2D SEISMIC INTERPRETATION AND PETROPHYSICAL ANALYSIS OF KABIRWALA AREA, CENTRAL INDUS BASIN, PAKISTAN

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<u>C e r t i f i c a t e</u>

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DEDICATION

"Dedicated to my beloved parents, teachers, and friends".

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ABSTRACT

Kabir wala area is prominent in the central Indus basin for its hydrocarbon (oil and gas) structural traps. The present study pertains to integrated seismic interpretation with seismic inversion and Petrophysical analysis. The key objective of this project is to delineate the subsurface geometry with the help of different seismic techniques in order to understand the petroleum system of the concerned area. Main emphasize is on the interpretation methodology adopted in order to illustrate the horizons and faults. The data used for this study consist of four seismic lines along with their navigation and well data of one well. Three horizons were marked with the help of a synthetic seismogram to delineate the structure of the study area. Samana Suk formation was marked the main reservoir in this area. Petrophysical analysis was performed on the Nandpur-2 well, which is located near our research area. The quantitative interpretation is based on the combined response of all the logs. In the Nandpur-2 well, a zone of interest was identified as having good probable reserves, effective porosities, and hydrocarbon saturation. To pursue qualitative interpretation, Model-based inversion is used. The information of the subsurface layer is obtained by model-based inversion in the form of acoustic impedances. In the final inverted sections, low impedances indicate promising hydrocarbon-bearing zones. The presence of source and cap rock in the zone was also established using model-based inversion. All the parameters have been integrated through seismic inversion which also show decrease in acoustic impedance along the Samana Suk limestone Formation. Results also reveal that producing wells lies in the low impedance and high porosity Zones. On the basis of this analysis some sweet spots were also marked which seems to be favorable for hydrocarbon accumulation.

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

There are three primary sedimentary basins in Pakistan: The Indus basin in the East, the Baluchistan basin in the west, and the pishin basin in the northwest. In the middle part of the Indus basin is the Punjab platform, which is the western dipping monocline. It is bounded in the north by Sargodha high, Sukkur Rift region in the south, and in the west, it merges into Sulaiman depression (Kadri, 1995).

Nandpur, located near Multan, in the Punjab province, is the current research area that is approved for exploration. The Oil and Gas Exploration Company Limited (OGDCL) discovered the field as the first gas field on the Punjab platform in 1984. With few other viable wells, OGDCL spread well to discover the prospective reserves in the area.

1.2 Study Area

The study area is in Pakistan's Punjab platform area of the central Indus basin. It is located in Punjab's Kabirwala and Khanewal districts and is part of the Rachna block, which covers an area of 1,189.55 square kilometers. Figure 1.1 shows the geographical map of Pakistan that shows various cities as well as the study area's location. Fatehpur and Multan, to the north of OGDCL, are two major concessions near the study area, as shown in figure 1.1

Figure 1.1 Geographical map of the study area (Naqi and Siddiqui, 2006).

1.3 History of exploration

(Khalid, et al., 2014) The Punjab platform's exploration history can be roughly divided into two categories: Paleozoic and Mesozoic reservoirs. Infra-Cambrian and Permian rocks have traditionally been considered prime exploration targets. Secondary exploration targets were thought to be the lower-middle Jurassic reservoirs.

1.3.1 Paleozoic Reservoir

Exploration activities in the study area began in the 1950s, Shell drilled karampur-1 which is the first exploratory well in the area. The presence of heavy oil in infra-Cambrian rock was discovered in this well. In 1960, India's Oil and Natural Gas Corporation (ONGC) drilled Puga-1 to explore the infra-Cambrian reservoirs, but it was unsuccessful. In the 1970s, Amoco Corporation drilled two more wells to explore the Salt Range and Permian formations, but no commercial discoveries were made. Shell Pakistan Limited has completed the drilling of two additional wells (Bahawalpur East-1 and Marot-1). Because of the lake of closure and low reservoir quality, both wells failed to find any hydrocarbons. The first gas discovery was made in the Permian reservoir of the Punjab platform by the Oil and Gas Development Corporation (OGDCL) in 1985 (Pamjpir-1). In the late 1980s, OGDCL drilled several additional wells based on this finding, but they all failed. OGDCL drilled another well (Fortabas-1) a few years later, but no hydrocarbon was found. In 1996, OGDCL drilled Bijnot-1 to assess the hydrocarbon potential of the infra-Cambrian reservoir, which is comparable to the Baghewala-1 discovery. Only strong heavy oil was seen in Bijnot-1. The Punjab platform inspired OMV to drill a well. Suji-1 was drilled in 2000 but it drilled into the basement without finding any infra-Cambrian reservoir.

1.3.2 Mesozoic Reservoirs

Amoco Corporation drilled Kamiab-1 and Budhana-1 to the Jurassic Samana Suk formation without finding any commercial hydrocarbons, which sparked interest in Mesozoic strata. POL drilled Ahmadpur-1 in the study area in 1992. OGDCL drilled Saro-1 (a dry hole) in 1992 to investigate a stratigraphic trap. In 2006, OGDCL discovered additional gas in the Samana Suk Formation (Bahu-1). The Punjab platform overall success ratio is extremely poor. As a result, hydrocarbon exploration is a high risk in the field. There are plenty of traps, but they’re either not charged or the source rock is of poor quality in the region (Khalid, et al., 2014).

1.4 Objectives of the study

The main purpose of this research work as follows:

a) The core objectives of research are the interpretation of subsurface structure of kabirwala area with the help of available seismic lines.
b) Petrophysical analysis for the hydrocarbon-bearing zones.
c) Reservoir Characterization using seismic post stack inversion.

1.5 Data required

Data used for seismic interpretation were seismic lines, well logs, and base map obtained from LMK Resources by the authorization of the Directorate General of Petroleum Concession (DGPC) Ministry of Energy. Next table comprises the well logs and seismic lines.

Table 1.1 Seismic lines and well logs

Seismic lines and base map	**Well logs of**
Line names	**Nandpur-2**
845-KBR-38	**Density log**
845-KBR-39	**Sonic log**
845-KBR-42	**Gamma-ray log**
845-KBR-43	**Neutron log**
	Resistivity log

The lines 845-KBR-42, 845-KBR-43 are dip lines and the remaining are strike lines.

1.6 Methodology

The approach adopted for this project consists of several chapters, shown in Figure, 1.2. And all of them contain a different set of data on behalf of analysis.

1.6.1 Phase 1

Seismic Interpretation

The fault is identified by closely observing the discontinuity in the wavelets, and the interpretation is carried out. Following fault demarcation, the next step is to pick a continuous train of wavelets that runs across the seismic section to mark reflectors. After that, cross-sections along dip and strike lines will be taken to better delineate the created lead/prospect.

1.6.2 Phase 2

Petrophysical analysis

Study properties and their interaction with fluids are supported by Petrophysical analysis. Nandpur-2 well logs were used to obtain Petrophysical data. Following Petrophysical properties are derived from well logs.

a) Lithology

b) Porosity

c) Density

d) Water Saturation

e) Hydrocarbon Saturation

1.6.3 Phase 3

Seismic Inversion

One of the most vital and widely used tools for hydrocarbon exploration is 3D seismic. It is the most suitable method to observe the subsurface geological conditions. The maximum information of the subsurface layers attains due to the relative differences in the acoustic impedances along with the depth during the propagation of seismic waves (Barclay et al., 2008). However, there are many ambiguities due to the heterogeneous nature of the earth, so to improve the resolution and quality of the reservoir characterization we incorporate the assistance of model-based inversion (Erryansyah et al., 2020).

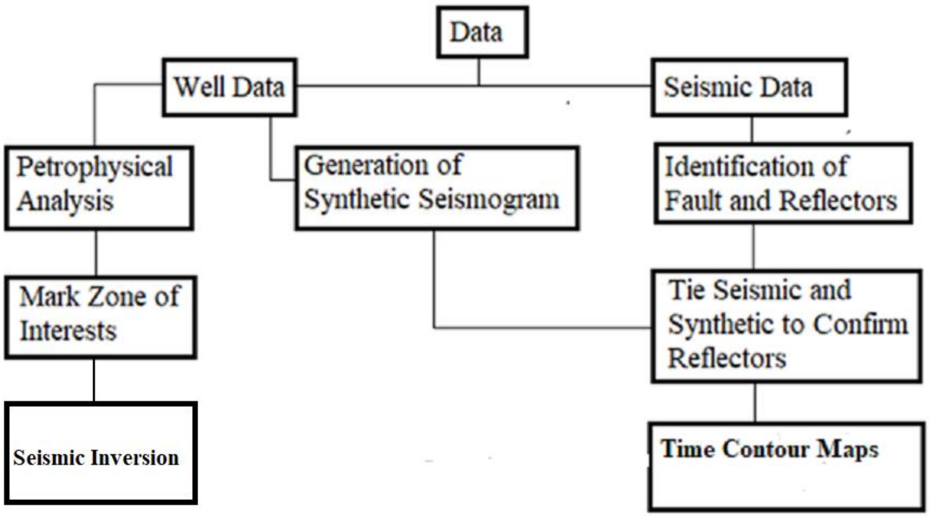

Figure 1.2 Flowchart showing the steps included in the methodology for the proposed research work.

CHAPTER 2

TECTONIC SETTING

2.1 Geological setting

The Indus basin, which is more divided into three basins, is the study field of the upper, central and southern Indus basin. In the central Indus basin, the Nandpur region is situated. From east to west, the Central Indus basin is more divided into three regions. The Punjab platform, Sulaiman depression, and Sulaiman fold belt are recognized as other divided regions. Central Indus basin is isolated from upper Indus basin on northern side by Sargodha high and Pezu uplift (Kadri, 1995). The Central Indus basin split into three regions Shown in figure 2.1.

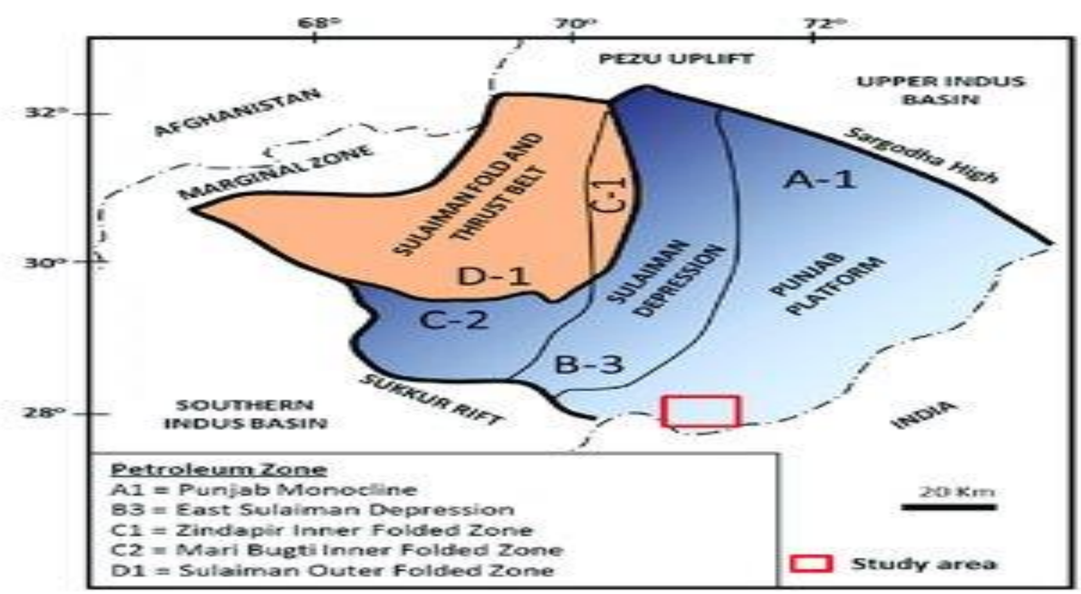

Figure 2.1 The Punjab platform lies in a westward dipping monocline (modified after Raza et al. 1989).

1. Punjab Platform
2. Sulaiman Foredeep
3. Sulaiman Fold belt

2.2 Punjab Platform Evaluation

Punjab Platform is tectonically a stable monocline that gently dips westward from the Indian Shield into the Mesozoic-Tertiary epicenter of the Sulaiman Foredeep. It is located on the western slope of the Indian Shield (Figure 2.1). Two Indian Shield protrusions, the Sargodha High in the north and the Sukkur Rift in the south, limit the Punjab Platform to the north and south. The western and eastern boundaries are configured to meet with the erosional limits of the Precambrian and Paleozoic sedimentary cover of the western Indian Shield, which are designated in the west by the Indus River and in the east by 74300 meridians (Kazmi and Jan 1997). The Punjab Platform lacks surface outcrop that may be used to determine the area's lithostratigraphy. It is determined based on the findings of drilling and seismic research. The lithostratigraphic nomenclatures are comparable to those used in the middle Indus basin.

2.3 Sulaiman foredeep

The Sulaiman Depression is named due to the occurrence of a subsidence zone in this location. Here is accurate and crosswise positioning of the stratigraphy along southern rim of Sulaiman foredeep (Kadri, 1995).

2.4 Sulaiman fold belt

A great number of anticline structures result from collision of Indian and Eurasian belts. Here are numerous apparent detachments and massive anti-clines in Sulaiman and Kirthar ranges. Furthermore, the flower structure is created by these particular types of position and tectonic activity. Flower structure of Pab Formation, Paleocene Ranikot Formation, and Cretaceous Lower Guru Formation is a result of large-scale wrench faulting and crude oil formation. During collision of Eurasian and Indian plates, the basement rocks were split into three distinct zones. Three faults categorize and distinguish these foundation rock zones or blocks, as well as isolate the Central Indus basin (Kadri, 1995).

2.5 Stratigraphy of Pakistan

The central Indus basin was in a passive margin setting at the same time that sediments were most likely laid down in interior rifts in a discontinuous relation with Tethys, most likely in a shallow, confined shallow marine environment. The Permian sequence is overlain unconformably by the Cambrian sediments. Shallow marine to paralic conditions existed all over the area up to Late Triassic. At some points during the early Jurassic, a thick succession of fine-grained clastic rock was deposited in response to passive margin thermal subsidence. The formation of a widespread carbonate platform over the region was caused by rising global sea levels. Shallow marine to deltaic shale and sandstone replaced the middle Jurassic carbonate platform. During the late cretaceous, the carbonate platform was replaced by a more clastic-dominated regime, resulting in the deposition of late Eocene carbonates on the passive margin in the north. The Indian Ocean coastline steadily moved southwards during the Oligocene, and marine conditions were eventually replaced by continental conditions. The collision of the Indian and Eurasian plates had resulted in substantial molasses deposits by the middle Miocene.

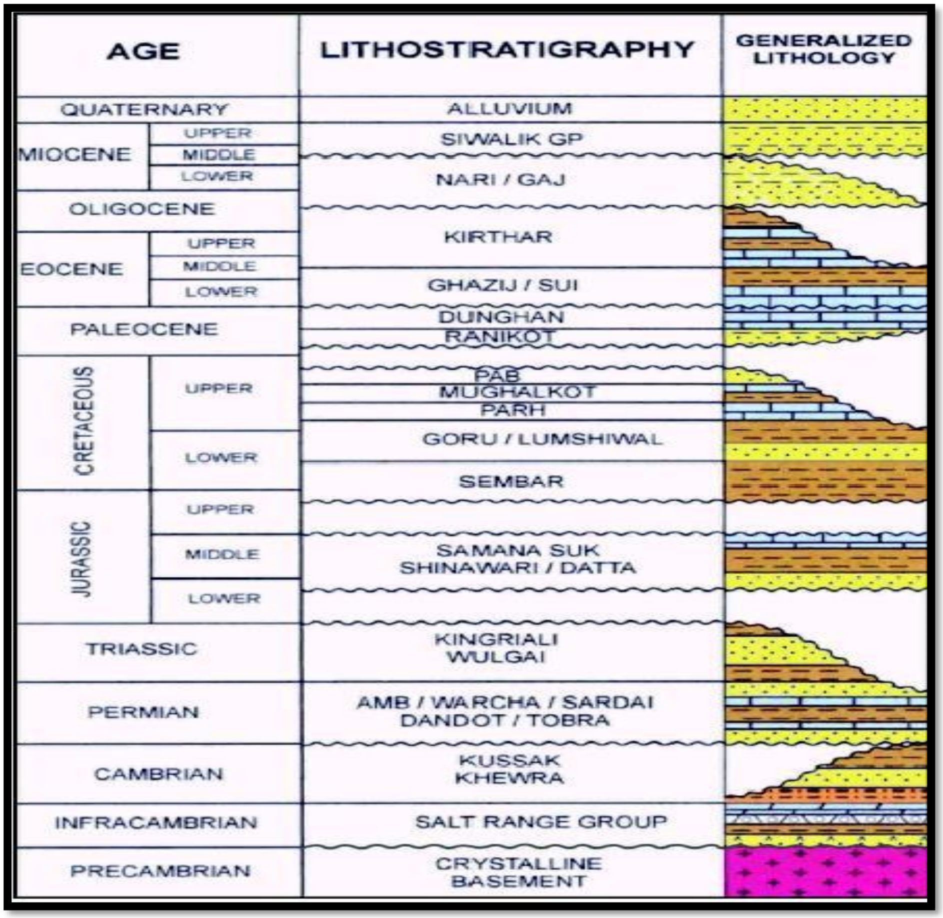

Figure 2.1 Generalized stratigraphic column of central Indus basin (Raza and Ahmad, 1990).

2.5.1 Miocene Age

2.5.1.1 Nagri Formation

Nagri formation is made up of conglomerate sandstone and subordinate clay. The sandstone is bluish-gray in places, calcareous and moderately to poorly cement. The beds of the conglomerate consist of igneous stone pebbles and Eocene limestone. The Hunting Survey Company (1961) regarded the formation period as Pliocene and assumed that it could stretch to late Miocene in the lower beds.

2.5.1.2 Chinji Formation

It's made up of red clay, ash grey, and brownish grey sandstone. In the Sulaiman Range, it unconformably overlaps Nagri Formation. The Nagri Formation overlaid in a conformable manner. This is the end of the Miocene age.

2.5.2 Eocene Age

2.5.2.1 Ghazij Formation

Formation consists of shale, sandstone, conglomerate, and coal seams. Grey and greenish-yellow shale, pale greenish grey shale, brown and olive-grey shale, calcareous, flaky, ferruginous, and gypsiferous. Sandstones are parallel-laminated, fine to very coarse-grained, cross-laminated, and have sole marks. They are yellowish-brown, greenish-grey, pale brown; light olive-brown, fine to very coarse-grained, parallel-laminated, and cross-laminated. White, cream and calcareous sandstones are among the others.

2.5.3 Paleocene Age

2.5.3.1 Dungan Formation

Shale and marl are part of Dungan Formation. Thin to medium bedded and conglomeratic, the limestone is gray to buff. Laterally, these formational facies are more diverse, with dense calcareous deposits at places while minor calcareous showings at places. It is regarded as a late Paleocene age, rarely exceeding the early Eocene.

2.5.3.2 Ranikot Formation

Ranikot category is often referred to as infra nummulitic. The Ranikot group was distributed into three groups: the lakhra (upper Ranikot), Bara (lower Ranikot), and the Khadro Formation. The lower section, along with shale’s and limestone, has brownish-yellow sandstone. Similarly, in the Lakhra Formation, the lower Ranikot has the variegated sandstone and shale is present.

2.5.3.2.1 Khadro Formation

"Khadro Formation" was termed by Williams in (1959). The type section of the formation is Khadro Nala (latitude 26° 07′ 06′ N, longitude 67° 53′ 12′ E) near Bara Nai in the Laki Range. Shale, marl, and sandstone make up the formation, with some limestone thrown in for good measure. Sandstone comes in a variety of colors, greenish grey including yellowish-brown and olive. It's fine to coarse-grained, graded, parallel, and cross-laminated, and has groove casts at the bottom.

2.5.3.2.2 Bara Formation

In the Laki Range, the Bara Formation (Shah, 1977) is well exposed in the type section at Bara Nai (lat. 26o 07/ 06/ N: long. 67o 53/ 12/ E). Sandstone, shale, and a few small volcanic rocks make up the formation. Thin to thick-bedded, fine to coarse-grained, massive and varicolored sandstone found in a variety of colors. It is cross-laminated and calcareous in parts. The colors of shale vary from bluish grey to greenish-grey to green.

2.5.3.2.3 Lakhra Formation

Along Laki Range, the Lakhra Formation (Shah, 1977) is exposed at the Lakhra anticline ((lat. 26o 11/ N: long. 67o 53/ E). Limestone, marl, shale, and sandstone make up the majority of the formation. Limestone is intraclasts, arenaceous, hummocky cross-stratified, cross-laminated, convolute laminated, and parallel-laminated. It is light grey, olive-grey, and dark brownish grey, intraclasts,. The intraclasts limestone also contains chert nodules and secondary origin bands.

2.5.4 Cretaceous Age

2.5.4.1 Lumshiwal formation

In Salt Range, the Lumshiwal Formation is exposed as a type location. The Lumshiwal formation is bedded as a dense one, and the exposed colour is grey, similar to the sandstone bedding, with important sandy, glauconitic, and silty shale formation towards the base. The feldspar sandstone found in the Lumshiwal Formation has a high carbon concentration. Lumshiwal Formation is Aptian in age in a location on the west side of Kohat, and upper Neocambrian to middle Albian in the southern section of Hazara near Nizampur.

2.5.4.2 Chichali formation

Due to having shale in the Formation, the Chichali Formation behaves like a source rock. Formation's color is typically dark green to grayish-green and dusty, silty and glauconitic shale. The Chichali shale's have three members, including the lower one with phosphatic nodules of the sandy shale.

2.5.5 Jurassic Age

2.5.5.1 Samana Suk Formation

Samana Suk Formation is compact, hard unit made up of grey, thin to thickly bedded limestone that is sometimes nodular. Also, the limestone has shelly beds. Also present are minor shale's and marl beds. All over the Formation, abundant fossils are present. It is assumed that the Samana Suk Formation was placed in an Environmental shallow marine carbonate platform (Tectostar, 1992).

2.5.5.2 Shinawari Formation

The Shinawari Formation is made up of grey sandy limestone and calcareous sandstone with small shale intercalations that are thin to medium bedded. It is mottled, bioturbated, and biosparitic, with brachiopods, echinoids, mollusk shells, nutiloids, and ammonites among its constituents. The Shinawari Formation includes transitional contacts with the Datta Formation under it and the Samana Suk Formation above it.

2.5.5.3 Datta Formation

The formation of Datta includes sandstone, shale's, siltstone, and mudstone. Sandstone act as a good reservoir rock while Datta shale's act as a good source rock. Datta Formation sediments are typically non-marine in origin. On basis of lower Toarcian ammonites, the period is called early Jurrasic, pre-Toarcian (Danilchik et al, 1967).

2.5.6 Triassic Age

2.5.6.1 Kingriali Formation

It consists of light grey-brown dolomite, thin to thick-bedded, massive fine to coarse textured and dolomitic calcareous with interbeds of shale and marl in the upper portion.

2.5.7 Permian Age

2.5.7.1 Amb Formation

The amb formation contains shale, limestone, and sandstone. Lower portion of formation occupied is by sandstone beds. The sequence limestone with some shale appears higher up. Wargal limestone has a conformable upper contact.

2.5.7.2 Warcha Formation

The sandstone is arkosic and cross-bedded, with medium to coarse grain, conglomeratic in certain parts, and shale interbeds. It lies flat on top of the dandot formation. With the transitional interaction, it is overlain by the sardhai formation. Age is early Permian.

2.5.8 Cambrian Age

2.5.8.1 Khewra Sandstone

It is the largest Cambrian reservoir, with Kussak and Jutana formation also having potential (kadri, 1995).

Table 2.1 Borehole stratigraphy of Nandpur-02

FORMATIONS	DEPTH(m)
NAGRI	0
CHINJI	623
SAKESAR	1345
NAMMAL	1411
DUNGAN	1592
RANIKOT	1626
LUMSHIWAL	1685
CHICHALI	1795
SAMANA SUK	1935
SHINAWARI	1986
DATTA	2094
KINGRIALI	2122

2.6 Petroleum System

A petroleum play is a collection of geologically connected scenarios with comparable source, reservoir, and trap conditions (Kadri, 1995). The occurrence of the play components within a basement plays an important role in the accumulation of hydrocarbons. The key elements of the oil play are as follow:

a) Source rock
b) Reservoir rock
c) Seal rock
d) Trap
e) Migration

2.6.1 Source Rock

Sembar of lower cretaceous, the study area's general source rock is cambrian salt range shale's, Permian Dandot and Tredian, Paleocene Patala, Jurassic Datta, Triassic Wulgai, and Eocene Ghazij shale.

2.6.2 Reservoir Rock

Samana Suk Formation of Middle Jurassic age is the reservoir rock.

2.6.3 Seal rock

Dungan formation of Paleocene age and Ghazij formation act is a seal rock. System's identified seals are made up of shale's that are interbedded with and overlie the reservoirs. Thin shale beds of varying thickness act as effective seals in producing fields. Impermeable above truncation traps, faults, and up-dip facies changes are an example of additional seals that may be useful (Wandrey, et al., 2004).

2.6.4 Trap

There are two types of traps in the study area, according to (Hasanay, et. al 2012). Structural traps, such as rollover anticlines or faulted traps, and stratigraphic traps, such as pinch-outs due to tilting and unconformities. Tectonic activity primarily formed structural traps. Stratigraphic traps are likely to be found in Jurassic to Eocene sedimentary packages, particularly in the cretaceous sandstone units.

2.6.5 Migration

Carbon stable isotopic values mean that the source rock in the study area is immature, while the reservoir gases are mature. This may mean deep-seated source rock in structural lows or long-distance hydrocarbon migration through faults conduits (Raza, et al. 2008).

CHAPTER 3

SEISMIC DATA INTERPRETATION

3.1 Introduction

The earth has consistently been three-dimensional and the oil reserves we try to discover or assess are contained in three-dimensional snares. The main value of seismic reflection in exploration is to gain information on the relative depths of the subsurface, i.e. the reflection of a specific layer is recognized along the seismic section through the reflected times determined at a different point on the line (Fitch, 1976). Interpreting the seismic data plays an important role in petroleum exploration which requires a lot of experience and expertise (Hilterman, 2001).

2-D Seismic analysis is the method or process that we are attempting to use. It helps to recognize subsurface geology as well as the related structural pattern in the earth. The subsurface images obtained by seismic data are processed in data processing units using mathematics and powerful computer technology. This offers a time structural image of geological characteristics from the transformation of seismic reflection data and eventually produces a time-depth map by implementing some appropriate velocities in travel time. The delineation of the surface features, measurement of its location, size of structure, are measured by seismic vibration data recorded on surface. A key purpose of the seismic interpretation is to map structural and stratigraphic characteristics and to find whether it is a hydrocarbon-bearing or water-bearing reservoir. Seismic analysis techniques contain together with the form of structural and stratigraphic approaches used on a geographic scale (basal studies) and a local scale (prospect generation) depending on the objectives of the research.

There are two major methods to the analysis of seismic data. The first method is well controlled, where seismic data are integrated with actual subsurface well data, and seismic which helps us to grasp the continuity among both seismic data and well for an area of interest. The second approach is in areas with no control well (wildcat areas) where seismic data provide both a description of the structure and assessments of the depositional environments.

3.2 Interpretation Process

In the interpretation process, we mark reflectors and faults. The reflection which is selected should be good and continuous. By loading the SEG-Y a base map was prepared in software Kingdom 8.8. Horizons were marked with the help of a synthetic seismogram. Faults were also marked on the section from which structures were obtained and then confirmed using different seismic attributes. The workflow of the present study is shown in figure 3.1.

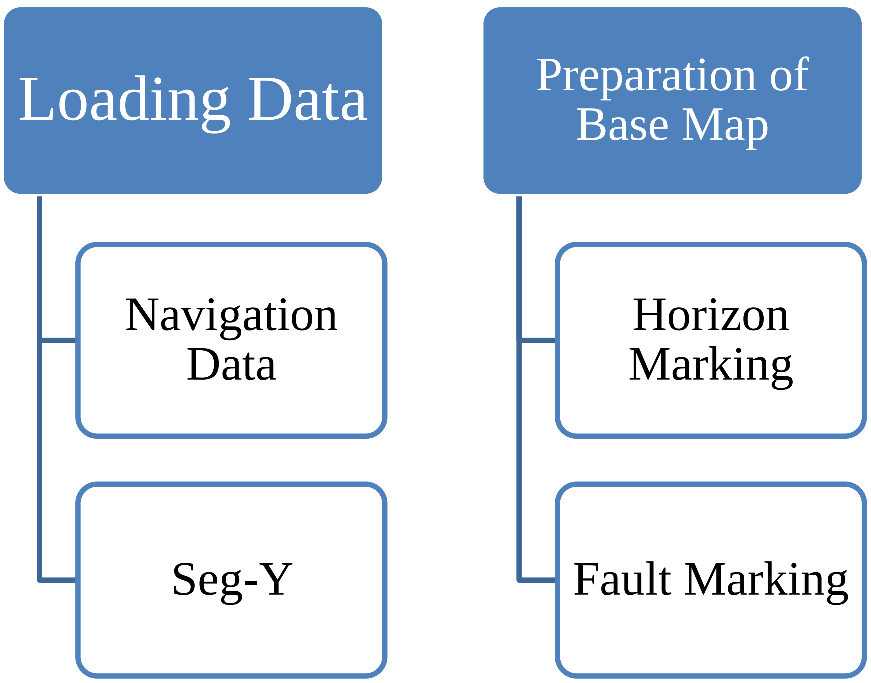

Figure 3.1 Generalized workflow of seismic data interpretation.

3.3 Structural Analysis

The objective of the structural analysis is to unearth and discover the potential structural traps on the seismic section. Prominent reflectors on the seismic section representing the variation in lithology and formation tops are termed horizon. For the identification of faults, the Interpreter aims to observe the significant displacement or movement on the seismic reflectors which represent the discontinuity in the rock. Marking of horizons over a fault is a crucial task for analysts. So, it is necessary to know the vertical displacement between both sides of a fault. After marking the horizons and faults, the next step carried out was to generate the images of different seismic attributes to confirm the interpretation and to indicate the presence of structures marked in the interpretation.

3.4 Base Map Generation

The data provided by the DGPC comprises navigation data and post-stack seismic data in SEG-Y format. The base map is generated by using the Kingdom software which covers the study area by 2D dimensional seismic lines. Figure 3.2 shows the base map of the study area.

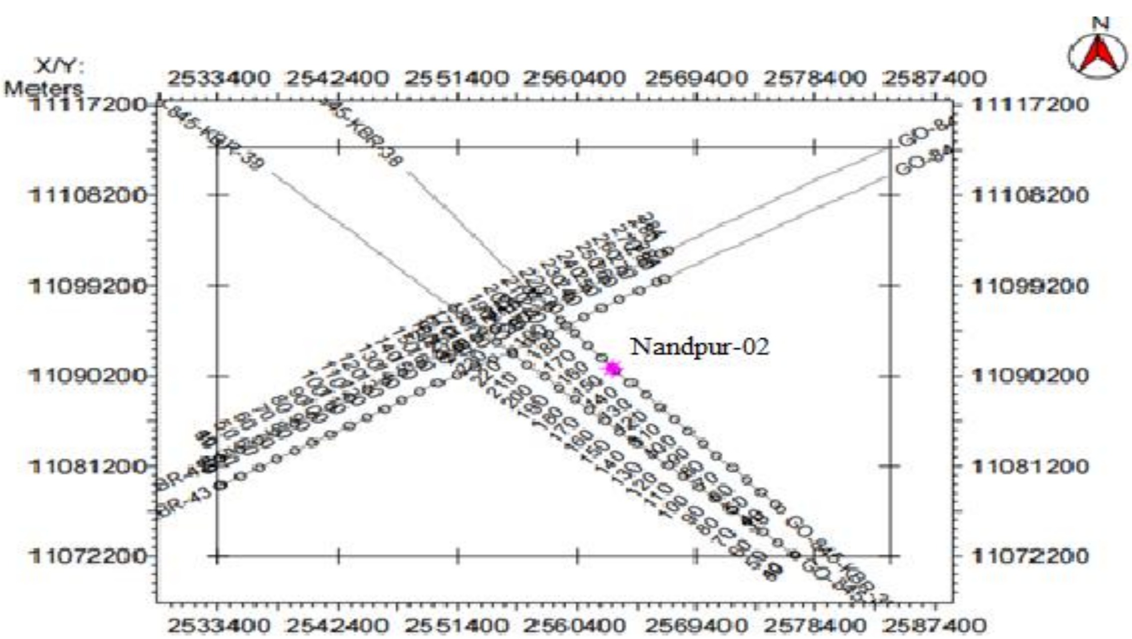

Figure 3.2 Base map of the study area.

3.5 Synthetic Seismogram Preparation

Generation of synthetic seismogram is a useful approach to correlate well and seismic data to identify the accurate position of horizons in the subsurface along with the seismic reflections. It provides the direct relation between the lithology experienced in a wellbore and those identified in the seismic section (Handwerger et al., 2004).

Sonic and density logs are essential for the generation of synthetic seismograms. Velocity and density are obtained from the sonic and density logs. The product of density and velocity gives us the acoustic impedance and then with the help of acoustic impedance we can generate the reflectivity series due to the contrast of lithologies in the subsurface. TD chart also incorporates during preparation of synthetic seismogram and we utilize Gr log as a reference log for the comparison between different formations. There appear a lot of ambiguities while extracting seismic wavelets with time-space and frequency. An ideal wavelet is extracted with the help of either a deterministic or statistical approach. Eventually, the extracted wavelet convolved with the reflection coefficient resulted in the generation of a synthetic seismogram. Synthetic seismogram of NANDPUR-2 is shown in figure (3.3).

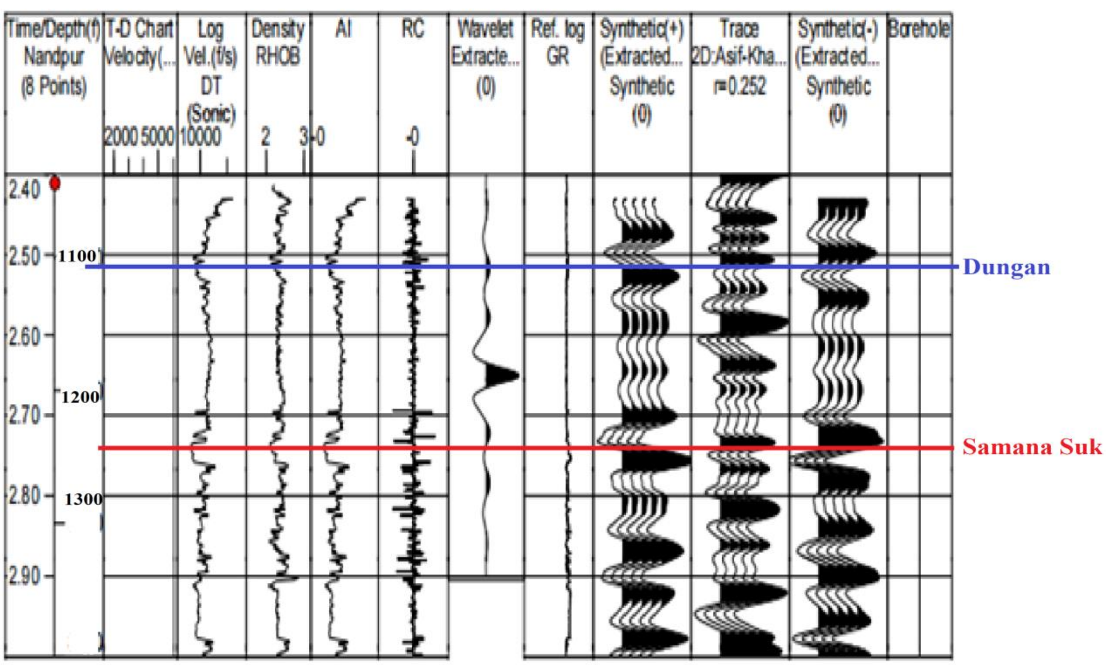

Figure 3.3 Synthetic seismogram generated from NANDPUR 2 Well.

3.6 Identification of Horizons

Horizons are marked on seismic time section based on the contrast in the acoustic impedance due to the different lithology at various depths in the subsurface. For horizon interpretation, the good data of both well Nandpur-2 has been taken under consideration and incorporated synthetic seismogram for seismic to well tie based on reflections visibility reflectors are marked. The basic task for interpretation is to identify the horizons. A good stratigraphic, as well as structural knowledge is required for horizon interpretation (Mavko et al, 2009). Three horizons Datta, Dungan, and Samana Suk were marked during the process of interpretation. The high reflections on the seismic section make them easier to pick so the horizons are marked on strong reflectors and the marked horizon are named according to the well top in Nandpur-2 well. Figure 3.4, 3.5, 3.6 and 3.7 showings interpreted seismic dip and strike lines.

3.7 Identification of Faults

Fault marking on the real-time domain seismic section is a fairly complex thing to do without understanding the area's tectonic background (Sroor, 2010). Faults are identified on the principle of a break in the continuity of reflection. This Discontinuity of the reflector indicates that the data is disrupted by the fault cuts. Fault identification on the seismic signature is the most crucial task for structural interpretation.

Breakage or discontinuity of reflectors observed on the seismic section indicates the presence of a fault. The background geological knowledge along with the structural history of the study area is considered to be the power tool for fault recognition. In an extensional regime, the movement of plates opposite to each other resulted in normal faulting and horst and graben structures are formed. While on the other hand, in compressional regimes, the movement of plates opposite to each other causes intense folding and reverse or thrust faulting. The area of our study lies in the extensional regime, horst and graben structures, and normal faulting experienced during the interpretation of whole seismic lines of the Kabir Wala area. Fault correlation characterizes the dip direction and describes the heave and throw of faults. Three faults

F1, F2, and F3 are marked on the seismic section exhibiting the downward displacement due to the normal faulting in an extensional regime.

3.8 Seismic Lines

3.8.1 KBR-42

KBR-42 is the east-west orientated dip line (Fig. 3.4). In comparison to line KBR-43, this line has more regional and linked faults. On the other hand, the overall pattern of the horst and graben structures is the same. On the basis of amplitude, all reflectors were marked and confirmed with a synthetic seismogram.

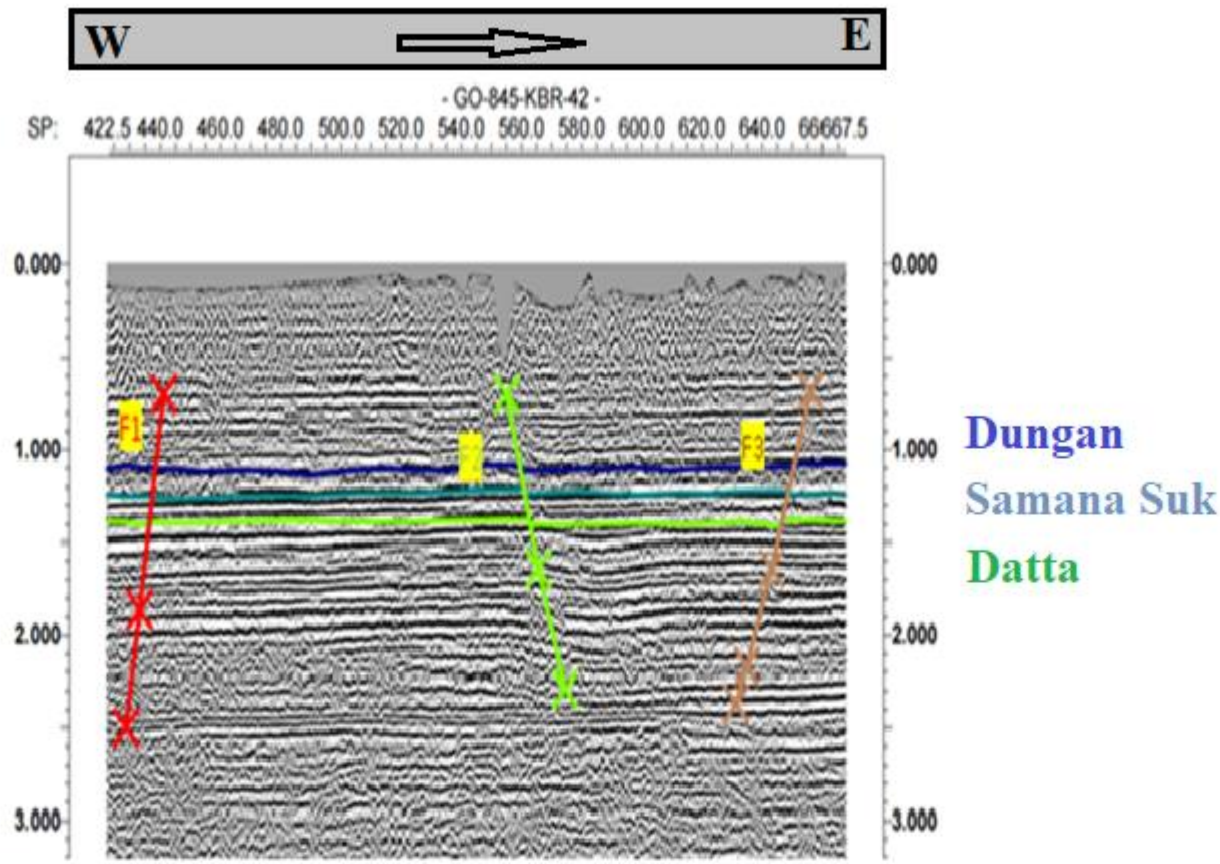

Figure 3.4 Interpreted seismic dip line KBR-42.

3.8.2 KBR-43

Another east-west oriented dip line, KBR-43, shows the similar horst and graben structural trend (Fig. 3.5). These varying throws illustrate the evolution of the structure over geological time.

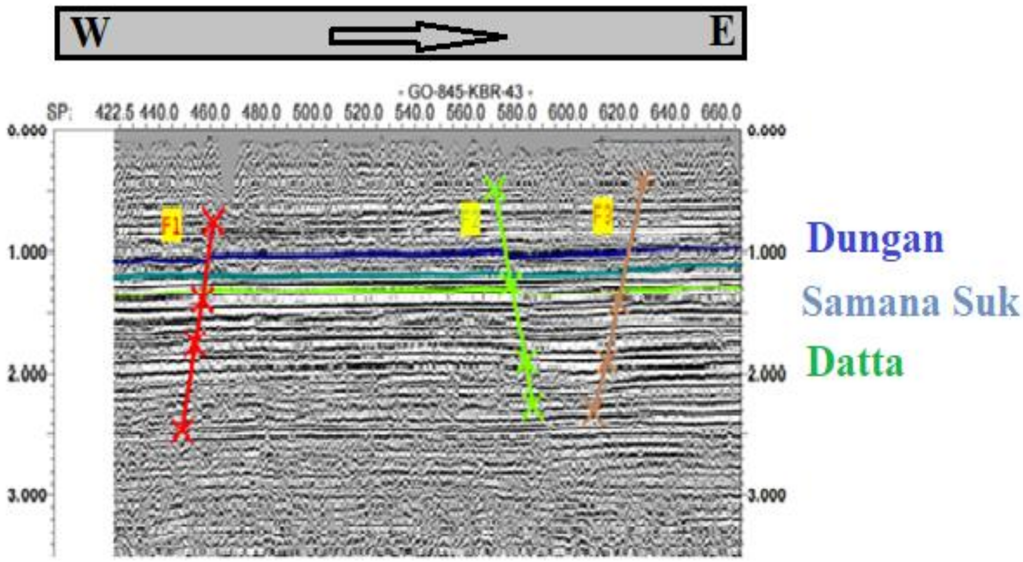

Figure 3.5 Interpreted seismic dip line KBR-43.

3.8.3 KBR-38

The strike line KBR-38 runs north to south (Fig. 3.6). The Nandpur-02 well was drilled on this line. For this well, synthetic is also generated and tied to the seismic line's reflectors. Line was then compared to the other Lines. On this striking line, all of the horizons were slightly bulging upward, and reflectors were marked and validated using synthetic seismograms.

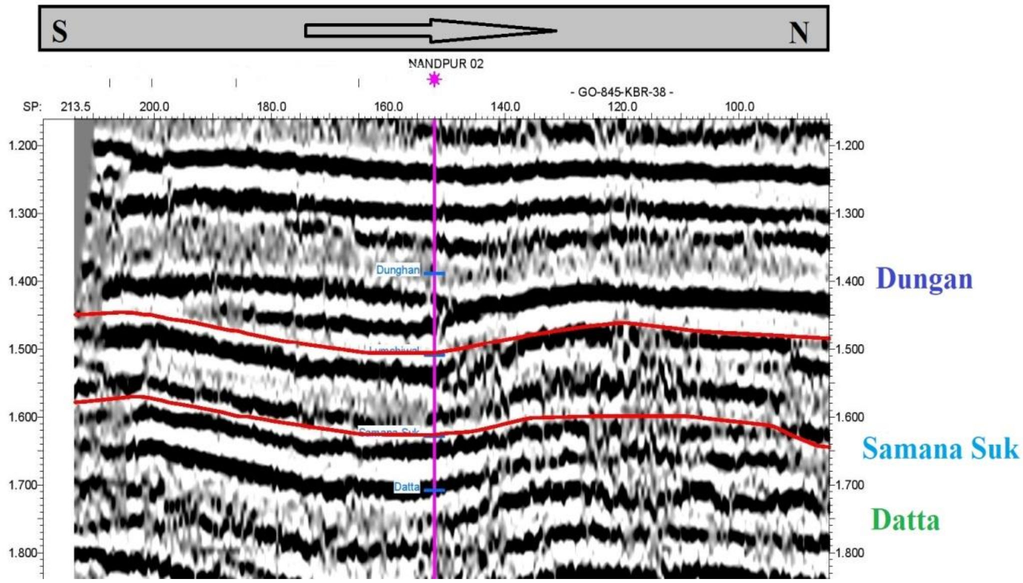

Figure 3.6 Interpreted seismic strike line KBR-38.

3.8.4 KBR-39

KBR-39 is north south oriented strike line (Fig. 3.7). Data quality of this line is not good when we utilize the auto-tracking method; we get distortion in the reflector. All the horizons were straight on this strike line.

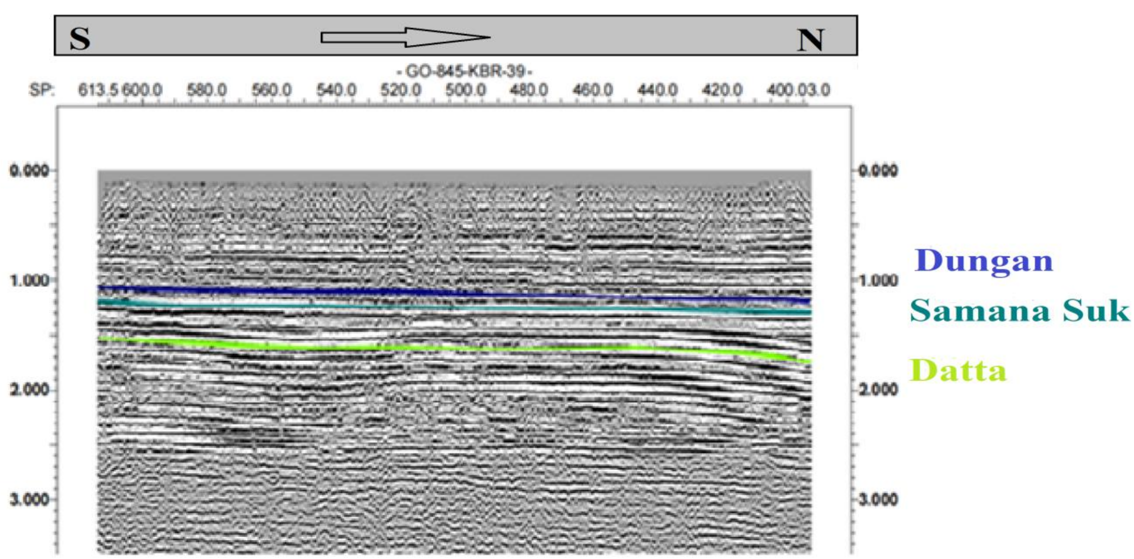

Figure 3.7 Interpreted seismic strike line KBR-39.

3.9 Contour Maps

Contour lines represent the same events which are demonstrated in map. The final product in exploration is mapping and countering which represent the line of equal time and depth around the map (Coffeen, 1984).

The steepness of the slope is the layout for the measurement of contour line. If the spacing is small or closer the slope will be steeper. Horizon with contour line represents a subsurface structural map of equal depth below a datum. The slope and structural relief of the formation including its dip and any faulting/folding is shown on contour maps. For contouring we use the map reading data in the arrangement of an XYZ. The contour maps are generated using Kingdom software.

3.10 Time Contouring

Time contours are the result of joining same time on the map of the area. A two way time contour is shown in Fig 3.5 and 3.6 with contour interval 0.008 sec. In the time contour map the red color specify the low time and the blue color specify the high time. Time contour maps of Dungan and Samana Suk formation are shown in figure 3.5 and 3.6. The contours are represents the interpreted horizons at the maps

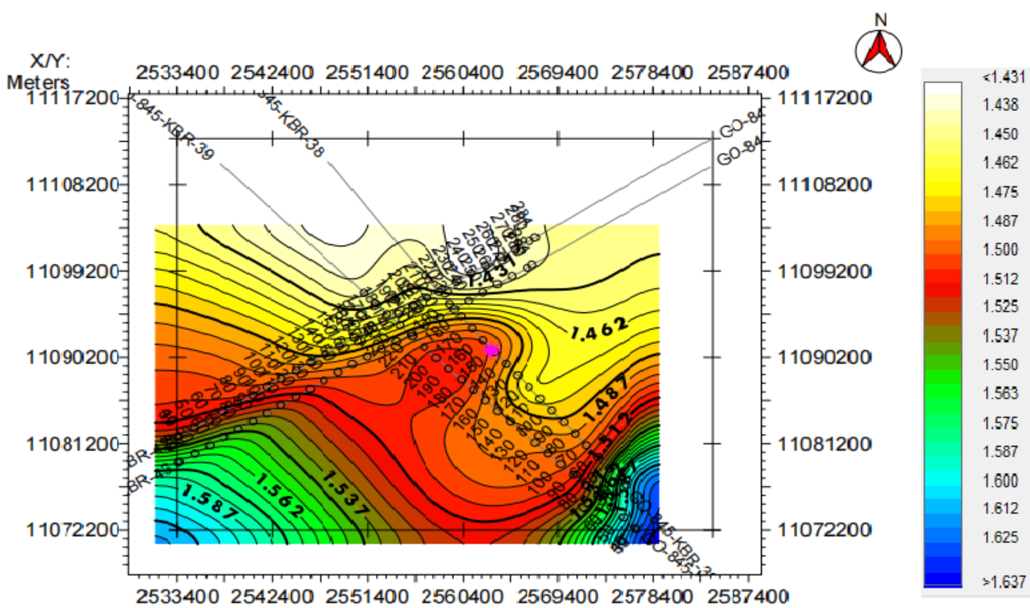

Figure 3.8 Time contour map of Dungan Formation.

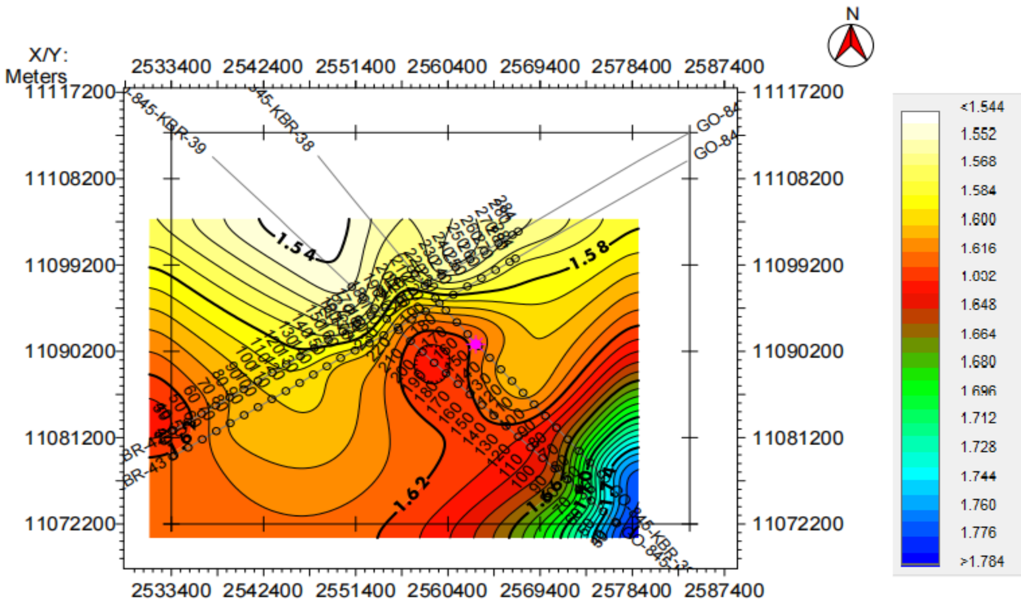

Figure 3.9 Time contour map of Samana Suk Formation.

CHAPTER 4

PETROPHYSICAL ANALYSIS

4.1 Introduction

The petrophysical analysis incorporates the physical behavior and chemical properties of rock and their interaction with fluids (Donaldson and Tiab, 2004). The main aim of petrophysics is to study the reservoir rock for hydrocarbon evaluation. The goal of the Petrophysicists is to identify and mark the prospective zone in reservoir which has potential and capability to hold the economical amount of hydrocarbons. The response of all the logs run within borehole studied and used to determine the physical properties of rock like porosity, permeability, water saturation, and hydrocarbon saturation for desired zone. Petrophysics relies upon the logs in wellbore which includes sonic log, gamma-ray log, resistivity log, etc. The major goal of the Geoscientist is to extract the maximum information of rock and fluid properties at the desired depths for the quantitative interpretation of the reservoir zone. The ultimate objective of the interpreter is to modify the raw log data into a useful and applicable form for anticipated quantities of hydrocarbon (Asquith and Krygowski, 2004).

Petrophysics deals with physical properties which are related to behavior of the rock bodies and fluid that are inside the rocks. Which is helpful in identification of potential zones bearing hydrocarbon in the reservoir (Cosgrove, 1998)? It is a procedure of interpretation of well logs and reservoir characterization helps in facilitating the fluid recognition and quantification in a reservoir. Well logging is the classy measurements of geological and geophysical parameters along with the depth of well. An instrument that is used for measuring physical and chemical properties in well logging is called "Sonde" (Rider, 1996).

The reservoir physical properties such as the volume of shale, porosity, and water and hydrocarbon saturation are required to identify possible hydrocarbon-bearing zones. The rock physics and petrophysics combinations allow us to realize the risks and opportunities in the area. It is the usage of edgy well measurements to promote the reservoir description. It is used by Engineers, Well logs and Core Analysts, Geologists, and Geophysicists (Dewar, 2001).

4.1.1 Types of Well Logs

Some various types of logs and some short explanation of geophysical well logs are as follow. The following logs are explained according to the tracks in which they are run also.

4.1.1.1 Lithology Track

In lithology track, the following logs are displayed which are explained as follows.

1 **Gamma-ray (GR)**
2 **Spontaneous Potential log (SP)**
3 **Caliper Log (CALI)**

4.1.1.2 Caliper Log

Caliper log tells us the irregularities and deviations of diameter along the borehole. It gives us knowledge about cavities, washouts, breakouts, and mud cakes. Due to these events, the borehole conditions get disturbed which causes their effects towards the response of other logs like porosity and resistivity values. Hence this log is also called the quality check for other logs. Because if anywhere there is a washout then in front of the wash out the porosity and resistivity log will not give the correct reading. Hence caliper log is very important in Petrophysical logs (Rider, 1996).

4.1.1.3 Gamma Ray Log

The primary goal of this log is to separate the sand and shale as it is the best lithology indicator. Spectral gamma-ray log (SGR) and Computed gamma-ray log (CGR) are also used to estimate the natural rations emitting from the different encountered formations and incorporate the effect of Potassium, uranium, and thorium. GR log is used for the calculation of the volume of shale. It can also be availed to differentiate the reservoir and the non-reservoir based on its deflection towards the high and the low values respectively (Asquith and Gibson, 1982). The other logs which are used to calculate the volume of shale is neutron-density combination and resistivity log (Hamada, 1996).

4.1.1.4 Spontaneous Potential Log

SP log measures the naturally occurring potential of geological formations where no artificial currents are injected. It gives deflection opposite to permeable beds since shale is impermeable so it gives a straight line opposite to shale known as shale baseline (Rider, 1996). It is used

1. To indicate permeable zone.
2. Identify bed boundaries.
3. To calculate volume of shale.
4. To calculate resistivity of formation water

4.1.1.5 Porosity Measurements

DT (Sonic), RHOB (Density), and NPHI (Neutron Porosity) are porosity logs that are used to calculate pore volume of formations. The combination of resistivity logs are used to calculate SW (Water saturation) of formations (Donaldson, 2015).

4.1.1.6 Sonic Log

Sonic log produce compressional waves and measure the transient travel time of waves. Where travel time is higher it is the indication of porous media because the wave is a name of progressive disturbance of media if media is porous travel time will be higher (George, 1982).

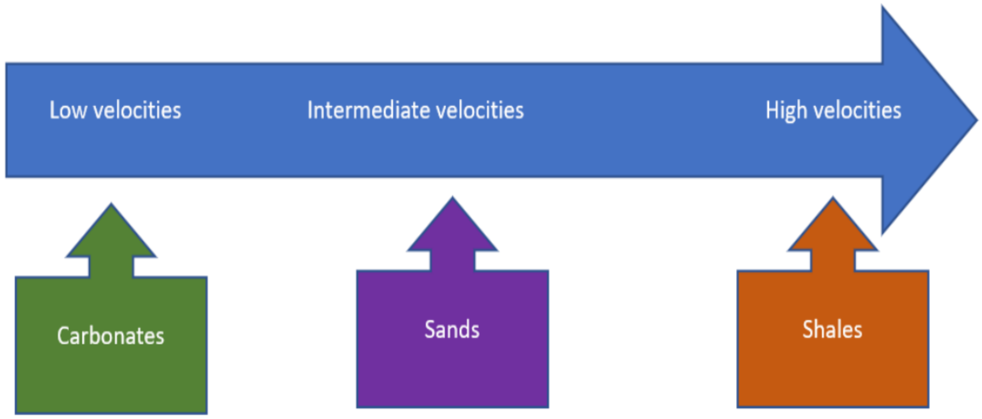

Figure 4.1 Rock distributions concerning velocity ranges (George, 1989).

The integration of this log with the other logs gives us wonderful information for petrophysical interpretation. Porosity can be calculated with the aid of interval transit time. Sonic log along with the NPHI and RHOB is the lithology indicator. The combination of sonic and density log also provides us with the mechanical properties of rock.

4.1.1.7 Density Log

Gamma rays are bombarded on formation which is scattered from formation; electrons with higher scattering will have higher electron density which is related to bulk density of rocks. Lower the density will have higher porosity of medium (Rider, 1996). It is used to measure the travel time of elastic waves passing through the formation. It usually comprises of two components transmitter and receiver. Once the sound waves are transmitted from the transmitter, they will travel through the formation and the transit time will be recorded on the receiver. Velocities are computed with the aid of this log.

The response of this log is a mixture of a matrix, fluids, and void spaces. The response of density log in the form of bulk densities is observed and measured for each formation throughout the borehole. The larger amount of fluids indicates the high porosity and different densities ratios for each fluid type (Javid, 2013).

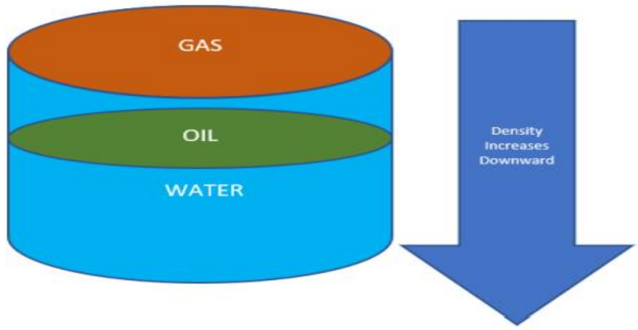

Figure 4.2 Density trends for fluids (Javid, 2013).

4.1.1.8 Neutron porosity Log

Porosity is one of the important keys to unlocking the physical behavior of rock for quantitative interpretation. The ultimate aim of the neutron porosity log is to evaluate the number of hydrogen ions in reservoir zone. A source tool comprised of americium and beryllium hung in the well which repeatedly emits neutrons and loses the energy when they collide with an atom of equivalent mass (Mendoza et al., 2006). The collision of hydrogen atoms present in the formation and neutron emitted from the NPHI tool resulted in the loss of maximum energy (Javid, 2013). The response of NPHI is low for the reservoir zone while on the other hand, its signature is high for a non-reservoir zone on the recording instrument. The reason behind the scene is that in reservoir zones there is huge number of hydrogen ions and neutrons which are emitted being absorbed instantly and do not travel a long path which resulted in their low values on the recording instruments. Similarly, in the case of a non-reservoir small amount of hydrogen ions and fast-moving neutrons are not absorbed rapidly and neutrons travel a long path and high values are recorded on the recording instrument (Asquith and Gibson, 2004).

4.1.1.9 Electrical Resistivity Logs

These logs measure the resistivities of formations within the borehole and indicate the presence of hydrocarbons. Furthermore, it provides an approach to compute the water saturation by determining the resistivity of formation water which has the inverse relationship with the conductivity (Amigun et al., 2012). Salinity of zones can be recognized through these logs. Water saturation can be determined by the amalgamation of these logs with the porosity log. It comprises of following logs.

1. Laterolog Deep (LLD)
2. Laterolog Shallow (LLS)
3. Induction Log

4.1.1.10 Laterolog Deep (LLD)

The assistance of LLD is incorporated for the examination of the uninvaded zone of deep penetration (5 – 7 inches laterally). It gives us useful results either in the case of saline muds or fresh mud zones by specifying the low and high resistivity values.

4.1.1.11 Laterolog Shallow (LLS)

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

4.1.2 Resistivity of water

The basic parameter for the calculation of the water saturation is the resistivity of water. In matured fields, the water samples are taken and tested in the laboratories. Drill stem test (DST) and repeat formation test (RFT) are employed to determine resistivity at various depths (Archie, 1942). Surface temperature, bottom hole temperature, water salinity in (ppm), and static spontaneous potential are the essential parameters to compute the resistivity of the formation water (Amigun et al., 2012).

4.1.3 Water Saturation

Percentage of water present in pore spaces of the rock is termed water saturation. It depends on the different variables like a, n, Rw, Rt, and Ø. To calculate the water saturation Archie Equation is adopted

4.1.4 Hydrocarbon Saturation

The percentage of hydrocarbon in the void spaces of the formation is termed hydrocarbon saturation. Hydrocarbon saturation can also be calculated by subtracting the percentage of water saturation from 100% (Alimoradi et al., 2011)

SH = 1-SW

SH = Hydrocarbon Saturation

SW = Water Saturation

Logs Used

1. Caliper log (CALI)
2. Gamma Ray log (GR)
3. Density log (RHOB)
4. Neutron log (NPHI)
5. Sonic log (DT)
6. Resistivity log (LLD and LLS)

4.1.5 Log Curves

The log information of Nandpur Well-02 was accessible in Logging ASCII Standard (LAS) format. All the parameters (hydrocarbon saturation, water saturation, volume of shale, and porosities) are calculated by using the information given in the header and LAS file. The method used is given in Fig 4.3, which shows the procedures of each analysis step by step. Fig 4.4 shows the petrophysical analysis of Nandpur Well-02. Hydrocarbon saturation was calculated from water saturation because of the inverse relation between water saturation and hydrocarbon saturation

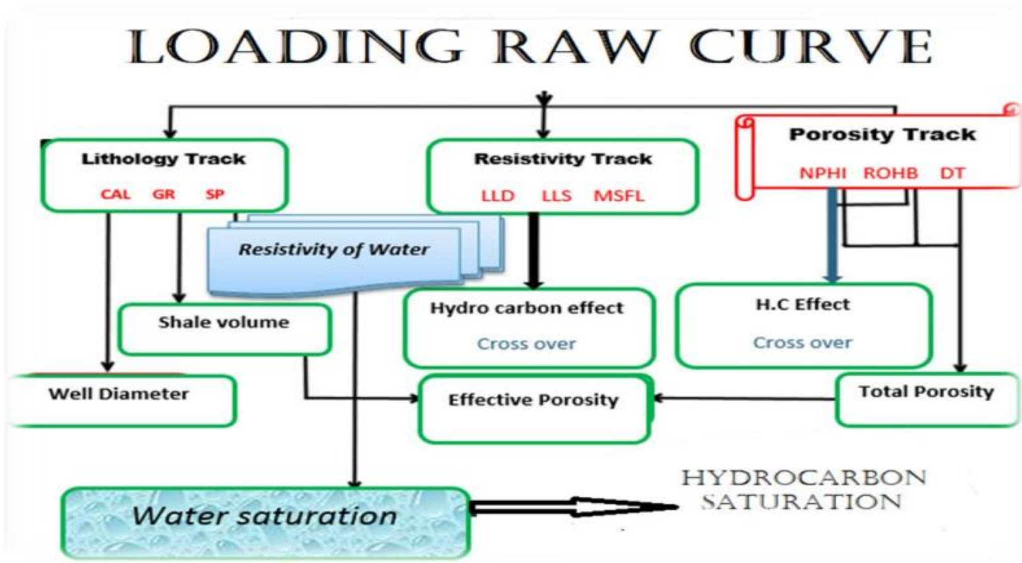

Figure 4.3 Workflow for Petrophysical analysis

4.1.6 Petrophysical Interpretation of the Nandpur well 2

The progressive petrophysical analysis was carried out by the Geographix Discovery software. The integrated response of all the logs run within the borehole of Nandpur 2 has been taken under consideration to evaluate the effective conclusion. The behavior of all the logs gives us a comprehensive image and scenario of the subsurface. The logs which are discussed earlier have been used for the analysis of this well. Zone of interest was marked within Nandpur 2 from depth range 1935 meters to 1955 meters total thickness of 15 meters in Samana Suk formation which is the major 15-meter thick reservoir in this zone. The values of the computed gamma-ray log are low in the marked zones which indicate the reservoir zone. The prominent indication of high resistivity values of fluid (oil and gas) can be verified by the separation of LLD and LLS. The crossover of NPHI and RHOB is the best indicator for hydrocarbon-bearing zones (Rider, 1996).

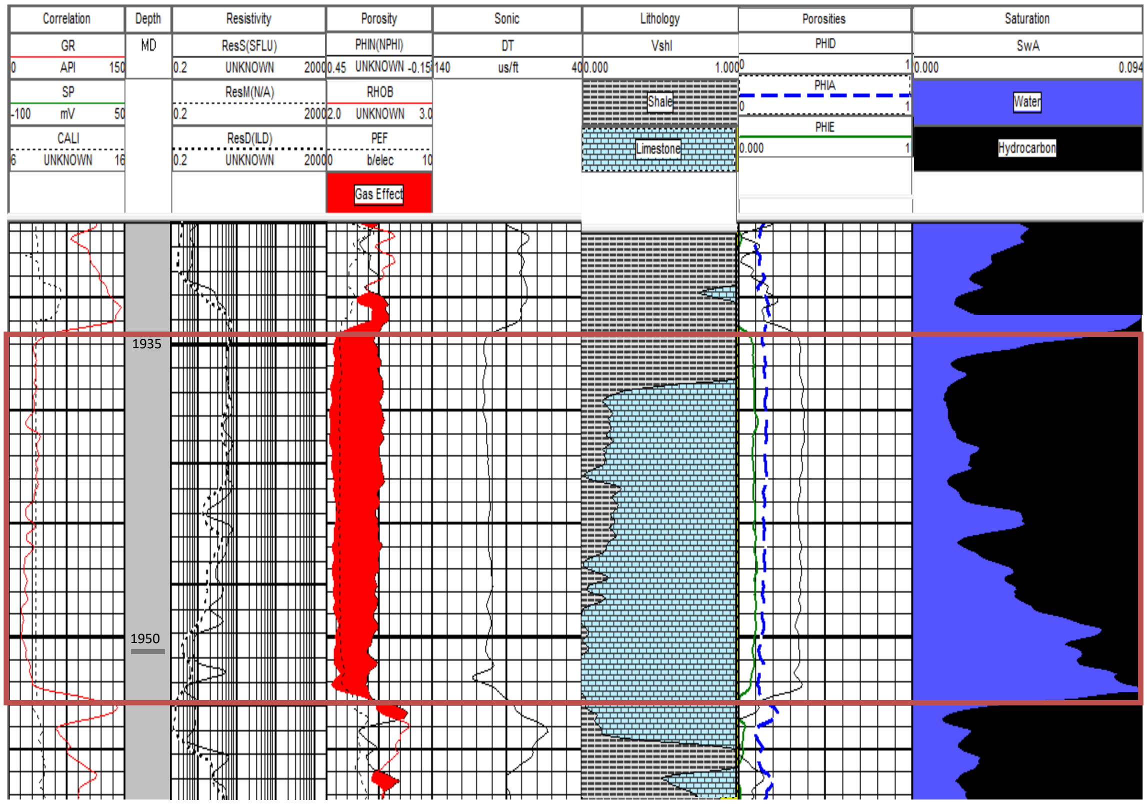

Figure 4.4 Output of petrophysical analysis of well Nandpur 2

4.1.7 Quantitative Petrophysical analysis

The zone of interest marked in the well Nandpur 2 of 15 meters thickness shows prominent hydrocarbons at this depth level. Qualitative analysis has been performed to estimate the actual quantity in the zone. The zone of interest has 92.8% limestone in which 7.3 total porosity is present which is favorable for the hydrocarbon accumulation. The quantitative analysis results are shown in table 4.1

Zone	Vsh %	Sh %	Sw %	PHIT %	PHID%	PHIE %
1	7.2	74.82	25.18	7.3	13.2	4.3

Table 4.1 Quantitative results of petrophysical analysis of well Nandpur 2

CHAPTER 5

SEISMIC INVERSION

5.1 Introduction

One of the most vital and widely used tools for hydrocarbon exploration is 3D seismic. It is the most suitable method to observe the subsurface geological conditions. The maximum information of the subsurface layers attains due to the relative differences in the acoustic impedances along with the depth during the propagation of seismic waves (Barclay et al., 2008). However, there are many ambiguities due to the heterogeneous nature of the earth, so to improve the resolution and quality of the reservoir characterization we incorporate the assistance of model-based inversion (Erryansyah et al., 2020).

Inversion is “a set of mathematical techniques to reduce the data for obtaining useful information related to the physical world based on assumptions drawn from observation” (Sen, 2006). In model-based inversion, we build a subsurface geological model by using the seismic data and well data as quality control. Reservoir characteristics can be analyzed by observing the acoustic impedance distributions throughout the study area (Erryansyah et al., 2020). Furthermore, it proposes the prospects for the developed fields and variations in the reservoir conditions due to the injection of certain fluids and extraction of hydrocarbons (Gavotti et al., 2014).

It is measured as

a) Physical rock properties like Impedance are produced when the acoustic seismic amplitude is inverted. Rock physics produces parameters such as porosity, layer depths, and fluid saturations which are used in flow simulation (Gunning and Glinsky, 2004).

b) The tuning effect of the wavelet is extinguished by Deconvolution which offers a high-resolution image.

c) The tie between seismic and well data is the result of acoustic impedance inversion which deals with the integration of well logs.

d) Compared to seismic amplitudes, Inversion propounds a much high resolve image and improved reservoir properties.

In terms of geology feasible to the occurrence of pore fluids the main intent of inversion into draw out subsurface geology. The output of seismic inversion is acoustic impedance which is used to calculate parameters like pore fluid, porosity, and water saturation. Figure 5.1 shows the difference between forward and inverse modeling.

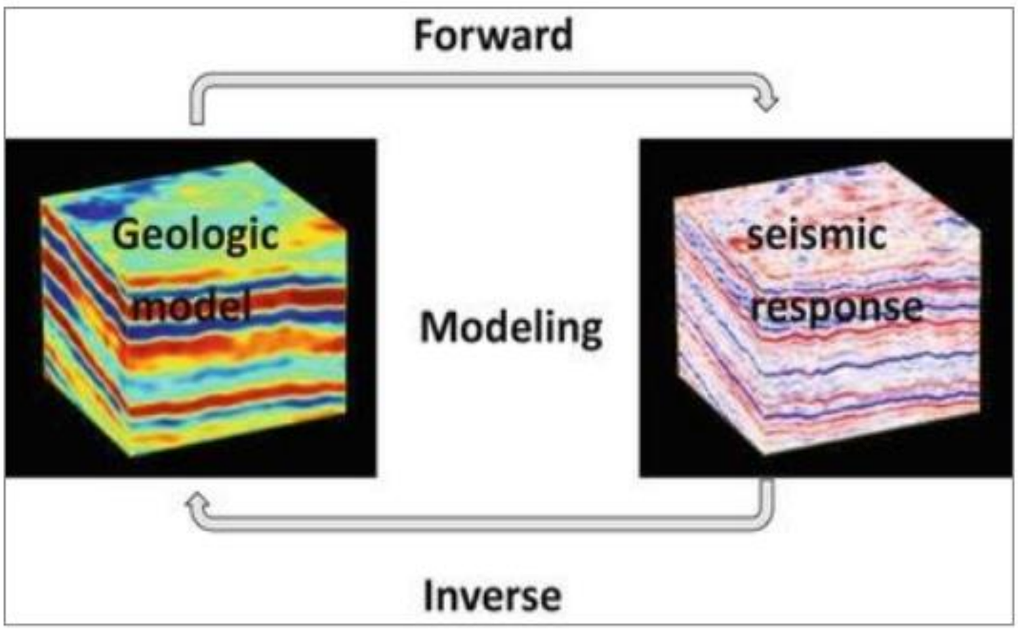

Figure 5.1 Seismic forward and inverse model (Image courtesy of arcis seismic solutions, TGS, Calgary).

5.2 Inversion Methods

Generally, the inversions methods are divided into two main categories which are Pre-Stack inversion and Post-Stack inversion. Their subdivisions are shown in figure 5.2

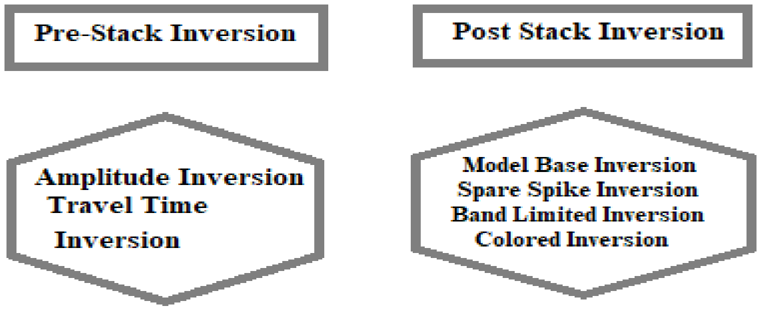

Figure 5.2 Methods of inversion (Russel, 1991).

5.3 Methodology of Inversion

Seismic inversion is a technique for determining the earth's acoustic impedance in which reflectivity is eliminated from seismic data using a convolutional model of the seismic trace based on the equation i.e. Seismic trace = Wavelet * Reflectivity + Noise. Reflectivity is the contrast between two interfaces where the impedance (Z) is the product between velocity and density.

$$\mathbf{R}_i = \frac{Z_{i+1} - Z_i}{Z_{i+1} + Z_i},$$

Here, Z_i and R_i are the acoustic impedance and reflectivity of a few particular layers. The inversion method can be helpful together with pre-stack and post-stack data (Russell, 1996). Both pre-stack and post-stack inversion techniques have distinct suppositions. Post stack inversion is zero offsets while pre-stack inversion is multi-offset. We have only post-stack data in the case of our dissertation we will perform the post-stack inversion.

5.4 Post-Stack Seismic Inversion

Seismic post-stack inversion is the most popular method because of its greater robustness and simpler assumptions. There are two approaches for post-stack inversion method, broadband, and band-limited inversion respectively (Russell, 2006). This type of seismic inversion deals with calculation of acoustic impedance by using post stacked seismic data, well data, and basic stratigraphic interpretations. There are three post-stacked inversions described which are mentioned as recursive or band-limited, sparse-spike, and model-based inversion (Hampson and Russell, 1991).

Band-limited inversion produces a band-limited inverted trace directly from the seismic data and then uses a geological model for integrating the low frequency. Spare-spike inversions estimate a set of sparse reflectivity from seismic data and then invert these RC series to make the acoustic impedance. Model-based inversion involves making a primary geological model which is then updated various times until the synthetic trace best matches the observed seismic response (Hampson and Russell, 1991). The sparse-spike and model-based inversion both produce a parallel result. If we talk about a sparse model then sparse-spike inversion produces better results but when we talk about real data, then it produces lower resolution compared to model-based inversion. Model-based inversion seems to be the most fascinating but to minimize the problem of non-uniqueness it has to be carefully imposed. In this we first built a model and then it is related to the seismic data the model is updated and the process of building, comparing, and updating the model is repeated until it best matches with the seismic data. It is possible that the matching between model and seismic is good but it may be wrong because there are many factors of velocity and depth pairs (Russell, 1996).

5.5 Model-Based Inversion Workflow

Seismic inversion is the reverse process as demonstrated by its name. When the wave passes through the earth it experiences the various lithologies and reflects from the boundaries due to the density alterations along with the depth. The product of density and velocity results in the acoustic impedance which is the property of each layer or horizon and AI relies on amplitudes. The difference in the impedance values provides us with the reflectivity series (RC). Then we convolve the series of reflectivity with the artificial wavelet and the net result of the process gives us the synthetic seismogram. An appropriate inverse filter is used to discard the effect of artificial wavelet and inverse the process by convolving synthetic with the inverse wavelet. The output of the reverse process gives us a series of reflections, which will further be divided into acoustic impedance (density and velocity information).

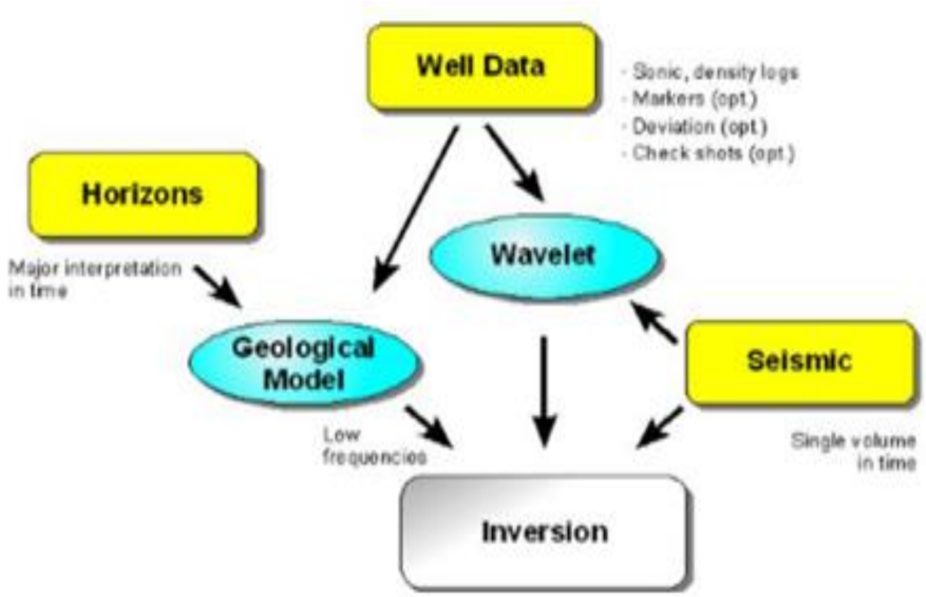

Figure 5.3 Workflow of model-based inversion.

5.5.1 Extraction of Wavelet

Wavelet is extracted from the seismic and it should have a constant phase (Minimum or zero). An inverse filter is used to inverse the wavelet and then convolves it with the seismic to produce the reflectivity series which is the combination of density and velocity. The wavelet is useful while doing the correlation between the extracted and inverted reflectivity series. Phase plays an extensive role in good and reliable inversion results. By shifting phase we relate our results by hit and trial method and select the convenient shift for our data set. Higher phase shift incorporates more complexities (Jain, 2013). The next most important step after extraction of wavelet is the computation of exact amplitudes which leads our results towards more authentication and validation. The extracted wavelet used in the Model-Based Inversion is shown in figure 5.4 and the properties of the wavelet are shown in table 5.1.

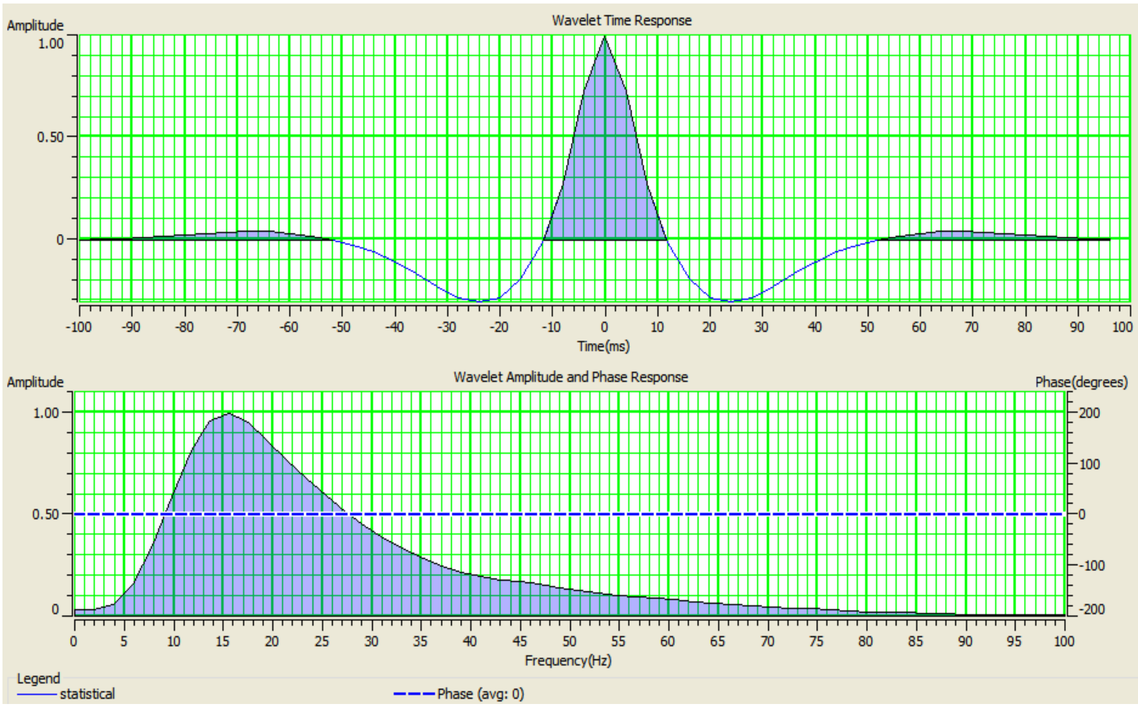

Figure 5.4 Frequency domain of Extracted Wavelet.

Extracted Wavelet	Dominant Frequency	Max. Amplitude	Phase
	15 Hz	1	Zero

Table 5.1 Properties of Extracted Wavelet.

5.5.2 Seismic to Well Tie

Seismic to well tie is the important step during model-based inversion as it demonstrates the accuracy and reliability of seismic inversion results. Correspondingly Kadanwari-01 well is used for the correlation and the wavelet extracted from the real seismic data which is recorded nearby the well and then convolved with the reflectivity (RC) series. One-dimensional (1D) modeling is shown in figure 7.5. Seismic to well tie portrays the 99% correlation results in this research. The time window has ranged from 1000 to 1500 m/s.

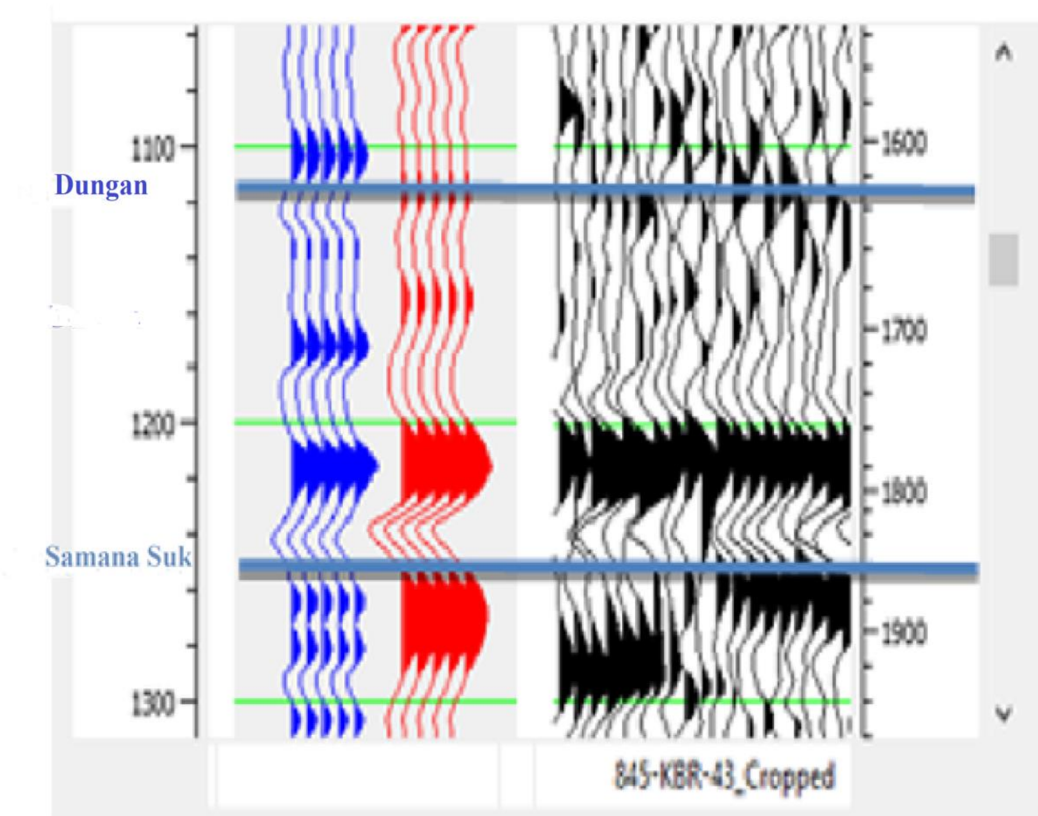

Figure 5.5 Seismic to well tie.

5.5.3 Initial or Low-Frequency Model

Low frequencies are not recorded during the seismic data acquisition due to the ground rolls and we waived out their effect during processing to enhance the signal-to-noise ratio. The absence of low frequencies in our final model causes the appearance of a false impedance layer which will affect our interpretation in the wrong direction. So, we have to incorporate the effect of these low frequencies to analyze thin layer lithologies. Velocity analysis, sonic logs, and geological models aided in the formation of a low-frequency model. Low frequencies play a crucial role while making the scale of impedance log (Lindseth, 1979) while on the other hand, the higher frequencies provide aid for comprehension of impedance log. we incorporate the low frequencies as an additional dataset for our interpretation.

Acoustic impedance is categorized by relative and absolute acoustic impedance. Relative acoustic impedance describes the relative property of a layer and employs for quantitative interpretation without incorporating the low-frequency model. While on the other hand, absolute acoustic impedance defines the absolute property of layer and yields both quantitative and qualitative interpretation. Absolute impedance can be obtained when we generate a low-frequency model (ranges from 0 – 15 Hz) by providing the sonic and density logs data to the inversion algorithms for inverting amplitudes (Cooke and Cant, 2010). The low-frequency model is shown in figure 7.6. It is essential to select the low cut-off frequency in band-limited inversion. The 15Hz cut-off frequency used in this research and below this we incorporated the log data and above which the seismic data is employed (Lindseth, 1979).

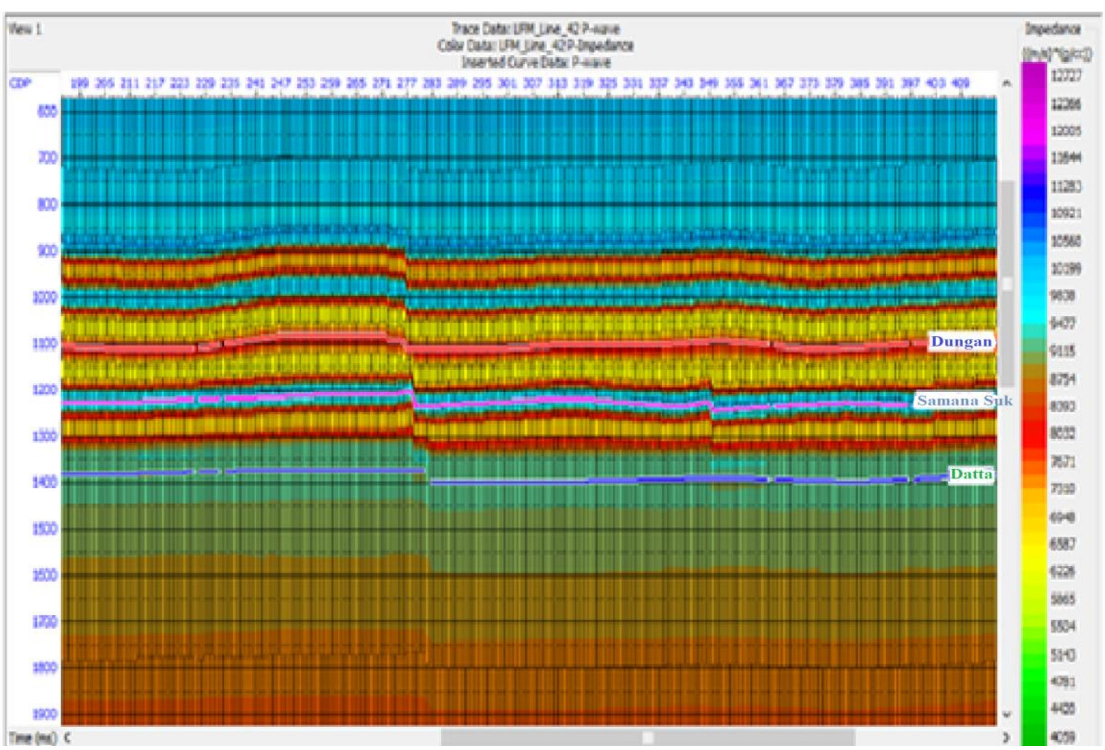

Figure 5.6 Showing the low-frequency model of seismic dip line KBR 42.

5.5.4 Inversion Analysis

Model-based inversion is executed at a single point of Nandpur 2 as shown in figure 5.7 and these traces assemble to form on whole seismic section. The impedance response is observed and noticed on the particular point and then interpolated o the entire zone. The wavelet is extracted from the time window range of 1000 to 1500ms. Correlation between the synthetic trace represented by red color and seismic trace represented by black color shows excellent results with the value of r= 0.99. The matching of Superimpose inverted and actual impedances exhibits valuable results. This matching was obtained by running 15 iterations in the model-based inversion analysis process.

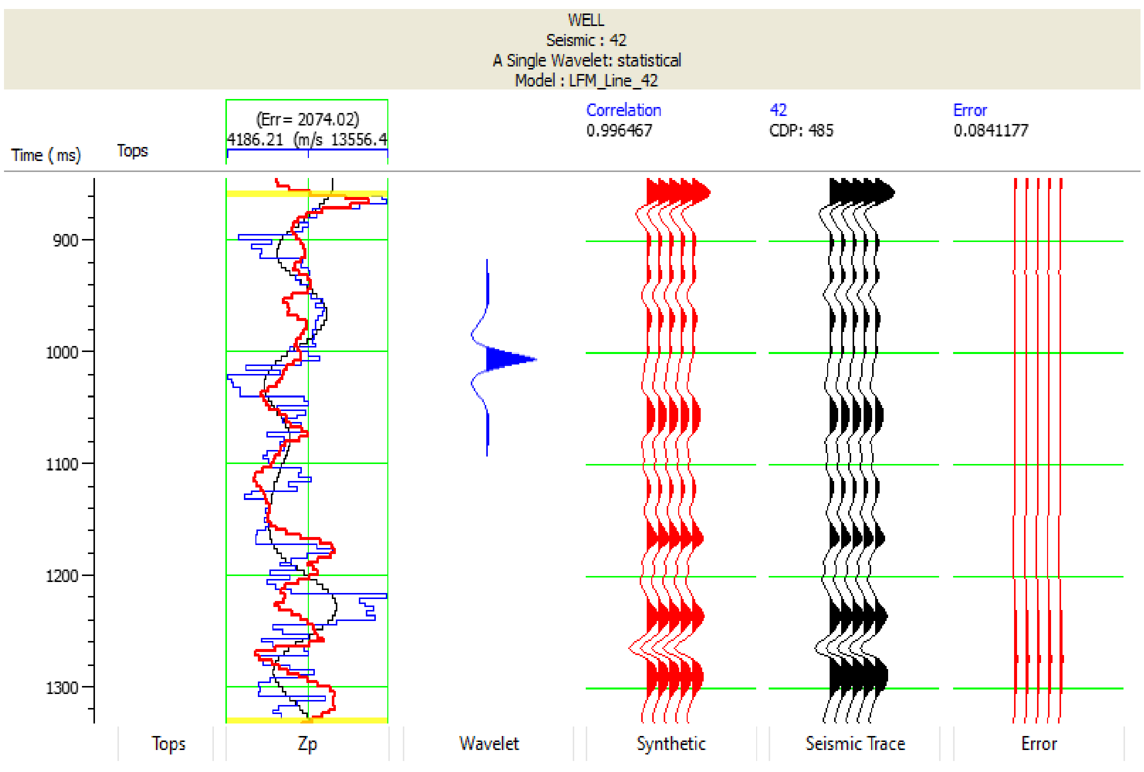

Figure 5.7 Inversion Analysis after running 15 iterations.

5.5.5 Model-Based Inversion Result

Model-based inversion applied on seismic section shown in Fig 5.8. Model-based inversion captures the lateral and vertical variation in acoustic impedance. Zone of interest Samana Suk Formation is starting at 1225ms has low impedance ranging from 5500 to 6500.The lower part of Samana Suk formation has lower impedance highlighted by yellow color which indicates the presence of hydrocarbons at this depth. The inverted seismic section captured the presence of reservoir in this zone. The blue and purple color below reservoir has higher impedance which indicates the presence of source rock in the obtained results. Vertical and lateral resolution of model-based inversion is greater and it also picks impedance variation within reservoir.

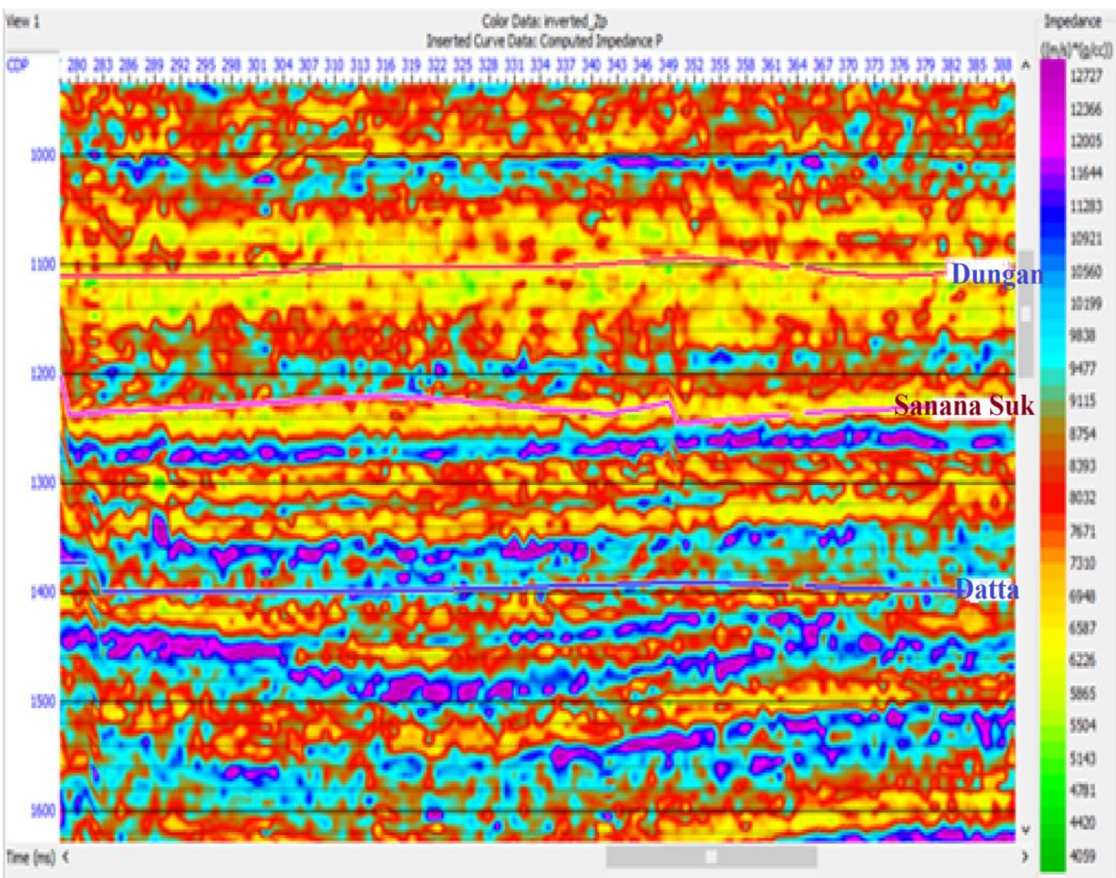

Figure 5.8 Inverted seismic section at the reservoir zone.

The inverted low impedance of 5500 to 6500 in the Samana Suk formation confirms the presence of hydrocarbons in the zone. Samana Suk formation is composed of limestone which naturally shows high impedance which is shown by red and blue color in the above figure and the low impedance in this limestone is due to the presence of hydrocarbons in the zone.

CONCLUSIONS

1. 2D seismic interpretation reveals the presence of normal faulting along with the horst and graben structures in Kabir wala area.

2. Three faults were marked based on structural discontinuities that shown horst and graben geometry in the area.
3. Three horizons were marked with the help of a synthetic seismogram to delineate the structures of the study area. Samana Suk formation was marked the main reservoir in this area.
4. Petrophysical analysis has been carried out at Nandpur 2 well which lies in the vicinity of our area of research. A combined response of all the logs is employed for the quantitative interpretation.
5. Zone of interest was marked as having good potential reserves, effective porosities, and hydrocarbon saturation in the Nandpur 2 well.
6. The quantitative interpretation showed the 15 meters thick more than 90% saturated zone of hydrocarbons
7. Model-based inversion is incorporated to pursue qualitative interpretation. Model-based inversion gives us information on subsurface layers in the form of acoustic impedances. Low impedances in the final inverted sections show good hydrocarbon-bearing zones.
8. The presence of hydrocarbons confirmed in the Samana Suk limestone through inversion by observing low impedance values in the limestone.

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