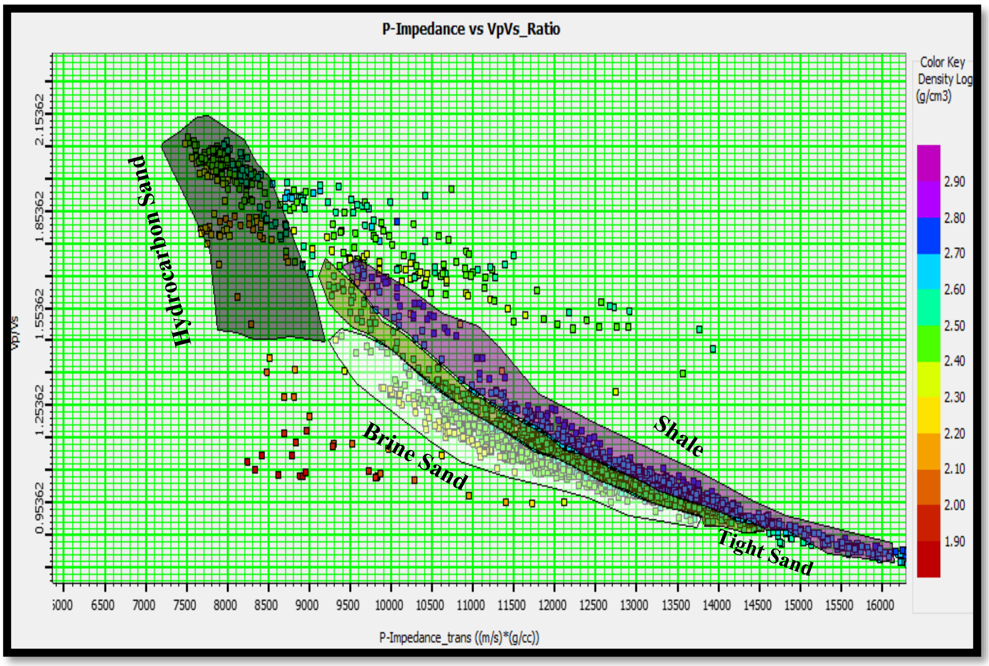

Figure 6.2 Cross plot of P- impedance and Vp/Vs ratio with color coded density

6.4. Cross plot Lambda-Rho against Vp/Vs

Variation of lambda-rho (Incompressibility) against Vp/Vs ratio for sand and shale sequences can be visualized by color coding with density in z-axis. HC charged gas sands are associated with low density while brine saturated, and shale zones show relatively higher magnitude of lambda-rho. It is better aligned toward lambda-rho axis, thus showing lambda-rho a better tool for discrimination of lithology. The ellipse marked separates gas sand; brine sands based on density color coding. Cross plot response of lambda-rho against Vp/Vs is shown in figure 6.3.

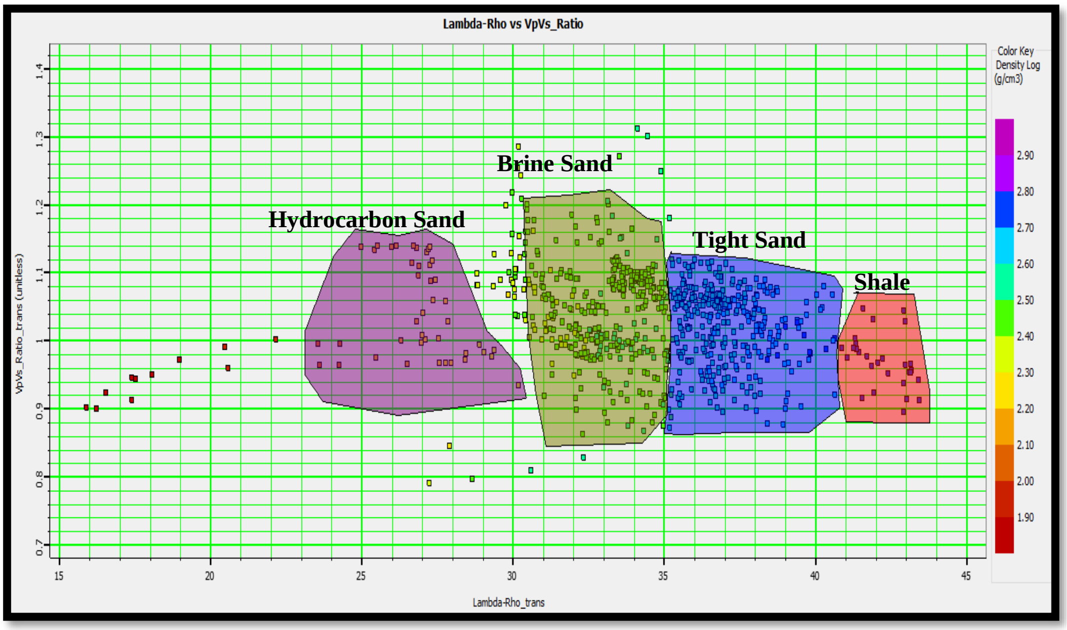

Figure 6.3 Cross plot of Lambda-Rho and Vp/Vs ratio with color coded density.

6.5. Cross Plot Mu-Rho against Lambda-Rho

Cross plot of lambda-rho and mu-rho is robust tool for the lithology identification and to observe fluid presence. Lambda-rho and mu-rho are cross plotted with color coded density. Cross plot is generated in the depth ranges of Pab Sands. Low values of lambda-rho ($\lambda\rho$) associated with moderate to high values of mu-rho ($\mu\rho$) indicate the presence of hydrocarbon within the sand reservoirs.

Cross plot show separation into three zone, probable shale zone, brine saturated zone and gas zone showing lowest possible values of density. As it can be visualized lambda-rho is more robust for analysis of fluid and the values of mu-rho for reservoir lithology. Cross plot response of mu-rho against lambda-rho shown in figure 6.4.

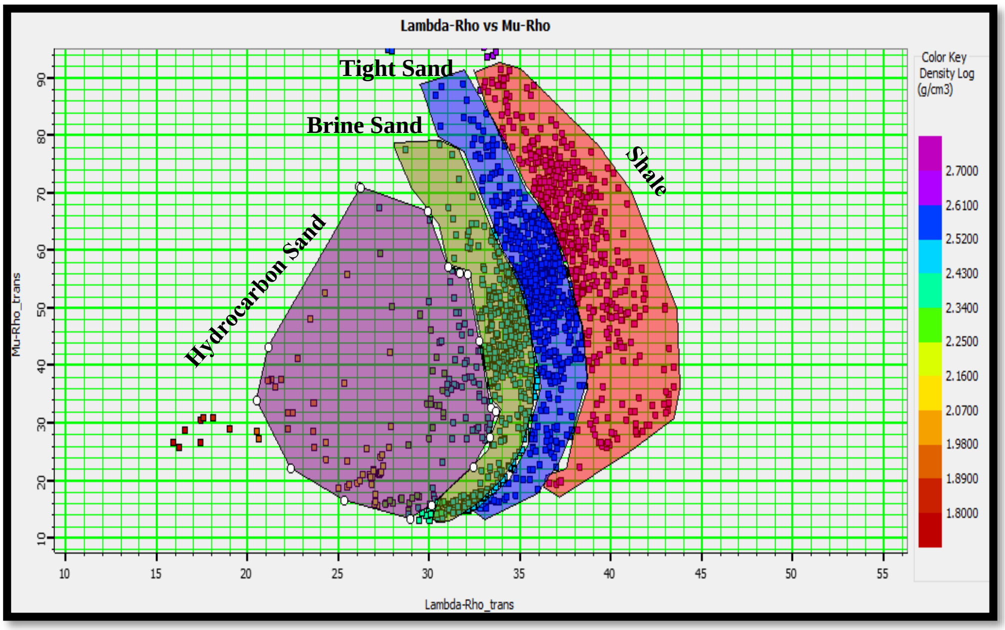

Figure 6.4 Cross plot of Mu-Rho vs Lambda-Rho with color coded density.

To characterize Pab Sands reservoir in term of fluid and lithology as well as to check the feasibility of inversion to be applied in the study area, LMR cross plots are generated. From the cross plots analysis, P-impedance, Lambda-rho, and Mu-rho attributes were found to be most robust in lithology and fluid discrimination within the reservoir. The LMR technique was able to identify gas sands, because of the separation in responses of both $\lambda\rho$ and $\mu\rho$ sections to gas sands versus shale.

CHAPTER 7

BAYESIAN CLASSIFICATION

In this study, the use of Bayesian categorization in a geophysical environment is discussed. Mukerji et al., (2001) and Avseth et al., (2005). In contrast to unsupervised approaches, the technique presented here is commonly referred to as supervised classification. We use a training set, such as wall data, to model the statistical properties of the litho fluid classes we want to predict in supervised classification. Techniques that are not supervised investigate natural clustering of seismic attribute data without using a priori geological information or referring to specific physical classifications. A good introduction to unsupervised techniques is given by Coleou et al., (2003). Comparison of the two approaches is discussed in Fournier and Derain, (1995) and Fournier et al., (2002). Unsupervised approaches are more suited to exploring situations where there are little or no well data. We limit ourselves to supervised classification in this part because it is more appropriate in the context of 3-D earth modelling using borehole and seismic data. Moreover, focus on 3-D and 4-D applications, in which classification is done at each voxel in 3-D attribute cubes, rather than 2-D classification, in which litho-facies maps are generated by categorizing attribute vectors taken from seismic traces. Due to the increased availability of several cubes of inverted properties from which lithology and fluid information can be retrieved, the technology described below has lately gained popularity. Recent 3-D case studies include for example the work of Nivlet et al., (2007) and Bertrand et al., (2002).

7.1. Bayesian Classification

The final phase in the characterization of reservoirs is to map the earth's elastic characteristics as a function of the lithofluid facies' probability model. The cross graph and the weighted pile, which have been discussed and illustrated above, are two often used methods for transforming elastic characteristics in tanks. This type of processing is also routinely done using histograms. However, the difficulty with these methods is that they are subjective in terms of the boundaries and polygons used, and they cannot account for the uncertainty that comes with classification. Advanced methodologies are employed for those classification systems that feature a Bayesian lithographic fluid classification scheme, which improve the classifications and quantify the uncertainty associated with these classifications, to overcome these limitations (Duffaut, et al., 2003).

7.2. Bayesian Technique

An objective recording of the intended lithographic fluid facies at each well location is necessary for lithology and classification of fluids. Next, look for probability density functions that could be useful. The optimal combination of elastic color characteristics classified by fluid litho facies produces bivariate and trevorite sets. After that, the elastic parameters are graded to produce probability volumes for each anticipated facies as well as the most likely facies (Nivlet et al., 2007 and Bertrand et al., 2002). The lambda-rho impedance are the best elastic parameters for estimating the fluid in this classification technique. The chance of facies forming in the area between and outside the wells was determined, along with the related uncertainty. Potential possibilities can be mapped using these facies volumes. Before started, let's go over some of the theory behind the Bayesian categorization approach. All details will be omitted because this is a computation algorithm (Nivlet et al., 2007 and Bertrand et al., 2002).

7.3. Generalized Bayesian Workflow

Following steps are use of Bayesian classification in the context of 3D seismic lithology and fluid prediction.

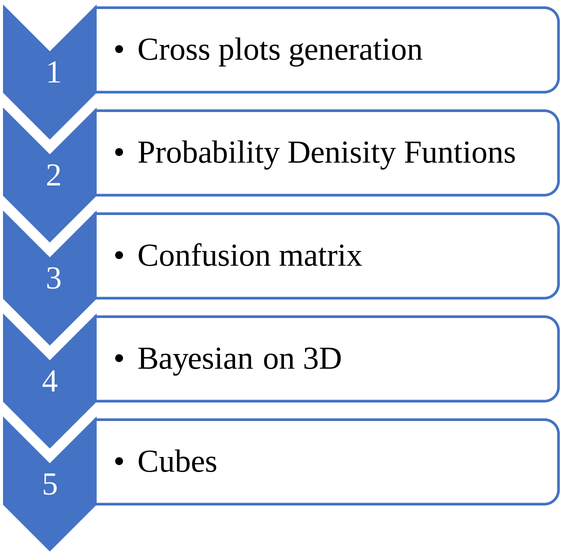

Figure 7.1 Workflow for Bayesian classification.

The methodology that is showed in figure 7.1 will be allowed to predict the lithology and fluid in Zamzama area with help of seismic and well data through Bayesian classifications.

7.4. Lithology, Fluid classification and probability

Lithology, fluid classification and probability are estimated for Pab Sandstone with help of cross plot and Bayesian analysis. There are different types of cross plot that are used for identification of lithology and fluid within formations, like Lamda rho vs Vp/Vs.

7.5. Pab Sandstone

The cross plot that is used to predict the lithology and fluid in Pab Sandstone. is Lambda- Rho vs Vp/Vs cross plot. The Lambda-Rho vs Vp/Vs cross plot tells the fluid type and lithologies as well. The variation of lambda-Rho (incompressibility) against Vp/Vs for sands and shale/sand/shale sequences. The plots are better aligned towards the lambda rho axis, thus making lambda rho a better lithology discrimination tool (Bello et al., 2015).

7.6. Lambda- Rho vs Vp/Vs cross plot

For the classification of lithology, the elastic attributes used were Lambda-Rho and the Vp/Vs ratio. The reason for using these attributes is that, they are both lithology responsive as described above for fluid impedance. Figure 7.2 shows the cross plot for lithology with density color coded attributes using Zamzama -03 well, here you can see a discrimination between low and high density. On this basis, reservoir zone four lithologies were selected to be classified as hydrocarbon sand, brine sand, shale, and tight sand. The polygon drawn for each lithology on the basis of their density. Figure 7.3 shows the PDFs calculated from these crossings, the closed contours in the center of each class represent a high probability and decrease as they move outward. You can see that there is overlap of the outlines and the calculation of the weighting for each lithology can not easily be calculated, so there is some confusion here. This can be ordered using a confusion matrix. Table 7.1 presents the confusion matrix for these three fluids. For example, there is a 85.22% probability of the presence of hydrocarbon sand when sand is encountered, 80.26% when there is shale, and 80.26% when there is sand. These confusion matrixes are based on computation and their result are not product, so to know the best result the probability of seismic slices should be considered. Confusion matrix is just giving an overview idea of parameter.

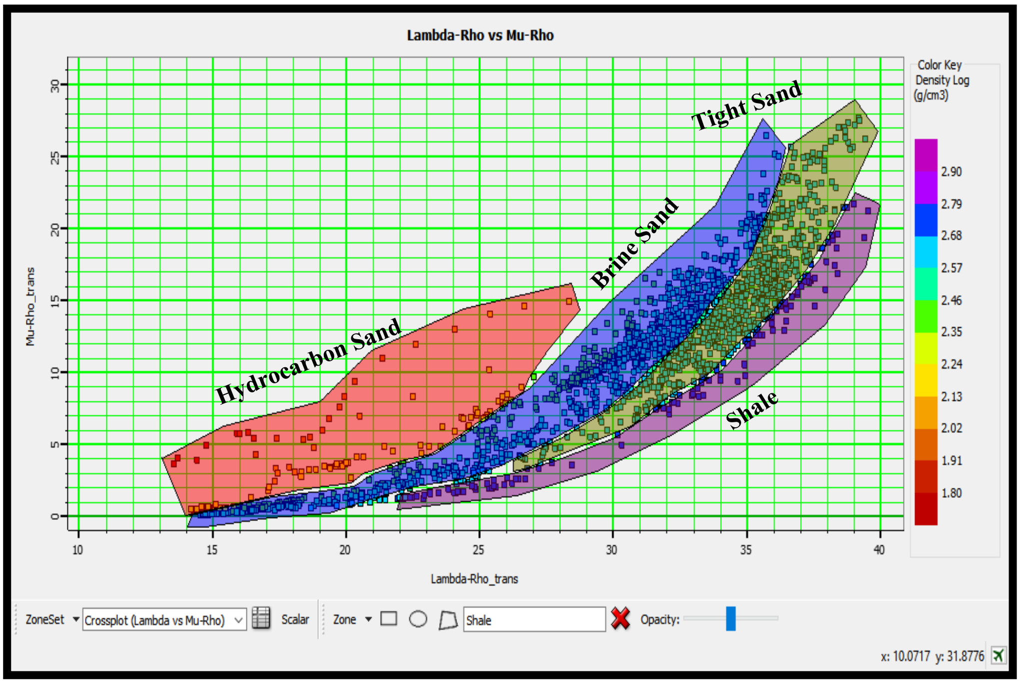

Figure 7.2 Cross plot Lambda Rho vs Vp/Vs ratio showing the Lithology in Pab Sandstone

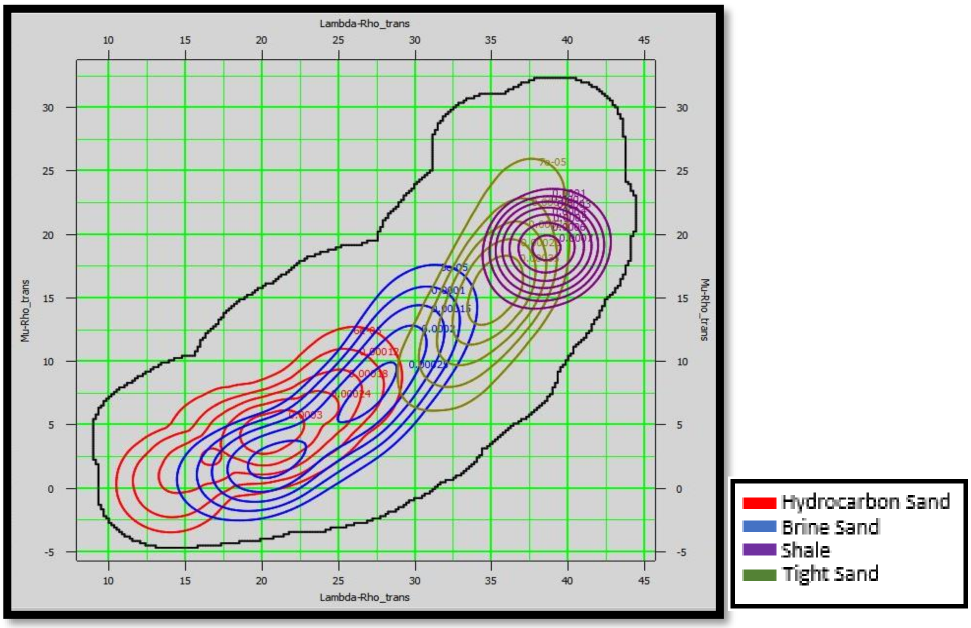

Figure 7.3 Probability density function based on lambda Rho vs Mu-Rho for Pab Sandstone

Table 7.1 Confusion matrix for upscale well logs.

	Hydrocarbon Sand	Brine Sand	Tight Sand	Shale
Hydrocarbon sand	85.22	0	7.83	8.27

Brine Sand	0	99.62%	0.20	0.12
Tight sand	7.83	0.20	93.33	7.47
Shale	8.7	0.12	7.47	80.26

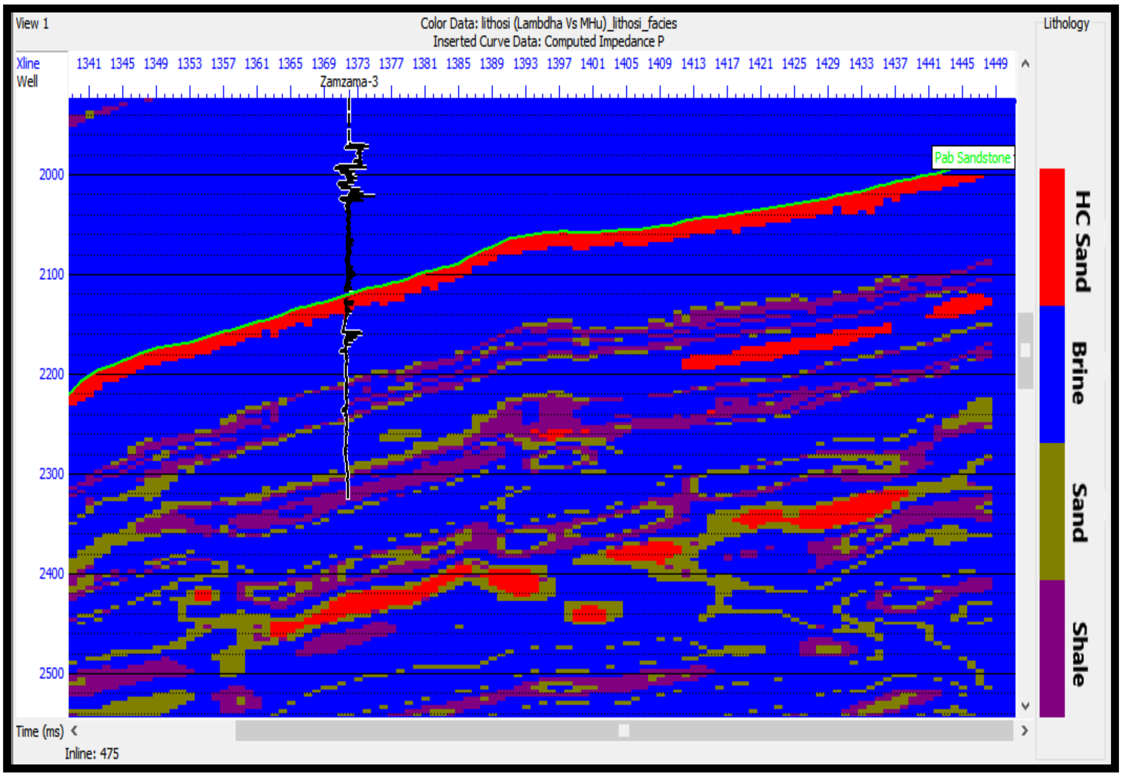

Figure 7.4 Bayesian classification run on 3D seismic to know the lithology preset in Pab Sandstone Formation.

Figure shows Hydrocarbon sand in red, blue like brine sand, in Olive colour and shale in green color. In Pab Sandstone Formation all four lithologies are encountered below the top of Pab sandstone (Green reflector). The Bayesian classification is run on the 3D seismic cube of P impedance. Figure 7.6 shown that near the well location all the fluid is encountered, firstly hydrocarbon sands are observed than brine sand and at the end shale are encountered. On western side there is excess of brine sand. The final mapping for hydrocarbon sand, brine sand, tight sand and shale is shown in figures 7.5, 7.6, and 7.7 and 7.8 respectively. These maps show the probability for each fluid, here the fluid chosen are the hydrocarbon sands, brine sand and shales for the mapping. The high probability in each map shows the fluids of good quality while the low probability that the fluid of poor quality, by quality means the variation in fluids according to probability.

On the slices given below it shows the probability of hydrocarbon sands, brine sands, shale and tight sands. The probability of the hydrocarbon sand lies in between 35-40%, that of brine is between 50-43%, for tight sand it is around 79-85% and for shales range is 58-70%.

Values for hydrocarbon sands is low on the western side and comparatively high towards north-eastern side. For Brine sands the values are lower on the south-eastern side and moderate all over the area. Similarly, for tight sands values are lower on northeastern side and high in the central part Finally for shales low values are seen on the north eastern side and south western side and we see scattered values in the middle of the area.

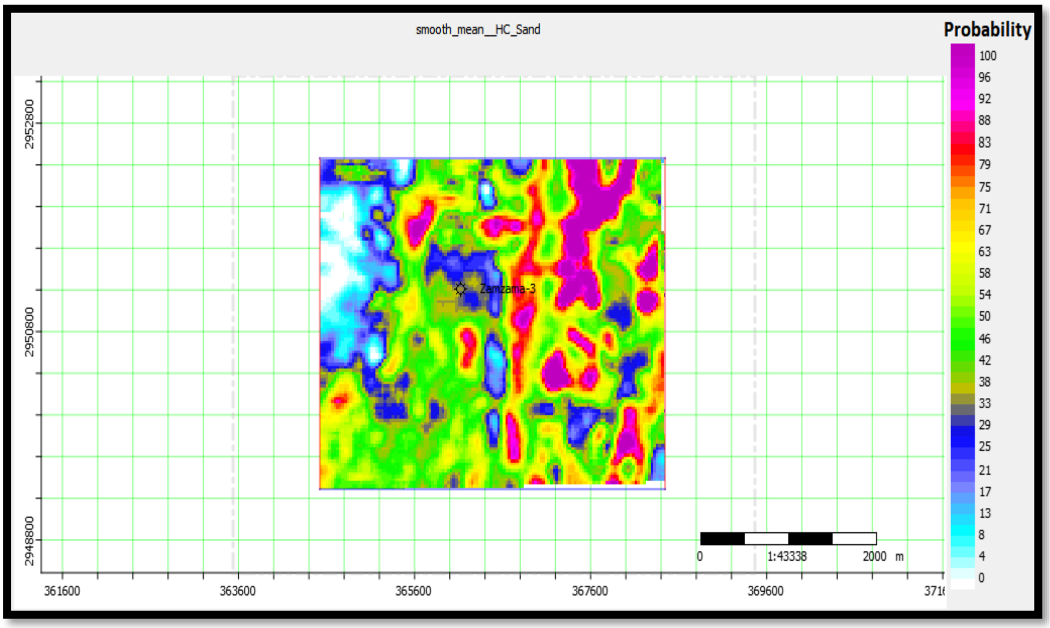

Figure 7.5 Map for probability occurrences of Hydrocarbon sand.

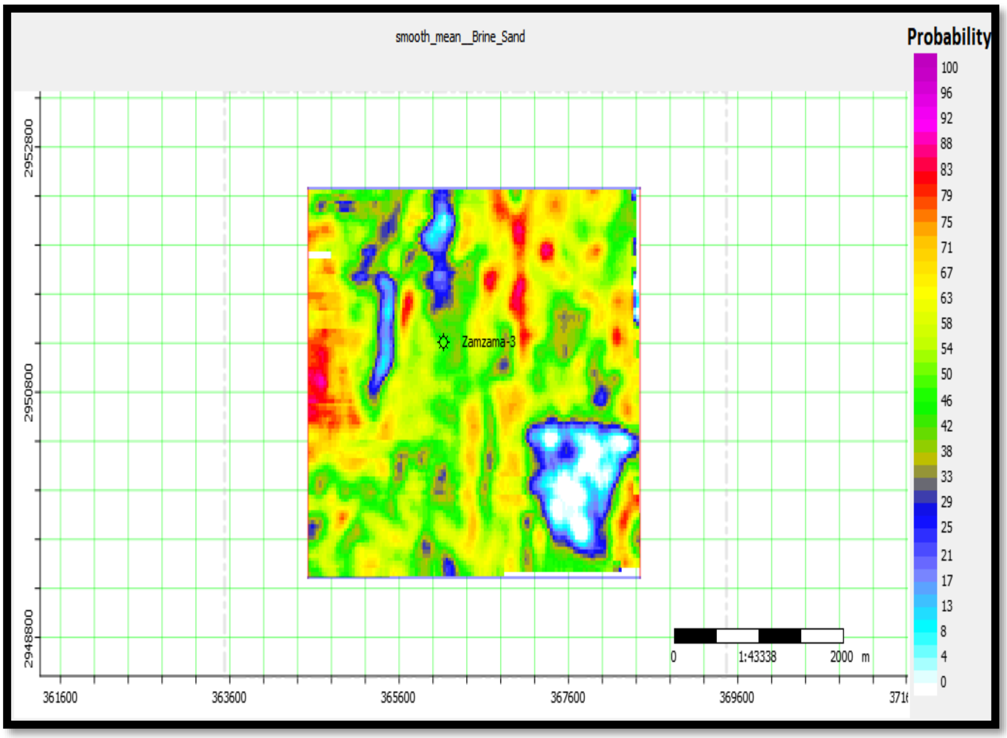

Figure 7.6 Map for probability occurrences of Brine sand.

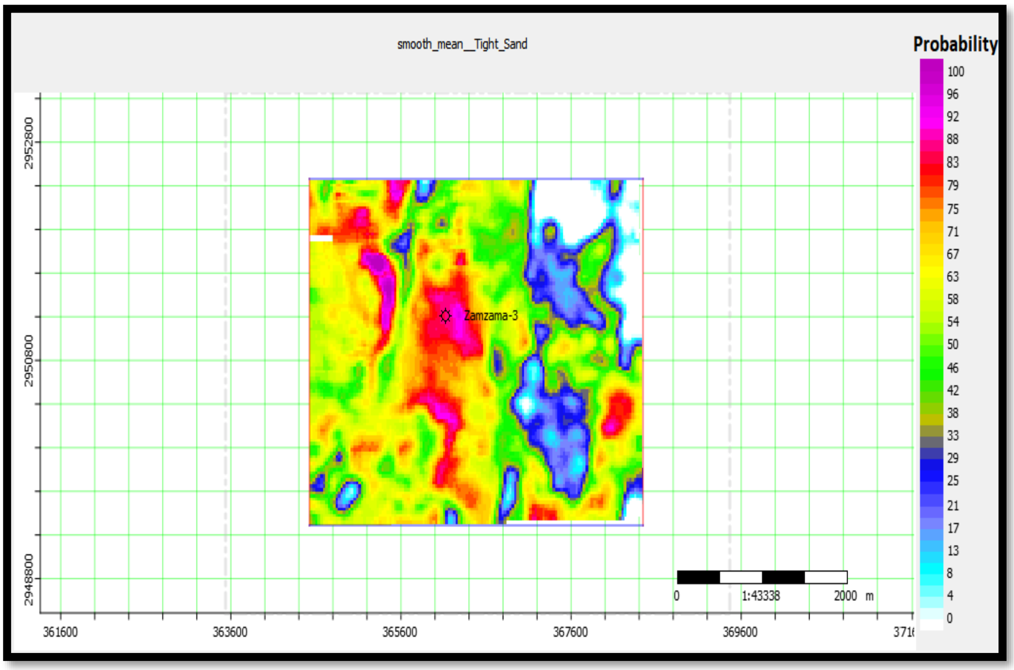

Figure 7.7 Map for probability occurrences of Tight Sand.

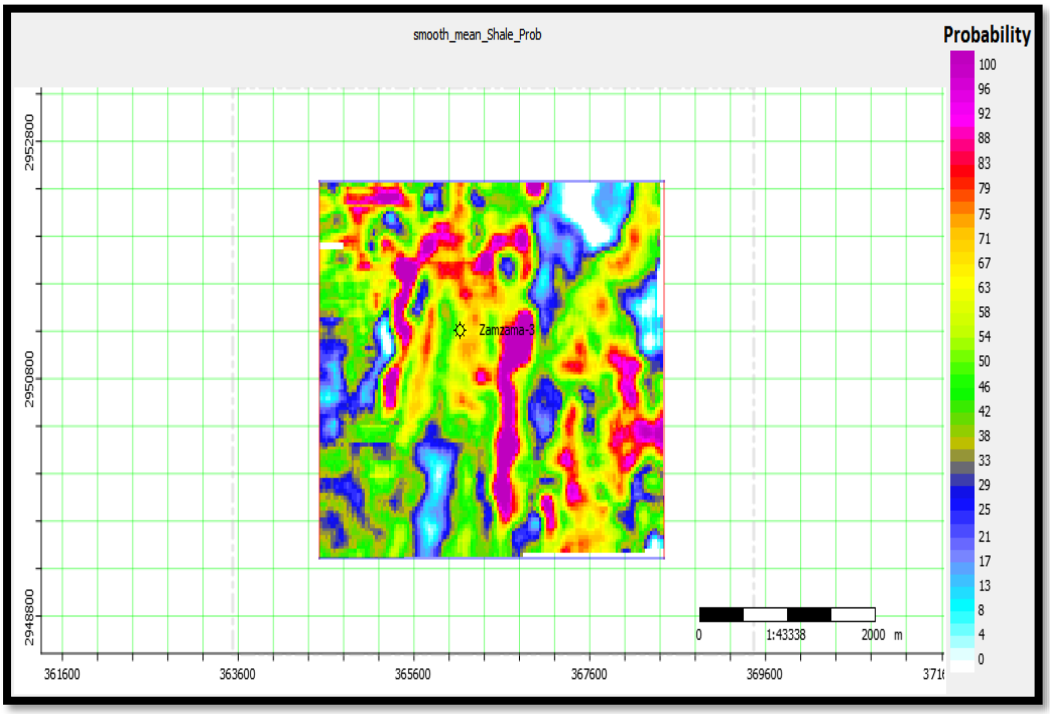

Figure 7.8 Map for probability occurrences of Shale.

CONCLUSION

Following are the conclusion drawn from research work which includes seismic interpretation, Petrophysical analysis, seismic inversion, Rock Physics modelling and Bayesian classification on Pab sandstone with the help of cross plots

1. Two horizons namely Dunghan Formation and Pab Sandstone Formation are marked on the seismic data concluded through the time contour and depth contour maps that there is no fault present in the subsurface structure of 3D seismic of Zamzama area
2. The petrophysical analysis of Zamzama-03 well calculated the reservoir properties of the well and proved that Pab Sandstone of Late Cretaceous age is the main reservoir with respect to hydrocarbon potential.
3. The model-based inversion applied the seismic data along with the Zamzama - 03 well logs demonstrate the change in the variation of acoustic impedance in the overall 3D seismic data cube. It was observed that there is drastic change in impedance near the well location due to the presence of different formations which are composed of various lithologies.
4. The inverted impedance volume was used for rock physics model.
5. Bayesian classification helped to predict the lithology and fluid in the Pab Sandstone. Lambda Rho vs Vp/Vs Vs give good result for lithology and fluid prediction

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