Integrated Study of Sinjhoro Block, using 2D Seismic Data And wireline logs, Southern Indus basin, Pakistan

By

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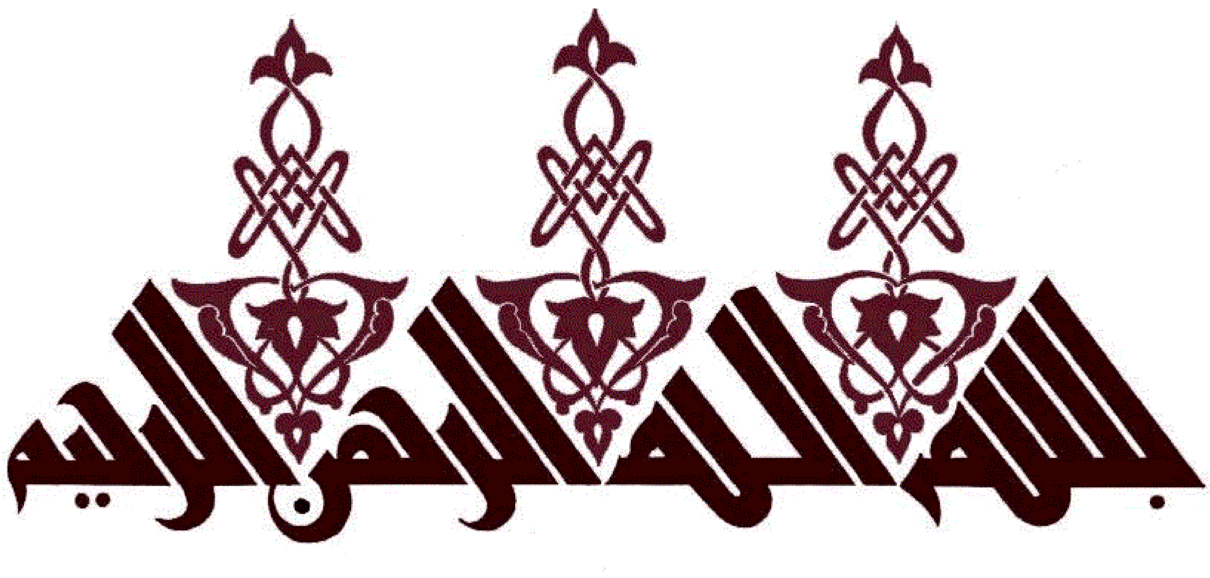
بسم الله الرحمن الرحيم

CERTIFICATE OF APPROVAL

This dissertation Muhammad Atif Hayat is accepted in its present form by the Department of Earth Sciences, Quaid-i-Azam University Islamabad as satisfying the requirement for the award of degree of **BS** Geophysics.

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DECLARATION

I hereby declare that the work presented in the following thesis is my own effort and that the thesis is my own composition. No part of the thesis has been previously presented for any other degree.

Muhammad Atif Hayat

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First praise is to Allah, the most Beneficent, Merciful and Almighty, on whom ultimately we depend for sustenance and guidance. I bear witness that Holy Prophet Muhammad (PBUH) is the last messenger, whose life is perfect model for the whole mankind till the Day of Judgment. I thank Allah for giving me strength and ability to carry out this study.

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Abstract

This dissertation contains the study and interpretation of 2D seismic reflection data of selected seismic lines of Sinjhoro area, Lower Indus Basin, Pakistan. The main objective of this research was delineation of subsurface structures favorable for hydrocarbon accumulation and attributes analysis.. This area is situated in the Sanghar District of Sindh Province and is licensed to Oil and Gas Development Corporation Limited (OGDCL).The data comprised four seismic lines and well tops of well CHAK 66-01.The names of lines obtained are: (20017-SNJ-03, 20017-SNJ-04, 20017-SNJ-05 and 20017-SNJ-08). Horizons are marked and named after correlating with well tops of CHAK 66-01, after well to seismic tie these horizons are correlated in whole area. In time structure maps, it was found that the area is under the Extensional Tectonic Regime which produced the Normal faulting in the region. Major Horst and Graben structures are formed due to process of rifting After Cretaceous only single major fault extends up to Chiltan Formation of Jurassic age. The lower cretaceous shale of sember formation is proven source for oil and gas discovered in the lower Indus basin, The Basal Sands of Lower Goru Formation are the main zones of interest in this area the upper goru formation as well as shale within the lower goru formation serves as cap rock for the underline sandstone reservoir. Time and depth contours were generated to for structural delineation. Seismic attributes are applied to identify the lithological distribution, structural deformation of the strata and for identifying the presence of hydrocarbon in the area. Instantaneous phase attributes are used for the purpose of identifying the lithological distribution and their lateral discontinuities. Envelope attribute is used to mark the possible location for hydrocarbon presence. The hydrocarbon potential of CHAK 66-01 is calculated by evaluating their petrophysical analysis of the Well logs.

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Chapter No.1

Introduction

1.1 Introduction

The rapidly growing world population and improving living standards lead to steadily increasing worldwide energy demand. Petroleum industry is a major unit which provides energy and sets standards for the world economy. Exploration, development and production are three phases of upstream stage in petroleum industry terminology. The upstream phase is served by geophysics, regional and structural geology, basin modeling, geochemistry and reservoir characterization as key specialists.

In petroleum exploration perspective, reconnaissance geophysical techniques (such as gravity and aeromagnetic prospecting) are employed at regional scale to distinguish the sedimentary basins. The basins are further divided into blocks, the block into fields and finally the field into reservoir compartments in order to enhance the production.

Seismology is the branch of geophysics which involves the analysis of ground motion for the understanding of Earth's interior. It is the major geophysical technique frequently employed in petroleum prospecting. The reflection seismology, analogous to the reflection optics, with sound waves as energy carrier rather than light waves in case of optical reflection, provides useful information about the subsurface.

Seismic interpretation has a basic premise to propose an equivalent geologic section from the seismic section (*Akhter et al, 2015*) in order to identify and demarcate the subsurface stratigraphic and/or structural trapping mechanism (*Badley, 1985*). Seismic section provides the subsurface image at high spatial resolution (and even higher in case of 3D seismic prospecting).

Well log analysis provides the subsurface image in terms of physical properties of the rocks as a function of depth at a higher vertical resolution. Well log interpretation ascertains the vertical distribution of petroleum play elements on the basis of their petro physical properties as well as the rock strength within elastic domain.

Seismic interpretation integrated with well log analysis of a region having substantial well control provides a high resolution subsurface model and hence deciphers the vertical as well as spatial distribution of the reservoir. In addition to the delineation of reservoir zone, its quality in production perspective is also predicted.

There are advanced algorithms developed for reservoir monitoring and by employing such models development wells can be avoided from any possible failure in future.

Introduction to study area:

Sanghar District is one of the largest districts in the Sindh province of Pakistan. Bounded by India on the east. The district capital, Sanghar, is itself a small city roughly 56 km south-east of the city of

Nawabshah.Sinjhoro is about 2.25 km North-west from Sanghar city, along shah dad-pur road shown in figure in 1.1.

Sinjhoro is part of Indus basin. The Sinjhoro E.L covering an area of 179.31 Square Km approximatly.It is extensional regime and normal faults are present here.

The location of area and its latitude and longitude is given below:-

- Latitude 26° 00' 00N to 26°15' 00 N
- Longitude 68° 48' 00E to 69° 05' 60 E

Fig 1.1 Satellite Image of the Sinjhoro Area (courtesy Google Images)

1.2 Data Used:

The Data set used in the study area consists of 4 2D-seismic lines shown in Table (1.1). A Single well is in the study data to understand the subsurface geology .Table (2.2)

Seismic Data:

Table1.1seismic lines used for Base Map

Serial no.	Seismic Lines	Line type
1	20017-SNJ-03	DIP
2	20017-SNJ-04	Dip
3	20017-SNJ-05	Dip
4	20017-SNJ-08	Strike

Well Data:

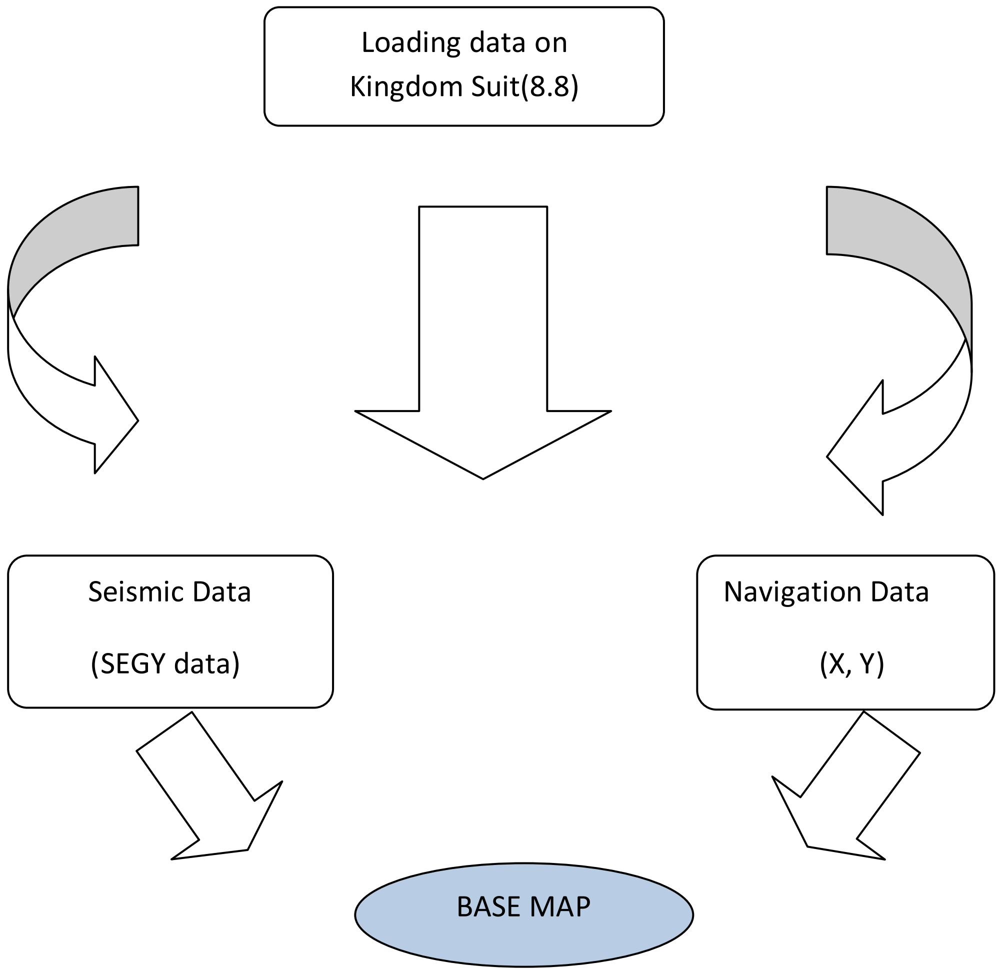
Well name	Well depth	Latitude	Longitude	Status
CHAK-66-01	2999.0	29º9' 54"N	68º52'34"E	Oil and gases

Table 1.2 Information for well Data

1.3 Base Map:

A base map is a map on which primary data and interpretations can be plotted. A base map typically includes the locations of concession boundaries, wells, seismic survey points with geographic reference such as latitude and longitude. Geophysicist typically use shot points maps, which show the orientation of seismic lines and the specific points at which seismic data were required to display interpretation of seismic data. The major requirement for the construction of the base map is the Navigation file (DBO format) and SEG-Y files.

Steps for the construction of the base map are elaborated by the flowing flow charts:


Loading data on
Kingdom Suit(8.8)
Seismic Data
(SEGY data)
Navigation Data
(X, Y)
BASE MAP

1.3.1 Base map of the area:

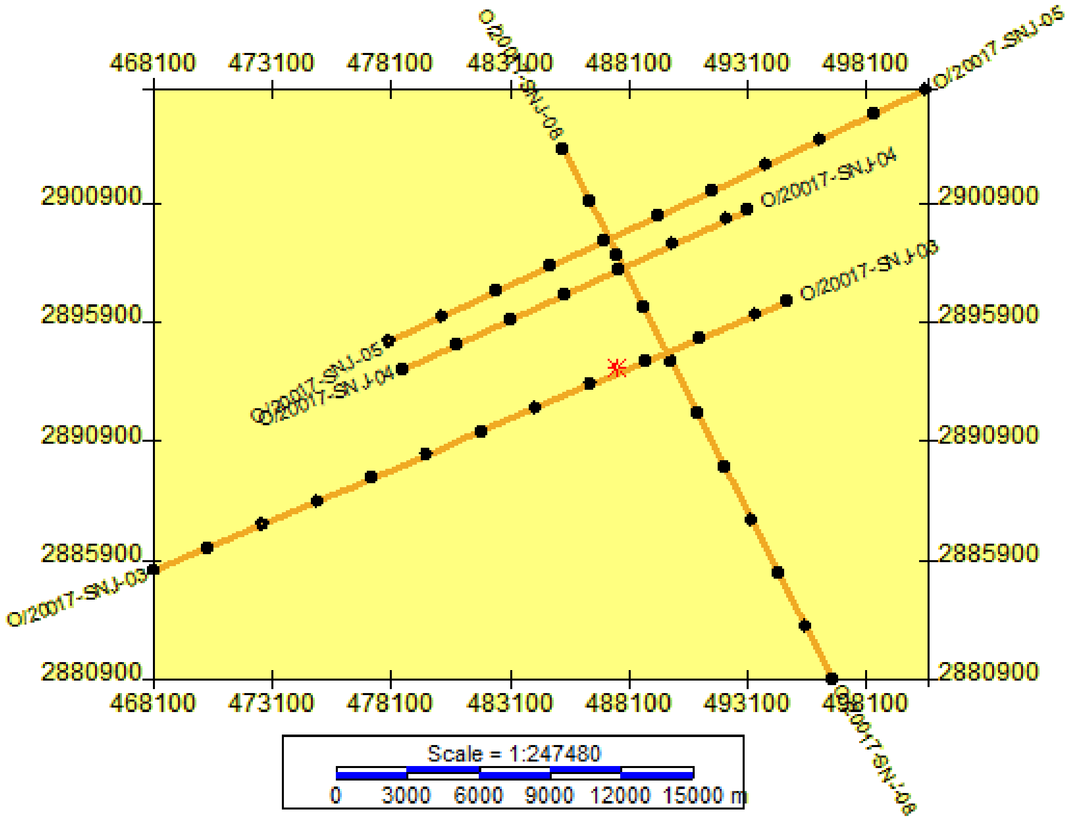


Fig 1.2 Base Map of the study area

1.4 Objectives of the Dissertation:

The dissertation aims to have a hand on the exploration basics in practical perspective. The main objective of this research work is to carry out a comprehensive interpretative study of the available seismic lines. However, a complete and reliable picture of the subsurface could not be obtained on the basis of the four available seismic lines. To have a slight grip over interpretation done, available literature was also taken in to consideration. This study contains the demarcation and delineations of the structural and regional fault trends in the area. This whole research gives an idea about the regional trends of the marked horizons, particularly the reservoirs.
Following are the objectives of the subject study.

- To develop an understanding of the tectonics and structural framework of the study area.
- To interpret the seismic data for the evaluation of the subsurface geology and structural features of the Sinjhoro Block.
- To identify and delineate the existing reservoirs and traps.

- To quantify and characterize the reservoir with the help of petrophysical analysis of the well data.
- To analyze the borehole data for the reservoir properties associated with rock strength within elastic domain.

1.5 Significance of Research Work:

This research work will be helpful for identification of subsurface structures of Shinjoro area that is favorable for hydrocarbon accumulation and trapping.

Petro-physics analysis that is done with help of the well data, gives information about the reservoir in the required area of interest. Rock Physics analysis plays a role of bridge between seismic properties and geologic properties particularly for the zone of interest. By integrating all these geophysical techniques possible hydrocarbons zones can be identified and new potential zones can be marked.

Chapter No. 2

General geology, Stratigraphy and Tectonics of the study area

2.1 General Geology of Sinjhoro:

As the project area is located in sanghar District, the southern part of the Indus basin. So we can define regional geology of sinjhoro area. The southern Indus is a strain basins characterized by tectonic faults up on the western edge of the Indo Pakistan sub-continent identifies. Several hypotheses have been proposed, the origin of these crusts explain functions, but Keller chains remain enigmatic. Thar platform gently sloping monoclinic analog Punjab platform controlled topography of the basement, the sedimentary wedge thins towards the Indian plates whose surface expressions in the form of nagarparkar high are available, it differs from the Punjab platform that it shows the buried formed by tectonic extension from the from the current counter clockwise movement of the Indian plate resulting structures. It is in the east of the Indian plate limited goes in Kirthar and Karachi trough in the west and in the north by mariBugti inner folded zone.

The platform by thar, Karachi built trough and offshore Indus stratigraphic structure cross-section clearly shows the stratigraphic and structural differences between the two sub-basins. The platform brands very good development of the early / mid-Cretaceous sand Guru, the reservoir for oil and gas (kadri, 1995).Wicky and horst ductile lithology of Upper Guru drapes, possibly along the dip to cut the post slate sand body by a Turonian disconformities forms the common Game Types (ECL,1988).

2.2 Indus Basin:

Pakistan comprises three major sedimentary basins, Indus Basin in east, Balochistan Basin in west and Pishin Basin in northwest. Indus Basin is separated from Balochistan by Ornach Bela Transform Fault. Pishin Basin is present between Indus Basin and Chamman Transform Fault. Indus Basin is the largest onshore sedimentary basin in Pakistan and covers about 5,3350 km2 area. Due to the convergence between Indian and Eurasian plate, it is suggested that Indus Basin is separated into two parts i-e.

1. Upper Indus Basin
2. Lower Indus Basin

Its further classification is given in figure 2.1

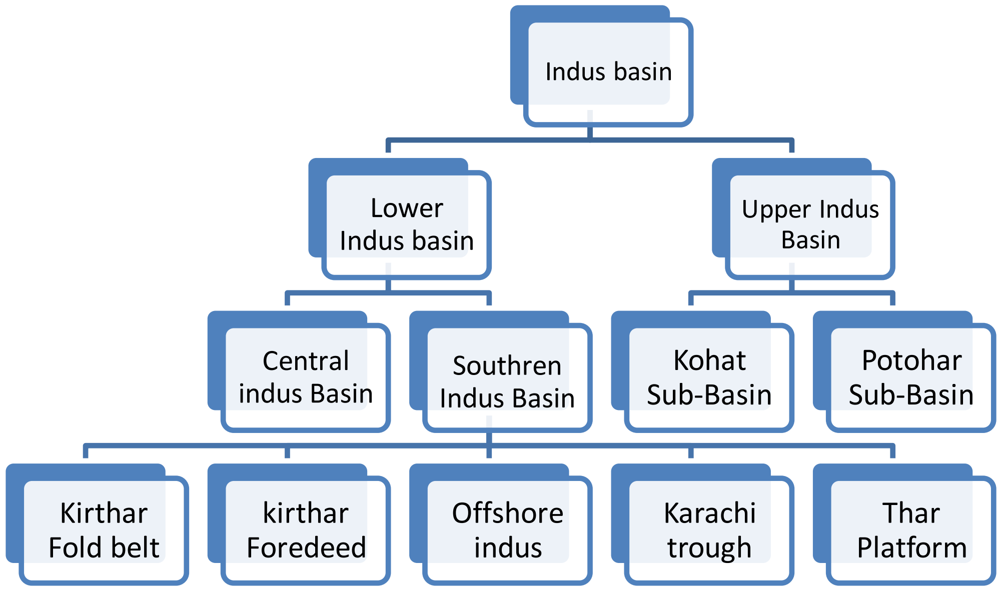
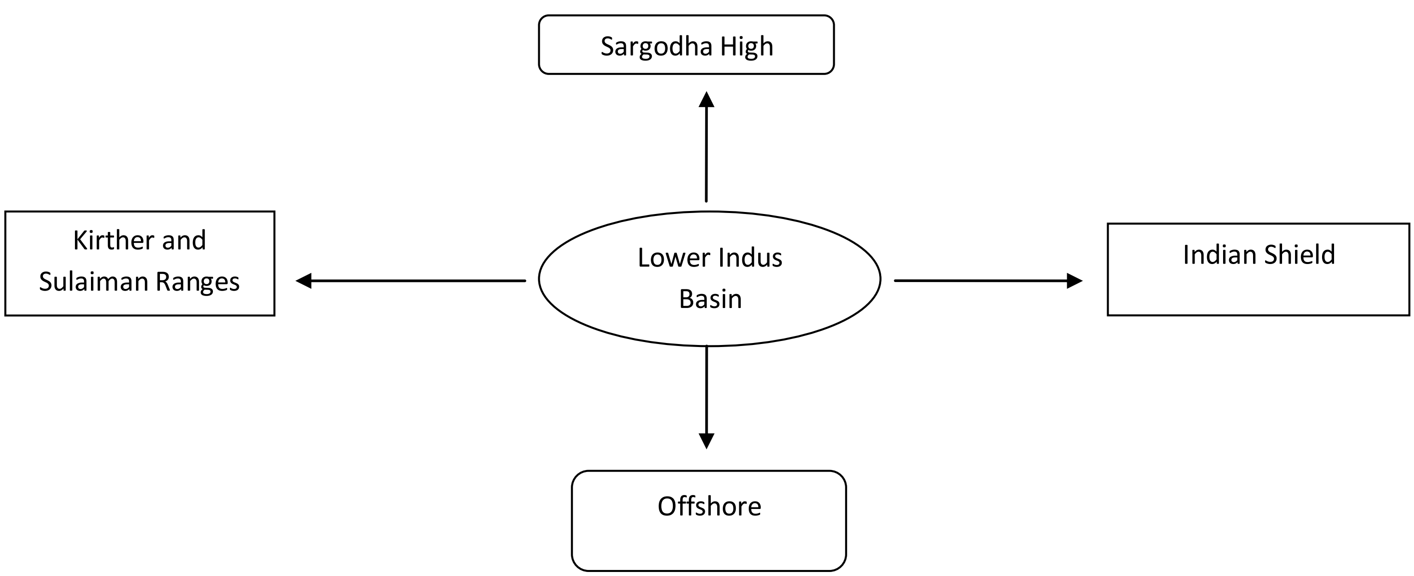


Fig 2.1 Classification of Indus Basin (Kadri I.B, 1996).

2.2.1 Stratigraphy and Tectonics Settings of Indus basin:

Tectonically Indus Basin is steady area than other zones of Pakistan (kadri, 1995). The basin is oriented in NE - SW direction. Basement exposed at two places, one in NE (Sargodha high) and second in SE corner (Nagar parker high). Geological boundaries of the area are in Fig 2.2



2.3 Tectonic Zone and Geology of Sinjhoro:

Sinjhoro E.L is a part of Thar Slope Platform area of Southern Indus Basin. It is bounded in the east by Indian Shield and in the west by Kirthar and Karachi Trough and in the north by Mari-Bugti

Inner Folded Zone. During the drift of the Indian plate towards the North-North East, which started in the Triassic, sedimentation took place along the leading edge of the plate in a marginal sag basin. Although several sedimentary cycles can be recognized within this phase, no major tectonic activity occurred until in the Cretaceous. In the lower Indus region, a depositional environment during the Paleocene resembled the pattern of the Mesozoic. However, later during the Eocene, the first orogenic pulse exercised its influence on the sedimentation by that time, the paleo geographic changed completely with the emergence of a volcanic island arc, North West of present day Pakistan. The sediments derived from the arc entered marine environments towards South East and independent decenters developed in various parts of Pakistan. The marine sediments became restricted to a narrow but rapidly subsiding trough in the Kirthar Area. The clastic supply from the rising Himalayas and from the local positive regions of the axial belt was so abundant that a spectacularly thick sequence of molasses sediments reached more than 7000m. Towards the end of the Paleocene, the Indus Basin was filled with sediments and must have resembled a vast flood plain with braided stream, the only elevation being the hills of the folded belts. This part of Lower Indus Basin represents progradational Mesozoic sequences on a westward inclined gentle slope. Every prograding time unit represents lateral facies variations from continental and shallow marine in the east to dominantly basinal in the west. In Thar Slope Area, all Mesozoic sediments are regionally plunging to the west and are truncated by unconformable volcanic (Basalt of Khadro Formation) and sediments of Paleocene age.Two broad geological divisions of this region the Gondwanian and the Tethyan domains are discussed. In this scenario Pakistan is unique inasmuch as it is located at the junction of these two diverse domains. The southeastern part of the Pakistan belongs to Gondwanian domain and is sustained by the Indo-Pakistan crustal plate. The northern most and western regions Pakistan fall in tethyan domain and present a complicated geology and complex crustal structure.

On the basis of plate tectonic features, geological structure, orogenic history (age and nature of deformation, magmatic and metamorphism) and lithofacies, lower Indus basin may be divided into the following broad tectonic zones shown in figure 2.3

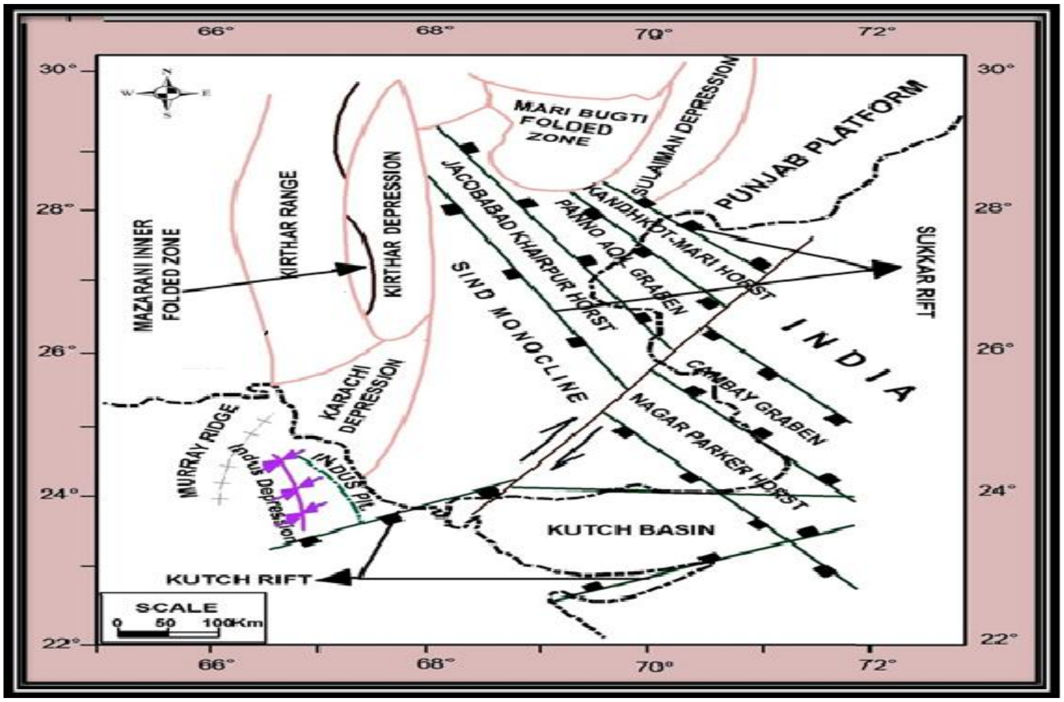
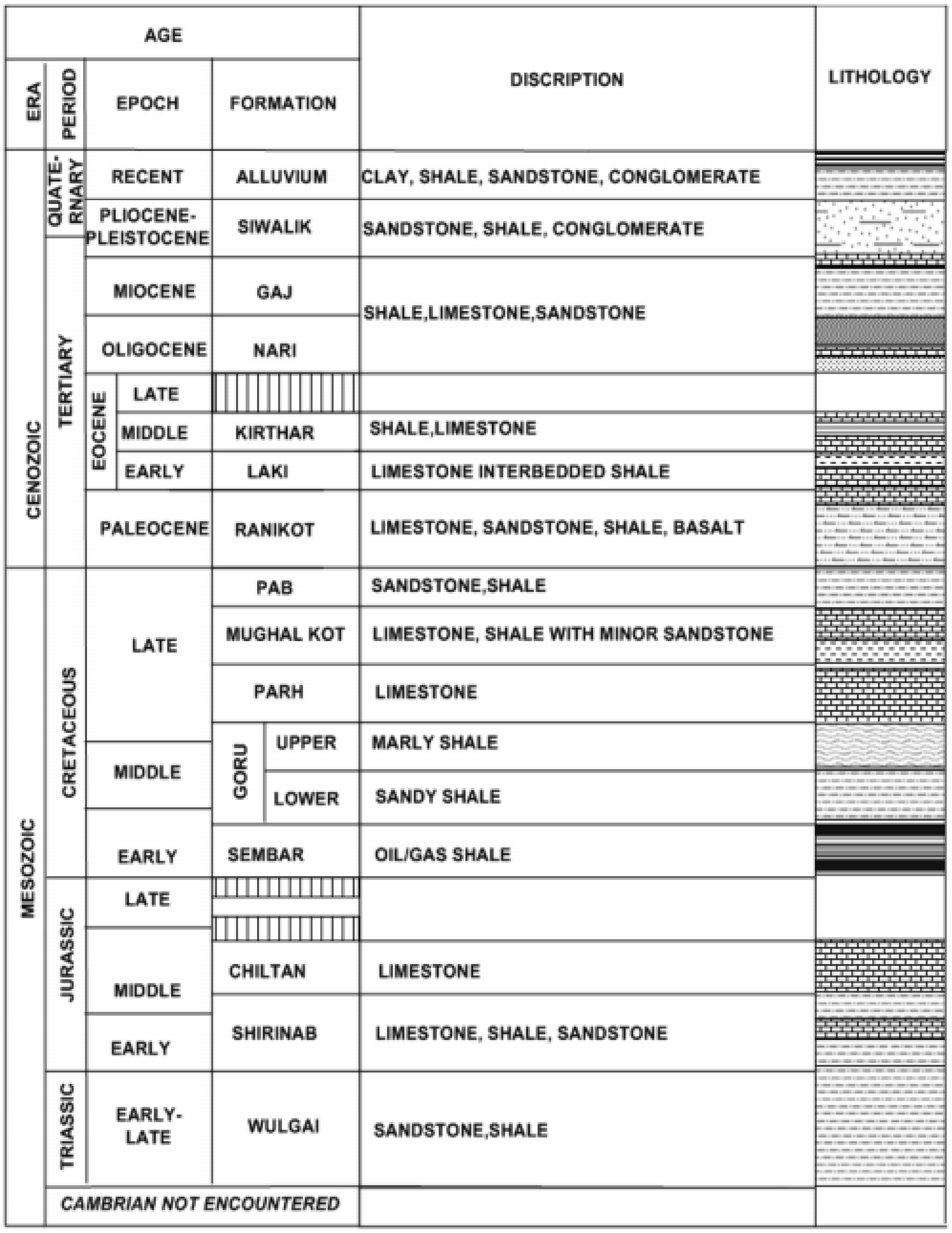


Fig 2.3 Map showing the Tectonic zones of Lower Indus Basin (RAZA 1990).

2.4 General Stratigraphy

The generalized stratigraphy of Lower Indus Basin is summarized in figure 2.4



`Fig 2.4 General stratigraphy of the area

2.5 Stratigraphy:

The area comprises a full range of formation with oldest rock in the area from Pre-Mesozoic till most recent formation of Eocene age. But major focus in the area due to petroleum play is on Lower Guru Formation which is of Cretaceous age which is acting as reservoir in the entire basin. See figure 2.5

2.5.1 Goru formation:

The sands of Goru are the most important entity in the southern Indus basin from the petroleum reservoir point of view. The thickest Goru sedimentation occurs within the Karachi Embayment. On the wells west of Badin platform, Goru is partially penetrated about 2,360 meters (kadri, 1995).Based on its lithological content, Goru Formation has been divided into upper and lower portions, with sand being rarer in upper portion. Upper portion is predominantly shale while the lower portion is the sandy member. This lower portion (lower Goru) is the most important reservoir in southern Indus basin. It contains all the hydrocarbons in Sindh Monocline (kadri, 1995).The wells drilled in Badin area exhibit a lateral facies change from east to west, from producible sand/shale sequence in Lower Goru to non-reservoir sand/shale facies, which in turn is entirely represented by shales further west (kadri, 1995).

2.5.2 Parh limestone:

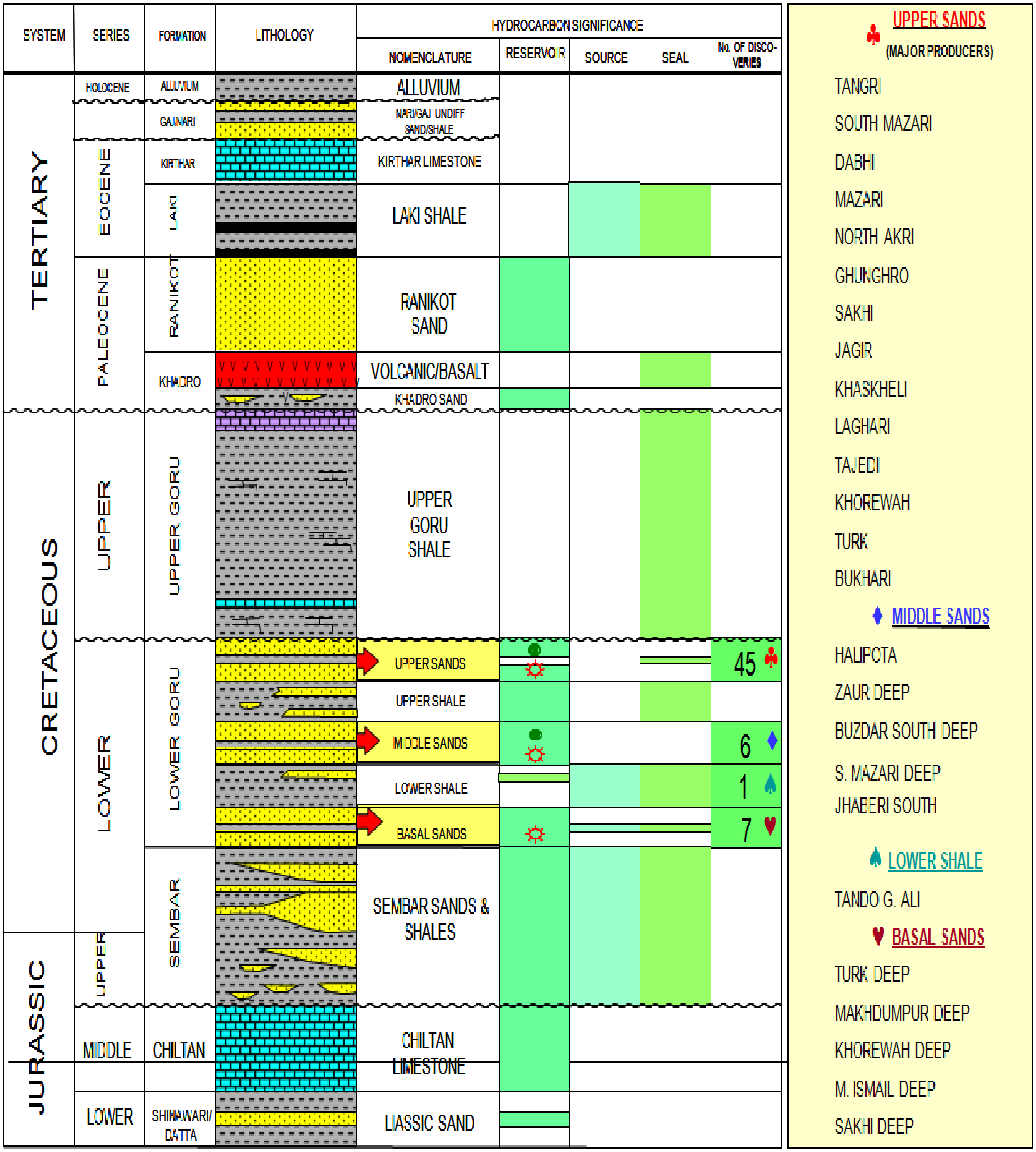
Although Parh limestone occurs widely throughout the Indus Basin, erosional truncation has limited the Formation distribution to an area lesser than Goru and Sember Formations (Qadri, 1994). Like in Badin platform area it is only present in southern portion and that too in the form of thin layer. No oil or gas shows have been found in the Parh limestone in the subsurface and no surface seeps are known.

2.5.3 Pab sandstone:

It is light grey to light tan to brown, quartzose, fine to coarse grained, hard to soft sandstone. It is occasionally conglomeratic and generally cross-bedded. It is considered to be deposited under shallow water environment characteristic of the MughalKot deposition. In the MughalKot seepage area, most of oil seeps are from Pab. It also forms petroleum reservoirs at Pirkoh, Loti, Dhodak and Rodho fields. It is considered to have no source potential (kadri, 1995).

2.5.4 Ranikot Formation:

One division of Ranikot group suggests that it comprise of three formations which are Khadro formation, consists of olive, yellowish brown sandstone and shale with interbeds of limestone. Keeping ascending Stratigraphy order, Above Khadro formation is Bara formation (Lower Ranikot sandstone) consists of variegated sandstone and shale. The upper one is the Lakhra formation (Upper Ranikot limestone) consists of grey limestone, grey to brown sandstone and shale. Various authors have given it different divisions.



(Fig 2.5) Stratigraphy of the Area.

2.6 Petroleum Prospect

Stratigraphic column shows that different rocks act as Source, reservoir and Cap rock.

2.6.1 Reservoir Rocks:

The depositional environment of the Lower Guru sands in the Sinjhoro field is interpreted to be a wave dominated, low stand shelf edge delta system with barrier sands and channel fills. The low acoustic impedance together with strong seismic amplitudes indicates the presence of reservoir quality sands. According to Iqbal qadri Petroleum geology of Pakistan, Reservoir quality sands are only present in the deposition allyup dip, i.e. the shallowest marine part of the lowstand wedge, as are found in the Sawan, Miano, Sinjhoro and Kadanwari Fields (Afzal, 1996).

2.6.2 Seal Rocks:

The known seals in the system are composed of shales which are interbedded with sands and overlying the reservoirs. In producing fields thin shale beds of variable thickness are effective seal. Additional seals that may be effective include impermeable seals above truncation traps, faults, and up dip facies changes. The upper Gurushale and interbedded shales of sui Main limestone are acting as seal in study area.

2.6.3 Source Rocks:

Source rock is the productive rocks for hydrocarbon. They also initiated the conversion of organic compound into oil and gas form. The Formations, which act as source rocks in the project area are as follows:

- **Sember Formation**: Sember Formation is believed to be the source of hydrocarbon in Sinjhoro field and huge gas accumulation in Suleiman province. Potential reservoir occurs within the sandstone of formation.

Hydrocarbon Potential in Middle Indus Basin

Lower Guru and Sember formations are considered as potential reservoir rock in Lower Cretaceous siliciclastic of Lower Indus Basin. Lower Guru sandstone is the reservoir rock in the study area. The presence of gas in the study area signifies the possibility of oil from the Early Cretaceous Sember, which acts as a source rock as well as reservoir. All producing well in the study area are of type 3-Kerogen source rock.(kadri, 1995).

Chapter No. 3

Seismic Interpretation

3.1 Objective of seismic Interpretation

The objective of seismic data interpretation is to extract all available subsurface information from the processed seismic data. This includes structure, stratigraphy, subsurface rock properties, velocity, stress and perhaps reservoir fluid changes in time and space. A good knowledge of geologic history of the area to be studied is important in making quality decisions during interpretation of the seismic data.

3.2 2D-Seismic Interpretations

Seismic interpretation conveys the geologic meaning of seismic data by extracting subsurface information from it and can be of different kinds, such as structural, stratigraphic and seismic stratigraphy. It depends on the geologic objectives linked to the phase of exploration and on the type of available data, its grid density and its quality(Nanda, 2016).
Interpretation reveals the geologic meaning of seismic data by extracting subsurface information from it. (Nanda, 2016)
Interpretation is the transformation of the seismic reflection data into a structural appearance by the application of correction, migration and time depth conversion (Dobrin, 1976).
The seismic data interpretation is the technique of determining information about the subsurface of earth from seismic data. It may determine general information about an area, locate prospects for drilling exploratory wells or guide development of an already discovered field (Coffeen, 1986).

Interpretation work flow is shown in Fig 3.1

Seismic data has been interpreted in two modes.

- The first mode is in areas of substantial well control, in which the well information is first tied to the seismic information, and the seismic then supplies the continuity between the well for the zone of interest.
- The second mode is in areas of no well control (frontier areas) in which the seismic data provide both definition of structure and estimates of depositional environments.

The main purpose is to make reflection as clear as possible to study structure and stratigraphy of subsurface. Geologic meaning of the reflection is the indication of the boundaries where there is change in the acoustic impedance. Seismic data has been interpreted with well control and the well information is used to tie with the seismic data.
There are two main approaches for the interpretation of seismic section:

- Stratigraphic Interpretation
- Structural Interpretation

3.2.1 Structural Interpretation

It is the study of reflector geometry on the basis of the reflection time. The main application of the structural Interpretation of seismic section is in the search for structural traps containing hydrocarbons. Most structural interpretation uses two way reflection times rather than depth. Time structural maps are constructed to display the geometry of selected reflection events. Seismic sections are analyzed to delineate the structural traps like folds, faults and anticlines. In this modern era of science and technology, software suits provide a great help in analyzing the seismic data both structurally and stratigraphically. Software helps the interpreter by automatically detecting the fault zones and then marking them on the whole project area. But for this the seismic data should be high resolution.

For this particular project, we emphasized more on the structural interpretation. Since we did not have digital copies of the seismic lines, horizon-marking and time-reading was done manually.

3.2.2 Stratigraphic Interpretation

Stratigraphic interpretation involves the subdivision of seismic sections into sequence of reflections that are interpreted as a seismic expression of genetically related sedimentary sequences. According to Dobrin&Savit, throughout the history of reflection method, its performance in locating hydrocarbons in stratigraphic traps has been much less favorable then in finding structurally entrapped oil and gas. Stratigraphic oil traps can result from reefs, pinch outs or other features associated with erosional truncations, facies, transition and sand lenses associated with buried channel, lacks are similar sources. Different software provide help in stratigraphic analysis as well by overlaying different seismic attributes on seismic sections to detect pinch outs, truncations etc.

3.3 Techniques for Structural Interpretation

Seismic sections give images of reflection arrival times. Variation along profile is called as time scanning. Structural Interpretation is done by:

1. Time Section
2. Depth Section

- **Time Section**

It is basically the reproduction of seismic section, Time section have two scales one is vertical scale consisting of time while the second is horizontal scale that consists on SP's.

- **Depth Section**

In seismic data interpretation and processing the important is the accurate measurements of seismic velocities. Following method listed below is used to determine the average velocity in order to construct the depth section

$$Depth = \frac{V * T}{2}$$

Where, T= Two way travel time of each reflector in seconds

V= Velocity of respective reflectors

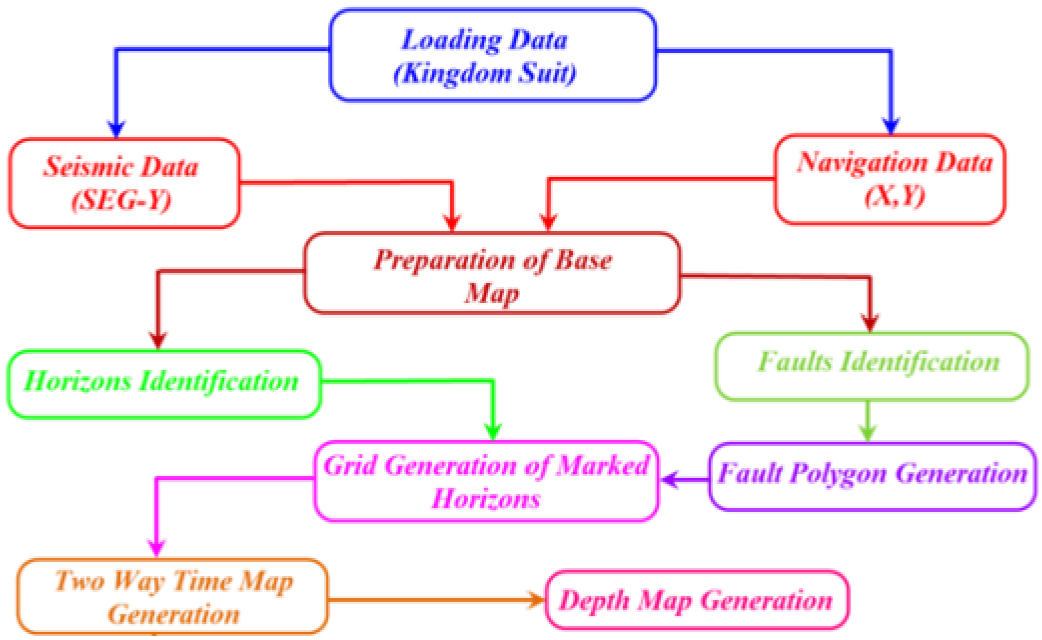


Fig 3.1 Interpretation work flow.

3.3.1 Structural Interpretation of Seismic Data

Brief stepwise methodology is given below which is used for interpretation:

3.3.2 Generation of Synthetic Seismogram

Synthetic seismogram is 1D forward model which assists in seismic-well tie. It is the result of the source wavelet convolved with the reflectivity series for normal incidence at the interfaces. A synthetic seismogram of well CHAK 66-01 is generated which is shown in **Fig 3.2**.
The procedure followed for synthetic seismogram generation is as follows:

1. Calculate the seismic velocities from sonic log and densities from the density log.

2. Determine the T-D curve by using sonic velocities for the borehole.

3. Determine the acoustic impedance which is the product of seismic velocity and density.

4. Calculate the reflection coefficient for normal incidence which represents the variation and contrast in acoustic impedances of the reflectors.

5. Convolve the reflectivity series with the seismic source wavelet (either obtained from the seismic trace adjacent to borehole or a theoretical wavelet is employed) to have the synthetic seismic trace (Kearey et al., 2013).

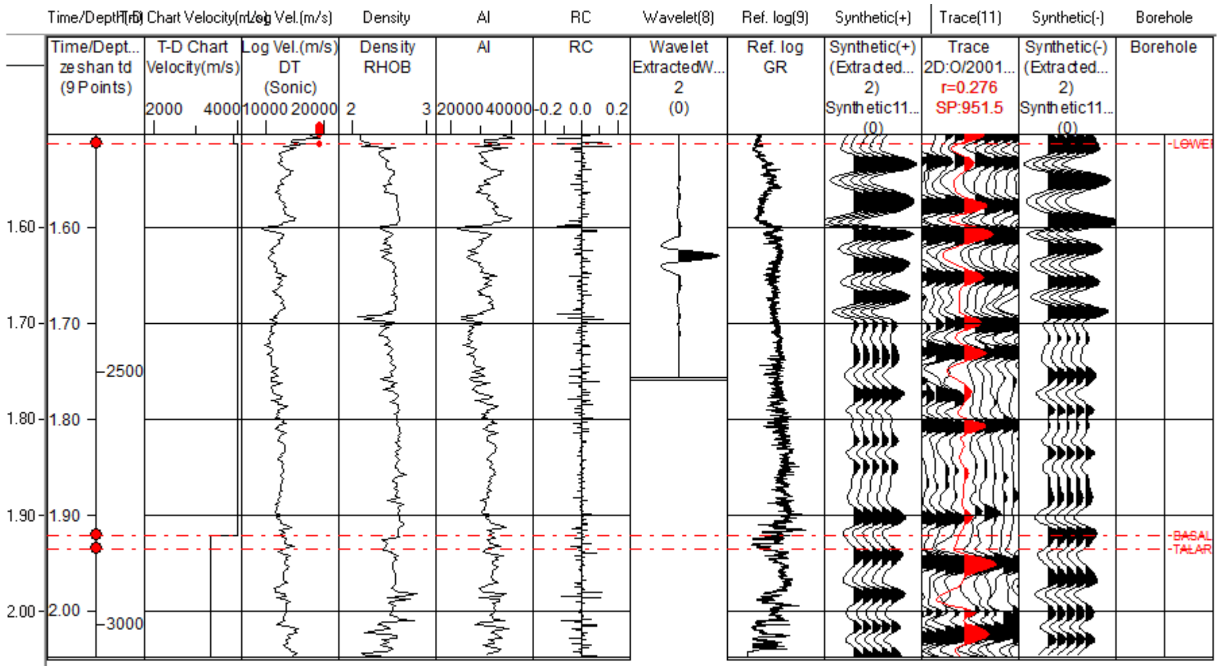


Figure 3.2 Synthetic Seismogram

3.3.3 Identification of Faults

On the basis of discontinuity on the reflections, faults are marked. On strike line no fault has been marked whereas faults has been marked on dip lines which clearly indicates the discontinuity and as the hanging wall moves down so on this base these faults can said to be normal faults. As the seismic sections were of fair quality it was not difficult to identify the faults on the basis of break in the continuity of reflector. The Middle Indus basin is characterized by normal faulting with strike slip component structures. As our interested formation was Lower Goru, it has normal faults. Many faults were marked on the basis of clear breaks in the continuity. All faults make horst and graben structure in the area.

3.3.4 Picking Horizons

After tying Synthetic Seismogram the respective reflectors has been marked on the section (Figure 3.4,3.5,3.6 and). On the basis of prominent coherency of reflections visible on seismic section from the subsurface interface the reflectors are marked. Then this information is shifted to other seismic lines by tying seismic sections. The reflection of all the prominent reflectors was recognized on the basis of the synthetic seismogram and their lateral continuity. Lower Goru and Basal Sand were marked on the basis of synthetic seismogram while Ranikot Formation was marked on well top bas

3.3.4 Interpreted Seismic Sections

As each seismic line demonstrates different type of information so each interpreted seismic section is discussed.

- **Line SNJ-03**

It is a dip line which has series of normal faults and showing series of horst and graben structures. Reflectors marked on this line starting from Ranikot formation to Basal sand (Figure 3.4). All these reflectors marked on the basis of continuous reflection while 6 faults are marked on this line. As discussed CHAK 66-01 well lie on this line and synthetic has generated from this well data and reflectors marked on this section after tying synthetic. All marked faults can be seen in this section. In this section Ranikot formation is at 1.006 second time, Lower Goru formation is at 1.35 sec, Basal Sand formation is at 1.922 sec.

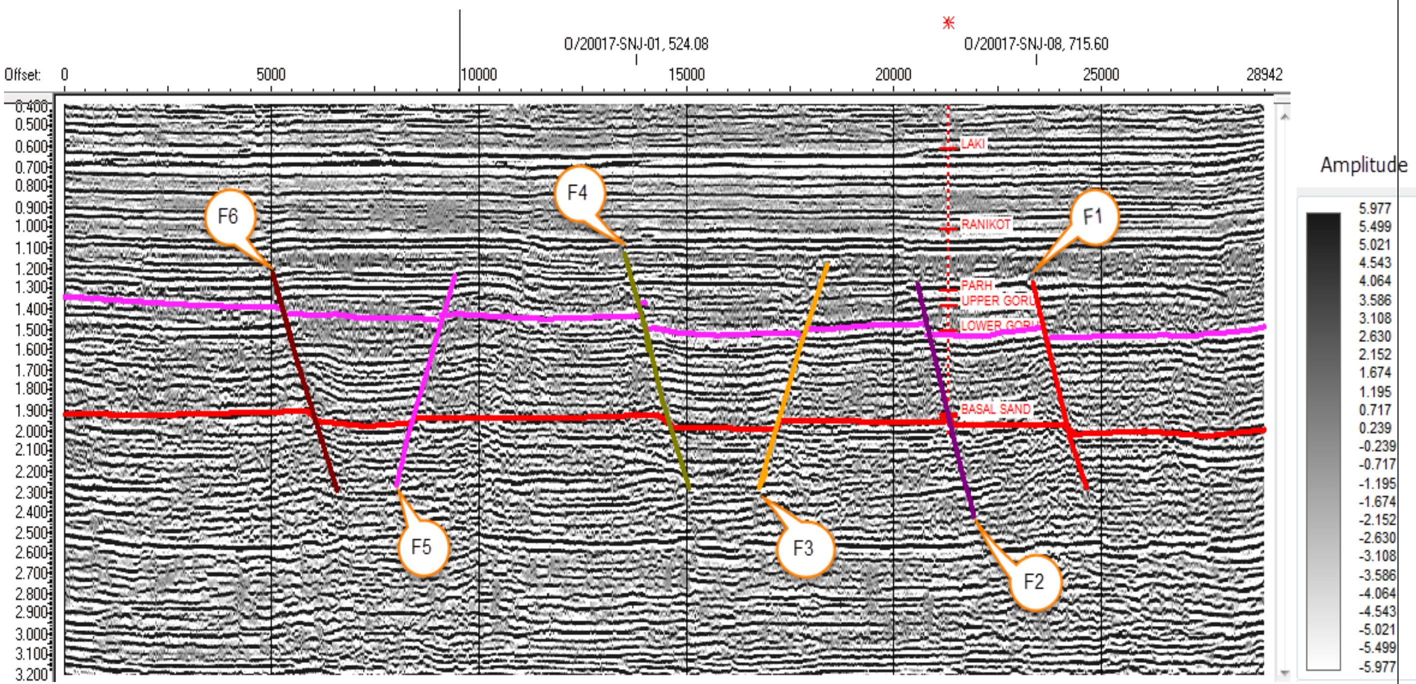


Fig 3.3 Marked Horizons and Faults are shown on seismic Dip line 20017-SNJ-03

Similarly other lines are shown as follows:

- **Line SNJ-04**

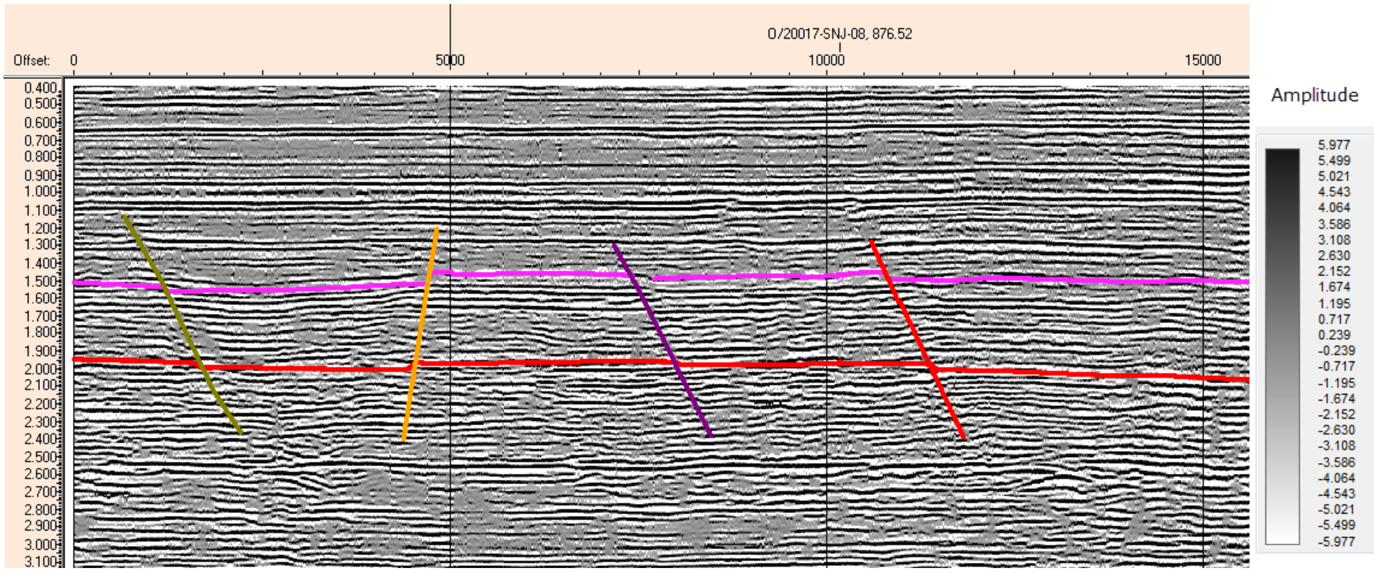


Fig 3.4 Marked Horizons and Faults are shown on seismic Dip line 20017-SNJ-04

- **Line SNJ-05**

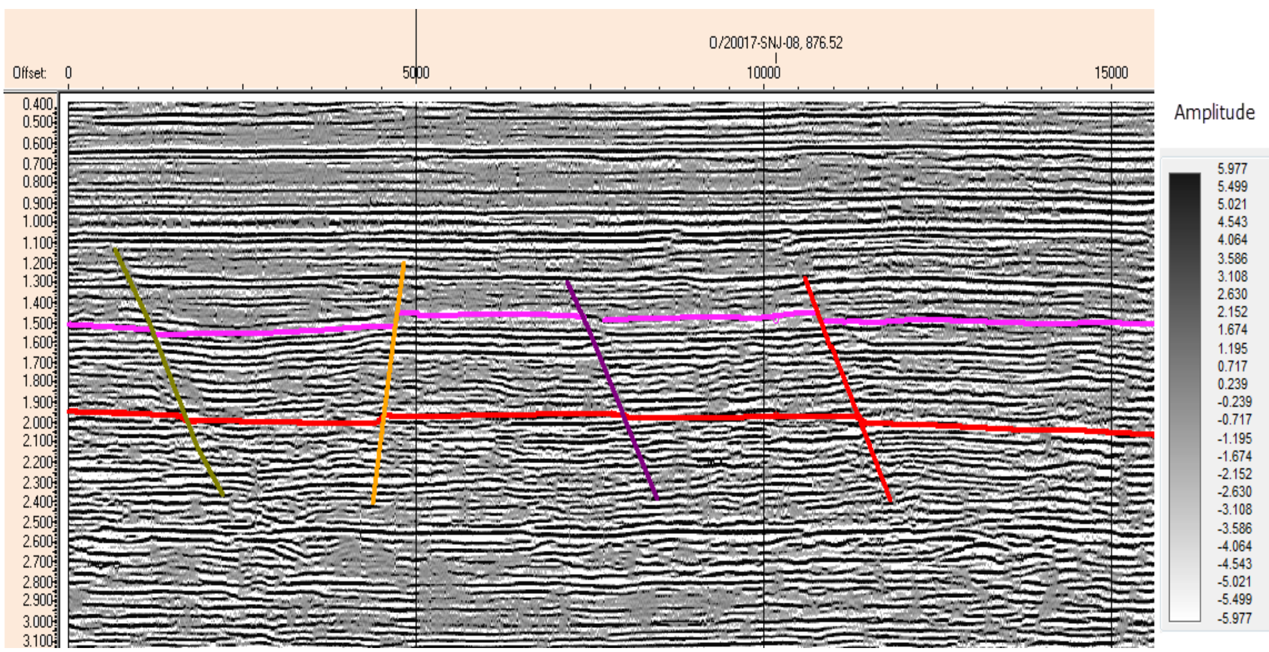


Fig 3.5 Marked Horizons and Faults are shown on seismic Dip line 20017-SNJ-05

- **Line SNJ-08**

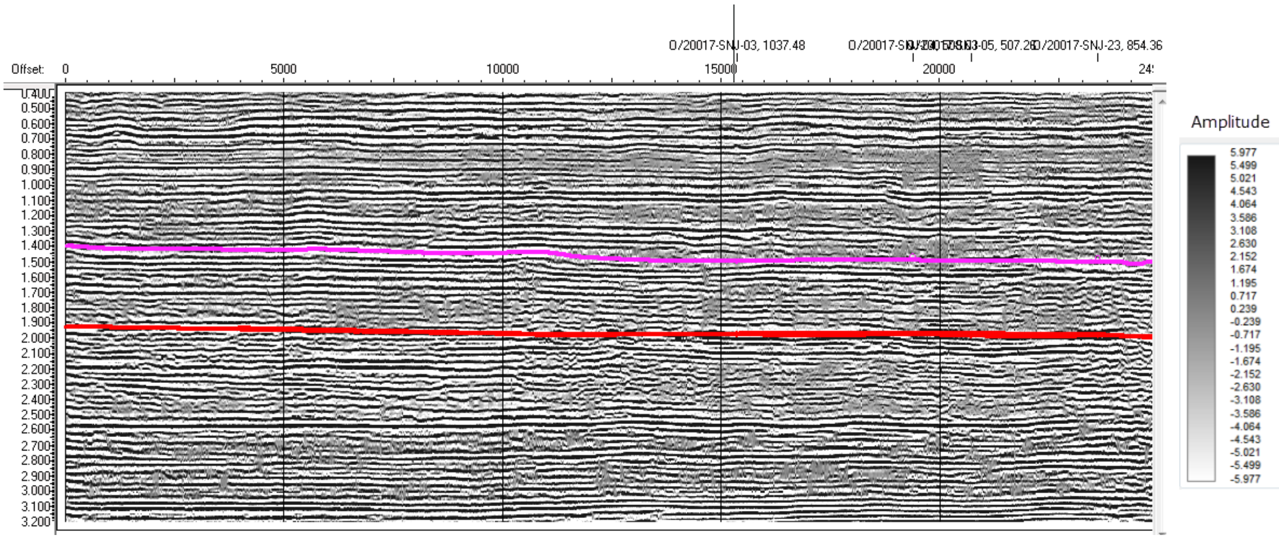


Fig 3.6 Marked Horizons and Faults are shown on seismic Dip line 20017-SNJ-08

3.4 Fault Polygon Generation

Before generation of fault polygons it is necessary to identify the faults and their lateral extent by looking at the available seismic data. If one finds that the same fault is present on all the dip lines, then all points (represented by a “+” or a “x” sign by Kingdom software) can be manually joined to make a polygon. Construction of fault polygons are very important as far as time and depth contouring of a particular horizon is concerned. Any mapping software needs all faults to be converted in to polygons prior to contouring. The reason is that if a fault is not converted into a polygon, the software doesn’t recognize it as a barrier or discontinuities, thus making any possible closures against faults represent a false picture of the subsurface. **Fig 3.6** formed at Chorgali level shows that after construction of fault polygons, the high and low areas on a particular horizon become obvious. Moreover, the associated color bar helps in giving information about the dip directions on a fault polygon if dip symbols are not drawn. Fault polygons are constructed for all marked horizons and these are oriented in NE-SW direction.

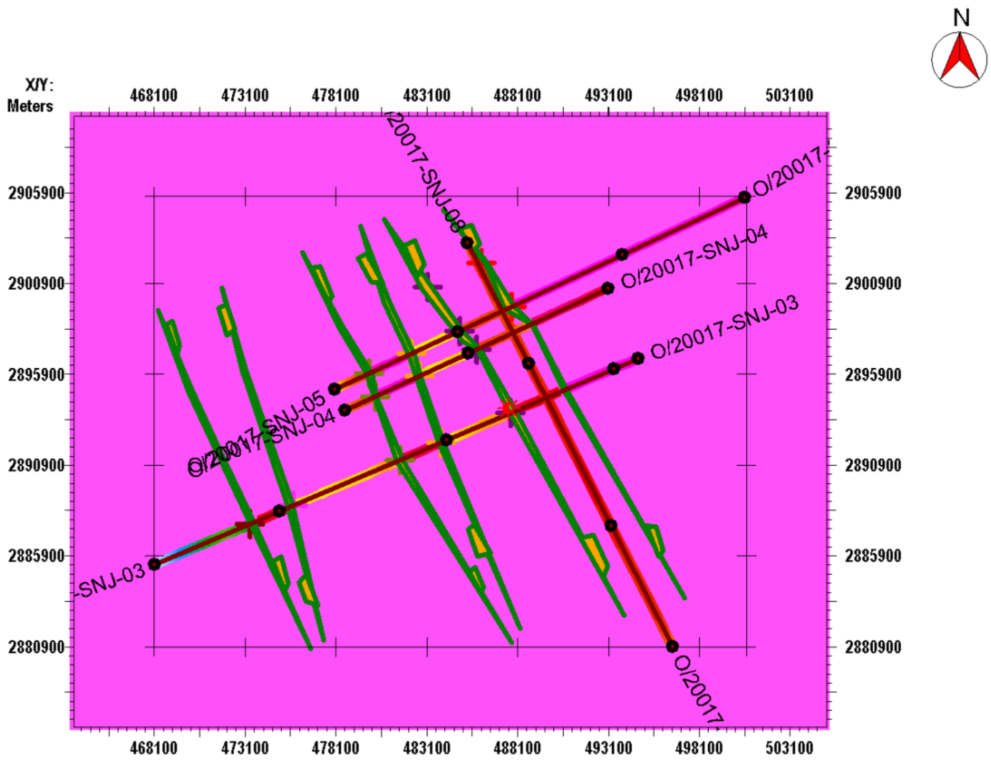


Fig 3.7 Fault polygons

3.5 Contour Maps

The results of seismic interpretation are usually displayed in the form of maps. Mapping is part of the interpretation of the data. The seismic map is usually the final product of seismic exploration, the one on which the entire operation depends for its usefulness. The contours are the lines of equal time or depth wandering around the map as dictated by the data (Coffeen, 1986).

In constructing a subsurface map from seismic data, a reference datum must first be selected. The datum may be sea level or any other depth above or below sea level. Frequently, another datum above sea level is selected in order to image a shallow marker on the seismic cross-section, which may have a great impact on the interpretation of the zone of interest (Gadallah & Fisher, 2009).

Contouring represents the 3D earth on a 2D surface. The spacing of the contour lines is a measure of the steepness of the slope i.e. closer the spacing, steeper the slope. A subsurface structural map shows relief on a subsurface horizon with contour lines that represent equal depth below a reference datum or two way time (TWT) from the surface. These contour maps reveal the slope of the formation, structural relief of the formation, its dip, and any faulting or folding.

3.5.1 Time and depth contour maps

Time and depth contour maps of Lower Goru and Basal Sand Formations are prepared in this study. The surface maps represent the lateral and vertical distribution of the formation. Time and depth contour maps of Lower Goru Formation (Figure 3.5a, 3.5b) indicate that the whole area is based on series of horst and graben structure which confirms that the area is in extensional regime. our well is drilled in horst structure. Likewise Lower Goru Formation, Basal Sand also indicates the same result. Its contour maps also indicate the horst and graben structure (Figure 3.5c, 3.5d). As the whole area is based on series of horst and graben structure so we should explain that horst is the elevated block which is the main target in hydrocarbon exploration while graben is the depressed block wich may act as kitchen for hydrocarbon generation. The fault cuts are dipping in east and west direction while they are trending in North and south direction.

The interpreted seismic data is contoured for producing seismic maps which provide a 3D picture of the various layers within an area which is limited by intersecting shooting lines. The picked times for each reflector is exported along with the navigation data in the form of an XYZ file to be used for contouring.

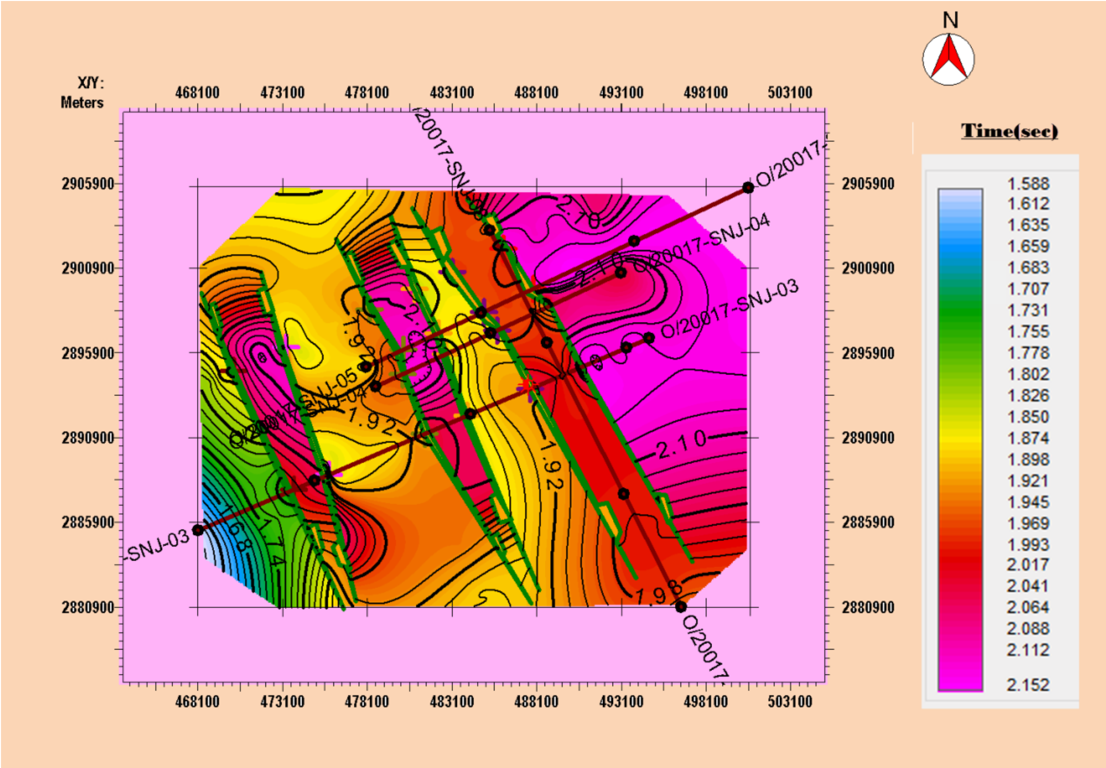


Fig 3.8 Time contour map of basal sand

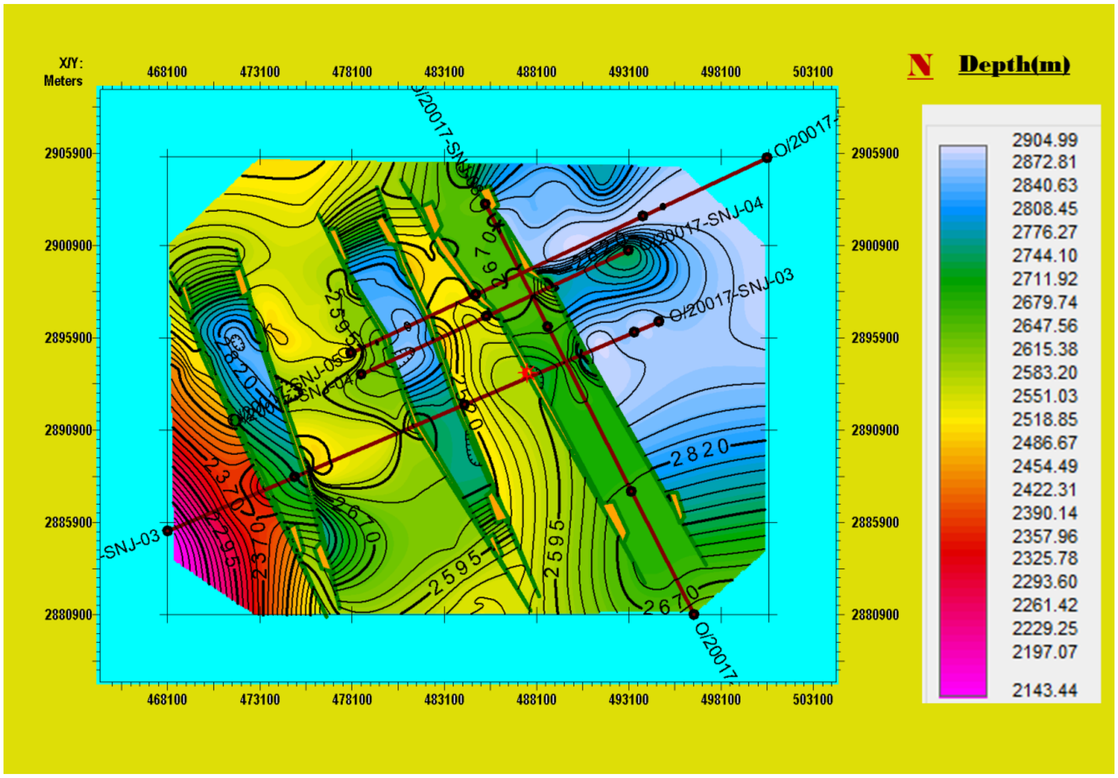


Fig 3.9 Depth contour map basal sand

Chapter No. 04
Seismic Attributes

4.1 Introduction

Seismic attributes can be conveniently defined as "the quantities that are measured, computed or implied from the seismic data". From the time of their Introduction in early 1970's seismic attributes gone a long way and they became a aid for geoscientists for Reservoir characterization and also as a tool for quality Control. Different authors introduced different kinds of Attributes and their uses. With the introduction of 3d Seismic techniques and associated technologies and Introduction of seismic sequence attributes, coherence Technology in mid 1990's, and spectral decomposition In late 1990's has changed the seismic interpretation Techniques and provided essential tools that were not Available for geoscientists earlier. With the Introduction of 3d visualization techniques, use of Seismic attributes has attained a new dimension. Development of a wide variety of seismic attributes warrants a systematic classification. Also a systematic approach is needed to understand the use of each of these attributes and also their limitations under different circumstances.

4.2 Classification of Seismic Attributes

Though the purpose of this paper is to understand the purpose of different attributes that can be used as tool in interpretation, it is useful to understand the classification of different attributes at this stage. The following classification is taken from the paper "*Seismic Trace Attributes and Their Projected Use in Prediction of Rock Properties and Seismic Facies*" by Rock Solid Images. The Seismic Attributes are classified basically into 2 categories:

1. Physical Attributes
2. Geometric attributes

4.2.1 Physical Attributes

Physical attributes are defined as those attributes which are directly related to the wave propagation, lithology and other parameters. These physical attributes can be further classified as pre-stack and post-stack attributes. Each of these has sub-classes as instantaneous and wavelet attributes. Instantaneous attributes are computed sample by sample and indicate continuous change of attributes along the time and space axis. The Wavelet attributes, on the other hand represent characteristics of wavelet and their amplitude spectrum.

4.2.2 Geometrical Attributes

The Geometrical attributes are dip, azimuth and discontinuity. The Dip attribute or amplitude of the data corresponds to the dip of the seismic events. Dip is useful in that it makes faults more discernible. The amplitude of the data on the Azimuth attribute corresponds to the azimuth of the maximum dip direction of the seismic feature.

We use following types of seismic attributes in our data :

- Instantaneous phase
- Trace envelope

4.3 Instantaneous phase Attribute applied on Seismic Line 20017-SNJ-08

Instantaneous phase attribute is given by

$$\mathbf{(t)=arc\ tan\ |H(t)/T(t)|}$$

The seismic trace *T(t)* and its Hilbert transform *H(t)* are related to the envelope *E(t)* and the phase (t) by the following relation:

$$T\ (t) = E\ (t)\ cos\ ((t))$$
$$H\ (t) = E\ (t)\ sin\ ((t))$$

Instantaneous phase is measured in degrees (-pi, pi). It is independent of amplitude and shows continuity and discontinuity of events. It shows bedding very well. Phase along horizon should not change in principle, changes can arise if there is a picking problem, or if the layer changes laterally due to “sink-holes” or other phenomena.

This attribute is useful as

- Best indicator of lateral continuity,
- Relates to the phase component of the wave propagation.
- Can be used to compute the phase velocity,
- Has no amplitude information, hence all events are represented,
- Shows discontinuities, but may not be the best. It is better to show continuities Sequence boundaries,
- Detailed visualization of bedding configurations
- Used in computation of instantaneous frequency and acceleration

When instantaneous phase attribute applied on seismic line 20017-SNJ-03 following results are obtained as shown in figure 5.1

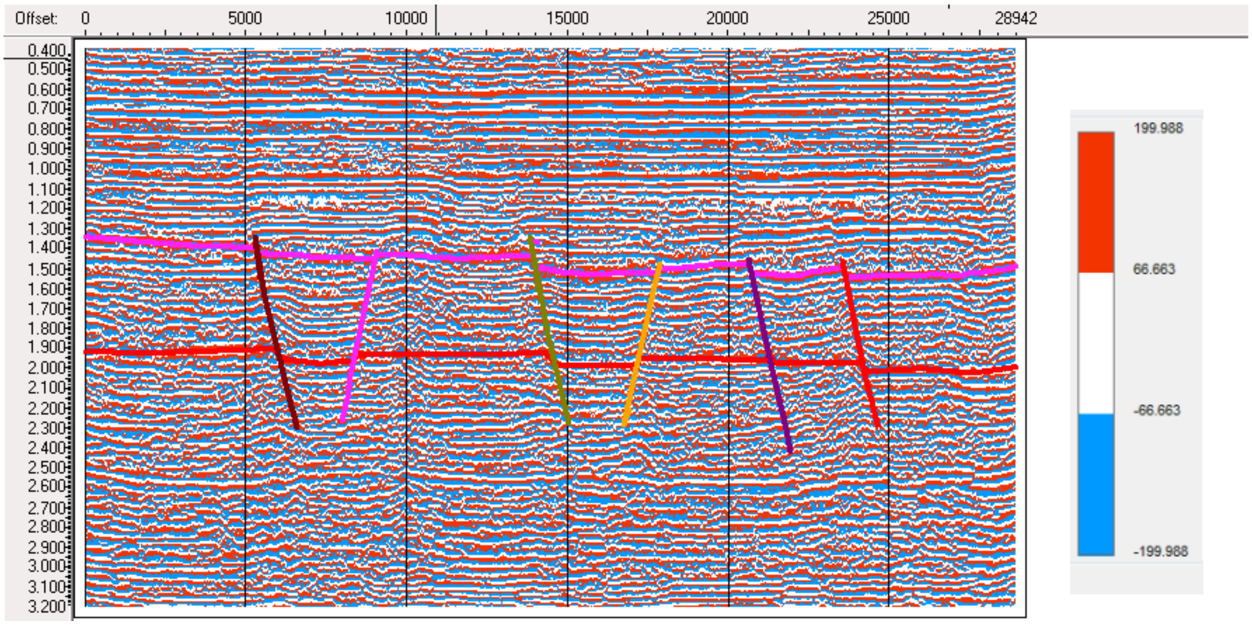


Figure 4.1 Instantaneous phase

It shows accurately the phase change of the reflectors from which we can check sequence boundaries.

4.4 Trace Envelope Attribute applied on Seismic Line 20017-SNJ-08

The envelope is the envelope of the seismic signal. It has a low frequency appearance and only positive amplitudes. It often highlights main seismic features. The envelope represents 61 the instantaneous energy of the signal and is proportional in its magnitude to the reflection coefficient. The envelope is useful in highlighting discontinuities, changes in lithology, faults and changes in deposition, tuning effect, and sequence boundaries. It also is proportional to reflectivity and therefore useful for analyzing AVO anomalies.

This attribute is good for looking at packages of amplitudes. This attribute represent mainly the acoustic impedance contrast, hence reflectivity. It always remains positive whether the reflection coefficient is positive or negative and it highlights the petroleum play as a bright spot. This attribute is mainly useful in identifying:

- Bright spots
- Gas accumulation
- Sequence boundaries, major changes or depositional environments Unconformities.

- Major changes of lithology.
- Local changes indicating faulting.

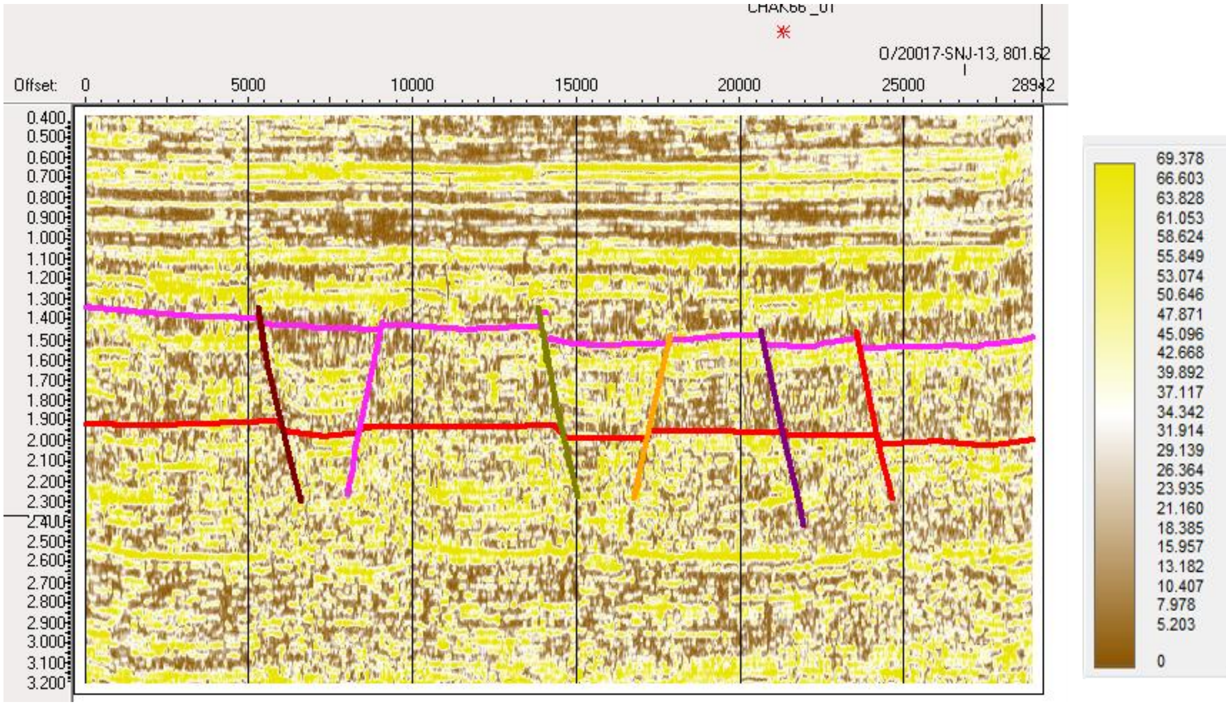


Figure 4.2 Trace Envelope

Local changes are clearly shown in above figure and our faults are accurately marked.

Chapter No. 5

Petrophysics

5.1 Introduction

To determine various properties of different lithologies and the actual depth, thickness, two way travel time and interval velocities of these lithologies is the main purpose of well logging. In well logging the cutting of different lithology which come up with mud filtrate give information about type of material, type of fossil in it and also give us the information about depositional history of that material. In well logging different types of logs are obtained with the help of a sonde. In early ages different sondes are used for different type of logging in the well but now a day we use only one sonde which has ability to do all type of logging both cased or uncased logging.

5.1.1 Logs Used

The well logs analysis was carried out by using the following logs:

- Density log
- Neutron log
- Resistivity log
- Gamma Ray log
- Sonic log

5.2 Petrophysics

Petro physical analysis is the detailed analysis of a carefully chosen suite of wire-line services provides a method of inferring or deriving accurate values for the hydrocarbons and water saturations, the permeability, the porosity, and the lithology of the reservoir rock (Dewar, 2001).

- Petro physics uses all kinds of logs, core data and production data; and integrates all pertinent information
- Petro physics aims at obtaining the physical properties such as porosity, saturation and permeability, which are related to production parameters
- Petro physics is generally less concerned with seismic, and more concerned with using wellbore measurements to contribute to reservoir description
- Petrophysics can provide things like porosity, saturation, permeability, net pay, fluid contacts, shale volume, and reservoir zonation

- Petrophysics is the interest of Petroleum Engineers, Well Log Analysts, Core Analysts, Geologists and Geophysicists (Dewar, 2001)

5.2.1 Density log:

Density logging is a well logging tool that can provide a continuous record of a formation's bulk density along the length of a borehole. In geology, bulk density is a function of the density of the minerals forming a rock (i.e. matrix) and the fluid enclosed in the pore spaces.

Density logs measure the bulk electron density of the formation, and are measured in kilograms per cubic meter (gm/cm3 or kg/m3). Thus, the density tool emits gamma radiation which is scattered back to a detector in amounts proportional to the electron density of the formation. The higher the gamma ray reflected, the greater the porosity of the rock. Electron density is directly related to the density of the formation (except in evaporates) and amount of density of interstitial fluids. Helpful in distinguishing lithologies, especially between dolomite (2.85 g/cc) and limestone (2.71 g/cc), sandstone (2.65 g/cc). (Schlumberger, 1974)

Formula used is:

$$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$$

5.2.2 Neutron log:

Neutron Logs measure the amounts of hydrogen present in the water atoms of a rock, and can be used to measure porosity. This is done by bombarding the formation with neutrons, and determining how many become “captured” by the hydrogen nuclei. Because shales have high amounts of water, the neutron log will read quite high porosities. Thus it must be used in conjunction with GR logs. However, porosities recorded in shale-free sections are a reasonable estimate of the pore spaces that could produce water. (Daling, 2005)

5.2.3 Resistivity log

Resistivity logs record the resistance of interstitial fluids to the flow of an electric current, either transmitted directly to the rock through an electrode, or magnetically induced deeper into the formation from the hole.
Types of Resistivity Logs:

- Lateral Log Shallow.

- Lateral Log Deep.

- Micro spherically Focused Log.

5.2.4 Gamma ray log:

Gamma ray logging is a method of measuring naturally occurring gamma radiation to characterize the rock or sediment in a borehole or drill hole. It is a wire line logging method used in mining, mineral exploration, water-well drilling, for formation evaluation in oil and gas well drilling and for other related purposes.
Different types of rock emit different amounts and different spectra of natural gamma radiation. In particular, shales usually emit more gamma rays than other sedimentary rocks, such as sandstone, gypsum, salt, coal, dolomite, or limestone because radioactive potassium is a common component in their clay content, and because the cation exchange capacity of clay causes them to absorb uranium and thorium.

5.2.5 Sonic log:

Sonic logs (or acoustic) measure the porosity of the rock. Hence, they measure the travel time of an elastic wave through a formation (measured in ΔT - microseconds per meter). Intervals containing greater pore space will result in greater travel time and vice versa for non-porous sections. They must be used in combination with other logs. Particularly gamma rays and resistivity, thereby allowing one to better understand the reservoir petrophysics.

Formula used:

$$\phi = \frac{t_{\log} - t_{\mathrm{ma}}}{t_f - t_{\mathrm{ma}}}$$

5.2.6 Volume of Shale:

Shale is more radioactive than carbonate or sand, gamma ray logs can be used to calculate volume of shale in porous reservoirs. The volume of shale can then be applied for analysis of 40 shaly sands. Calculation of gamma ray index is the first step to determine the shale volume from gamma ray log (Schlumberger, 1974).
The following formula is used to find volume of shale

$$V_{sh} = I_{GR} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}}$$

IGR = Gamma ray index
GRlog = Gamma ray reading of formations
GRmax= Maximum gamma ray
GRmin= Minimum gamma ray

5.2.7 Calculation of Resistivity of Water (Rw):

The Resistivity of Mud Filtrate at Zone of Interest (Reservoir Formation) is calculated by the equation given below:

$$Rmf_2 = Rmf_1 * (T_1 + \frac{6.67}{T} - 6.67)$$

Where

Rmf1=Resistivity of mud filtrate at surface temperature
T1 =surface temperature
T2= formation temperature
Rmf2= resistivity of mud filtrate at formation temperature

5.3 Calculation of water saturation:

The fraction of pore spaces containing water is termed as Water Saturation (Sw) which is calculated by from the Archie's formula given by; (Schlumberger, 1974)

$$S_w = (\frac{R_w}{R_t} * \emptyset_m)\frac{1}{n}$$

Where

R_w= Resistivity of Water
R_t =True Resistivity
Φ =Porosity
m =Cementation factor
n = Wet ability factor

5.4 Calculation of Saturation of Hydrocarbon:

The fraction of pore spaces containing Hydrocarbons is known as Hydrocarbon Saturation and mathematically given by the following equation;

$$S_{hc} = 1 - S_w$$

Where

S_{hc}= saturation of hydrocarbon 42

S_w= saturation of water

5.5 Results of Well CHAK 66-01

The well log of the CHAK 66-01 well has been interpreted by using the KINGDOM software (Figure 4.1) .The petrophysical analysis has been carried out in order to measure the reservoir properties of the sinjhoro area using the borehole data of Chak66-01. We used the log curves including spontaneous potential log (SP), Gamma ray (GR), Sonic log (DT), Latero log deep (LLD), Laterolog shallow (LLS), Neutron log, density log and Photo electric effect log (PEF). For petrophysical analysis the following parameters are calculated for reservoir rock.

- Volume of shale (Vsh)
- Porosity of reservoir (Sonic, Density and Neutron logs)
- Water saturation (LLD, LLS and SP logs)
- Hydrocarbon Saturation (Sh)

Determining the porosity and true resistivity of a zone is the first step in converting the raw log data into estimated quantities of oil, gas, and water in a formation. These estimated quantities are used to evaluate a zone and to determine whether a well completion attempt is warranted. (Asquith et al., 2004.)

Lower goru is our reservoir which has different type of sands. Reservoir has Various Zones in the well which have been observed on the basis of logs interpretation. Due to the fact that log data only recorded in depth starting from 2000m to 3000 m but we cropped the zone of interest only from 2120m to 2065m. This has done due to fact that there is no major anomaly or difference identified in other logs and behavior of logs is another reason which restricts us from marking other zones. The results shows that also there are clean sand in Zone of interest because of low shale value and high matrix value indicated but water saturation increases in this zone and hydrocarbon is less in this zone (Figure 4.1), but it has good effective porosity with few amount of hydrocarbons are also present which may be recovered. From all this we can conclude that CHAK 66-01 may be a hydrocarbon producing well. Zone depth ranges from (2020-2065) Meters Lower Goru reservoir. Results are shown in Table 4.1

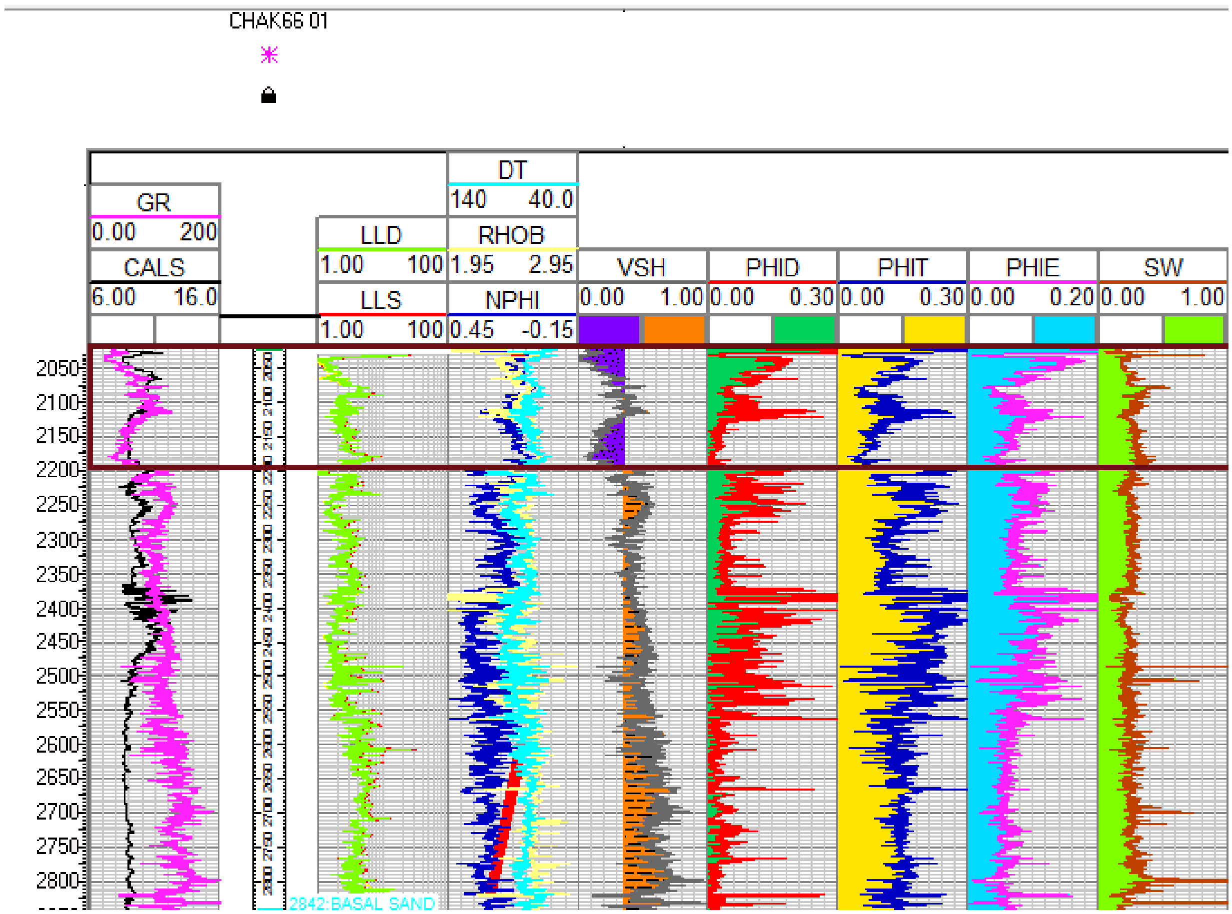


Fig 5.1 Pertophysical behavior of potential hydrocarbon zone of Lower Goru in Chak 66-01

Table 4.1 Results

Serial Number	Calculation Parameter	Percentage % (2020-2065)m
1	Average Volume of Shale=Vsh_{avg}	13
2	Average Porosity Obtained From Density log= $\emptyset_{davg}$	14
3	Average Porosity in(PHIT) Percentage=$\emptyset_{avg}$	15
4	Average Effective Porosity in Percentage= $\emptyset_{eavg}$	13
5	Average water Saturation in Percentage=S_{wavg}	22
6	Average Hydrocarbon in Percentage= $\boldsymbol{S_{havg}}$	78

Chapter No.6
Model Based Seismic Inversion

6.1 Introduction

2D seismic surveys are one of the best tools for identifying potential exploration targets. These seismic data volumes are used to identify the geometry of reflectors and ascertain their depths. This is possible because seismic waves reflect at interface due to contrast in acoustic properties of the material (Barclay et al., 2008).
Seismic reflection data contain more information than reflector position. The amplitude of reflection is controlled by the impedance which is the product of velocity and density. Seismic amplitude data can be used to invert for the impedance using seismic inversion procedure. Acoustic impedance is a layer property and amplitude of seismic trace is an interface property. By correlating these seismically derived impedances with values measured in borehole (i.e. porosity, water saturation), interpreters may extend well information throughout the reservoir scale. The process is called seismic inversion for reservoir characterization that is used in optimum field development (Barclay et al., 2008).

Physical sciences are used to make inferences about physical parameters from data. Inversion involves the process of guessing, computing and comparing to draw inferences from real data acquired in the field. Inversion can be defined as "a set of mathematical techniques for reducing the data to obtain useful information about the physical world on the basis of inferences drawn from observations" (Sen, 2006).The purpose of seismic inversion is to estimate reservoir properties i.e. porosity by using the inverted impedance. Seismic inversion helps in well planning, characterizing reservoir and to monitor changes in the rock properties resulted from fluid injection or production (Gavotti et al, 2014).

Russell and Hampson (1991) categorized the poststack inversion in to three following methods:

- Classical recursive or Band limited inversion
- Sparse Spike Inversion
- Model Based Inversion

The topic of our research is Model Based inversion and Sparse Spike Inversion. Both these inversion methods produce analogous results. The Sparse Spike inversion produces better results for a complete sparse model. When these two methods are applied to real data then Model Based inversion gives better resolution than Sparse Spike Inversion (Hampson and Russell, 1991).

6.2 Model Based Inversion Theory

The Earth's acoustic impedance is estimated by the process called seismic inversion. Seismic data is in the form of amplitude that is the property of an interface. The acoustic impedance is a layer property which is used for quantitative interpretation of seismic data. The impedance estimated from inversion is used in identification of lithology, porosity and water saturation of the reservoir zone (Kneller et al., 2013).

A generalized linear inversion algorithm is used for Model Based inversion. This algorithm assumes that the seismic trace (S) and the wavelet (W) are known and tries to modify the initial guess model until the synthetic trace match with the actual trace to an acceptable level (Gavotti et al., 2014). In other words, the geological model is altered until the error between synthetic and original seismic trace is minimized. This approach is competent if we have a significant knowledge of geology and a consistent model can be created (Kneller et al., 2013).

The hard constrained (well data) controls the small amount of noise or modeling errors. Additional information such as initial guess model can also be incorporated by using soft constrained (variogram model) but generally hard constrained are suggested for inversion procedure (Gavotti, 2014). The work flow for model based inversion is shown in Figure 6.1.

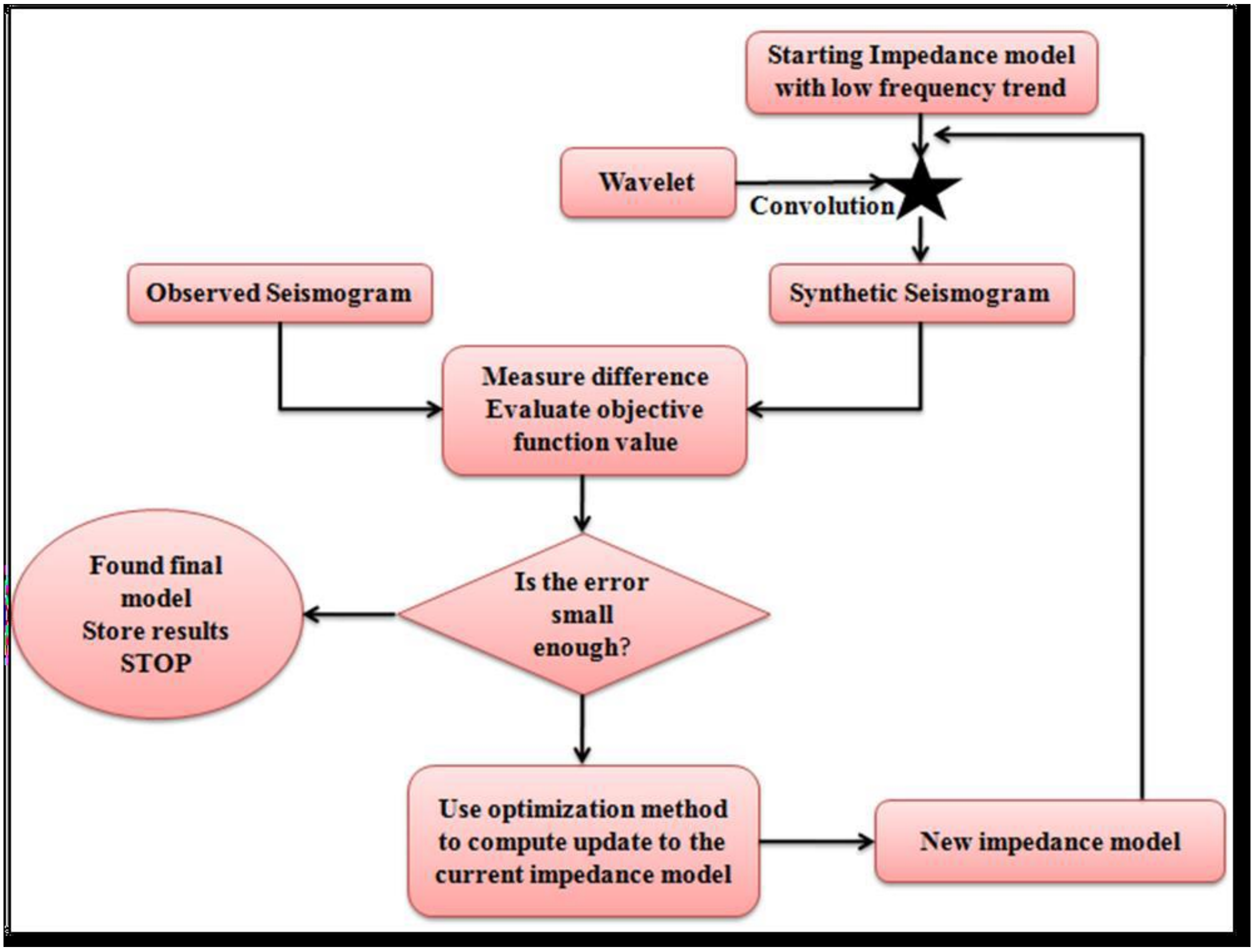


Figure 6.1 An impedance estimation scheme based on model based inversion (Sen, 2006)

6.3 Extraction of wavelet

A constant phase wavelet shown in Figure 6.2 was estimated to perform the correlation of extracted reflectivity and inverted reflectivity from seismic at well location. Wavelength of the wave is 100m. This wavelet is also used for 1D forward modeling. The algorithm used to extract wavelet uses seismic data near the well and well logs.

Seismic inversion is based on the convolution model i.e. convolution of reflectivity series with extracted wavelet to get synthetic trace (Cooke and Cant, 2010). To get desirable results for seismic interpretation and inversion the wavelet should be zero or minimum phase. The amount of phase shift in input wavelet greatly affects the inversion results. The greater the phase shift, the higher will be the error in resultant impedance (Jain, 2013)

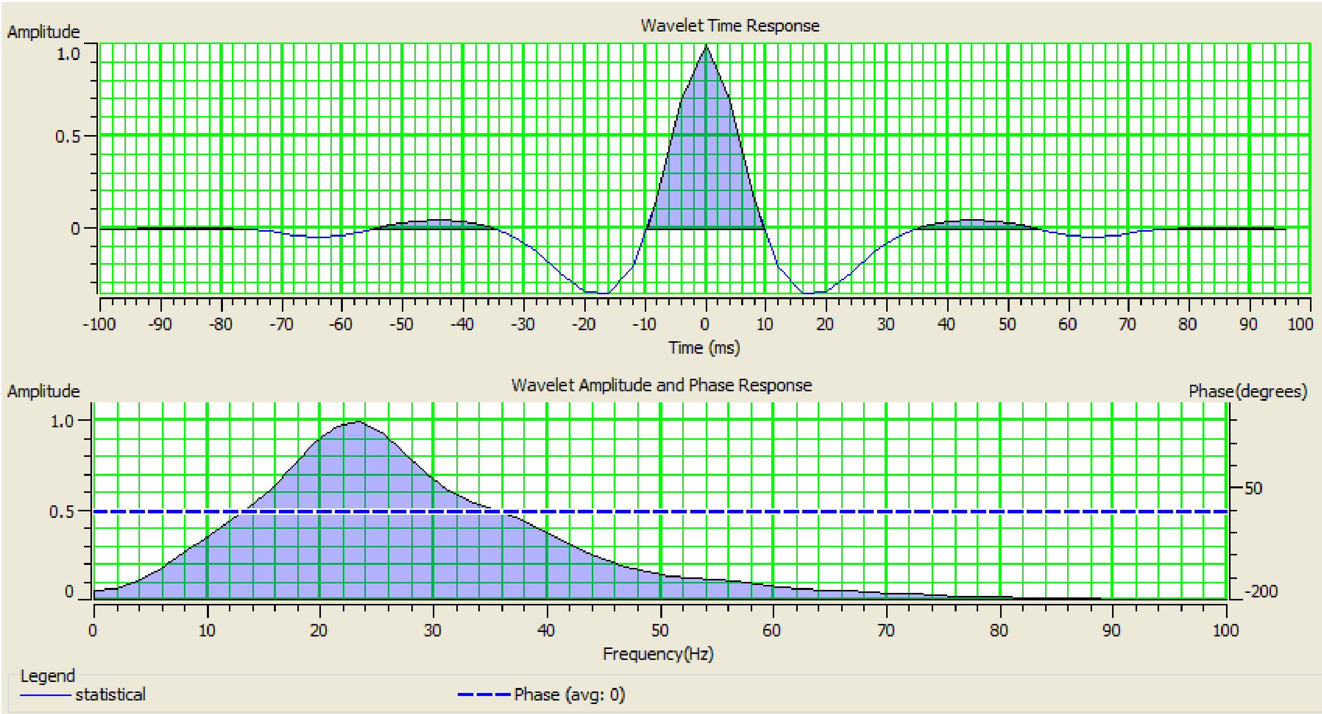


Figure 6.3 Geostaticsitcal wavelet extracted from seismic data with its amplitude spectra. The dotted line show the average phase of the wavelet.

6.4 Initial Model/Low frequency Model

Two terms are used for acoustic impedance that are relative acoustic impedance and absolute acoustic impedance. Relative acoustic impedance does not involve the generation of low frequency model for its calculation. It is the relative layer property and is used for qualitative interpretation. The absolute acoustic impedance is obtained when a proper low frequency component (approximately 0-15 Hz) is given to inversion algorithm to invert the given amplitude data (Cooke and Cant, 2010). In Model Based inversion low frequencies are added as a part of inversion algorithm rather than generating a separate low frequency model while in Sparse Spike inversion low frequency model is added separately (Cooke and Schneider, 1983). Absolute acoustic impedance is an absolute layer property and is used for both qualitative and quantitative interpretation (Cooke and Cant, 2010). A low impedance model generated for model based inversion is shown in Figure 6.3.

To get absolute acoustic impedance from inversion results a low frequency model must be added from hard constraints such as sonic and density logs. Adding a low frequency model assure more realistic results (Lindsith, 1979).

Several authors suggested the solutions for building an accurate low frequency model such as Linear Programming algorithm and autoregressive process (Oldenburg et.al., 1983) and

Generalized Linear inversion (Cooke and Schneider, 1983). All these approaches face the issue of non-uniqueness because there is more than one model compatible to seismic response (Gavoti, 2013).

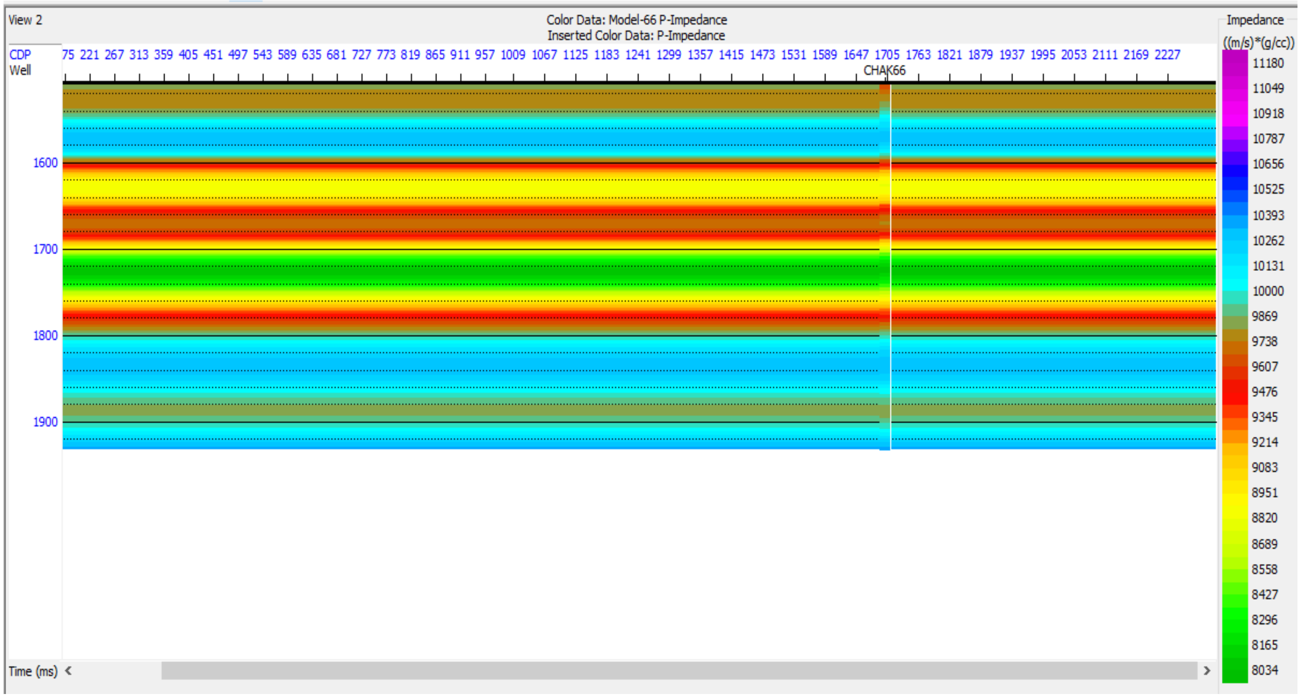


Figure 6.4 A low impedance model built by applying a lower and upper impedance limit.

6.5 Inversion Analysis

Following the analysis at the well location the model based inversion was performed on the given 3D seismic cube. A statistical wavelet was extracted in time window from 1600-2200 ms. Frequency range of extracted wavelet was adjusted by comparing inverted trace at well location and the synthetic trace. The correlation between synthetic and seismic trace is good with high correlation coefficient (0.995343) is shown in Figure 6.4. The estimated RMS error between the synthetic and seismic trace is 0.0964357. The estimated RMS error between the inverted trace and the impedance log was 7129.69 (m/s)*(g/cc).

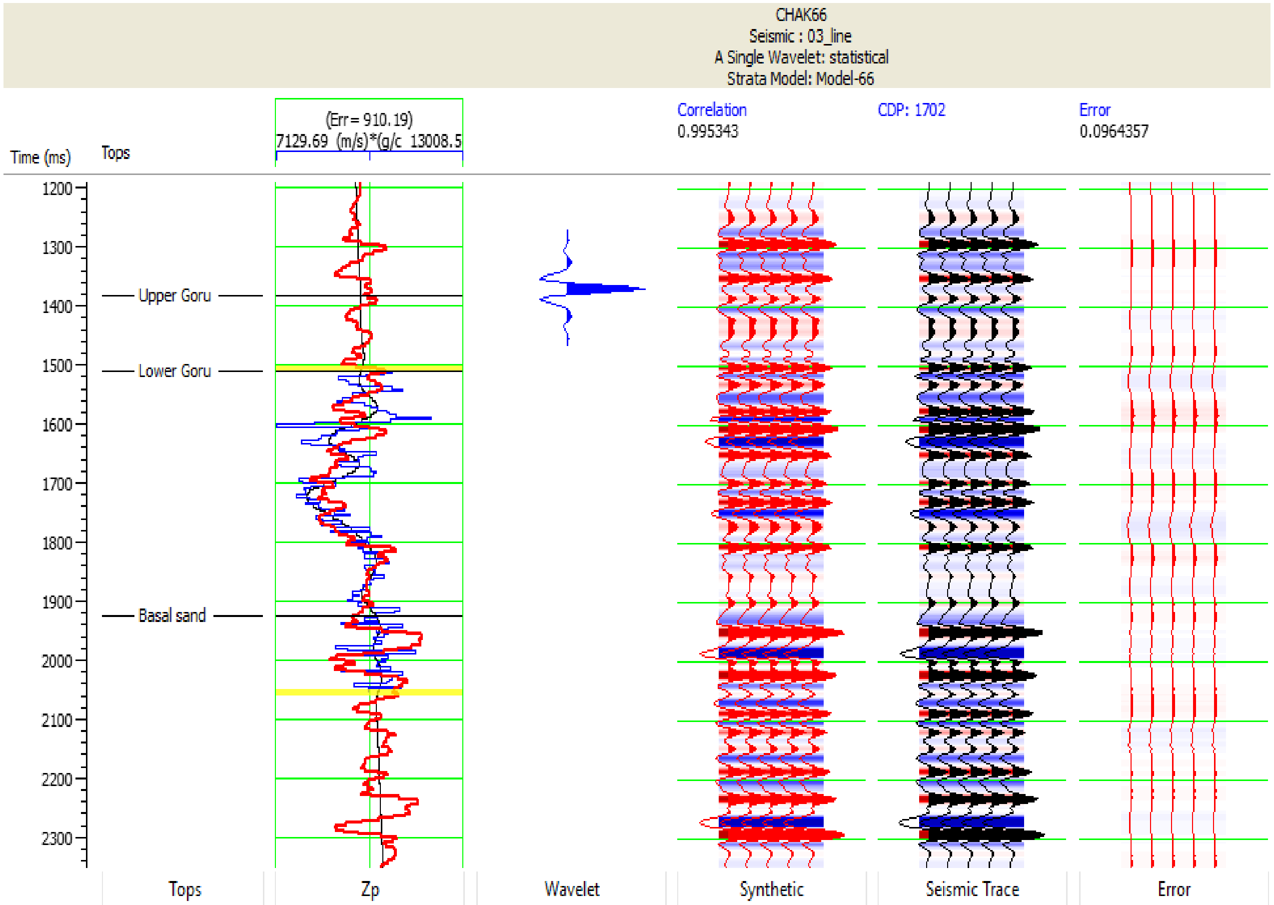


Figure 6.5 Analysis of the post stack inversion at well Chak 66-01 with initial model

The results of Model Based inversion for line 20017-SNJ-03 are shown in Figure 6.6. The inversion was performed only on the selected time. In which the horizons of interest lie. The inversion results show colored layers displaying different values of acoustic impedance for each layer. Our zone of interest which is Lower Goru lies at 2150 ms depth known from check shot data. Petrophysics results discussed in previous chapter also highlight a favorable zone at the same depth.

Green color indicates the reservoir zones it is the zone of low acoustic impedance surrounding by high acoustic impedance. Figure 6.6 show we have two reservoirs.

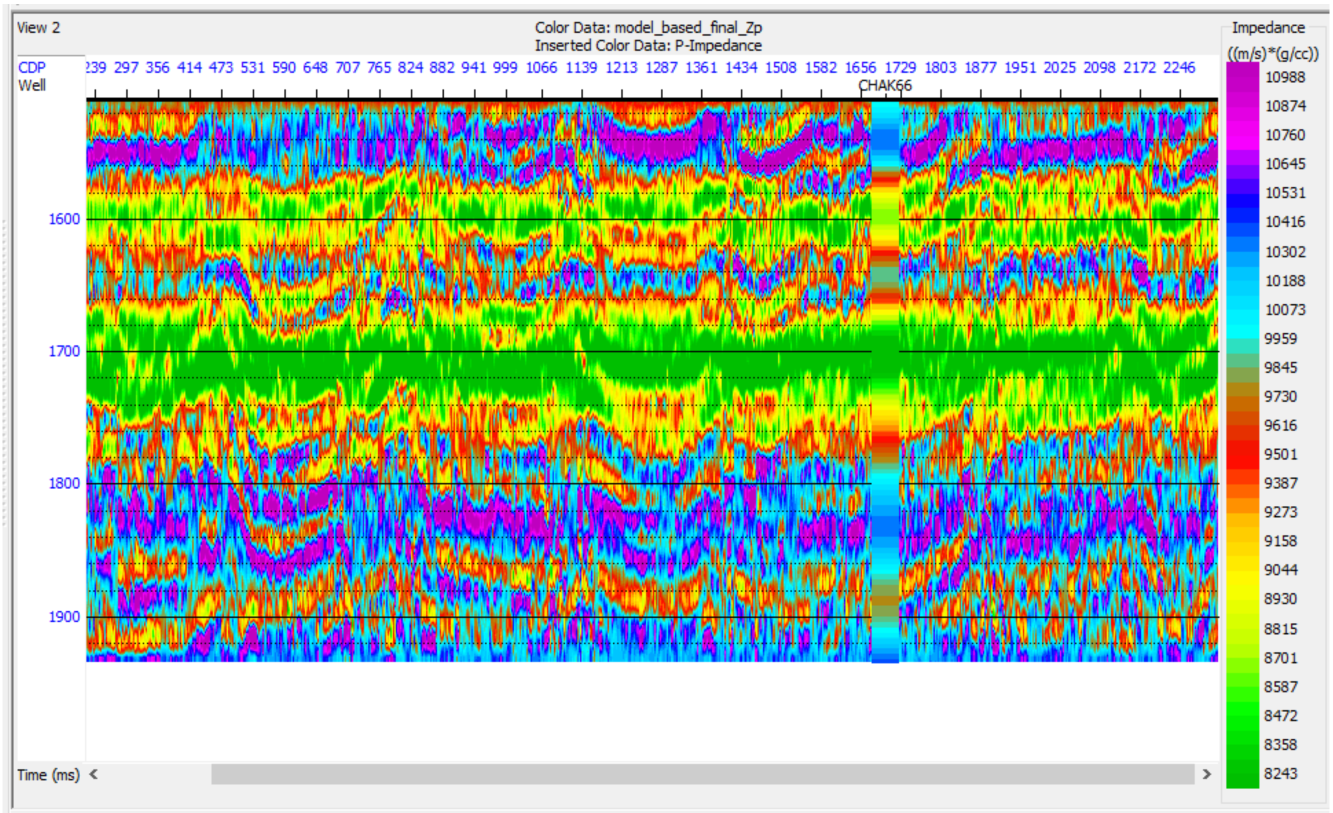


Fig 6.6 Final model based inversion

The model based inversion results show good lateral variations in acoustic impedance which can be used for depicting shalling out sequence while in sparse spike inversion cannot give good result.

Conclusion:

Research work was carried out using data of three seismic lines and single well. It is not sufficient data to accurately approve a zone as potential zone for hydrocarbon. The main purpose of this research was to find the structural trap and zones of the reservoir of Sinjhoro field i.e. Lower Goru that has intercalations of shale and siltstone by using seismic and well log data and to propose a new well location on the basis of seismic data interpretation.
Geologically the study area is located in extensional regime. The rifting occurred dunring geological past is responsible for extensional features. Three geological formations have been marked on seismic section, namely Ranikot, Lower Goru and basal sands. Now dew to the extensional regime horst and graben structures are present in the area. The seismic line is showing series of horst and graben structures. The fault cuts are dipping in east and west direction while they are trending in North and south direction. Normal faults have very less throw of approx 5ms. Most of the faulting can be observed at cretaceous level, while the faults die out as we move towards younger formation.

Firstly, these faults are deep-rooted into the Sember source shale, and therefore they can act as conduits to primary hydrocarbon migration.

Secondly, these faults can act as a barrier and thus provide a lateral seal to trap the hydrocarbons within the structure. To evaluate whether these faults are a sealant, a fault seal analysis should be conducted. In one of the above figure, it is clear that the faults near the top of the Lower Goru Formation are predominantly oriented in a NNW to SSE direction. The southern limits of these faults are not obvious due to a lack of seismic data in the study region.

It is concluded from surface Geology of the area that horst and graben structure prevail the whole area. Extension of the structure is in the North-South direction. And clues of horst and graben structure are clear from the normal faulting in the interpreted seismic sections and time, depth sections of Lower Goru Formation and Basal Sands. These structures are largely oriented in a NNW to SSE direction and are a part of the regional rift system of the Lower Indus Basin. Following conclusions has been deduced:

1. Two horizons on all the sections have been marked along with the major and minor faults.

2. Six major faults prevail in the area given names as Fault-A, Fault-B, Fault-C, Fault-D, Fault-E and Fault-F. These all faults are normal faults. .
3. The generalized structural trend of the faults and intervening blocks is NW - SE direction. Throw of these faults is prominent.
4. Time and depth contour maps were prepared to analyze the overall behavior of the structure. There are small anticlinal structures bounded shown by these maps bounded by

two normal faults which is clue towards either Horst or Graben or negative flower structures to some extent.

5. Petrophysical portion of thesis includes the interpretation of well CHAK66-01. From all the results it is concluded that water saturation is decreasing as we move towards the reservoir zone.
6. Volume of shale also decreases in the reservoir zone as compared to other lithologies. From petrophysical analysis it has also seen that some lithologies (from Gamma ray log and other characteristics interpreted as sands) have good saturation of hydrocarbons and have good porosity. From this result it can be concluded that these lithologies are may be the part of oil reservoirs.

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