Shale Oil Potential of Patala Formation in Balkassar Area, Potwar Basin, Using integrated Wire-line logs, 3-D Seismic Inversion and Attributes Analysis.

By

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Abstract

Balkassar field is located in Chakwal district, Punjab Province of Pakistan. Geologically, the area is in Potwar Basin which is eastern part of Upper Indus Basin. The Basin is heavily thrusted and folded because of collisional tectonics regime. The stratigraphic sequence is composed of pre-Cambrian to recent deposits. The prime purpose of this study is to examine and evaluate the Shale oil prospective of Patala Formation in Balkassar area. In this dissertation, seismic 3-D data and well log data of Balkassar-OXY-01 well are used. Seismic 3-D data is used for delineation of the sub-surface features. The 3-D Seismic cube given by the Directorate General of Petroleum Concessions is interpreted by using Kingdom Software. The general structural trend in the study area is northeast to southwest, however, the seismic interpretation of available 3-D cube does not show any fault. The seismic reflectors show almost planner behavior because the available 3-D cube belongs to one of the limb of the fold where there is no fault has been encountered, which is also confirmed by the seismic attribute analysis. For Petro-Elastic or Petro-Mechanical properties well log data of the Balkassar-OXY-01 is used. Using shear Sonic log (DT), properties such as brittleness Index, Young's modulus and Poisson's ratio are calculated which shows that the Shale of Patala Formation is brittle and suitable for hydraulic fracking. Geochemical Parameters such as TOC, Vitrinite reflectance, LMI and Kerogen volume depicts that the Patala Formation's Shale is enough mature and can produce economic quantity of Shale oil. P-wave impedance is calculated through Model Based Inversion and Band Limited Inversion. Due to the absence of frequency control in the Model Based Inversion, Band Limited Inversion resolved Patala Formation with relatively better accuracy.

Candidate's Certificate

I solemnly declare that research work presented in this thesis titled **"Shale Oil Potential of Patala Formation in Balkassar Area, Potwar Basin, Using integrated Wire-line logs, 3-D Seismic Inversion and Attributes Analysis"** is solely my own intellectual work and no portion of this thesis has been plagiarized and any material used as reference is properly referred / cited.

I undertake that this research has not been submitted by anyone before to neither any other institute nor does it contains any verbatim of the published source. I fully understand the international copy rights and plagiarism law and in case of any violation I will be fully responsible for the consequences.

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Certificate

It is hereby certified that this thesis is based on the results of study carried out by ***Mr. Sajid Ali*** and it is in our kind judgment that this thesis is of the sufficient standard and accepted in its present form for the award of degree in Master of Philosophy (Geophysics) from the Department of Earth Sciences, Quaid-i-Azam University Islamabad, Pakistan.

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Dedication

To

“My Parents

and

all well-wishers”

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CHAPTER 1

INTRODUCTION

1.1 Introduction

In geophysics, from 1915 the practice of seismic methods started which is helpful in resolving subsurface geological structures, mapping of hydrocarbon depositional features, migration, stratigraphic and structural traps. Further, this method can help us in examining and understanding of the reservoir active behavior (Chopra and Marfurt., 2005). In the very beginning, the method of seismic refraction was in use but it did not succeed because it was not able to provide subsurface images thoroughly and highlighting deep geological structures anomalies. To prevail over these difficulties and to intensify the effectiveness, in 1919s the method of seismic reflection was familiarized. With the every passing day the seismic reflection method gets more and more importance and became almost all over the world one of the extensive used technique apparently in all geophysical exportations.

The technique of seismic reflection has basic role in the search of hydrocarbons. While acquisition of the seismic 3-D data in the field which may acquire be at specific time interval, in the reservoir different kind of variation can be detected including fluid substitution and pore-pressure (Yilmaz., 2001). The 3D seismic data can provide significantly good quality images of subsurface structures and survey with dense sampling can apparently some time depict the quality of reservoir and hydrocarbon i.e. gas and oil distribution (Bacon *et al*., 2007). These descriptions can aid to understand the reflections, discontinuity and also can describe the geology and subsurface potential of hydrocarbon (Badely., 1985). In the different interfaces of formation, faults can be considered as leading elements for the mapping (Stewart., 2012).

For the source and reservoir description data of well log have much importance. The essential source and reservoir parameters can be find through petrophysics i.e. volume of shale, total & effective porosity, water & hydrocarbon saturation and the reservoir zonation (Avseth *et al*., 2010). To understand the trend of the rock properties with the seismic amplitude, the extracted properties from source or reservoir through petrolphysics can be interrelated with seismic by using specific cross plots (Fischetti *et al*., 2002).

In the seismic post stack inversion at initial stages at each trace data of seismic 3D seismic amplitude can be converted into Acoustic Impedance volume (Sukmono *et al*., 2002). By seismic inversion the elastic properties of a rock can be determined through seismogram contains the travel time, amplitude and phase information. By using the seismic post stack inversion the imaging of the subsurface can be enhanced and most of common properties of rock can also be inverted through it which include acoustic impedance, porosity, density, permeability, Poisson's ratio and elastic moduli etc.

1.2 Objective of the Research

The generalized objectives of this study are as follow:

- Seismic 3-D structure interpretation of Balkassar area for Patala Formation
- Qualitative Seismic interpretation by application of advanced seismic attributes for Shale identification and other relevant properties
- Examine the petroelastic behavior of the Patala Formation
- Source potential of Patala Formaation
- Seismic post stack inversion for Shale

1.3 The Study Area

In 1945 Attock Oil Company discovered Balkassar Field which is an exclusive development and production of the POL. As shown in the location map in figure 1.1 the Balkassar Field is situated in Chakwal District of Punjab around 110 km in south-western part of Islamabad. Geologically the study area is located at the middle part of the sub-basin Potwar, northern part of the Uppar Indus Basin with geological coordinate 72.32° - 72.47° E and 32.51° - 33.02°N.

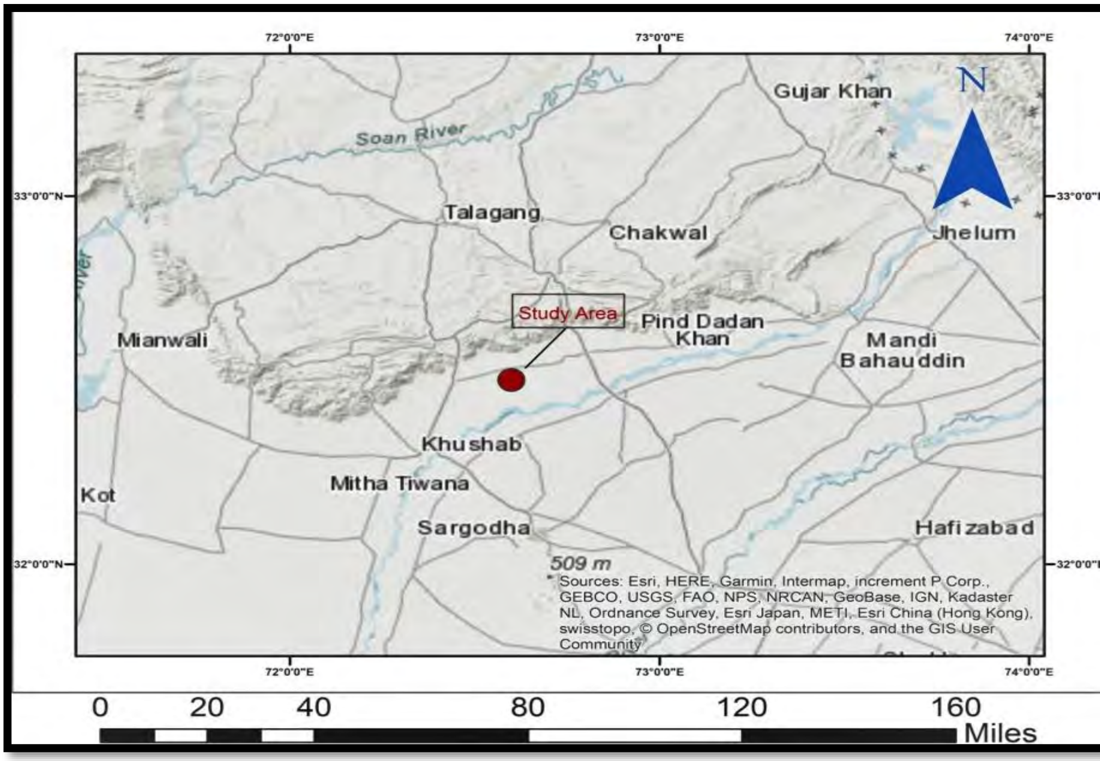

Figure 1.1: Location map of Balkassa area (ARC GIS, 2020).

Geographically, in the South Balkassar share border with Kalar Khar, while in the East lies Chakwal and towards West lies Talagang city. Regionally, the area is mainly lying at appendage of one of the famous Soan syncline at complex thrust and fold belt of the Himalaya region (Hasany and Saleem., 2010).

1.4 Data Set Used

For the completion of the desired research work seismic 3-D and borehole data is used. For improved source rock characterization well logging data and seismic data is correlated by the use of synthetic seismogram. Table 1.1 shows the details of utilized 3-D seismic data and borehole data provided by the DGPC.

Table 1.1: Seismic and well data used in the study.

3D Seismic Data and Well Data Used in Interpretation		
Well Name		**Balkassar-OXY-01**
Line Name	Minimum Value	Maximum Value
Inline	72	189
Crossline	180	337

1.5 Research Methodology

Before starting the dissertation first important step is literature review to get insight into the study area and to understand the regional and local tectonic regime, depositional environment, petroleum play and faults nature etc. For this purpose help from number of research papers and books have been taken. The next step is acquisition of the requisite data. LMKR with the approval of Authority i.e. DGPC provided the Seismic 3-D data and Well data. Before loading data into software quality control (QC) of the data is essential. In QC of data one has to make sure availability of at least navigation data, seismic data (SEG-Y) in case of three dimensional data, well data which includes well logs and formation tops etc. For the current study SMT Kingdom software has been used for basic seismic structure and petro elastic interpretation. Below mentioned steps are adopted for the completion of this dissertation:

- After loading data to software synthetic seismogram was generated by using well logs data at the well location of Balkassar-OXY-01 to correlate well and seismic data and to identify the horizon i.e. Patala Formation.
- For the purpose of the best seismic and well correlation, well-seismic tie operation was carried out.
- Horizon was picked and marked on the inline where well is located and was extended on given seismic cube.
- Qualitative seismic interpretation was performed by applying different attributes.
- Time grid was generated on the whole seismic cube before contouring to interpolate the marked horizon.
- Time and depth contours were generated for the Patala Formation.
- To examine the unconventional reservoir behavior of the Patala Formation elastic properties were calculated especially Young's modulus, Poisson's ratio and brittleness index to find out possible zone for well stability and hydraulic fracking.
- For estimation of the unconventional reservoir potential of the Patala Formation geochemical properties like TOC, kerogen volume and vitrinite reflectance were calculated.

- By using Hampson-Russell Suit software various post stack seismic inversion techniques were performed for the confirmation of interpretation.

Simple workflow chart for adopted methodology is shown in figure 1.2:

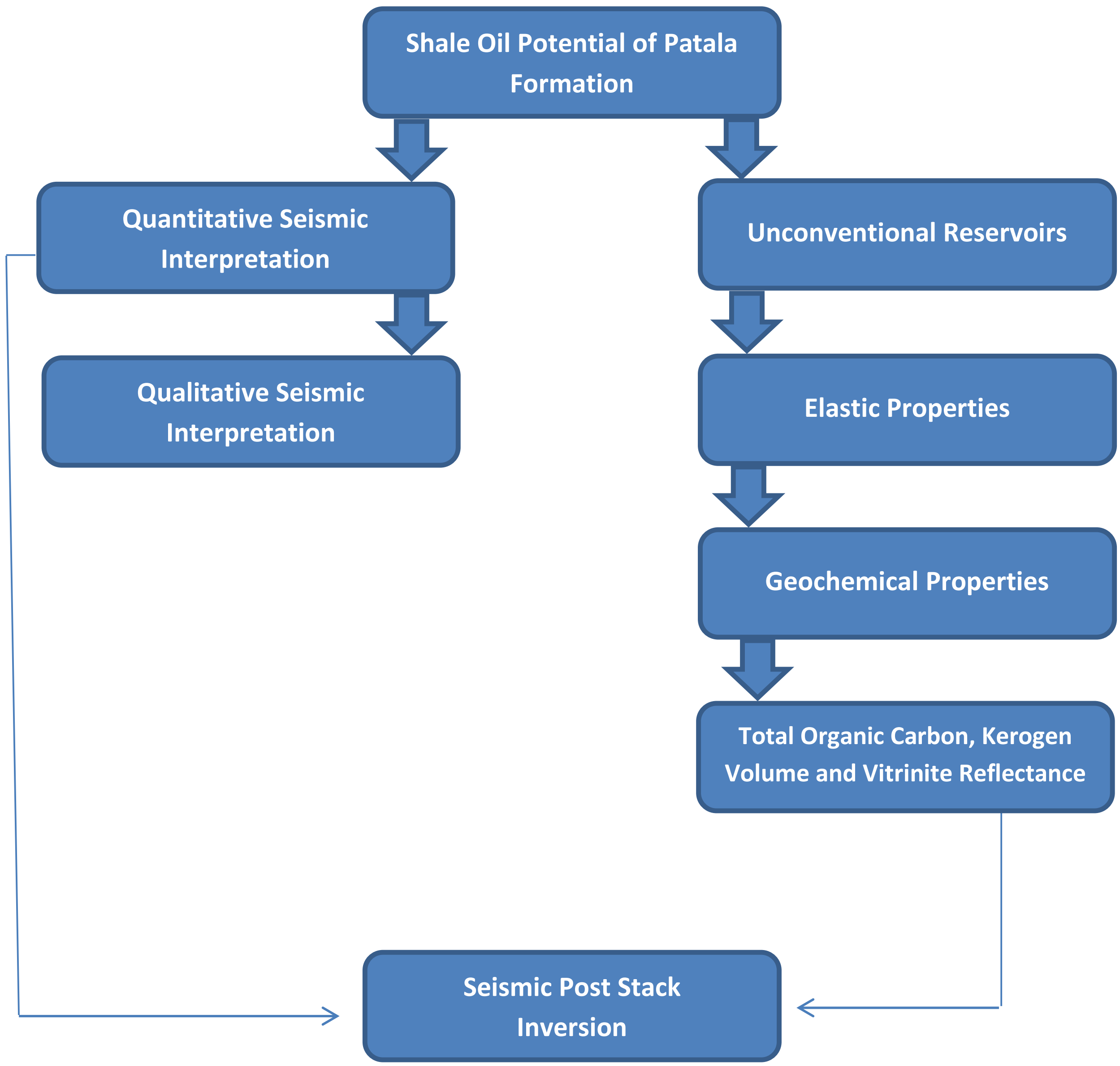

Figure 1.2: Generalized workflow chart of methodology.

CHAPTER 02

GEOLOGY AND STRATIGRAPHY

2.1 Introduction

Knowledge regarding the Geology and structure of the locality is an essential clue for interpreter in order to conduct accurate interpretation of seismic data. The basic cause behind that, in numerous cases identical signature is obtained from different lithologies and contra wise. Now, to counter with such complexities, background knowledge of geology about the area and its stratification, unconformities and major structures of the area under study are the most vital tools for an interpreter (Kazmi and Jan., 1997). This chapter deals with some description relevant to the study area's tectonics settings, structural geology and stratigraphy.

2.2 Regional Tectonics Settings

In late Paleozoic Pangaea broke into two parts, in late Mesozoic time (Cretaceous), the northward drift of Indian plate started and the trend went up till late Eocene. As the plate collided with Kohistan Island arc, the formation of the Island arc came into being during Cretaceous time because of Calcium Alkaline Activity around the subducting oceanic crust, and the formation of Himalayas finally came to existence due to this northward drift. From Paleozoic time to present, the events associated with the movements of the tectonic plate has resulted the structural and stratigraphic features of Pakistan. Starting from Permian through middle Jurassic period, Indus Basin, as it is known today, its location was in the southern Hemisphere. Laurasian, Tethyan and Gondwanaland domain are the main geological subdivisions of Pakistan. Thus it truly depicts that the particular position of Pakistan as it lay up at the junction of two convergent Indian and Eurasian plate. Gondwanian domain is originating the southern part and comprising of the crustal Indo-Pak plate, both the northern and western territories of Pakistan are existing in Tethyans realm and thus representing a complex crustal structure and a intricate geology (Kazmi and Jan., 1997).

2.3 Basins of Pakistan

Basins are considered as area of regional subsidence, in which sediments are preserved for geologically longer period of time. Tectonically, Pakistan is divided into following three main basins:

- Indus Basin
- Baluchistan Basin
- Pasheeen Basin

2.3.1 Indus Basin

The Indus basin is originated to the sort of extra-continental down wrap. The basin is elongated as well as oriented in Northeast and Southwest direction in shape. The platform, the fordeep comprising depressions, inner and outer folded zones are the vital tectonic features of Indus basin (Kazmi and Jan., 1997). The Indus basin has been fragmentized into compression regime, basement uplift and extensional regime in upper Indus, central Indus and lower Indus basin respectively. Considering the structures, Indus Basin is further fragmented into two parts:

- Upper Indus Basin (North)
- Lower Indus Basin (South)

In the northern side of Pakistan there lies the Upper Indus Basin and Sargodha High splatted it from lower Indus Basin. Main Boundary Trust lying in the northern side of Upper Indus Basin, while in the east and west strike slip faults Jhelum and Kalabagh are positioned respectively (Kazmi and Jan., 1997). Upper Indus basin is further subdivided into two segments:

- Potwar Basin
- Kohat Basin

2.4 Potwar Basin

Topography of the Potwar Basin is undulating and characterized by the sequence of synchronized ridges and valleys, commonly expanded in E-W direction. Geologically it is regarded as a part of the foreland zone of the NW Himalayans fold and thrust belt

(Monalisa and Azam., 2004). Potwar Basin contains molass sediments goes back to the age from Miocene to Pleistocene. Along the ranges in the south, Pre-Cambrian to Tertiary sequence are exposed (Shami and Baig., 2003).

2.4.1 Structures of Potwar Basin

The complete structural trend is east to west or northeast to southwest. Synclines are separating the core salt anticlines in eastern Potwar. Hinterland and foreland verging faults are mostly bounding these structures and it is thought that due to strike slip movement popup zones are formed. North Potwar Deformed Zone (NPDZ) is the northern part as it is more intensively deformed area. To the south NPDZ is followed by soan syncline, southern flank gently northward dipping along the salt range and along the NPDZ steeply dipping northern limb. Several east-west broad and gentle folds comprise its western part. Strike sharply changes in to north-east in eastern part and the structure comprise tightly folded anticline and broad syncline. Anticlines in axial zone mostly dip steeply or overturned (Pennock *et al*., 1989).

In the western and central Potwar, between NPDZ and salt range less than 1 Km shortening and the thrust wedge has been transported southward as a coherent slab with little internal deformation (Baker *et al.*, 1988), while, in contrast eastern Potwar, due to increase basal traction and fault cut upsection, the deformation has been telescope, producing different type of structural style characterized by fault-folds, triangles and pop-up zone because of which in this region 24 Km of shortening has occurred (Pennock *et al*., 1989). Potwar has thin skinned tectonic without significant involvement of basement Tectonic (Kazmi and Jan., 1997).

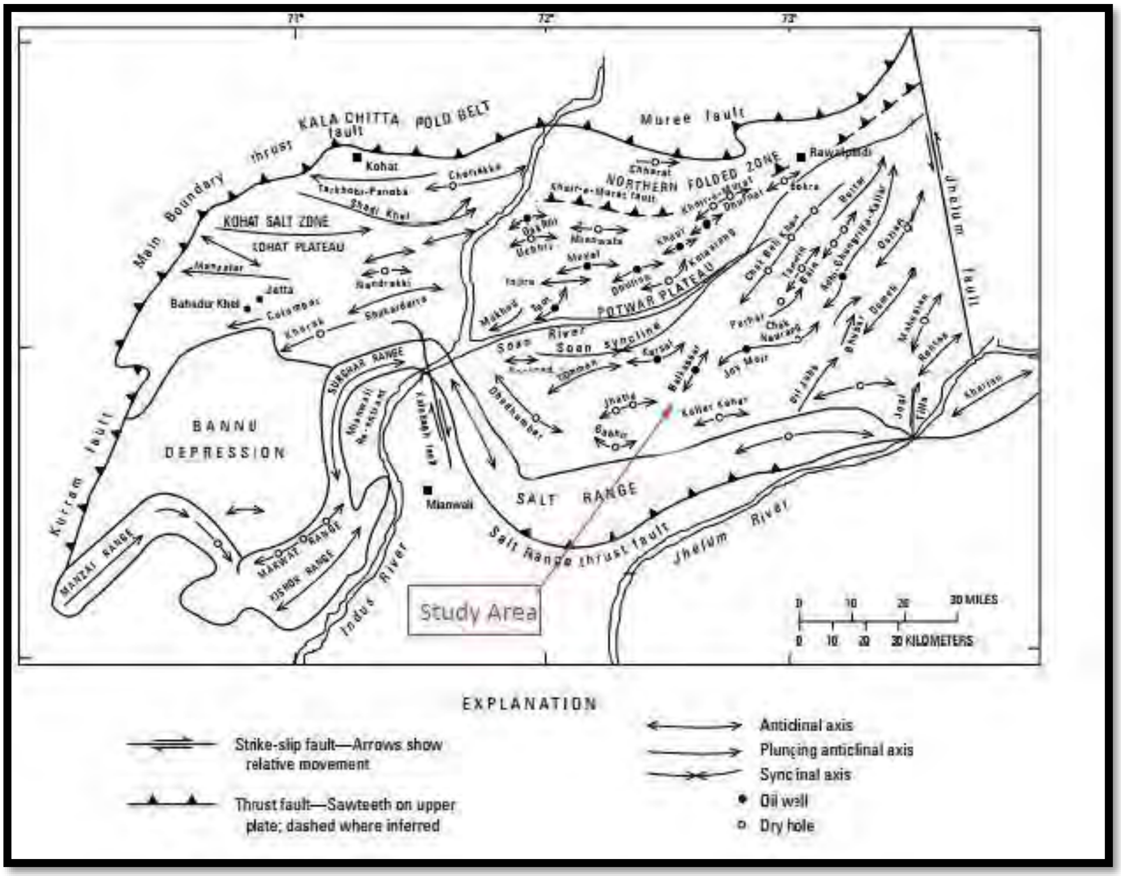

Figure 2.1: Structural map of the study area (Shami *et al*., 2002).

2.5 Potwar Basin Stratigraphy

Depositional sediments in the area ranges from Precambrian to Pleistocene. The deposition was however interrupted several times. The stratigraphy of the Potwar plateau is established from outcrops as well as from the well log sections (Kemal., 1991; Jaswal *et al*., 1997). In the subsurface, the Potwar Plateau preserves the sediments from Pre-Cambrian to Quaternary age, while surface expressions of these formations are exposed in the Salt Range. Detail account on each stratigraphic unit, its sedimentological record and regional distribution is beyond the scope of this study, therefore, a table summarizing brief details of each unit is given in table 2.1(Kemal.,1991; Jaswal *et al*., 1997; Kadri.,1995).

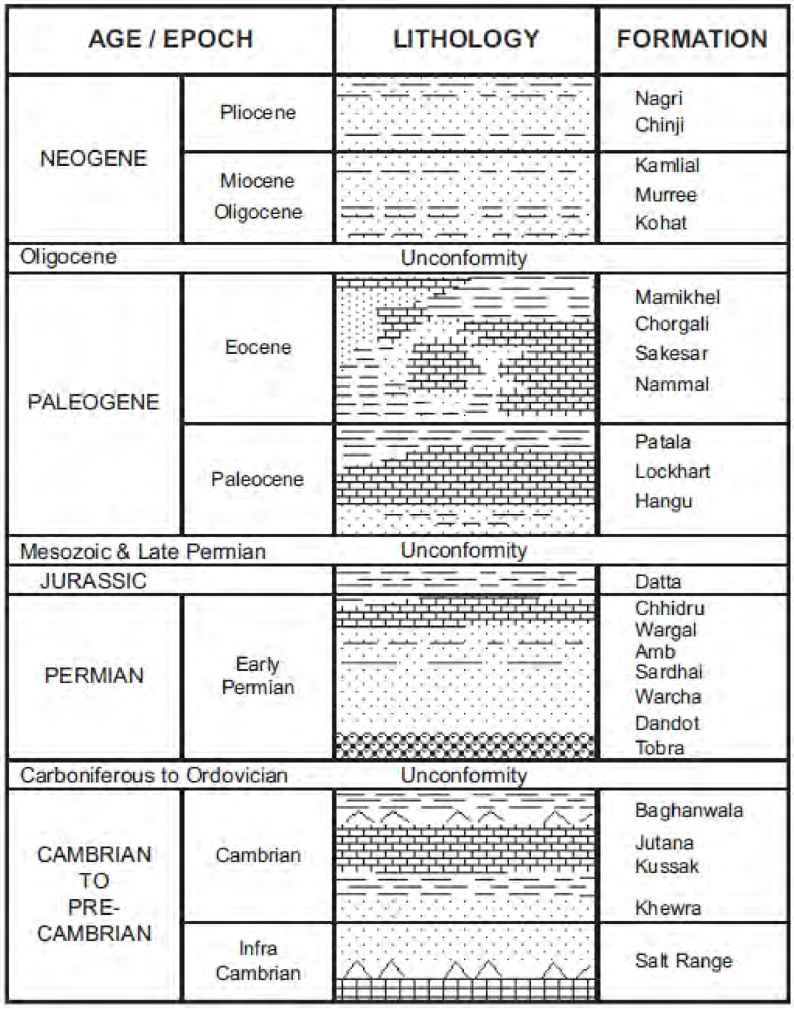

Figure 2.2: Generalized stratigraphic column of the Upper Indus Basin (Wandrey *et al*., 2004).

2.6 Petroleum Prospectivity

The USGS recognizes that there are several separate total Petroleum Play Systems in this Kohat-Potwar sub-basin. (Wandrey *et al*., 2001).

2.6.1 Hydrocarbon Potential

The Salt Range Potwar-Foreland Basin (SRPFB) belongs to the category of extra continental down warp basins, which accounts for 48% of the world known petroleum (Riva., 1983). Presence of continental margin, thick marine sedimentary sequence, potential source, and reservoir and cap rocks make this region suitable for suitable for hydrocarbon accumulation. It contains a thick overburden (about 3000 m) of fluvial sediments, which provide the burial depth and optimum geothermal gradient for seeps found in this area (Moghal *et al*., 2003). The (Salt range-Potwar foreland basin with an average geothermal gradient of 2 °C/100 m is producing oil from the depth of 2750-5200m (Shami and Baig., 2003)

2.6.2 Source Rocks

Followings are considered as source rocks of area under study.

- Shale of patala formation, having organic content in the range of (0.5-3.5) %. (Khan *et al*., 1986)
- Lokhart limestone has a fair amount of organic matter round about 1.4 % so it is considered as source rock to some extent, (Kadri., 1995).
- Shale of Khewra, Kussak, Jutana formation having woody and coaly content, having (27 - 36) % total organic content (Shami and Baig., 2003).

2.6.3 Reservior Rocks

Reservoir rocks of Potwar basin are following:

- Khewra sandstone with porosity (10-12) %, Tobra, Dandot and Warcha formation at Adhi field. Amb and Wargal formations at Dhurnal field.
- Sakesar and Chorgali formations form fractured reservoir in Joyamir area. (Hasany and Saleem., 2001)
- Generally in Potwar basin oil bearing reservoir belongs to early Eocene limestone.

2.6.4 Seal Rocks

The following formations act as seal rocks.

- Shales of Chorgali formation.
- Shales or Claystone of Murree formation, it provides efficient vertical and lateral seal to Eocene reservoirs in Salt Range Potwar- Foreland Basin where ever it is in contact (Shami and Baig., 2003).

2.6.5 Traps

In Potwar basin faulted anticline structure act as trap which are mostly Salt cored, occasionally highly asymmetrical to overturned fault propagation fold and pop-up structures are common deformation style in that area. Secondary traps may also be present within major thrust sheets, particularly at the leading edge of the thrust sheet and above footwall ramp.

2.7 Oil and Gas Fields in Upper Indus Basin

Below table 2.1 display oil and gas fields of Upper Indus Basin with their productive formations and production. Figure 2.3 is the structural map of Kohat-Potwar Pleatue depicting oil and gas fields of area and boundaries of Potwar.

Table 2.1 Oil and gas fields of Upper Indus Basin.

Age	Formations	Lithology	Oil & Gas Field	Productin
Eocene/Paleocene	Lockhart/Sakessar/ Chorgali	Limestone	Dhurnal, Dakhni,Balkasser & chak Naurang	Oil
Jurassic	Datta & Samanasuk	Sandstone & limestone	Dhulian, Toot & Meyal	Oil
Permian	Tobra, Nilawahan & Zaluch	Conglomerate & Limestone	Adhi & Dhurnal	Oil
Cambrian	Khewra sandstone	Sandstone	Adhi & Missa Keswal	Gas

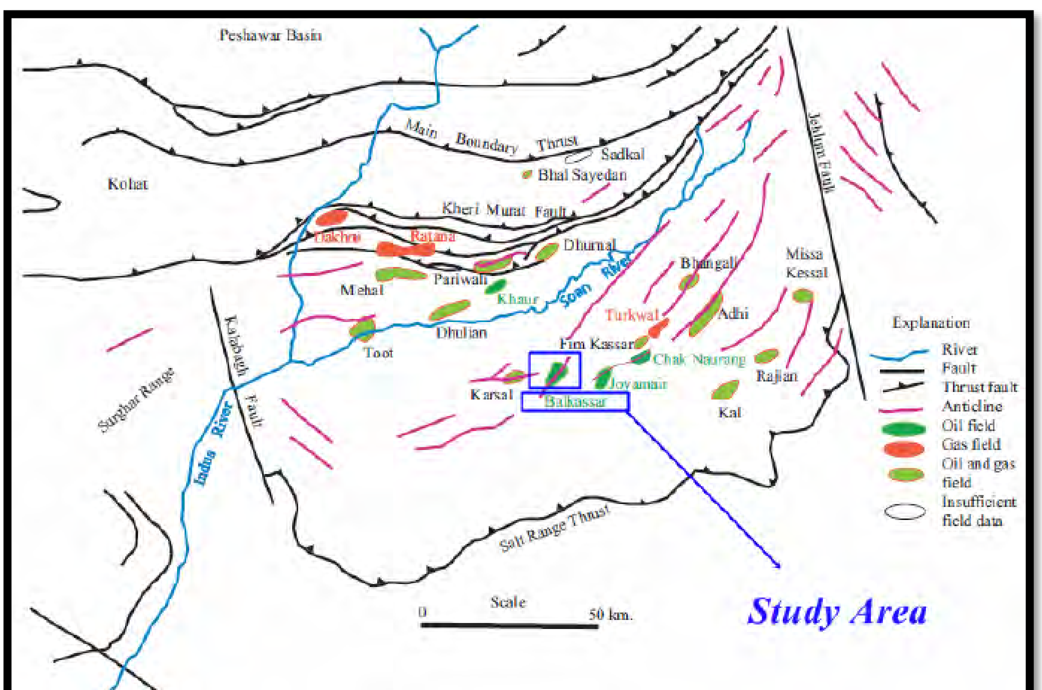

Figure 2.3: Structural map of Kohat-Potwar Pleatue depicting oil and gas fields (Wandrey *et al.,* 2001).

CHAPTER 03

SEISMIC INTERPRETATION

3.1 Seismic Interpretation

The main objective behind interpretation of the seismic data is to draw out valuable information or possible subsurface seismic imaging through processed data. The extracted information may consist of subsurface rock properties, velocity information, structure, stratigraphic, stresses information and with passage of time fluids saturation changes in the reservoir. The knowledge regarding the local and regional geology either from the existing literature or field outcrop sample along with subsurface well data, the acquisition of data with possible parameters and then best quality processing are the key steps required for the good interpretation (Enwenode., 2014). Workflow chart adopted for the interpretation is shown in figure 3.1.

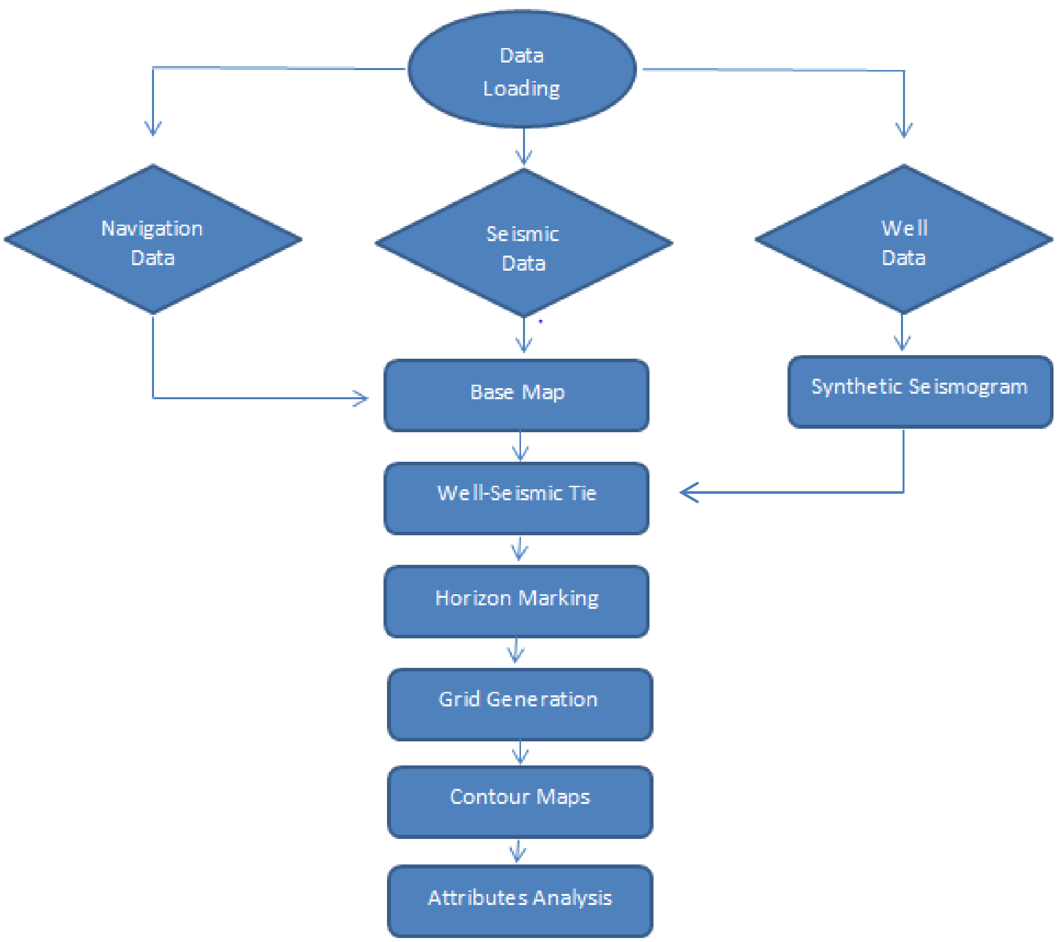

Figure 3.1: Interpretation workflow.

To unveil the regional history of tectonics, one of the valuable tool is seismic profile. Seismic profiles are useful when seismic sections are tied to the well data and the surface outcrop. To map the structures of the subsurface geology seismic reflection profiles are most commonly used (Robert., 1999).

3.2 Structure Interpretation

Two types of approaches are in field to interpret the seismic data i.e. Seismic Structure and stratigraphic interpretation. In stratigraphic interpretation seismic sequences are studied as expression of the lithology while in structure interpretation reflections geometries of the two way travel time are studied. By seismic modeling both types of analysis can be understood. For layered earth model synthetic seismogram is generated to analysis the physical event. As we have amplitude versus two way time data, therefore, structure analysis mostly carried out by using two way travel time instead of depth. By applying velocity functions like stacking velocity derived locally from the acquired seismic data during acquisition or from borehole i.e. sonic log, time maps can be converted into depth maps. So in complex geological structures the successful development of the oilfield depends on 3D seismic data (Kearey *et al*., 2002).

This study is focused on structural interpretation of the 3-D seismic data of the Balkassar area of the Upper Indus Basin, Pakistan. Regionally study area is extensively folded and fault. Provided data cube have not shown any fault, as the available 3-D seismic data cube contains data of one of the limb of fold which do not have a fault at that position. From the well log data, synthetic seismogram was generated with the help of which horizon of interest i.e. Patala Formation is marked. In the subsurface, to examine the overall generalized trend of the horizon, the time grid was generated which interpolate the values of time between time grid nodes. An appropriate function of velocity is multiplied with time grid to convert it into depth map which provides the end product of seismic structure interpretation.

3.3 Base Map of the Study Area

Generally Geophysicists used shot point maps, which have specific seismic lines orientation and location of the well with latitude and longitude. It also has specified position for shot points at which seismic data is acquired for interpretation purposes. The study area's base map is shown in figure 3.2 wherein Inline traversed from 72 to 189, Crossline from180 to 337 and Balkassar-OXY-01 well is located at Inline 168 and Cross 249.

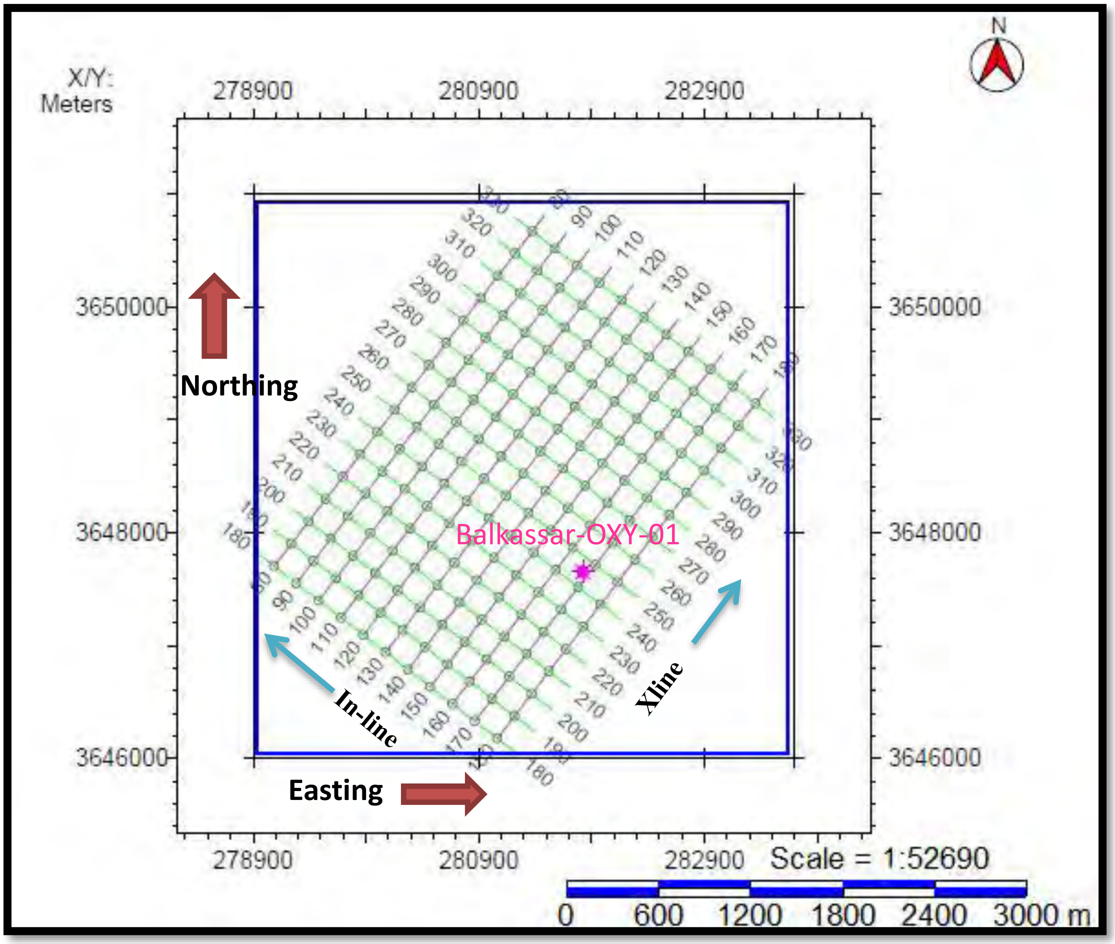

Figure 3.2: Base map of the study area.

3.4 Synthetic Seismogram

By using sonic log data and density log, an artificial reflection record has been made in depth domain. The product of sonic and density logs gives an acoustic impedance and function of reflectivity in time which is later convolved with an appropriate source pulse or wavelet i.e. Ricker wavelet. By using following relation reflectivity series or function is calculated:

$$RC = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_1 v_1 + \rho_2 v_2} \qquad (3.1)$$

Where:

ρ_1 and ρ_2 are densities of first and second layer respectivel.

V_1 and V_2 are velocities of first and second layer respectivel. (Dobrin *et al*., 1990)

In layered earth model synthetic seismogram is generated by convolving source wavelet s(t) with earth reflectivity series r(t) depicting the acoustic impedance contrast (Keary *et al*., 2002).

$$x(t) = s(t) * r(t) \tag{3.2}$$

Where:

$x(t)$ is synthetic seismogram

$s(t)$ is seismic source wavelet

$r(t)$ is earth reflectivity series

In the synthetic model Multiples are either incorporated or not incorporated. By using ray tracing method synthetic seismogram for more complex model can be generated. Figure 3.3 shows synthetic seismogram of the Balkassar-OXY-01 well:

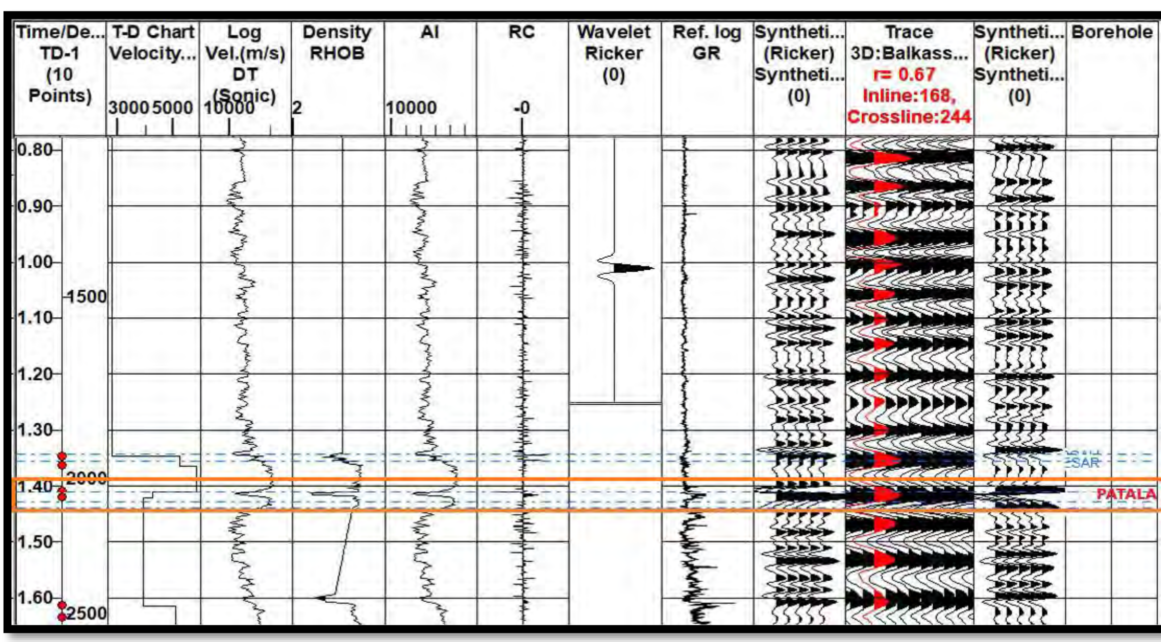

Figure 3.3: Synthetic Seismogram of the Balkassar-OXY-01 well.

3.5 Horizon Picking and Marking

By using available information of formation tops, seismic horizon is identified and interpreted. Patala Formation is interpreted on the seismic section whereas the shale line is marked at about 1.4 second between Sakessar Limestone and Lockhart Formation by using well data of Balkassar-OXY-01. Normally, the study area contained thrust and reverse faults but in the provided 3-D data cube the seismic reflector at the interpreted time is showing planner behavior where no fault is being encounter.

3.5.1 Inline 168

Balkassar-OXY-01 displayed on the Inline 168 with its formation tops and time information. The main theme of this study is to find out the source potential of the Patala Formation. For this purpose only one Formation of our interest was identified through well data and marked at 1.4 second. Figure 3.4 shows interpreted Patala Formation on seismic section Inline 168:

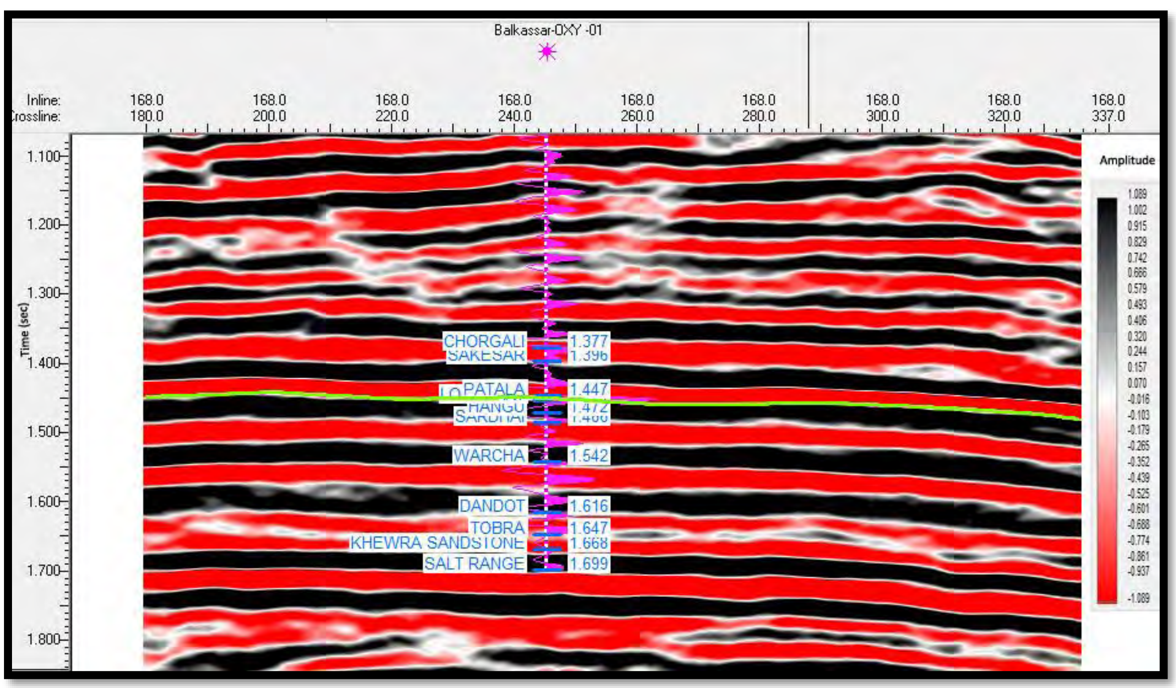

Figure 3.4: Interpreted Patala Formation on seismic section Inline 168.

3.5.2 Crossline 249

Figure 3.5 shows section of crossline 249. Direction of the crossline is parallel to the strike direction. The seismic section does not show any structural variation in this direction with respect to time.

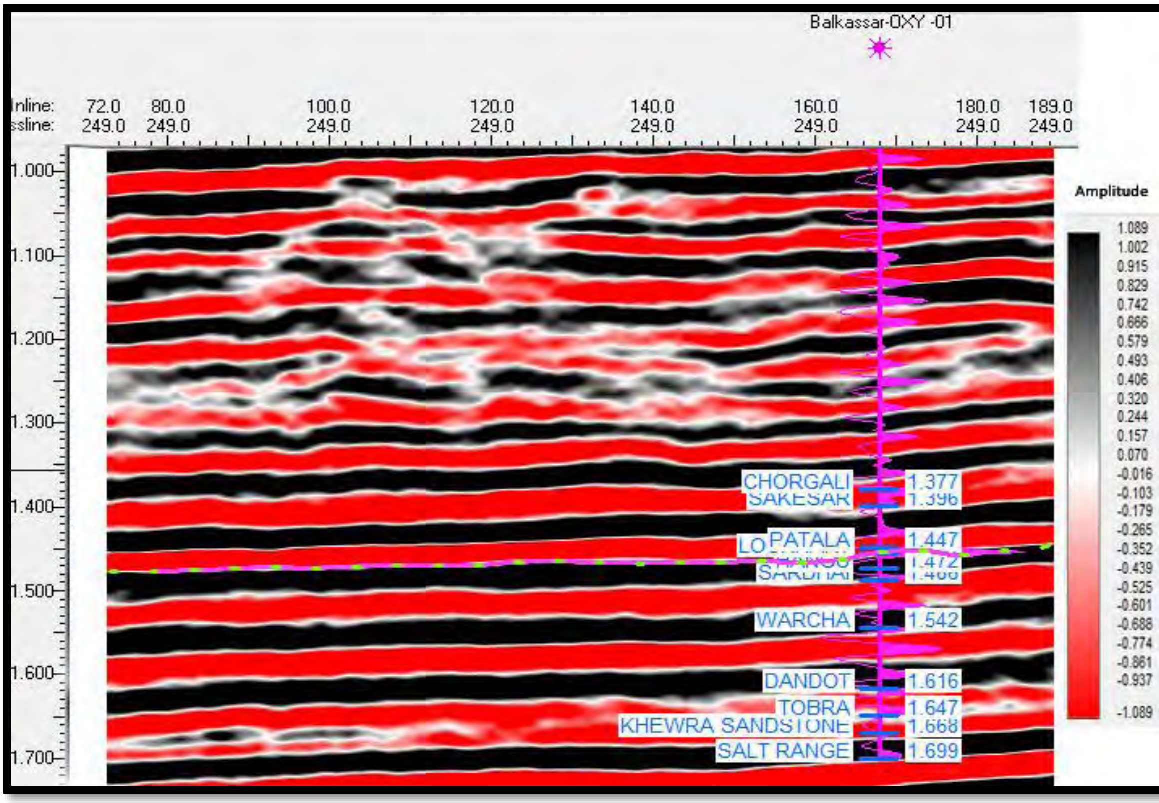

Figure 3.5: Interpreted Patala Formation on seismic section crossline 249.

3.6 Grid Generation

To interpolate values for the missing points, grids are generated before the time or depth contouring. Generation of grids tells about any change in the physical parameters such as depth, time etc. temporally and spatially. First seismic 3-D data is digitized and grid is generated at the interval of the horizon of interest. Grid is generated at the interval of the horizon of interest i.e. Patala Formation where time varies from 1.486 to 1.438 seconds. Figure 3.6 shows time grid of Patala Formaton.

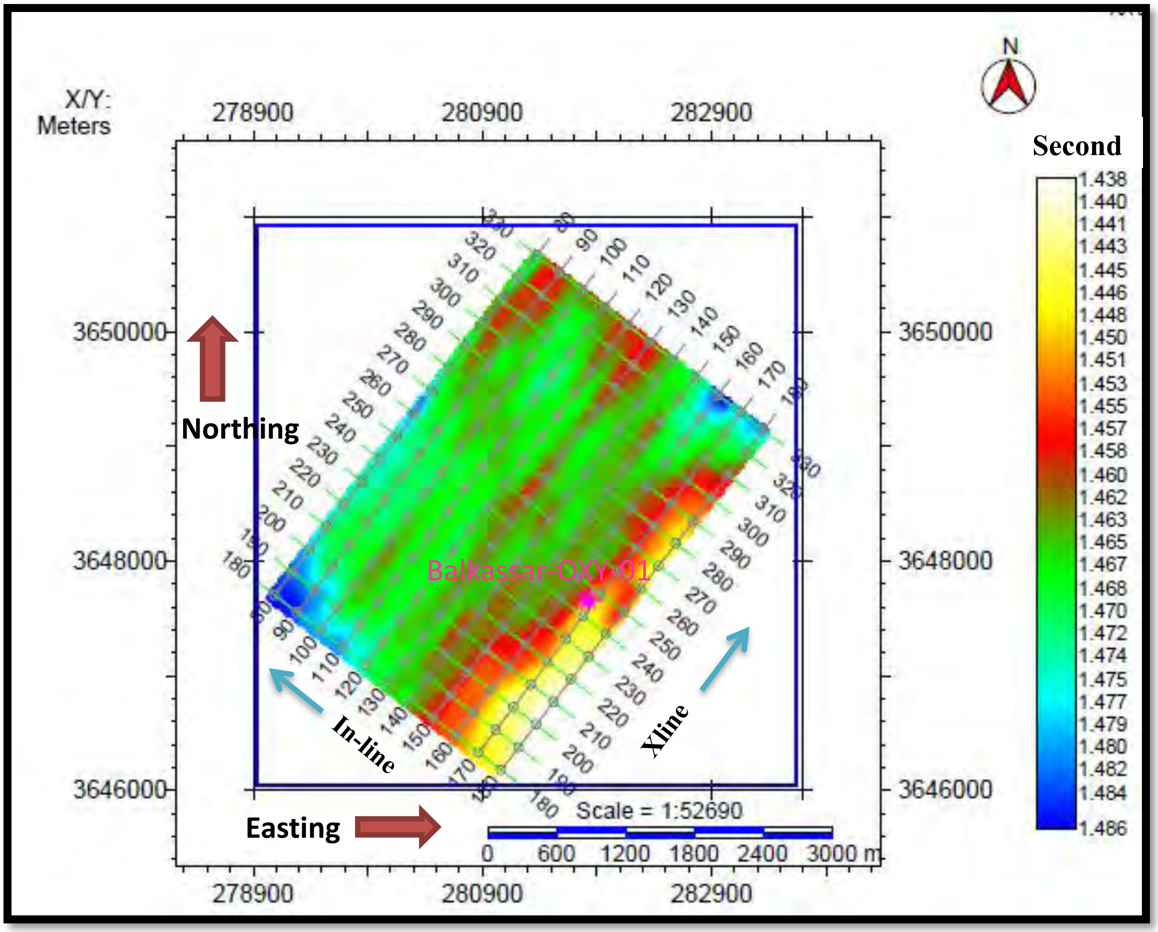

Figure 3.6: Time grid map of Patala Formaton.

3.7 Contour Mapping

The points of same physical properties in space and time are connected to obtain contour lines. Time-depth maps of the Patala Formation show the position of horizon and the type of the structure developed at tis horizon in time and depth domain respectively.

3.7.1 Time Contour Map

Time of Patala Formation varies from 1.4387 to 1.4862 seconds with contour interval of 1.25 milliseconds. Time variation on contour map is confirming almost the planner behavior of the Patala reflector shown in seismic interpretation. Figure 3.7 shows time contour map of Patala Formation, where Patala Formation is encounted in well at 1.44 second.

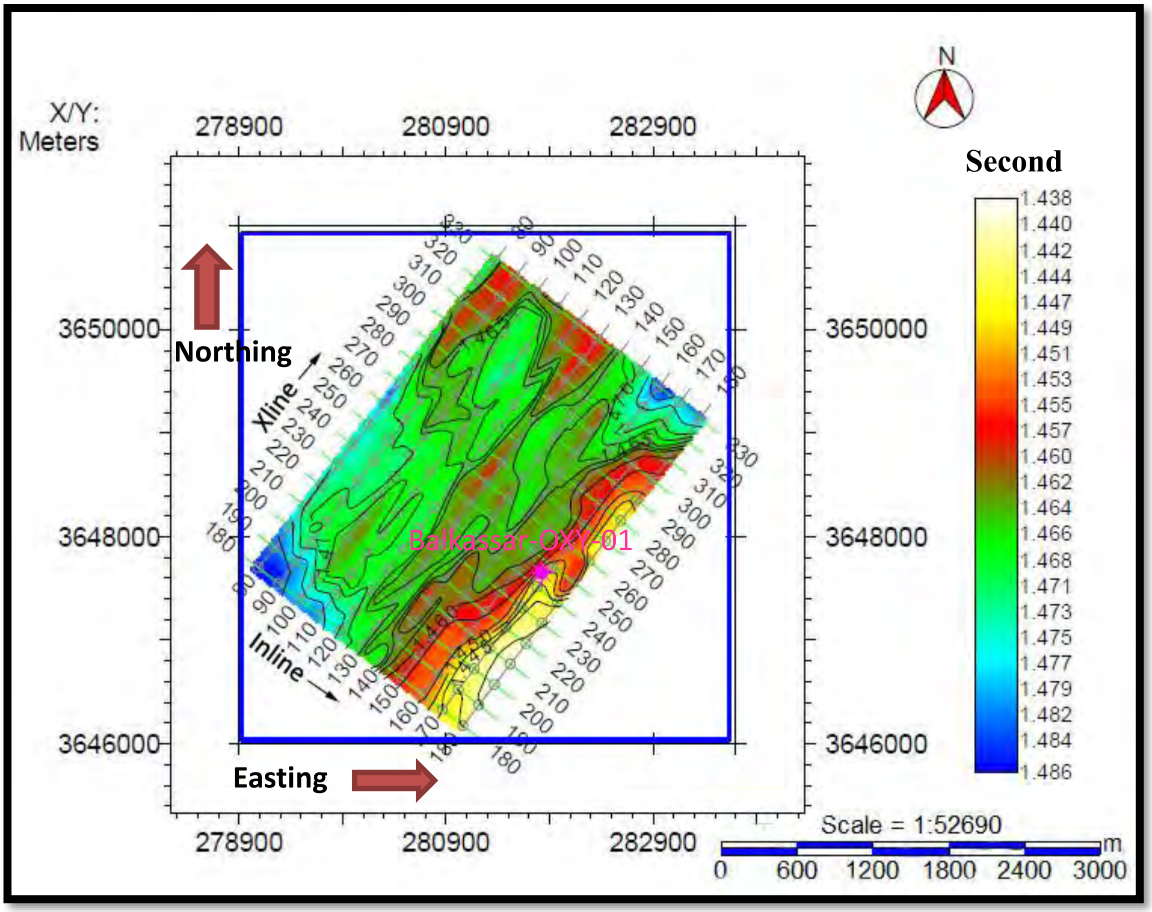

Figure 3.7: Time contour map of Patala Formation.

3.7.2 Depth Contour Map

Depth of Patala Formation varies from 2585 to 2675 meters with contour interval of 5 meter. The depth variation on contour map is also confirming seismic interpretation that there is almost planner reflector. Figure 3.8 shows depth contour map of Patala Formation, where Patala Formation is encountered in well at 2611 meter.

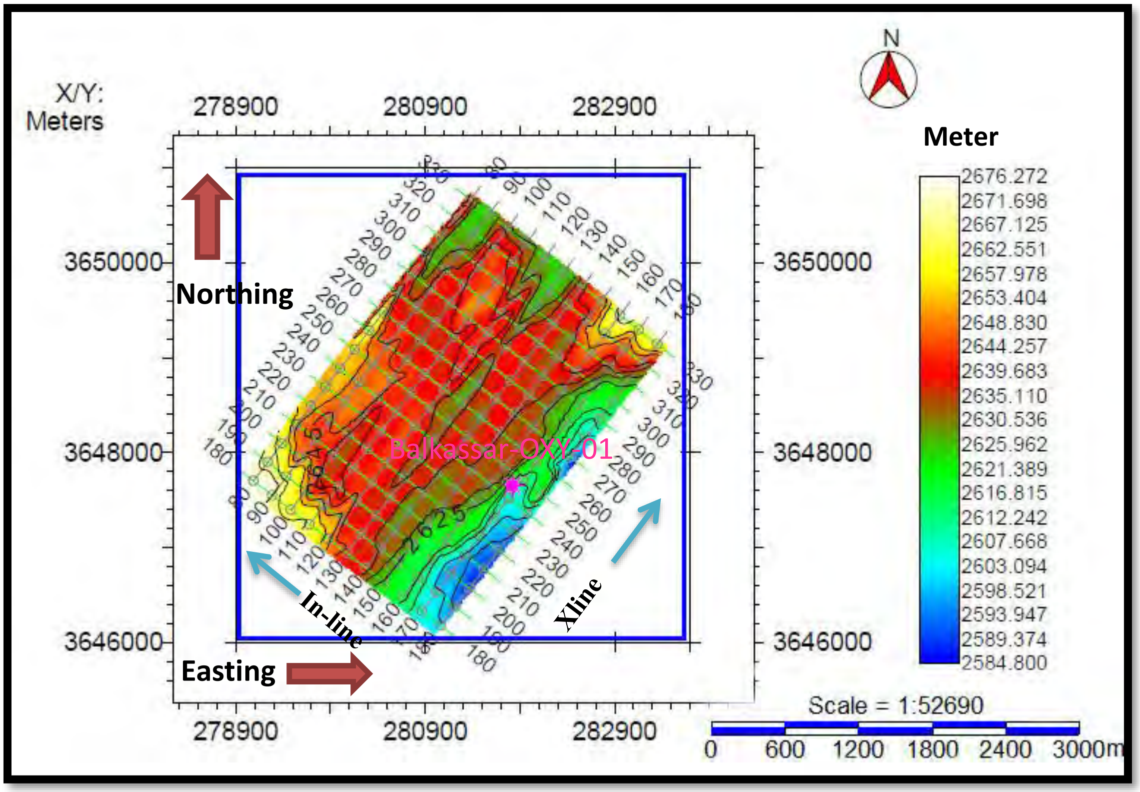

Figure 3.8: Depth contour map of Patala Formation.

3.8 Seismic Attributes Analysis

Seismic attributes are source for any information extracted either by the direct measurement from seismic data or by indirect experience and logic based. Seismic attributes has gained considerable popularity since its advert in 1970 for qualitative interpretation, fluid and lithology detection and reservoir characterization. The subsurface geometry and other physical properties are provided through qualitative interpretation by the seismic attributes (Chopra and Marfurt., 2005).

In frequency domain physical parameters like acoustic impedance, velocities, reflection coefficient and absorption coefficient etc, of seismic wave in earth layers are given by the amplitude content of seismic data. A phase spectrum is the principle component for finding geometric configuration and shape of the reflector. The generic objective behind applying the attributes on seismic data is to provide the correct and elaborated information about stratigraphy, structure and any other seismic properties of the acquired data to Geophysicist (Chopra and Marfurt., 2005). Generally, attributes are classified by the different authors into different types, classification of seismic attributes based on the characteristic of different domain are:

3.8.1 Pre-Stack Attributes

As CDP gathers are given as data input in pre-stack attributes. The pre-stack attributes contain information related to angle and azimuth. The volume of the pre-stack is large, but it contains valuable information like fractures sets propagation and fluid contents. Attributes like AVO (amplitude versus offset), velocity and attribute related to azimuth are included in pre-stack inversion.

3.8.2 Post Stack Attributes

In post stack data stacked CDP data is used as input. Stacking term generally refers to averaging technique where information related to azimuth and angle or offset are not preserved. For initial reconnaissance study when dealing with huge data seismic post-stack attributes are most capable. Post-stack attributes are applied for the purpose of detail investigation about seismic data (Taner., 2001). Classification of attributes based on relation to geology are:

3.8.3 Physical Attributes

Geological properties varying spatially and temporally are described by the physical attributes which are related to quality and quantity. For identification of lithology and characterization of reservoir physical attributes are applied. Attribute like trace envelop, magnitude is related to acoustic impedance and frequency is influenced by the bed thicknesses (Taner., 2001).

3.8.4 Geometrical Attributes

The geometrical attributes describes geological properties which varies spatially and temporally. As lateral-continuity attribute determined by semblance algorithm which indicates bedding discontinuity and identical beds. With the help of geometrical attribute stratigraphic interpretation can also be done just like attribute can easily define such different characteristic, event and spatial (Taner., 2001).

3.9 Attributes Analysis

For qualitative interpretation following attributes are applied:

3.9.1 Shale Indicator

To detect the possible shale beds in any clastic environment, the Shale attribute is applied, which is hybrid attribute and combine several primitive attributes for Shale detection. Due to depositional history of shale it has thin beds and high lateral continuity. Shale indicator is considered as one of the combined output attribute of parallel bedding indicator, similarity, instantaneous frequency or wave number and variance attribute. Shale indicator attribute can be interpreted as (Taner., 2001).:

- The higher output values of template indicate the higher possibility of Shale while possibility of other rocks such as sands and carbonates increases when template shows lower values (www.rocksolidimages.com/attributes; www.ihskingdom.com/mathematics-behind-shaleindicator-attribute/).
- Figure 3.9 shows seismic time slice having maximum value at 1.4 seconds and indicating the presence of shale.

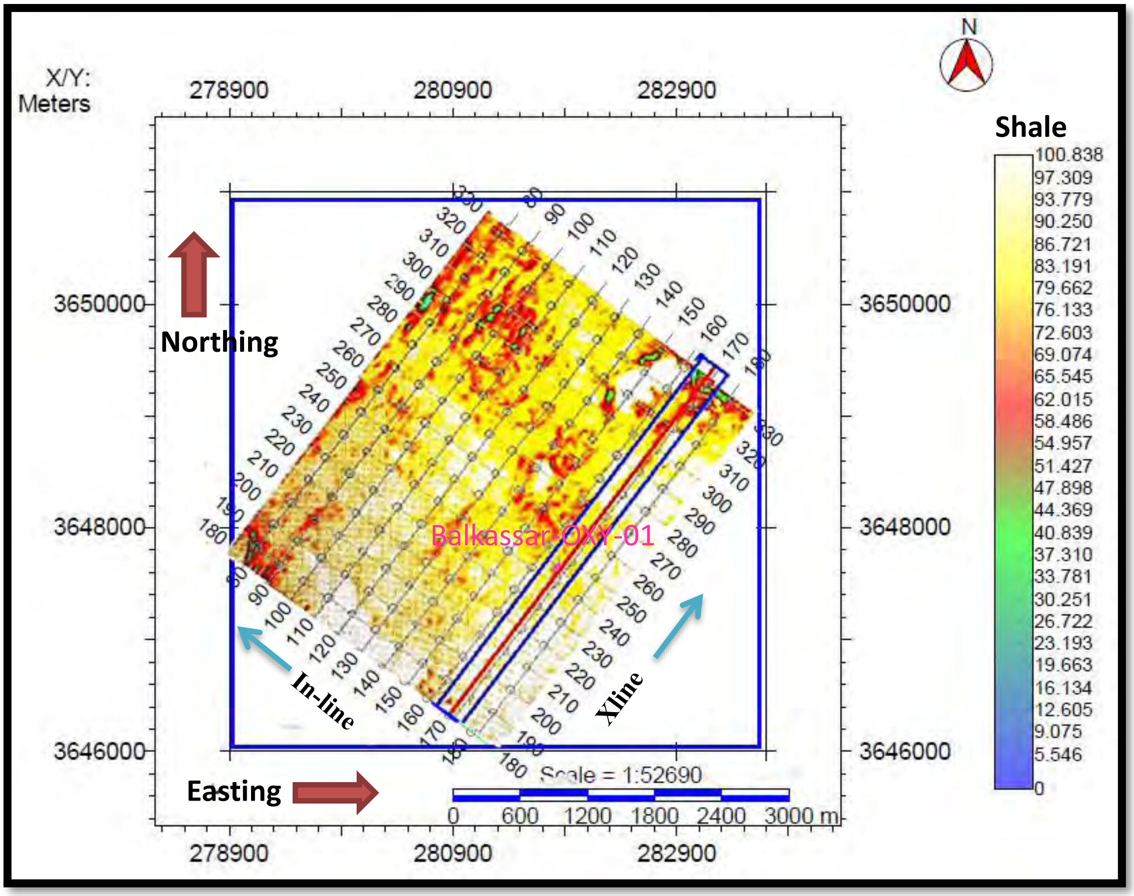

Figure 3.9: Seismic time slice at 1.4 seconds for shale indicator.

3.9.2 Sweetness

To extract the sweet spots (places that are oil and as prone) such as channels and thick clean reservoir, a composite seismic attribute from seismic section which is known as sweetness attribute is applied. The sweetness seismic attribute is very useful tool for proper description of the depositional environment and lithofacies discrimination. This attribute is normally calculated by dividing instantaneous amplitude by the square root of the instantaneous frequency. To original seismic trace Hilbert transform is applied to obtain the amplitude envelop or instantaneous amplitude. In the seismic section when at specific zone amplitude values are higher and frequency shows lower value it indicate highest value of sweetness which most likely indicate oil and gas and same is shown in figure 3.10 (www.wiki.seg.org/wiki/Sweetness).

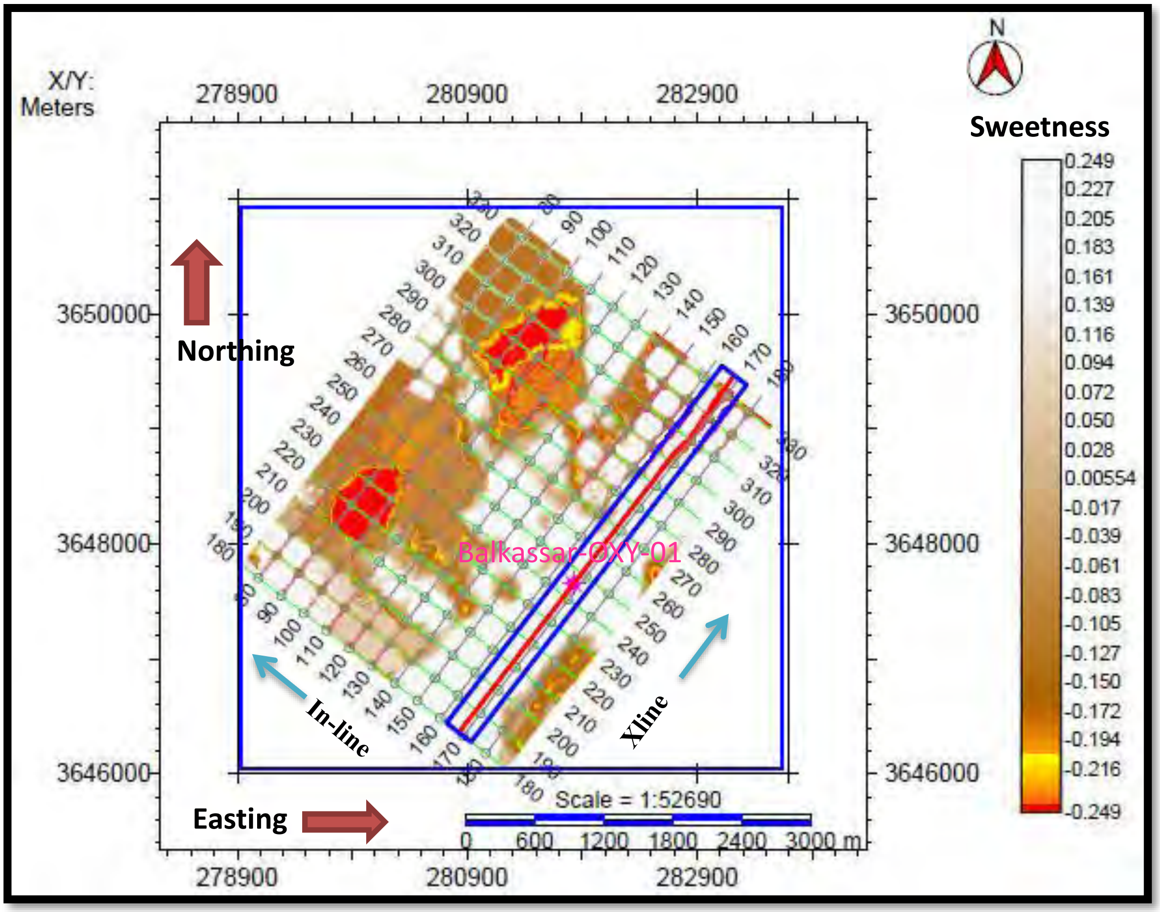

Figure 3.10: Seismic time slice at 1.4 seconds for sweetness attribute.

3.9.3 Instantaneous-Dip Attribute

A post-stack attribute that computes, for each trace, the best fit plane (3D) or line (2D) between its immediate neighbor traces on a horizon and outputs the magnitude of dip (gradient) of said plane or line measured in degrees. In figure 3.11 instantaneous dip attributes is applied on seismic inline 168 time slice extracted at 1.4 seconds. As there is almost linear dip on the time slice which tells that there is no fault in that available data cube.

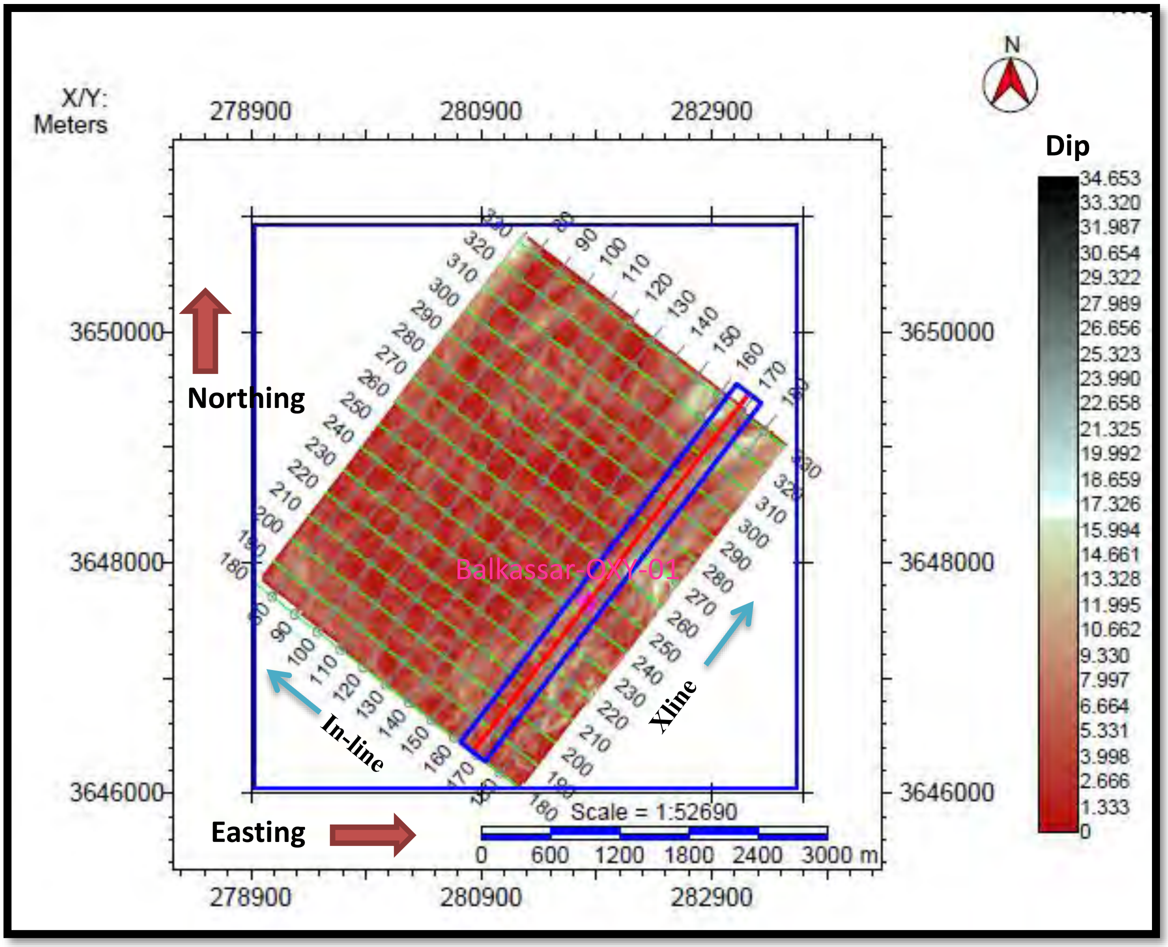

Figure 3.11 Seismic time slice at 1.4 seconds for Instantaneous dip attribute.

Seismic structural interpretations are hence confirmed by the application of various rock solid attributes. The applied attributes also confirmed the existence of shale layer and sweet spots at that particular time i.e. 1.4 second.

CHAPTER 4

PETRO-ELASTIC PROPERTIES

4.1 Introduction

The mechanical properties and mineralogy are vital for better completion and stimulation and its know-how of a rock in case of unconventional Shale oil reservoirs. The understanding of these properties lead to considerable information and has a far reaching impact into deciding the well drilling location, hydraulic fracturing into the zone of interest and pivotal to eliminating the drilling risk and increasing well and reservoir productivity. By using P-wave velocity, S-wave velocity and density, Elastic modulus can be calculated. Many parameters can define the fracability of source rock (Altowairqi., 2015). Some of the parameters implemented in this study are Young's modulus (E), Poisson's ratio (σ) and brittleness index (B). Figure 4.1 shows basic workflow chart of this chapter.

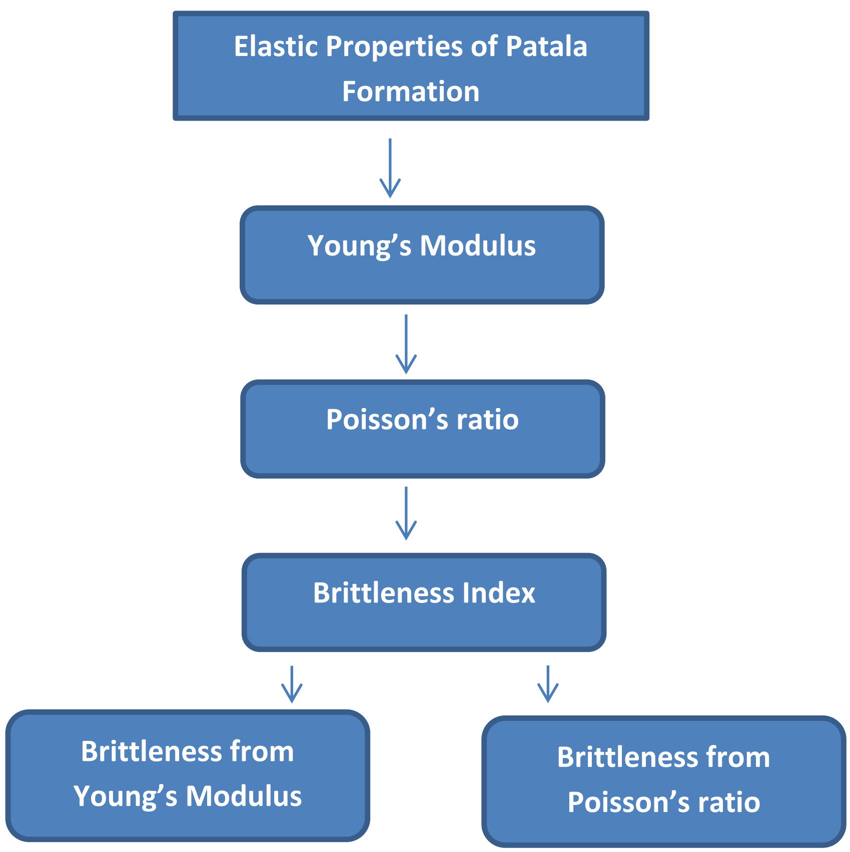

Figure 4.1: Workflow chart of Petro-Elastic properties.

4.2 Young's Modulus (E)

The measurement of linear stiffness of material or the ratio of linear stress over strain is known as Young's modulus (E) of material. Mathematical relationship among Young's modulus (E), bulk density (ρ), P- Wave velocity (Vp) and S-wave velocity (Vs) is given by Mavko *et al.,* (2009):

$$E = \frac{(\rho V_s^2(3V_p^2 - 4V_s^2))}{(V_p^2 - V_s^2)} \tag{4.1}$$

While bulk density (ρ) is obtained from RHOB log, Compressional wave velocity (Vp) is obtained from DT4P log, Shear wave velocity (Vs) is obtained by using Castagna's equation whereby DT4P log values are utilized to generate Vs log shown in figure 4.2. In the zone of interest Vp is relative high than Vs and Young's modulus is also decreasing.

4.3 Poisson's Ratio (σ)

The measurement of transverse strain over axial strain is known as Poisson's ratio (σ). The range of this value come across 0 to 0.5. The values for rocks approaching towards 0.5 have higher clay and kerogen content whereas high quartz content depicts values falling towards 0. As shown in figure 4.2, in zone of interest poisson's ratio values are between moderate to high range. Mathematically, the relation between Poisson's ratio and wave- velocities can be written as (Mavko *et al*., 2009):

$$\sigma = \frac{(\frac{V_p}{V_s})^2 - 2}{(2(\frac{V_p}{V_s})^2 - 2)} \tag{4.2}$$

Whereas;

V_s is P-wave velocity,

V_s is S-wave velocity and

σ is Poisson's ratio

As shown in figure 4.2, value calculated by using above relation is about 0.49 which shows presence of high organic content.

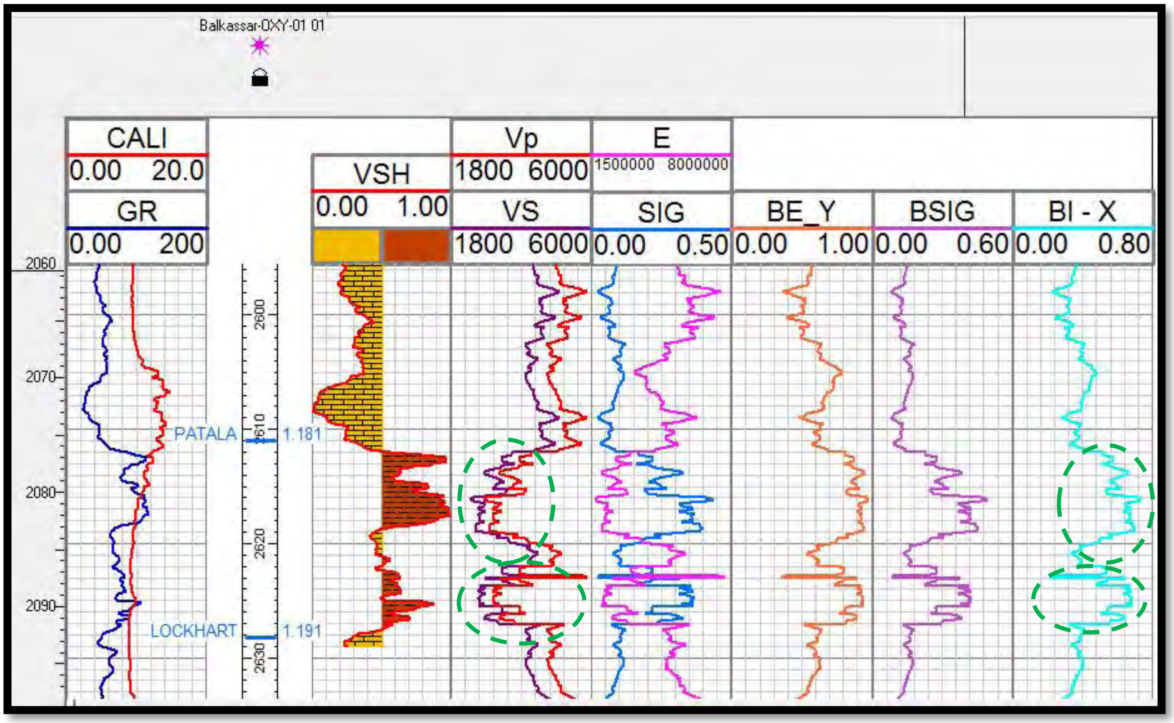

Figure 4.2: Petro-elastic properties of Patala Formation. Whereas CALI is Caliper log, GR is Gamma Ray log, VSH is Volume of Shale, Vp is P-wave velocity,VS is S-wave Velocity, E is Young's Modulus, SIG is Poisson's ratio, BE_Y is Brittleness calculated from Young's Modulus, BSIG is Brittleness calculated from Poisson's ratio and BI-X brittleness Index.

4.4 Brittleness Index (BI)

The idea of rock brittleness is attached with Young's modulus (E) and Poisson's ratio (σ). These parameters show the rock capacity in order to sustain under stress (Poisson's ratio) and gets fracture (Young's modulus). This depicts the amount of energy that a rock body can withstand until it get fractured. Shale rocks of ductile behavior is not good unconventional reservoir and refill the natural fractures, however, it act as good seal rock that traps the hydrocarbon emitting out of the brittle shale which are good for hydraulic fracking and act as unconventional reservoirs. This technique is generally considered as "seismic derived brittleness" initiated by Rickman *et al* (2008). The brittleness index of about 0.65 – 0.70 is calculated using previously calculated Young's modulus (E) and Poisson' ratio (σ) as shown in figure 4.2 (www.subsurfiwiki.org/wiki/Brittleness).

$$\text{Brittleness (B)} = \frac{1}{2}\left(\frac{(E_{min}-E)}{E_{min}-E_{max}} + \frac{\sigma_{max}-\sigma}{\sigma_{max}-\sigma_{min}}\right) \quad (4.3)$$

Or

$$B = \frac{B_e + B_\sigma}{2} \tag{4.4}$$

$$B_e = \frac{E_{min} - E}{E_{min} - E_{max}} \tag{4.5}$$

$$B_\sigma = \frac{\sigma_{max} - \sigma}{(\sigma_{max} - \sigma_{\min})} \tag{4.6}$$

Whereas;

E_{min} is lowest value of Young's modulus,

E_{max} is highest value of Young's modulus,

σ_{min} is lowest value of Poisson's ratio,

σ_{max} is highest value of Poisson's ratio,

B_e is Brittleness calculated from Young's modulus and

B_σ is Brittleness calculated from Poisson's ratio.

In addition to that, brittleness is also dependent on mineralogy of the rock as mentioned by Perez and Marfurt (2013). Jarvie *et al.,* (2007) suggested brittleness attachment with mineral components as discussed below.

$$Brittleness = \frac{Quartz}{Quartz + Carbonate + Clay} \tag{4.7}$$

The aforementioned equation 4.7 describes that quartz is participating towards the brittleness of the rock. High siliciclastic Shale is far brittle. Petro-elastic attributes are measured for Balkassar-OXY-01 well and depicts that Patala Formation perhaps have Shale oil potential having medium to high Poisson's ratio, relatively lesser Young's modulus and excessive brittleness index at the Patala Formation in figure 4.2. So the Patala Formation can be utilized as unconventional reservoir at Balkassar area.

CHAPTER 05

GEOCHEMICAL PROPERTIES

5.1 Introduction

In order to determine the unconventional shale oil / gas potential geochemical parameters are used. In case of developing countries on numerous occasions, well core cuttings are not available in order to calculate the geochemical parameters and evaluation of primary axis rock potential. So in that regard, geoscientists are doing their efforts to counter this problem globally with calculating the aforementioned parameters from logs data which is certainly trustable enough and easier, rapid and less expensive. Multiple empirical and graphical techniques are implemented using seismic and well log data of Balkassar-OXYl-01 well for this study to derive many geochemical parameters for Patala Formation i.e. Log derived Maturity Index (LMI), Vitrinite reflectance, Kerogen volume as well as Total Organic Content (TOC) etc. Figure 5.1 shows work flow chart of this chapter.

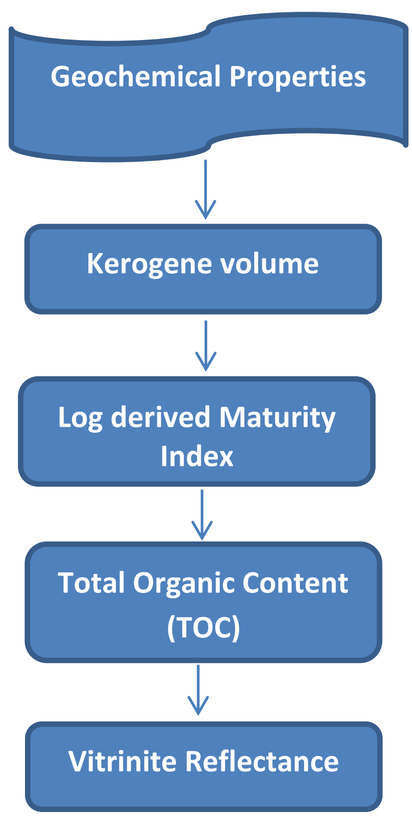

Figure 5.l: Adopted workflow for Probable Source Rock Potential.

By using formation temperature (FT), vitrinite reflectance is calculated according to Hill *et al*., (2007). Kerogen volume is calculated by Shazky *et al*., (2013). Formation temperature effects vitrinite reflectance and window of oil and gas introduced by Machel *et al.,* (1995). Using the concept of Labani and Rezace., (2012) Log derived Maturity Index (LMI) is calculated Total Organic content (TOC) is calculated by Schmoker's 1979 and Passey's 1990 empirical relation.

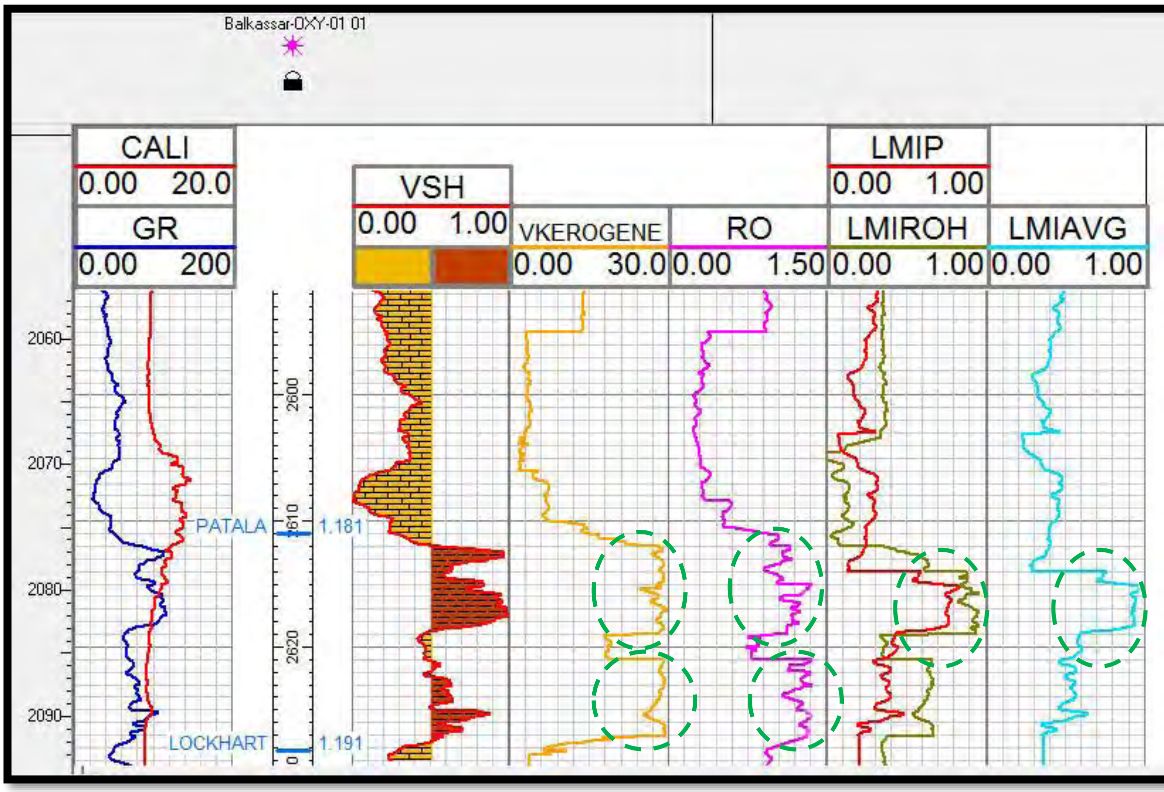

Figure 5.2: Geochemical properties of Balkassar-OXY-1. Whereas CALI is Caliper log, GR is Gamma Ray log, VSH is Volume of Shale, VKEROGENE is volume of Kerogen, RO is vitrinite reflectance, LMIP LMIROH and LMIAVG are Log derived Maturity Index calculated from sonic log, density log and average of both respectively.

5.2 Kerogen Volume ($V_{Kerogen}$)

Using bulk density 2.6 g/cm of the compacted shale sequence, the volume of Kerogen is calculated. The empirical relation given by Shazley et al, (2013) is used in order to derive the Volume of kerogen.

$$V_{Kerogen} = \frac{\rho_b - \rho}{1.378} \tag{5.1}$$

Where:

$\boldsymbol{V_{Kerogen}}$ is the fractional volume of kerogen or organic matter,

$\boldsymbol{\rho_b}$ is the bulk density of non-organic matter and

$\boldsymbol{\rho}$ is the log values from RHOB log.

Figure 5.2 shows that high kerogen values are observed in the Patala interval whereas, the value above the zone of interest are on lower side in Sakassar Limestone but in the zone of interest i.e. Patala Formation in figure 5.2 depicts the approximate kerogen volume of about 25 - 27%.

5.3 Log derived Maturity Index (LMI)

The high value of the LMI shows that the formation is thermally mature whereas the low LMI values describe immature rock formation. The range of LMI value is from 0 to 1. The higher value depicts the higher thermal maturity for corresponding shale layer and the Lower value indicates highly immature formation. For the calculation of LMI, the logs used are neutron log, density log and volumetric photoelectric absorption log for suitable approximation of thermal maturation. Initial LMI is derived for singular log as described above then take average of all three logs to reduce the error and the impact of individual log (Labani and Rezee., 2012).

$$LMI_{\varphi} = \frac{NPHI - NPHI_{max}}{NPHI_{min} - NPHI_{max}} \quad (5.2)$$

$$LMI_{\rho} = \frac{RHOB - RHOBI_{max}}{RHOBI_{min} - RHOBI_{max}} \quad (5.3)$$

$$LMI_{u} = \frac{U - U_{max}}{U_{min} - U_{max}} \quad (5.4)$$

Now taking simple average of all above three equations and calculating average LMI by using the relation:

$$LMI_{avg} = \frac{LMI_{\varphi} + LMI_{\rho} + LMI_{u}}{3} \quad (5.5)$$

whereas:

LMI_{avg} is Log derived Maturity Index from all three logs

LMI_{φ} is Log derived Maturity Index from RHOB log

$LMI_u$is Log derived Maturity Index from NPHI log

LMI_uLog derived Maturity Index from Uranium log

Figure 5.2 shows relatively high values of LMI at Patala Formation. The mean values for LMI is approximately 0.91 which lies in the range of high maturity.

5.4 Total Organic Content (TOC) Estimation

5.4.1 Schmoker's Method

By using the empirical relation introduced by Schmoker *et al.,* (1979) the TOC of any formation can easily be calculated.

$$TOC\ (wt\%) = \frac{154.497}{\rho_b} - 57.261 \quad (5.6)$$

$\rho_b$is the bulk formation density derived from the well data . This TOC value can gives Total Organic Matter (TOM) value by multiplying with a factor of 0.32 for all ancient sediments which is applied by Schmoker *et al*., (1983) to various sedimentary basins. TOC obtained through this method is about 2.47 wt% which is in the good to very good range as shown in figure 5.3.

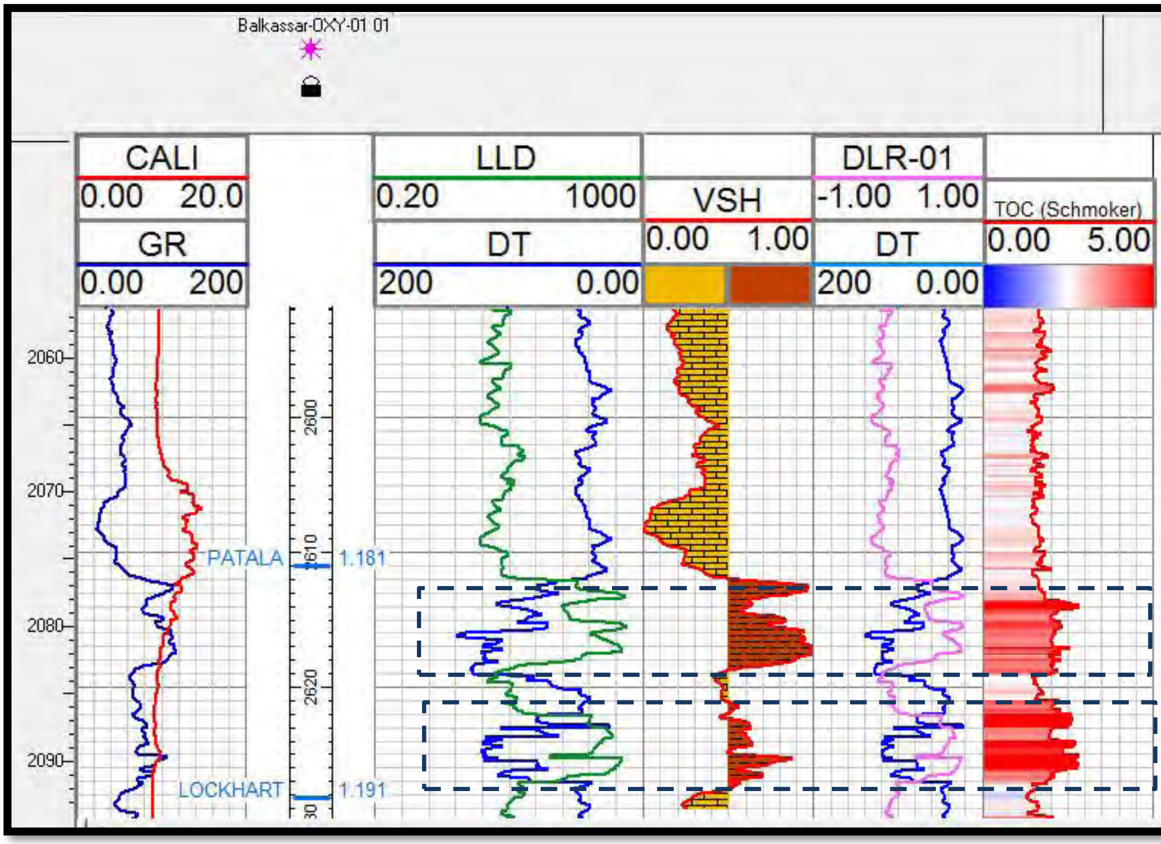

Figure 5.3: TOC calculated from well log data from Schmoker's method. Whereas CALI is Caliper log, GR is Gamma Ray log, VSH is Volume of Shale, LLD is volume Lateral Log Deep, DLR-01 is resistivity log and DT is Sonic Log.

Table 5.1: TOC ranges describing source rock generation (Peters, 1986).

S.No.	Quality	TOC (wt%)
1	Poor	0 – 0.5
2	Fair	0.5 – 1.0
3	Good	1.0 – 2.0
4	Very Good	2.0 – 4.0
5	Excellent	>4

TOC can also be estimated by the relation given by Myers and Jenkyns., (1992) as follows:

$$TOC\ (wt\%) = \frac{0.85+\rho_{ker}\emptyset_{ker}}{((\rho_{ker}*\emptyset_{\mathrm{ker}})+\rho_{ma}(1-\emptyset_{ft}-\emptyset_{ker})} \quad (5.7)$$

Where:

$$\emptyset_{ft} = \frac{\rho_{ns}-\rho_{ma}}{\rho_{ft}-\rho_{ma}} \quad (5.8)$$

$$\emptyset_{ker} = \frac{\rho_{s}-\rho_{ma}}{\rho_{ker}-\rho_{ma}} \quad (5.9)$$

Where:

ρ_{ns} is the density of rock other than source rock obtained from log.

ρ_{s} is the density of source rock obtained from log data.

ρ_{ma} is the mud rock density taken normally as 2.7 g/cm^3.

ρ_{ft} is the fluid taken as water whose density is 1 g/cm^3 and

ρ_{ker} is kerogen density taken as about 1.2 g/cm^3.

5.4.2 Passey's ΔLogR Method

Another method that is used to calculate TOC is the ΔlogR method for clay rich rocks and to consider the empirical relationship given by Passey *et al*., (1990) as mentioned below:

$$TOC\ (wt\%) = \Delta LogR * 10^{(2.297-0.1688*LOM)} \quad (5.10)$$

The calculation of ΔLogR came to existence from the separation of resistivity curve with DT log. Higher the separation greater will be the rock maturity, the value of LOM value can be graphically calculated by Alyousaf et al., 2011 or Labani and Rezee., 2012 by using TOC from Schmoker's 1979. Schematic response of sonic-resistivity log at multiple reservoir conditions is depicted in figure 5.4.

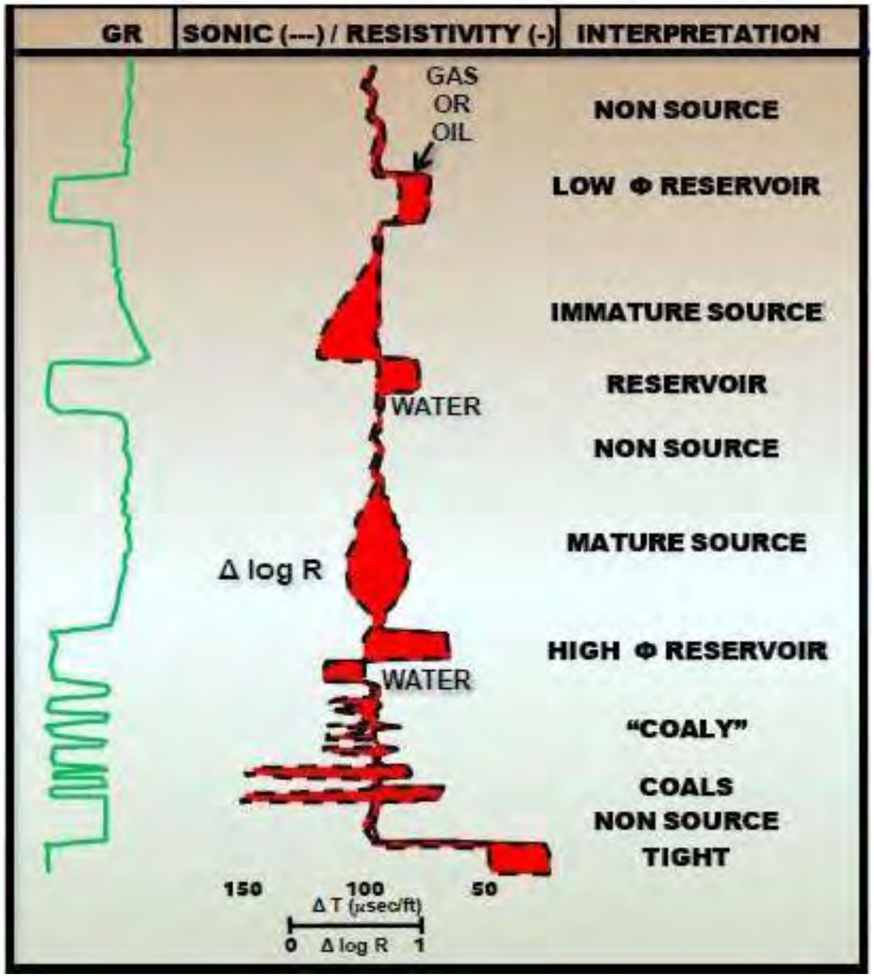

Figure 5.4: Schematic log response in variety of situation (Passey's et al, 1990)

The direct relation always comes among ΔLogR and TOC values. LLD and DT logs are scaled in a certain way that two cycles of LLD is equal to 100μs/ft established by Passey *et al.*, (1990). TOC obtained through this method is about 2.51 wt% which is in the good to very good range as shown in figure 5.6.

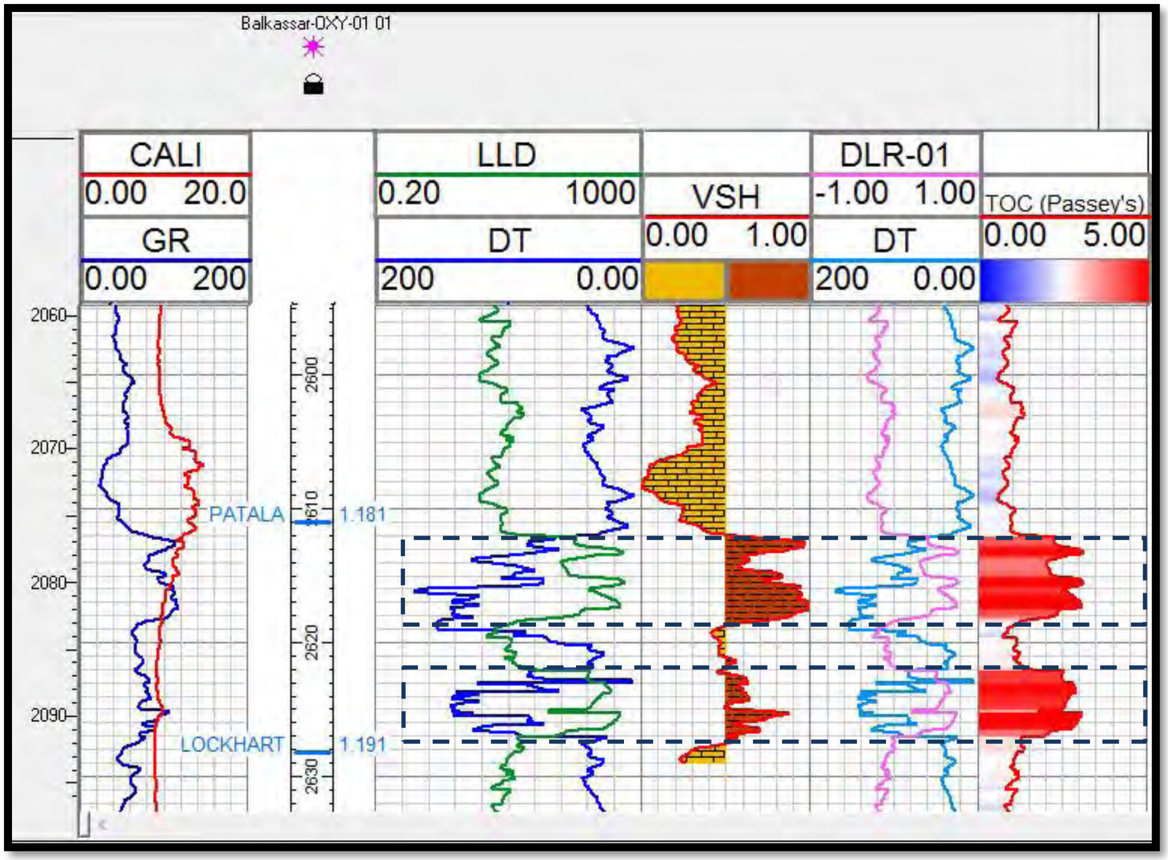

Figure 5.5: TOC calculation from Passey's method. Whereas CALI is Caliper log, GR is Gamma Ray log, VSH is Volume of Shale, LLD is volume Lateral Log Deep, DLR-01 is resistivity log and DT is Sonic Log.

5.5 Vitrinite Reflectance Calculation (R_o)

First value of LOM are calculated and then transformed into Vitrinite Reflectance value (Lecompte and Hursan., 2010).

$$R_o = -0.0039LOM^3 + 0.1494LOM^2 - 1.5688LOM + 5.5173 \quad (5.11)$$

After the use of calculated LOM values, the vitrinite reflectance value is about 1.38% that depicts peak oil producing source as shown in Table 5.2:

Vitrinite reflectance of 1.4% is calculated by Mallick and Raju, 1995 shown in figure 5.2 which shows late oil or peak gas;

$$R_o = 1.11 - \frac{DT}{140}$$

Table 5.2: Generalized Interpretation scheme for vitrinite reflectance (Dembicki, 2016).

Oil-Porn Generation		Gas-Porn Generation	
Generation Stage	R_o(%)	**Generation Stage**	R_o(%)
Immature	**<0.6**	**Immature**	**<0.8**
Early Oil	**0.6 – 0.8**	**Early Gas**	**0.8 – 1.2**
Peak Oil	**0.8 – 1.0**	**Peak Gas**	**1.2 – 2.0**
Late Oil	**1.0 – 1.40**	**Late Gas**	**>2.0**
Wet Gas	**1.40 – 2.0**		
Dry Gas	**>2.0**		

CHAPTER 6

SEISMIC POST STACK INVERSION

6.1 Introduction to Inversion

In order to achieve the goal of integrated study of available seismic data, well log data is substantial (Torres *et al*., 2004). For economic potential development of the field, Seismic reservoir characterization is an imperative and critical tool to envisage the reservoir properties (Karbalaali *et al*., 2013). A very thorough and precise study of reservoir behavior is required by applying different geophysical techniques in order to identify and decrease the risk for the new drilling sites (Karbalaali *et al*., 2013).

3D seismic data has high resolution to detect the formations interface between upper and low lying lithology whereby there is higher contrast. This is because of seismic wave reflect back from the interface of lithology having contrast in acoustic impedance (Barclay *et al*., 2008). Acoustic impedance is the product of density of formation and velocity of seismic waves passing through it. Hence rather than full reservoir characterization, formation interface properties can be studied in detail with the help of 3D seismic amplitude data (Latmier *et al*., 2000).

3D seismic amplitude is the property of interface and with the help of 3D seismic data we cannot characterize the full reservoir rock properties (Penderal *et al*., 2007). Seismic inversion technique is used extensively in geophysical field to overcome this limitation of 3D seismic data for obtaining rock properties through seismic data.

Through Seismic post stack inversion technique, in initial stages 3D seismic amplitude data is converted into acoustic impedance volume on each trace (Sukmono *et al*., 2002). Elastic rock properties can be evaluated in Seismic inversion by seismogram which may contains travel time, phase and amplitude information. The imaging of subsurface can be improved using seismic post stack inversion. For the reservoir characterization different seismic inversion techniques are used commercially. This research work follows two types of inversion analysis, by using P-wave Impedance on inverted seismic 3D data:

- Model Based Post Stack Inversion
- Band Limited Post Stack Inversion

Through Band Limited Inversion, P-Impedance is recovered additionally on full 3D base map along with Inline 168 where well is laying. Model based inversion comparatively contributes more accurate and clear results when applied on the real data (Hampson and Russell, 1991). Results of both these Inversion are nearly similar but Model based Inversion is performed at Inline from which Acoustic Impedance is recovered.

6.2 Model Based Inversion

In order to enhance the resolution of results in Model Based post stack inversion, density and DT logs are combined with seismic data. Model based inversion is highly appropriate method for inverting the reservoir properties through Seismic amplitude data as it minimize the risk of recursive inversion by continuously changing the low frequency model in order to provide the best least square fit (Russell., 1991). Acoustic impedance of earth is gained by the seismic inversion through which lithological properties can be calculated (Kneller *et at*., 2013).

6.2.1 Algorithm of Model Based Inversion

Model Based Inversion's basic assumption is to reduce and measure error (Misfit) between the synthetic and real seismic data. Approach used in MB inversion algorithm has a basic purpose to minimize the function which is shown in Equation 6.1 (Gavottiet *et al*., 2014).

$$J= Weight_1 x(S-W*R) + Weight_2 x\ (M-H*R) \quad (6.1)$$

Where;

J= Error between the real and Seismic trace which have to reduce upto acceptable level

S= Original seismic trace
R= Reflection coefficient series
W= Extracted seismic trace at well location.
M= Initial guess low frequency geological model or interpreted horizon.
H= Final integration operator which gives the resultant Impedance by convolution with reflectivity series R

Background algorithm used in MB Inversion is relatively simple. In this algorithm software assumes that Wavelet (W) and seismic Traces (S) are already known. While applying this algorithm initial low frequency guess model is altered repeatedly until the matching between the synthetic trace and actual trace reaches to a proper acceptable level (Gavottiet *et al*., 2014). In simple words initial guess low frequency geological model is altered until the error between original and synthetic trace become minimized. This error can be reduced upto larger level, if we have strong background geological knowledge of that field (Kneller *et at.,* 2013). Figure 6.1 shows schematic workflow chart of Model Based Inversion (Sen., 2006).

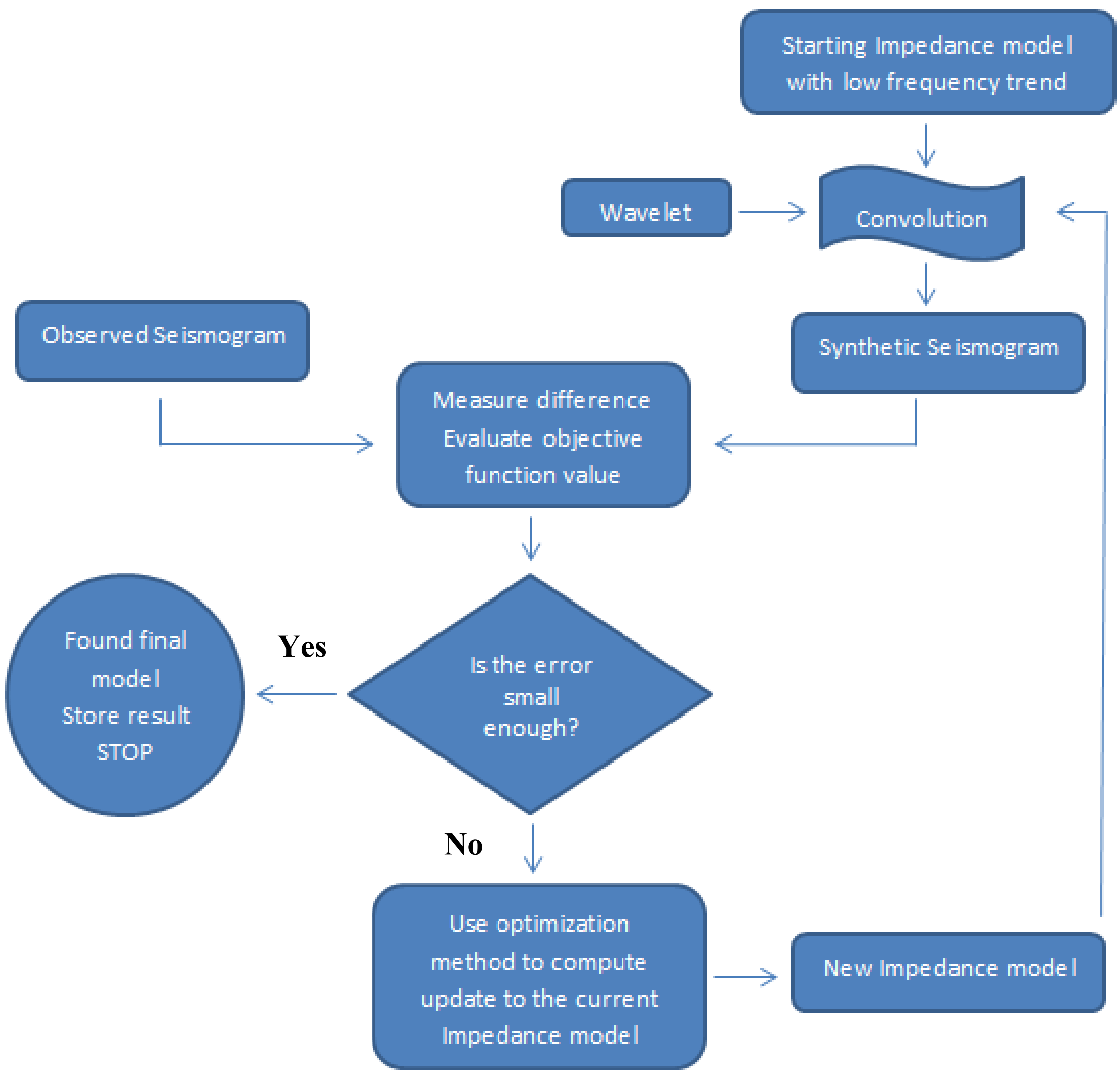

Figure 6.1: Schematic workflow flow chart of Model Based Inversion (Sen., 2006).

6.2.2 Wavelet Extraction Process

In inversion process wavelet has fundamental importance, because it is used in correlation with seismic trace. Wavelet is mainly estimate of wave pulse for a seismic source which may contains many frequencies and is time limited (Cooke and Cant., 2010).

To perform the seismic inversion, a zero phase wavelet is extracted through HRS software, which is then used in correlation of inverted and original extracted reflectivity series at well location of Balkassar-OXY-01. Such type of wavelet is also used in synthetic generation as discussed in chapter 3 to mark the horizon for seismic interpretation.

In 3D seismic data interpretation and Post stack inversion analysis, extracted wavelet should be zero or minimum phase to get the correct and appropriate results (Jain, 2013). For inversion analysis, phase shift amount of input extracted wavelet plays a key role. The larger phase shift leads to quite higher error in final impedance results (Kallweit et al., 1982).

As shown in figure 6.1 the total length of extracted wavelet is 100 ms and phase of extracted wavelet is set to be constant. The straight line that cross the frequency domain wavelet illustrates the phase of wavelet.

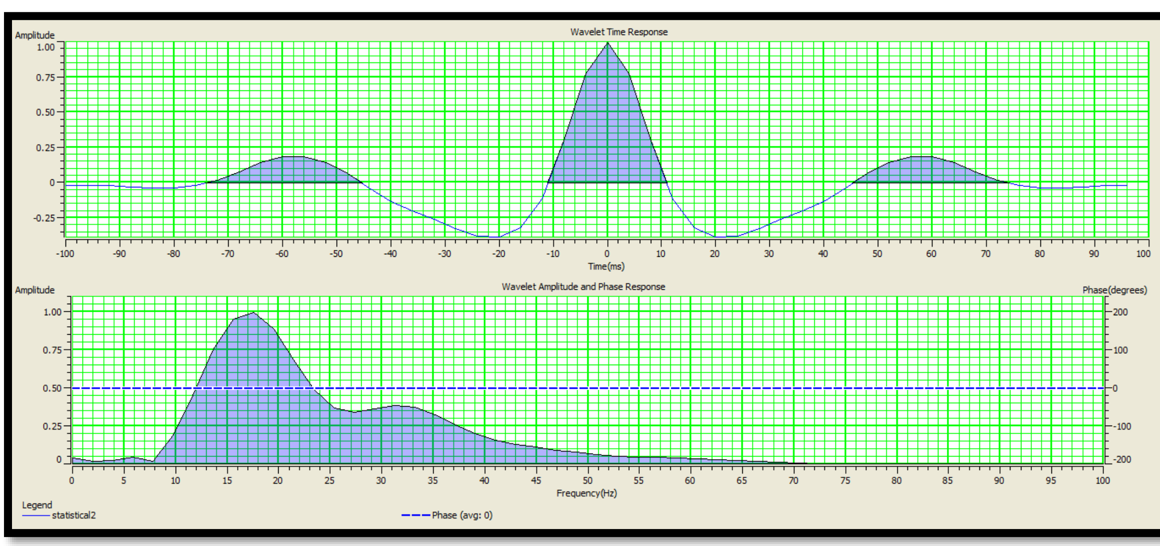

Figure 6.2: Full wavelet in time and frequency domain.

6.2.3 Inversion Analysis

At well location of Balkassar-OXY-01 inversion analysis is performed for Model Based Inversion on provided 3-D Seismic data cube. First of all a statistical wavelet was extracted in time window of 1000 - 1700 milliseconds to cover the targeted range of source rock i.e. Patala Formation. The Impedance extracted from well log data is compared with the inverted impedance in time window of 1000 - 1700 milliseconds.

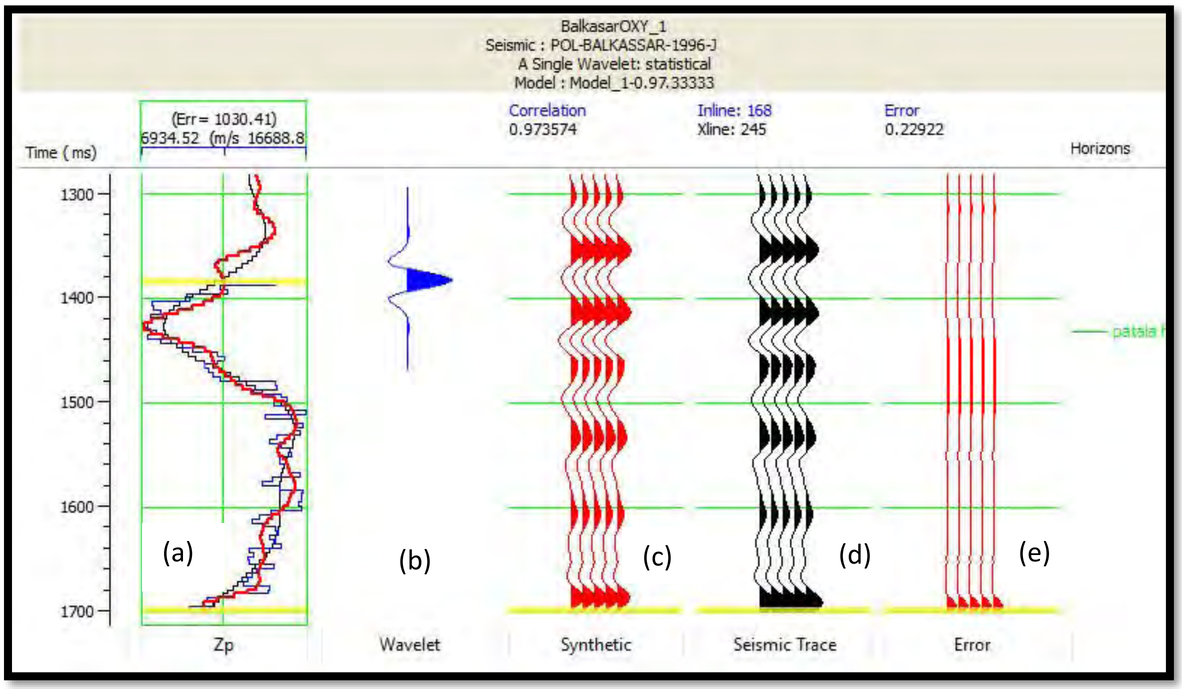

Figure 6.3: Inversion Analysis for Model Based Inversion.

From figure 6.3 (a) it is clear that inverted Impedance (Red curve) nearly follow the same trend as original impedance from well (Blue curve) with an error of (1030.41 (m/s)*(g/cc)). While the black curve is representing the background low frequency Impedance curve.

Next window (b) is representing the extracted constant phase statistical wavelet while in window (c) and (d) there are synthetic and seismic trace respectively. It is clear from the figure 6.3 that there is vast correlation between the synthetic and seismic trace with higher value of correlation coefficient 0.973574 which shows that results of inversion analysis are correct and consistent. RMS Error between both these traces is quite low with value of only 0.22922 as shown in figure 6.3.

6.2.4 Inverted Acoustic Impedance

The inverted acoustic impedance result for inline 168 is shown in figure 6.4. Model based inversion is performed on the time window 1000-1700 milliseconds generally to cover the targeted source zone i.e. Patala Formation. As literature review shows that in Balkassar area Chorgali is producing reservoir with major hydro-carbon component as oil. From source potential analysis in chapter-04 it was predicated that there is a good productive zone at 2611-2624m in Patala Formation where there is quite higher kerogen and suitable cross over between the LLD and DT. This high kerogen zone is also predicted on inversion results as shown in figure 6.4 with low acoustic Impedance. The upper layer from the Patala Formation with yellow color having relatively higher Acoustic Impedance is limestone layer of Sakassar Limestone.

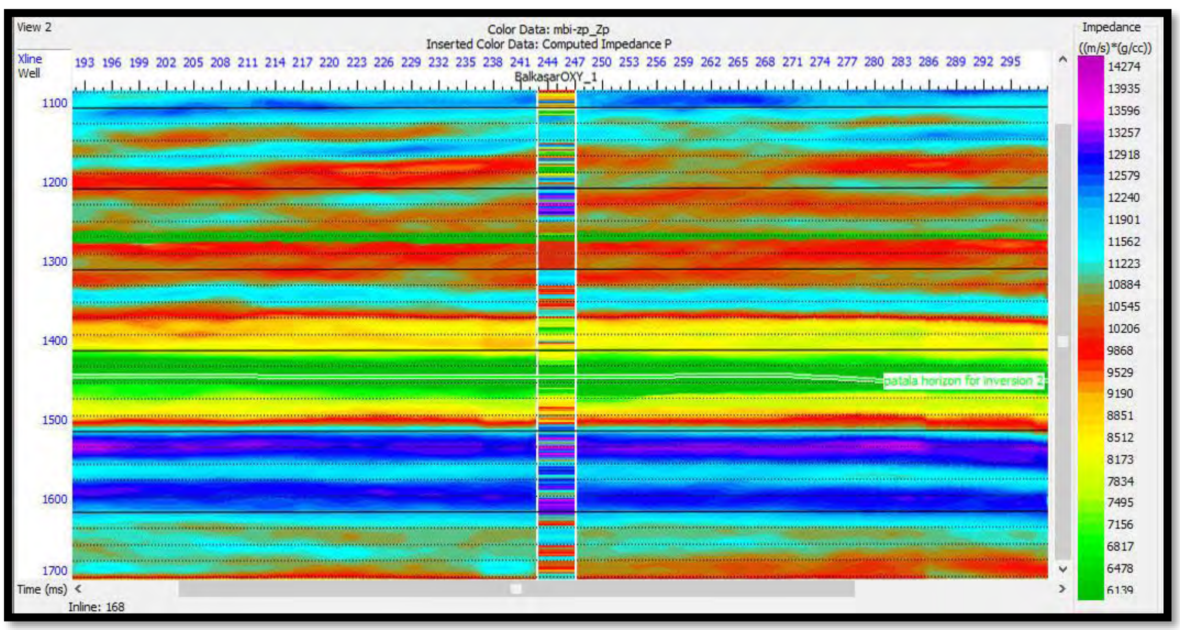

Figure 6.4: Model based Inverted Acoustic Impedance results for inline 168.

The relative higher Acoustic Impedance value in Sakasser Limestone may possibly due to reason that it is not so good productive reservoir in Balkassar as compared to Chorgali. At the time of between 1245 to 1255 milliseconds on inline 168 there are low Acoustic Impedance layers which can be predicted as possible Chorgali reservoir in the Balkassar area.

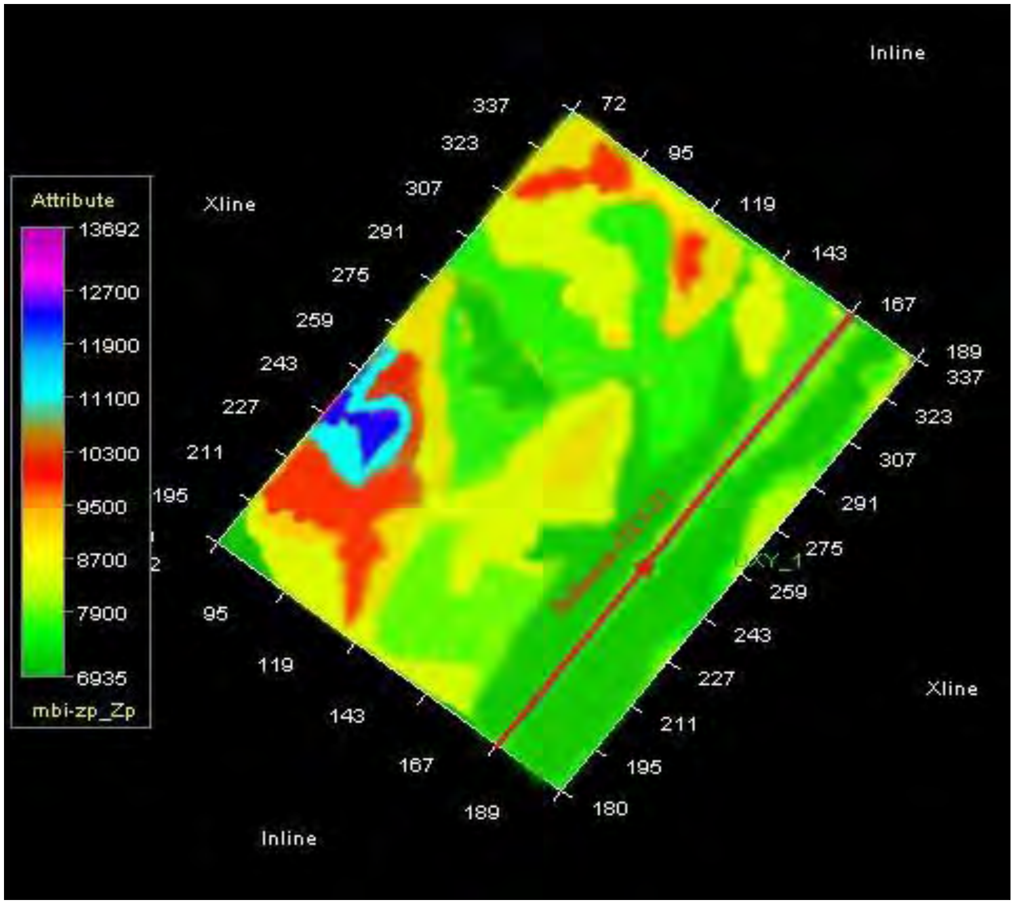

Figure 6.5: Model Based Inverted Acoustic Impedance time slice at 1444 milliseconds.

Figure 6.5 shows inverted Acoustic Impedance time slice at 1444 milliseconds. Inversion results also show the good lateral variation in Acoustic Impedance and also the inverted section as in figure 6.4 provide better subsurface image as compared to original seismic section. Hence Model Based Inversion can be used as a helpful tool in delineating the source rock and also for their hydrocarbon potential.

6.3 Band-limited Inversion (BLI)

Like other inversion algorithms, Band-limited Inversion is also used for inverting impedance, P-wave velocity and density of the post stack data. Band-limited inversion algorithms also constraints the upper frequency limit of the inverted model. Before embarking to band limited inversion, it is mandatory to define the inter relationship between actual seismic trace and seismic impedance (Ferguson and Margrave., 1996). Using equation for zero offset reflection coefficient:

$$Z = V \times \rho \tag{6.1}$$

$$\mathrm{r_i} = \frac{Z_{i+1} - Z_i}{Z_{i+1} + Z_i} \tag{6.2}$$

$$AI_N = AI_1 exp(\sum_{i=1}^{N} \mathrm{r_i}) \tag{6.3}$$

Where:

Z is Acoustic Impedance,

V is P-wave velocity,

ρ is density,

$\mathrm{r_i}$ is reflection coefficient of ith layer,

AI_N is Acoustic Impedance of Nth layer and

AI_1 is Acoustic Impedance of first (top) layer.

Now solving the above equation (6.2) for $(j+1)^{th}$ layer with the help of equation (6.3)

$$Z_{j+1} = Z_j \left(1 + \frac{2r_j}{1-r_j}\right) = Z_j \left(\frac{1+r_j}{1-r_j}\right) \tag{6.4}$$

If the impedance of first layer is known, nth layer impedance can be calculated by equation (6.4)

$$Z_n = Z_1 \left(\frac{1+r_1}{1-r_1}\right)\left(\frac{1+r_2}{1-r_2}\right) \dots \dots \left(\frac{1+r_{n-1}}{1-r_{n-1}}\right) \tag{6.5}$$

Acoustic Impedance of the first layer should be calculated from a continuous layer laying above the zone of interest (Maurya and Singh, 2015a). Now the Acoustic Impedance of jth layer can be found by equation (6.5).

$$Z_{n+1} = Z_1 \Pi_{k=1}^{j} \left(\frac{1+r_k}{1-r_k}\right) \tag{6.6}$$

Dividing equation (6.6) by Acoustic Impedance of first layer (j^{th}) and taking logarithm of both sides:

$$\ln\left(\frac{Z_{j+1}}{Z_j}\right) = \sum_{k=1}^{j} \ln\left(\frac{1+r_k}{1-r_k}\right) \approx 2\sum_{k=1}^{j} r_k \tag{6.7}$$

Solving for Z_{j+1}, equation written above become

$$Z_{j+1} = Z_1 exp\left(2\sum_{k=1}^{j} \mathrm{r_k}\right) \tag{6.8}$$

For scaled reflectivity, seismic trace could be modeled as:

$$S_k = \frac{2r_k}{\gamma} \tag{6.9}$$

Now above equation can be written as:

$$Z_{j+1} = Z_1 exp\left(\gamma \sum_{k=1}^{j} S_k\right) \tag{6.10}$$

By solving the exponential of equation (6.10) gives the resultant impedance (Maurya and Singh, 2015a).

6.3.1 Band Limited Inversion Analysis

At well location of Balkassar-OXY-01 inversion analysis for Band Limited technique is performed on provided 3-D Seismic data cube. As similar to Model Based, a statistical wavelet was extracted in time window of 1000 - 1700 milliseconds to cover the targeted range of source rock i.e. Patala Formation. The Impedance extracted from well log data is compared with the inverted impedance in time window of 1000 - 1700 milliseconds.

Parameter used for band limited inversion in this study is as follows:

- High cut frequency : 24 Hz

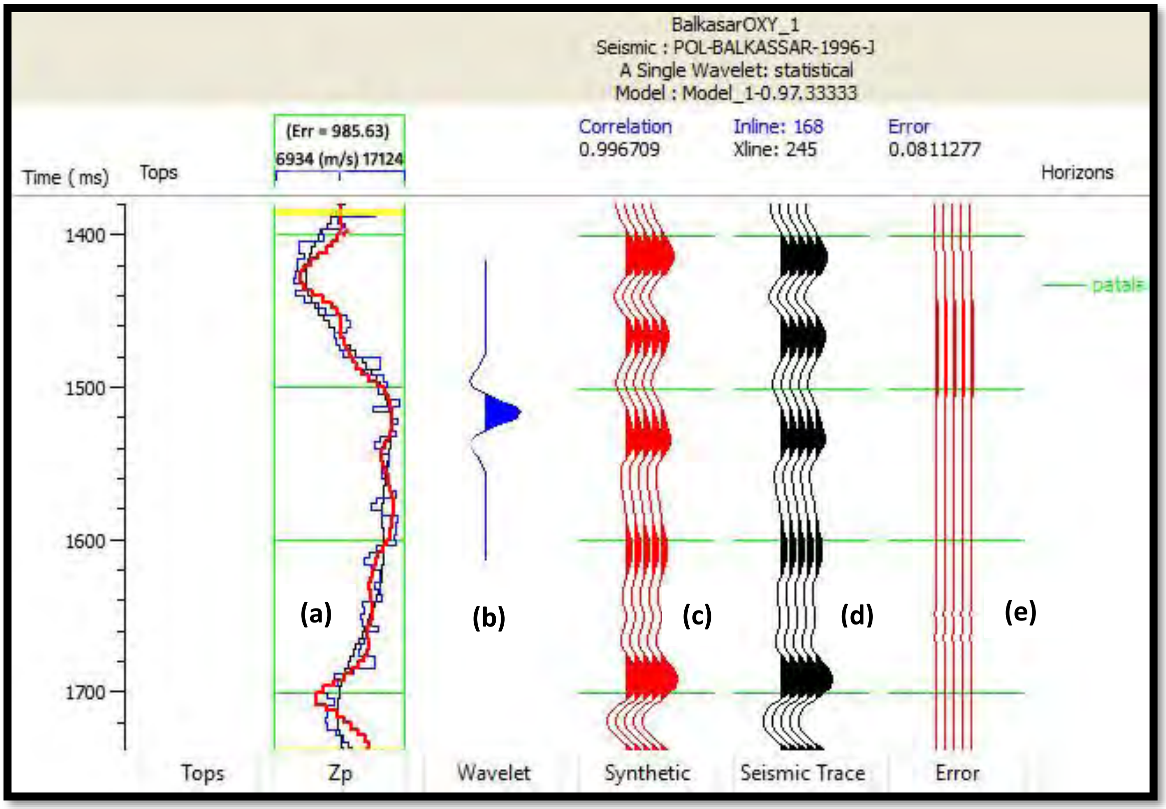

Figure 6.6: Inversion Analysis for Band Limited Inversion.

From figure 6.6 (a) it is clear that inverted Impedance (Red curve) nearly follow the same trend as original impedance from well (Blue curve) with an error of (985.63 (m/s)*(g/cc)). While the black curve is representing the background low frequency Impedance curve.

Next window (b) is representing the extracted constant phase statistical wavelet while in window (c) and (d) there are synthetic and seismic trace respectively. It is clear from the figure 6.6 that there is vast correlation between the synthetic and seismic trace with higher value of correlation coefficient 0.9967 which shows that results of inversion analysis are correct and consistent. RMS Error between the both these traces are quite low with value of only 0.08112 as shown in figure 6.6 (e).

6.3.2 Band Limited Inverted Acoustic Impedance

The inverted Acoustic Impedance results of Band Limited inversion for inline 168 is shown in figure 6.8. Band Limited inversion is performed on the time window 1000-1700 milliseconds generally to cover the targeted source zone i.e. Patala Formation. The high kerogen zone with low acoustic Impedance is comparatively more accurate predicted by Band Limited inversion than Model Based Inversion as shown in figure 6.8 and figure 6.5 respectively. The upper layer from it with yellow color having relatively higher Acoustic Impedance is limestone layer of Sakassar Limestone.

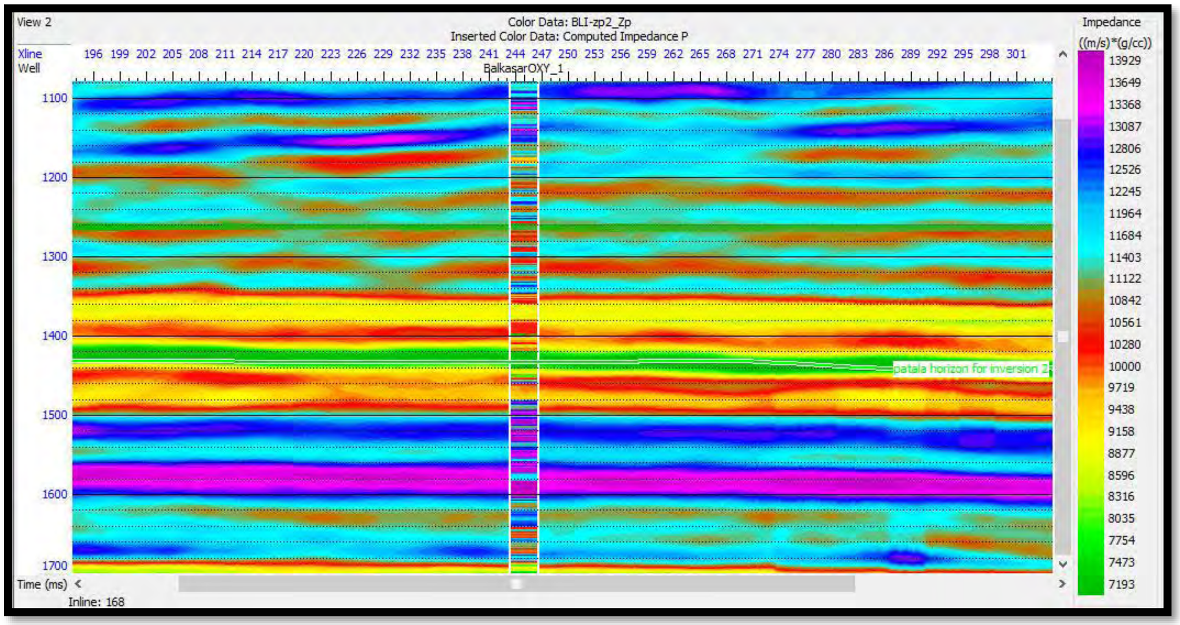

Figure 6.7: Band Limited Acoustic Impedance results for inline 168.

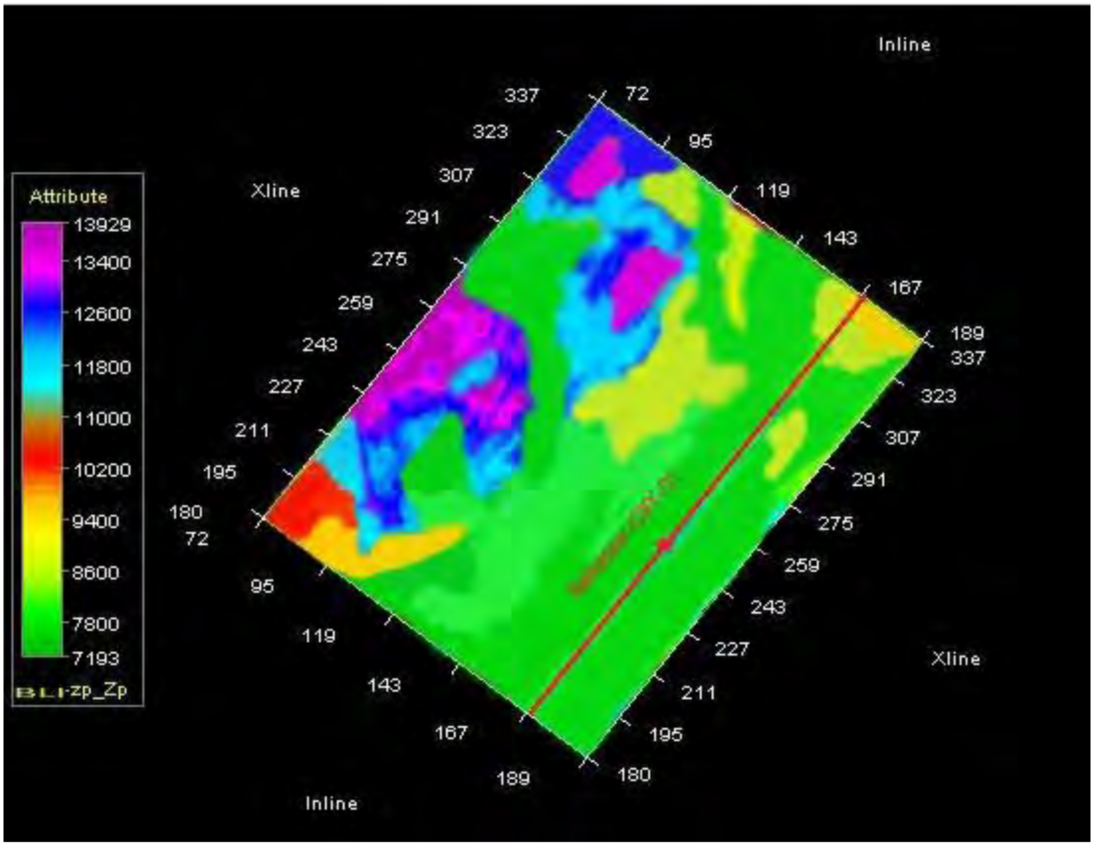

Figure 6.8: Band Limited Acoustic Impedance time slice at 1444 milliseconds.

Figure 6.8 shows Band Limited inverted Acoustic Impedance time slice at 1444 milliseconds for Patala Formation. Inversion results also showing the good lateral variation in Acoustic Impedance and also the inverted section as in figure 6.7 provide better subsurface image as compared to original seismic section. Model Based Inversion however, marked the impedance boundary of Patala Formation at 1444 milliseconds but with high uncertainty. This is due to the absence of frequency control in Model Based Inversion algorithm. In Band Limited Inversion, frequency band of the inverted model is controlled during inversion process by constraining upper frequency limit to 24Hz but Model Based Inversion do not have any scheme in their algorithm to incorporate frequency information. The upper frequency constraining limit is selected on this basis of frequency spectrum of the seismic data. Lack of frequency information also have effect in correlation value and produce large RMS errors of 1030.41 (m/s)*(gm/cc) in case of Model Based Inversion.

Conclusions and Discussion

In the characterization of unconventional reservoir of the Patala Formation, the key parameters that play vital role include Seismic structure Interpretation, Petro-elastic or Petro-mechanical properties and Geo-chemical properties. The main theme of the study was to examine the Shale oil potential of the Patala Formation and the study successfully provided initial insight into unconventional reservoir potential of the Patala Formation's Shale. Seismic Inversion also confirmed the result.

Below are drawn conclusions from the study:

- Seismic structural interpretation of the available cube has shown almost planar seismic reflector with little to no major undulations.
- The qualitative interpretation i.e. attributes analysis of seismic data confirmed the planar behavior of the reflector and presence of shale lithology.
- Elastic moduli, TOC, brittleness and seismic inversion all are related to each other and can explain geo-chemically and geo-mechanically. Rocks having less Poisson's ratio value and greater Young's moduli value have more brittleness index and more quartz content, which means that TOC is low. Vice versa is more ductile and has a high amount of clay content and TOC is likely to be high.
- The Patala Formation has a potential for unconventional Shale oil reservoir. The probable sweet spot has moderate to high brittleness of 0.65. TOC obtained through Schmoker method is about 2.47 wt% while that through Passey method is about 2.51 wt% and overall average TOC of about 2.49 wt.% is in the good to very good range and relatively high values of LMI (0.91) at Patala Formation indicates that the formation is probably in the high maturation stage. The formation has sufficient kerogen volume ~25 - 27% and vitrinite reflectance of 1.4%.
- At Balkassar-OXY-01 well, inversion analysis for Band Limited and Model Based techniques are performed on 3-D Seismic data cube. To cover the targeted range of source rock i.e. Patala Formation, a statistical wavelet was extracted in time window of 1000 - 1700 milliseconds. Model Based inversion has shown correlation between the synthetic and seismic traces with high value of correlation

coefficient of 0.973574 which shows that results of inversion analysis are correct and consistent. RMS Error between synthetic and seismic traces is relatively low with value of 0.22922. In Band Limited inversion vast correlation between the synthetic and seismic trace with higher value of correlation coefficient of 0.9967 has been observed which is indicating accuracy and consistency of the inversion results. RMS Error between the both synthetic and seismic traces is quite low with value of only 0.08112. In Band Limited Inversion, frequency band of the inverted model is controlled during inversion process by constraining upper frequency limit to dominant frequency on this basis of frequency spectrum of the seismic data but Model Based Inversion do not have any scheme in their algorithm to incorporate frequency information. Band Limited inversion identified and marked shale beds of Patala Formation better than Model Based Inversion due to absence of frequency control in Model Based Inversion.

Limitations

Following limitations should be carefully handled while exploring unconventional shale reservoirs:

- First geological complexity and heterogeneities are the serious issues specially in Upper Indus Basin of Pakistan due to collisional regional tectonic. Higher concentration of clay and less quartz in some Shale Formation is also problematic which should be studied very carefully and in detail.
- Most importantly directional drilling and hydraulic fracking in the low permeability Shale Formation by methane and other fluids can cause contamination of ground water quality.
- Unavailability of geochemical data, lack of technical expertise and infrastructure must have to take into consideration.
- The hydraulic operation during the drilling may induce micro seismic events known as induced seismicity due to high pressure fluids in well.

Recommendations

- The already available wells which are not producing hydrocarbons should be used for unconventional reservoir studies instead of drilling new wells.
- An advanced study such as stochastic inversion is recommended to be able to capture any uncertainty during seismic inversion.
- Vertical Seismic Profiling data should be provided for comparison of surface seismic with borehole seismic for better understanding of horizons depth and structure.
- Core sample data should be provided so that more authentic and reliable geo-chemical and geo-mechanical properties can be calculated.
- Micro-seismic monitoring is recommended before hydraulic fracking.
- Mechanical earth model should be generated from elastic moduli calculated from core samples to understand the in-situ stress conditions, pressure required for hydraulic fracking, type of fractures set generated and its orientation.
- Environmental impact assessment study should be conducted by Environmental Protection Agency to ensure that there is no harmful influence of hydraulic fracking on ecology.
- Government with help of Petroleum industry should provide financial and technical support to research scholars and institutes to encourage their capabilities, accommodate the growing energy demands and future energy challenges because the Shale oil policy could be a global gam changer in the long run.

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