Characterization of Hydrocarbon Potential in Lower Goru sands of Badin Block utilizing Advanced Geophysical Applications

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(2018-2020)

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CERTIFICATE

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Dedication

Dedicated To My Beloved Parents and My Supportive Teachers

Acknowledgement

First and foremost, I am deeply grateful to Almighty Allah who gave me the strength to complete my work with determination and fortitude. His countless blessings and favors eased out my work and gave me the aptitude to do this research with purpose and produced meaningful results. This thesis appears in its current form due to the assistance and guidance of several people. It gives me great pleasure to express my gratitude to all those who supported me and have contributed in making this thesis possible.

I express my profound sense of reverence to **Dr. Aamir Ali** who gave me the opportunity to work under his supervision. His continuous support, motivation and untiring guidance have made this thesis possible. His vast knowledge and calm nature motivated me to starve for pleasant results. Thanks to him for bearing my mistakes and whenever I could not meet the deadlines.

Besides my supervisor, I am thankful to my respectable seniors *Rehmat Ali, Aliya bibi and Yawar Amin* for their cooperation and guidance during this work. I am extremely thankful to all of my teachers for their prayers and encouragement and my special appreciation to my family who indirectly contributed in this research.

Maryam Mazhar
(MPhil 2018-2020)

Abstract

Seismic interpretation is a necessary tool for demarcation of oil/ gas reservoir which is the primary step for extraction of hydrocarbons. This tool however lacks the analysis power of characterization of the rock and is dependent upon other procedures to carry out that task. Analysis of AVO data is one such procedure which provides a variation of rock property, the Reflection coefficient at interface, with angle. This variation with angle provides important information about the characteristics of the reservoir under observation in terms of enclosed gas. In context of AVO analysis, fluid substitution technique is convenient in modeling various possible subsurface scenarios which could be studied in comparison with the insitu conditions of the well for further analysis of the reservoir.

The study focuses on integrated analysis of Lower Goru reservoir in Badin area, Lower Indus Basin using demarcation of the reservoir, structural interpretation of the locality, petrophysical parameter estimation, fluid substitution modeling and AVO analysis. Gassmann's method was utilized for fluid substitution while Aki and Richards approximation aided with estimated elastic parameters for each scenario gave the AVO curve for the respective scenario.

The Lower Goru formation within the Badin block was marked using 3D seismic cube correlated with Buzdar South–01 well. The faults marked were of normal nature, formed under extensional forces, enclosing horst and graben structures within the region. Petrophysical parameter estimation of the Buzdar South – 01 well showed favorable effective porosity of 16 % and a hydrocarbon saturation of 91 % for the zone of interest marked within the Lower Goru formation. Gassmann's equation used for elastic parameter estimation for multiple scenarios using fluid substitution resulted in progressive underestimation in P wave velocity (Vp) and S wave velocity (Vs) for a comparative increase in water saturation levels (30% to 100%) with respect to the insitu condition while an increase in density was observed.

AVO curves generated for the selected scenarios showed a decreasing RC response with increasing angle, a positive intercept value and a negatively sloping gradient. Intercept vs gradient cross-plot showed an increasing intercept values for increasing saturation levels ranging from 0.02 in case of 30% Sw to 0.05 in case of 100% Sw. The curves analyzed therefore confirmed the marked zone of interest to lie within the Class I sands.

The unavailability of the pre-stacked data caused the research to halt at synthetic generation of AVO models for multiple saturation scenarios. A further research could be carried out for inverting the parameters under observation for the whole seismic cube via geostatistical correlation between the generated synthetics using AVO modeling and a pre-stacked data for the study area.

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Chapter 1

Introduction

1.1 General Statement

The extraction of hydrocarbons from several sedimentary basins acts a foundation for the economy of any country specially developing country like Pakistan. With increasing population, energy demands are aslo increasing day by day, thus the exploration sector explore the new energy sources to meet the country's need. To recognize and foresee the hydrocarbons there is a useful technique named, Seismic method. It is very useful method to identify the effective properties and monitor the subsurface reservoir (Chopra, 2005)

While seismic interpretation is vital to pin point any reservoir, it still remains a seemingly simple technique which lacks the multidimensional characterization faculty. The method is further simplified under the processing technique of stacking which, although facilitates the accurate horizon projection on the data, takes away the response of wave at intersection with an interface under the influence of angular variation. Amplitude versus offset therefore is a key tool for any geophysicist to move a step ahead in characterization of the subsurface zone of interest. Through this modeling system, interpretation of the wave response for angular intersection with an interface becomes possible. The fact that the input variables can be varied in an attempt at inverse modeling of the earth makes AVO modeling even more desirable (Chopra and Castagna, 2014).

The study area (Badin) is the part of Lower Indus Basin, which is the principal hydrocarbon producing basin in Pakistan (Munir et al., 2014). The various structural ups and downs (horst and graben) geometry in the study area is authenticated by seismic interpretation. The key structures for the production of hydrocarbons are grabens (Munir et al., 2014). Petrophysics is an important technique, which thoroughly analyze the geophysical and geological analysis of an area. Gassmann's fluid substitution is performed for fluid identification.

The number of small oil fields are present in the mature Badin block which renders for about 50% contemporary oil production of Pakistan. Inclusively the number of wells that have been drilled in the area are 220 (Karagül et al., 2004). Various studies were executed to characterize and quantify the reservoir properties of Badin block based on petrophysical analysis, structural interpretation, f-xy filtering technique, unconventional analysis ((Munir et al., 2014; Taimur et al., 2019; Aziz et al., 2018) but no one applied the Gassmann's fluid substitution model to analyze the reservoir production. This study approximates the AVO analysis and modeling using different rock physics templates.

To identify the reservoir's position and other mechanisms like trapping, structural features etc, the seismic data must be interpreted. Seismic interpretation helps to identify the geological/structural and stratigraphic picture of the subsurface to locate prospects for drilling new exploratory wells (Stoker et al., 1997). It involves identifying proper geologic structures (i.e. orientation of faults, information about reflections i.e. horizons and depositional settings) for likely hydrocarbon accumulation. By using seismic data seismic interpretation is the paramount process in geophysics to ascertain the subsurface information (Cofeen,1986). After interpretation previous tectonic history and depositional information can be understood.

Well logging is the governing tool which helps to find the petrophysical properties. For the identification of different pay zones the petrophysical analysis has the fundamental importance (Das et al., 2017)The reservoir properties like (porosity, water saturation, volume of shale and hydrocarbon saturation) are estimated. It basically helps to delineate the hydrocarbon bearing zones, evaluate fluids in the reservoir and gives information about physical properties i.e. lithology, density, velocity and resistivity (Munir et al., 2014)

The reservoirs are further analyzed with the help of AVO analysis and modeling using different rock physics templates. Amplitude variation with offset commonly known as the AVO analysis is a tool used to identify the gas reservoirs and their type. Amplitude of seismic data must be preserved during AVO modeling (Ostrander, 1984). In this research it is analyzed that how intercept-gradient attributes and amplitude versus offset/angle plots can help in classification of different types of reservoirs. It helps in separating the productive and non-productive zones. Gassmann's fluid substitution is used to analyze the gathers at different saturations. AVO synthetics evaluated for different fluid saturations helps in identification of gas and brine saturation directly from seismic data.

1.2 Objectives

The main purposes of this dissertation are as following:

- Detailed seismic analysis for the identification and delineation of possible hydrocarbon traps and prospective zones.
- Wireline log analysis in order to estimate the important reservoir characterization.
- Amplitude versus Offset (AVO) modeling at different saturation levels to analyze the reservoir performance.

1.3 Data used

The study area is a three dimensional (3D) seismic cube and well data of Badin Block. The well provided is Buzdar South-01 which is drilled in the Badin Block uptill the Lower Guru Formation in Lower Indus Basin of Pakistan. The upstream Exploration and Production companies utilizes the 3-D Seismic Data for better visualization of the subsurface and importantly increased signal to noise ratio. (Gaarenstroom, 1984). The target formation in the area is the Lower Goru Formaton of Cretaceous age. The Badin block in the Lower Indus Basin, 160 km away from the East of Karachi (Munir et al., 2014; Alam et al., 2002) having Latitude ($24^o5'$ N to 25^o $25'$ N) and Longitude (68^o $21'$ E to 69^o $20'$ E). The data used for the study was provided by DGPC (Directorate General of Petroleum Concessions).

1.4 Brief Methodology

The primary motive is to apply different geophysical techniques to demarcate the petroleum plays of the study area in terms of prospects. The methodology that is followed in research work is shown in Fig 1.1. The workflow followed of research work is discussed below.

The first chapter is the complete analysis of the whole research work and provided data set. To better understand the seismic data interpretation second chapter narrates the geological importance and tectonic history of the area. Then third chapter is seismic interpretation in which favorable structures are marked to understand the petroleum play and probable one for hydrocarbon accumulation. The petrophysical analysis is executed by using well data. For fluid documentation Gassmann fluid substitution is performed.

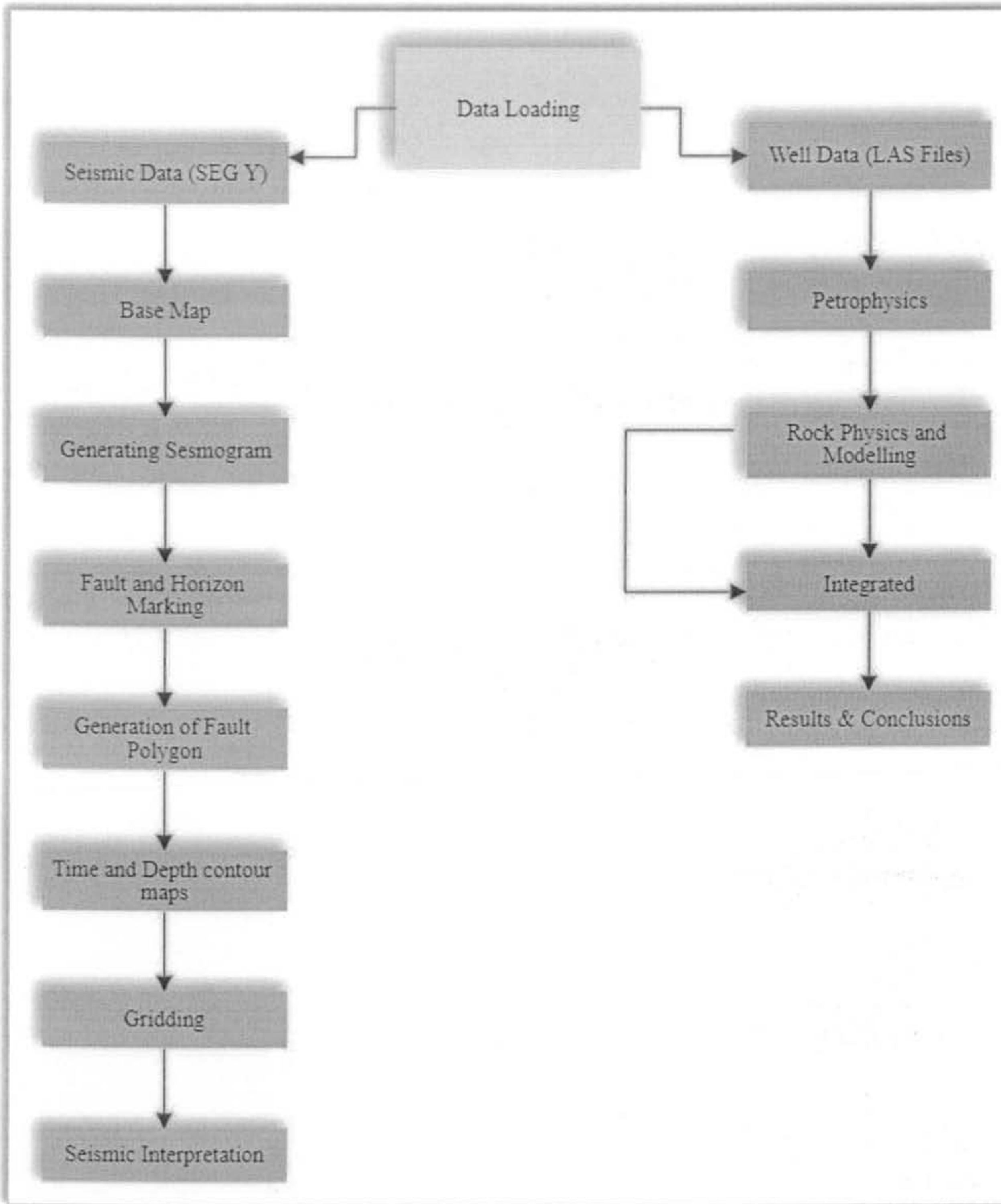

Figure 1.1: Flowchart of the research work.

Chapter 2

General Geology and Stratigraphy

2.1 Introduction

Concerning different geological histories and petroleum plays, Pakistan has three main basins, Indus Basin (part of Gondwana), Balochistan Basin and Kakar Khorasan. We are interested in the Indus Basin which is segregated into Upper IB and Lower IB. Upper Indus basin is segmented into Potwar Basin and Kohat Sub-Basin. Our point of interest i.e. the Lower Indus Basin is subdivided into Central and Southern Indus Basin. Moreover the Lower Indus Basin comprises of Punjab platform, Kirthar Foredeep, Belt of Kirthar and Indus Offshore (Kadri, 1995)

Our area of interest lies in the district of East Badin with the geographic coordinates (Latitude 24^{o} 5′ N to 25^{o} 25′ N: Longitude 68^{o} 21′E to 69^{o}20′ E) in the province of Sindh, Pakistan. Hyderabad lies towards the North Side of this, Raan of Kutch and Arabian Sea are in the Southern part. In the east lies Mirpurkhas and Tharparker and towards the west is districts of Thatta and Hyderabad (Munir et al., 2014).

2.2 Structural and tectonic setting of badin area

Due to the widespread tectonic activity in Cretaceous time the rift zone is formed in Lower Indus Basin. ((Farah et al., 1984; Gnos et al., 1997; Mahoney, 1988). So the Badin rift forms the Sargodha high which is then responsible for the division of Indus Basin into Upper and Lower Indus basin (Kadri, 1995). The result of rifting is seen in the form of horst and graben structures in the area (Alam et al., 2002). The area was majorly apart in terms of distance from the main tectonic zone, so the rate of deformation was almost negligible. It increases westward thus the Badin area which lies in the eastern part of Lower Indus basin is dominated by Normal Faulting. In Badin block the hydrocarbons are trapped by fault related traps in Lower Goru Sandstone (Farah et al.,1984 ; Kemal, 1991; Ebdon et al., 2004). The tectonic setting of Pakistan is shown in Fig 2.1 below.

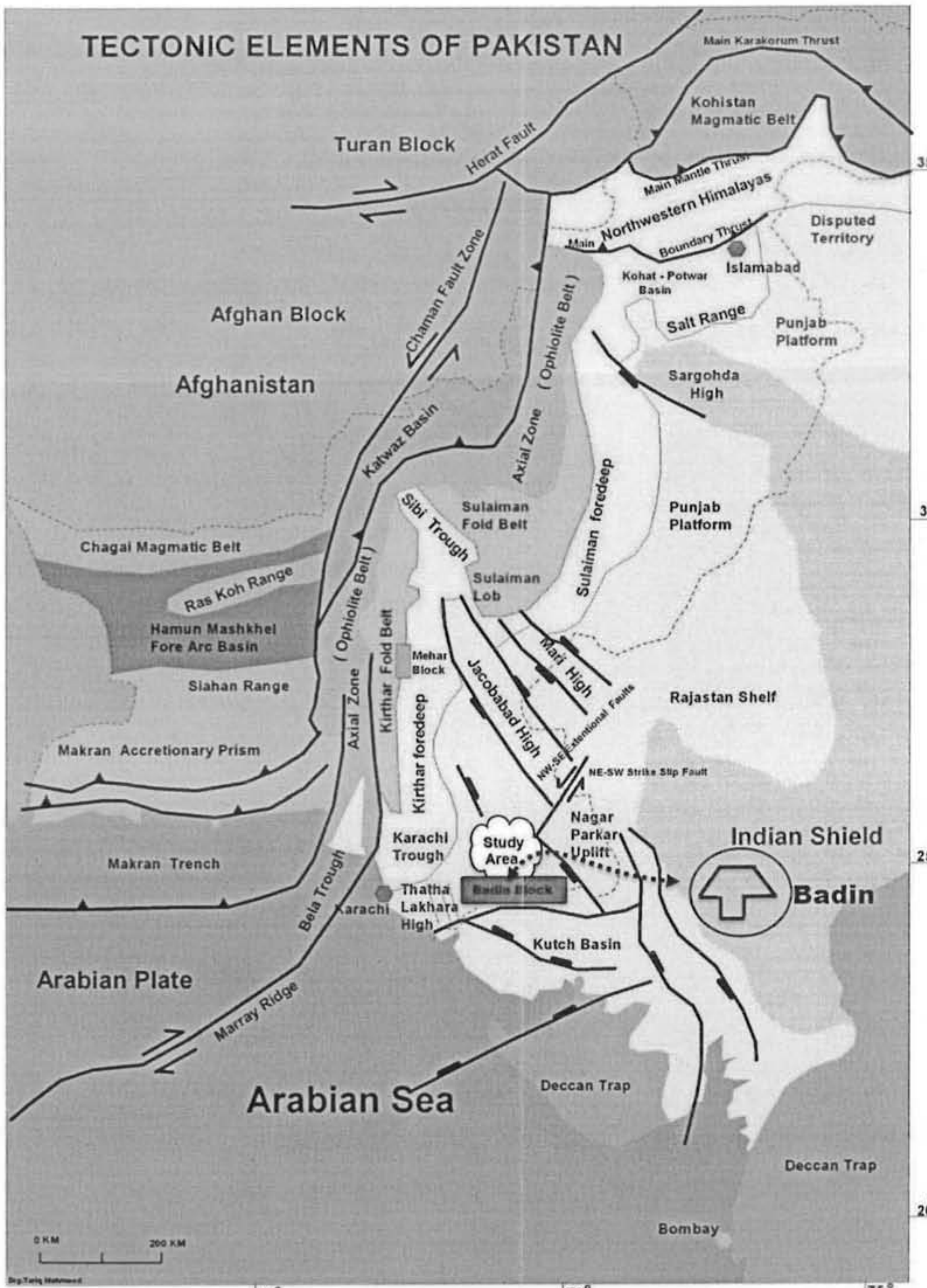

Figure 2.1: Map shows geological and tectonic setting of Pakistan marked by the coordinates (Ali et al., 2019)

2.3 Stratigraphy of the region

The stratigraphic chart is displayed below in the Fig 2.2. According to (Alam et al., 2002) this chart exhibits the age of rocks is ranging from Jurassic to Tertiary age. The Triassic sequence lies above the Jurassic age Chiltan Limestone. The early createceaus sequence comprises of Sembar Formation in the lower most part containing beds of shale with high organic content (610 m thick) lies above the Jurassic sequence. Above the Sembar formation there lies the major source rock i.e. Lower Goru Formation. Lower Goru is additionally sub-divided into five major sub-units in the manner that the Sembar formation is overlain by Lower Basal sands. Lower shale overlies Basal sand, Lower shale underlies Middle sand, while the Upper shale which is the fifth unit lies in between the Middle and Upper sand of Lower Goru formation. Upper sand is observed as the best reservoir in Lower Indus basin, having the shallow marine to deltaic depositional environment (Alam et al., 2002).

2.4 Petroleum Play

The information about seal mechanism and source reservoir of the study area is provided by petroleum plays. It is basically a bunch of prospects in the same region that is governed by same geological environment. In hydrocarbon buildups, petroleum plays have a powerful role.

2.4.1 Source rocks

The shale of Sembar formation consisting shales of Cretaceous Age is considered to be the source rock in Middle Indus and Lower and basins having considerate lateral and vertical extensions and fair amount of Total Organic Content (TOC) throughout the basins (Aziz et al., 2018)

2.4.2 Reservoir Rocks

Lower Goru at the same time acts as source and reservoir but is primarily an exceptional reservoir from Cetaceous era. Basal sand, Middle sand and Upper sand are the units in Lower Goru which acts as reservoir (Alam et al., 2002). Chiltan limestone of Jurassic, Paleocene and Eocene formations may have hydrocarbon targets (Zaigham, 2000).

2.4.3 Cap Rocks

Sembar formation, Laki-Ghaij, Bara-Lakhra and Kirthar formation in Southern part acts as seal (Zaigham, 2000). Lower Goru formation is also like Upper Goru having interbedded shales act as primary productive seal bith vertically and laterally (Kadri, 1995).

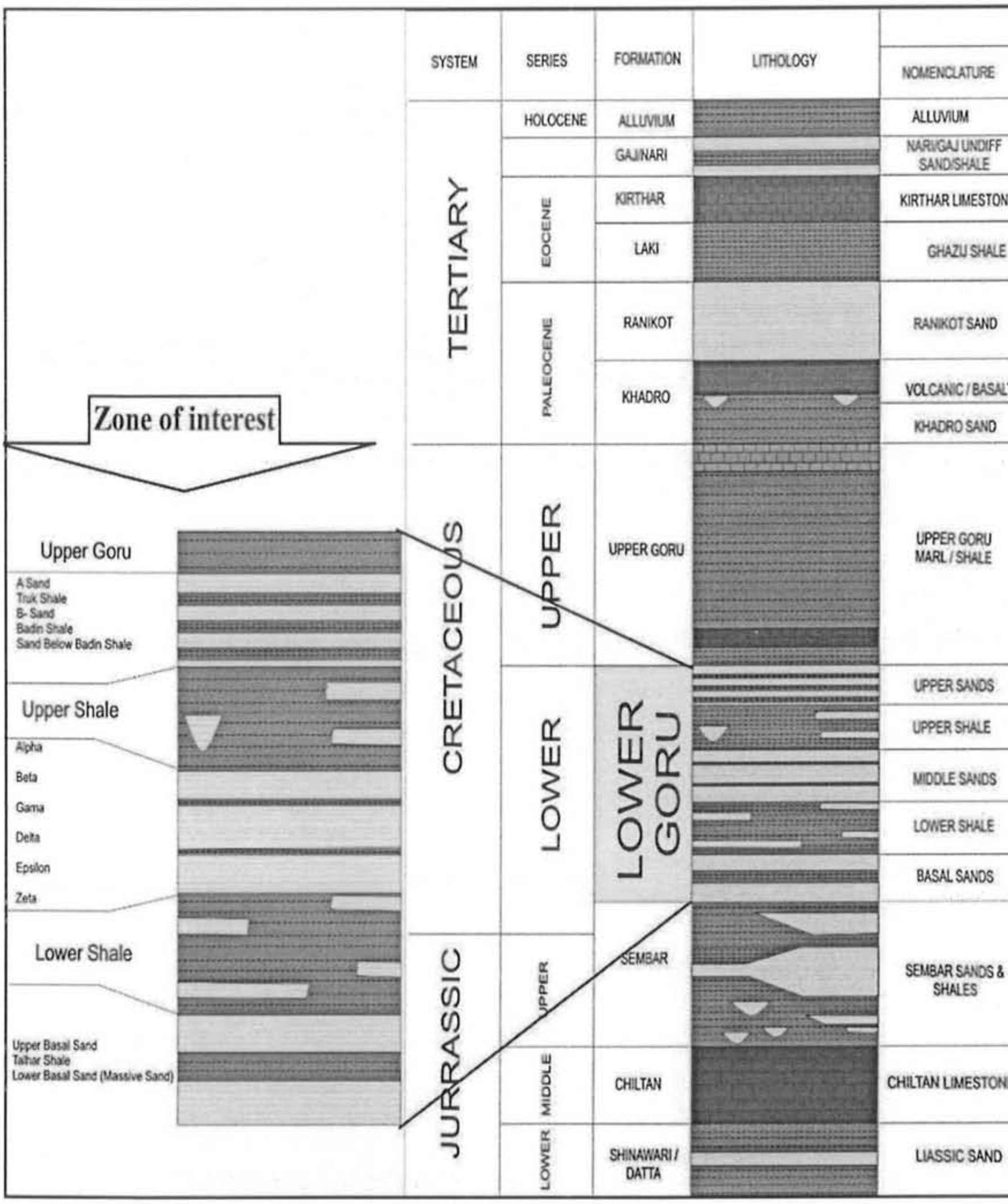

Figure 2.2: Generalized Stratigraphic Chart of Lower Indus Basin (Kazmi and Abbasi, 1997)

2.5 Confirmation of structure through seismic interpretation

To identify the structural traps is also very crucial and important step as many producing fields have been discovered on the termination of normal faults (Chillingar,1982). For hydrocarbon accession, structures evolved in different tectonic frameworks are of prime importance (Harding, 1979; Rollinson et al., 2014; Munir et al., 2014). For discovering new oil and gas reserves in the study area tectonic progression's well apprehension is required. So to unravel the evolution of structures, seismic data interpretation is used (Cooper ,2008). Due to extensional regime, normal faulting is present in Badin block (study area) and it is also confirmed through the seismic interpretation of the data. The geology and seismic sections are interconnected retaining interpretation's significance (Stoker et al., 1997) Faults not only gives the trapping mechanism but also helps hydrocarbons to migrate from source to reservoir rocks (Munir et al., 2014). Fig 2.3 shows the seismic section of inline 637 confirming geology.

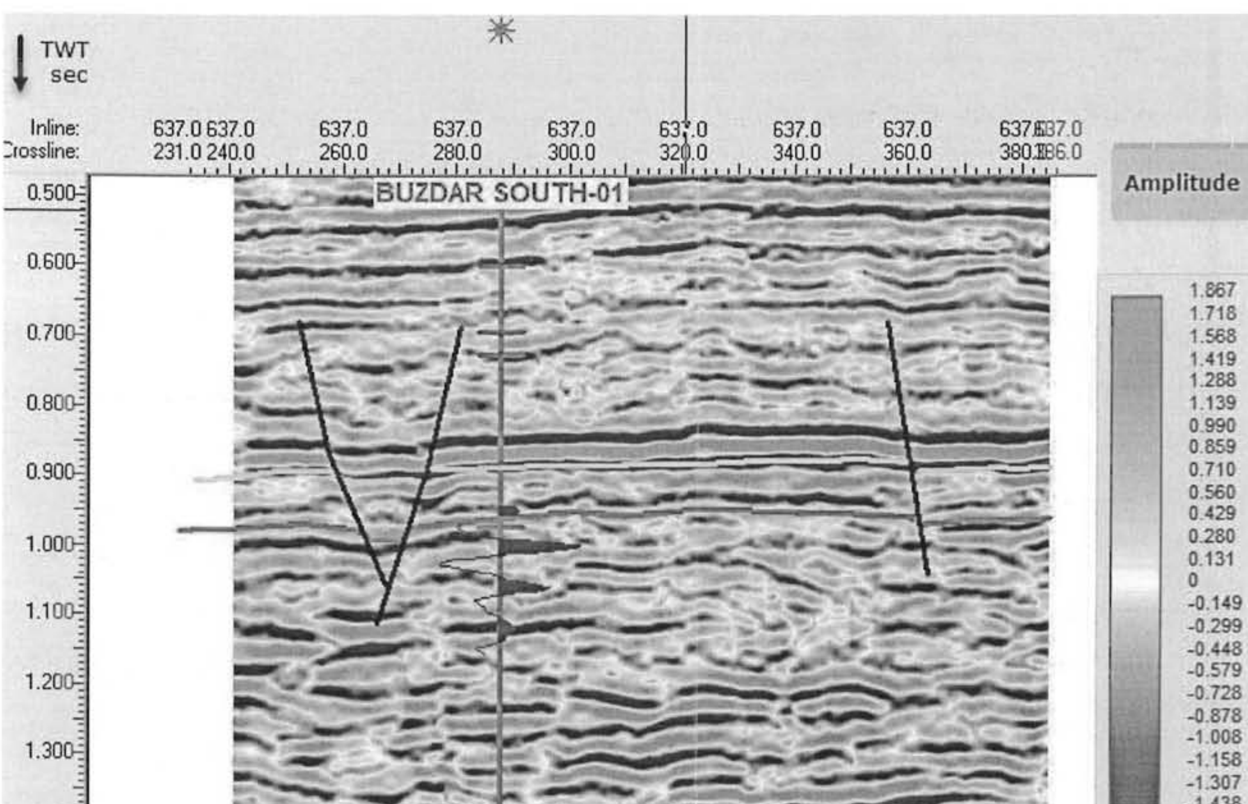

Figure 2.3: Seismic section of inline 637 affirming geology of the area.

Chapter 3

Seismic Interpretation

3.1 Introduction

The science of concluding the geology at some depth from seismic record is seismic interpretation. Three dimensional (3D) seismic interpretation have various benefits to oil and gas exploration concerning interpreting subsurface features. 3D seismic is the very powerful tool in seismic, characterizing the hydrocarbon potential zones (Admasu, 2006; Aurnhammer, 2000). The information about the hydrocarbon presence is provided by the structural and stratigraphic interpretations (Coffeen, 1978). For a better interpretation the interpreters must have a strong geological understanding of the area so that they could pick the most predictable interpretation from different insightful interpretations that the data allow (Robinson and Coruh, 1988)

3D seismic data have almost higher resolution than the 2D seismic data. It is more reliable in a manner that it directly describes the problems regarding exploration, production and development to develop seismic stratigraphic workflows. (Paumard et al., 2019). The first step in interpretation is to mark the prominent reflectors. Reflector is basically Horizon, which is the boundary between two rock units. Reflections are being marked and mapped on seismic to delineate the subsurface structure and hydrocarbon potential of the area. If the target horizon is not prominent then the above and below horizons are being picked to reach that target horizon later (Yilmaz, 2001). Sometimes it is possible that the reflector smoothly continuing over a fault into another reflector. Thus, to reduce the incorrect interpretation, the fault surface should be known (Bakker, 2002)

Interpretation of the seismic data involves three categories lithologic, structural and stratigraphic. Lithologic interpretation finds the fractures identification, fluid porosity and lithology and much more from seismic data. The structural traps are found from structural interpretation which hold the hydrocarbons. In the subsurface different structural styles like horst and graben, duplexes, flower structures, pop-up structures and growth faults are present (Pennock et al., 1989). The aim of structural interpretation is to locate the potential zones to extract the hydrocarbons. Stratigraphic analysis gives episodic depositional events. New techniques for interpretation and mapping used to intensify the structural interpretation (Bouvier et al., 1989)

In seismic interpretation there are also some drawbacks which fall into three categories; velocity, geometry and recording and processing.Velocity pitfalls causes apparent interval changes on seismic section. Geometry pitfalls include sideswipes, diffractions. The third category includes distortion and other factors (Tucker, 1979). New techniques for interpretation and mapping used to intensify the structural interpretation (Bouvier et al., 1989)

3.2 Methodology

The data is loaded in SEG-Y format in Kingdom suit with the help of navigation files. The wells are loaded in LAS format. Seismic events are tied with formation tops with the help of synthetic seismogram (Bacon et al., 2017). Synthetic is generated by convolving source wavelet with reflection coefficient. It uses time-depth (TD) chart and gives information of depth along with time, So the horizons depth can be estimated on its specific time from seismic data. Ultimately horizons can be marked. Upper Goru and Lower Goru are picked on seismic section at each 10 line interval. Synthetic Seismogram is generated for Buzdar South-01.

Nevertheless, as study area lies is prone to an extensional regime so normal faults are present which are supplemented with horst and graben structures. Then the grids are generated after faults and horizons picking. Lastly, the time and depth contour maps are generated. The workflow is shown in Fig 3.1.

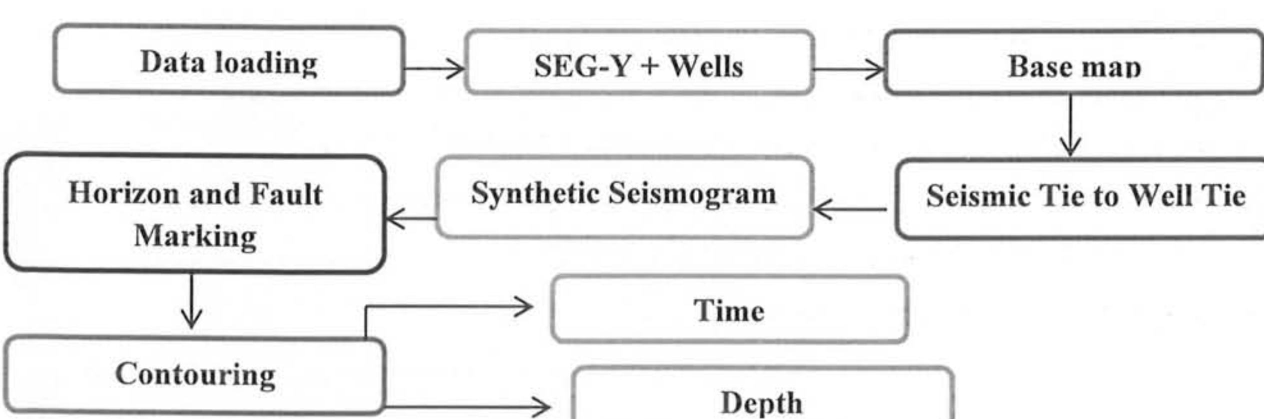

Figure 3.1: Schematic Workflow followed for seismic interpretation.

3.3 Detailed seismic interpretation analysis

3.3.1 Base map

Base map shows detailed information regarding the well locations, in-lines and cross-lines of the area under study. With respect to its geographical references i.e. latitude and longitude it comprises of a 3D cube. Base map is created with **SEG-Y** and navigation files of the seismic lines is imported in the Kingdom Suit. **LAS** format is used for loading the wells. The Fig 3.2 shows the base map of Badin area. The well named **Buzdar South-01** is used for interpretation.

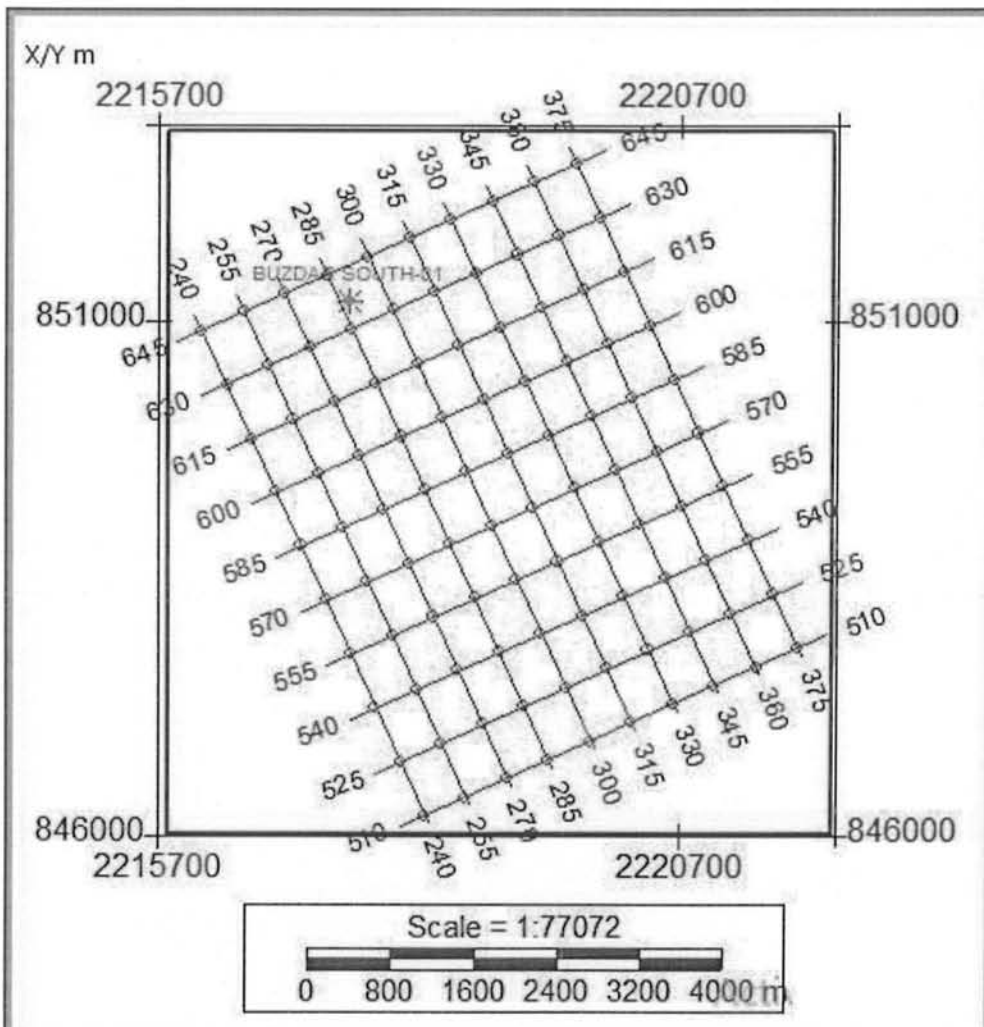

Figure 3.2: Base map highlighting the study area

3.3.2 Seismic tie to well tie

To match wells position with seismic line precisely, the idea was proposed by (White and Simm, 2003) and implemented to all seismic line data. Mis-tie analysis have been done for all the seismic lines and removed to match wells and seismic position. Seismic to well tie has been done by using standard practices.

3.3.3 Synthetic seismogram

Synthetic trace is generated by convolving wavelet with reflection coefficient. Reflection coefficient is produced using sonic transit time (DT) and density (RHOB) logs available in well data. Source wavelet was generated using the seismic line having well located on it. Sonic log gives delay time and its inverse is velocity which is multiplied with density to yield acoustic impedance series. This acoustic impedance will create the reflection series. Synthetic seismogram is important to tie horizons information on seismic key profiles. It used time-depth chart and eventually gives information of depth along with time. Synthetic Seismogram for Buzdar South-01 is shown below in Fig 3.3.

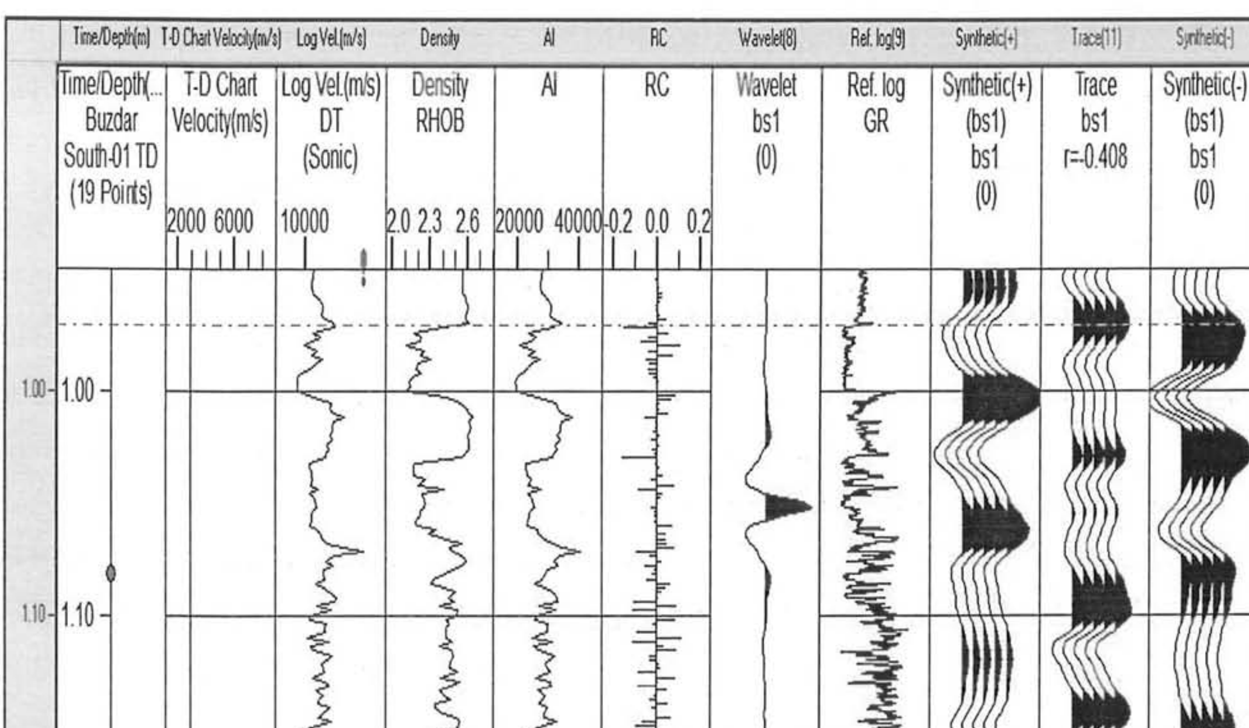

Figure 3.3: Synthetic seismogram of the study area in Well Buzdar South-01

3.3.4 Horizon and fault marking

The target horizons Lower Goru and Upper Goru are marked using synthetic seismogram. Upper Goru is marked at TWT~0.9 sec and Lower Goru sand is marked at 0.98 sec. After each ten line interval horizons are marked throughout the seismic data. The study area i.e Badin lies in Lower Indus basin so normal faulting is observed on seismic section. Three faults named F1, F2 and F3 are marked from left to right respectively. **Fault polygon** has been drawn in order to foresee the fault's regional trend. The Fig 3.4 shows horizons and faults.

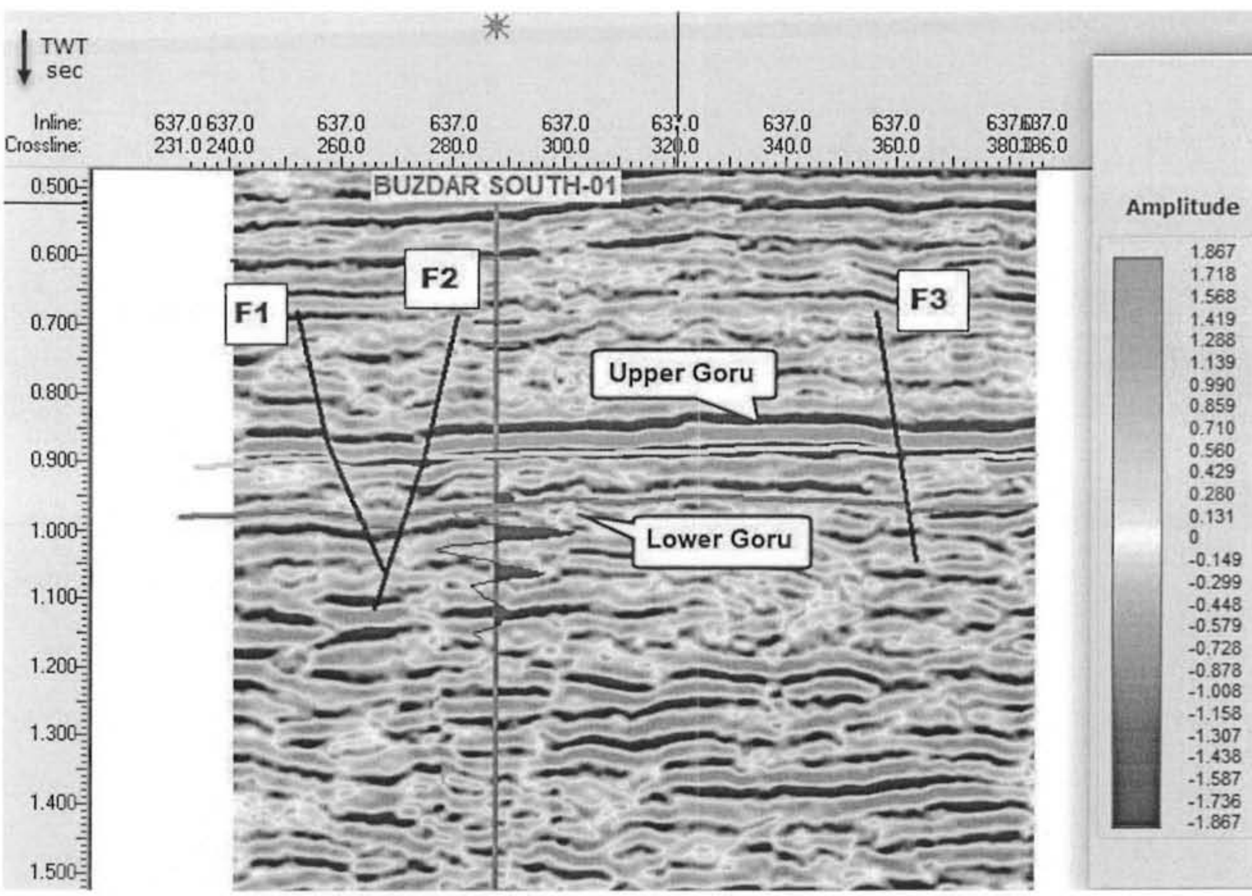

Figure 3.4: Interpretation of seismic section of inline 637

3.3.5 Contouring

Depositional geometry and structural movements of geologic features is demonstrated by seismic contours. After horizons and faults are picked and the next stage is to generate contours related to depth and time. Time grid was created through the time contours and by using TD chart, velocity is multiplied to get the depth grid.

3.3.5.1.1 Time contour map

Time contours for Upper and Lower Goru have been mapped by taking the time window in which the reservoir lies. Time contour maps give the reliable picture of the subsurface geological structures. Due to extensional regime all the faults are normal. Faults are trending from NW-SE. Minimum time values are depicts the lower depth levels which represents the horst block and vice versa representing graben. Lower Goru is the potential reservoir in the study area. Fig 3.5. shows the Lower Goru formation's Time Contour Map

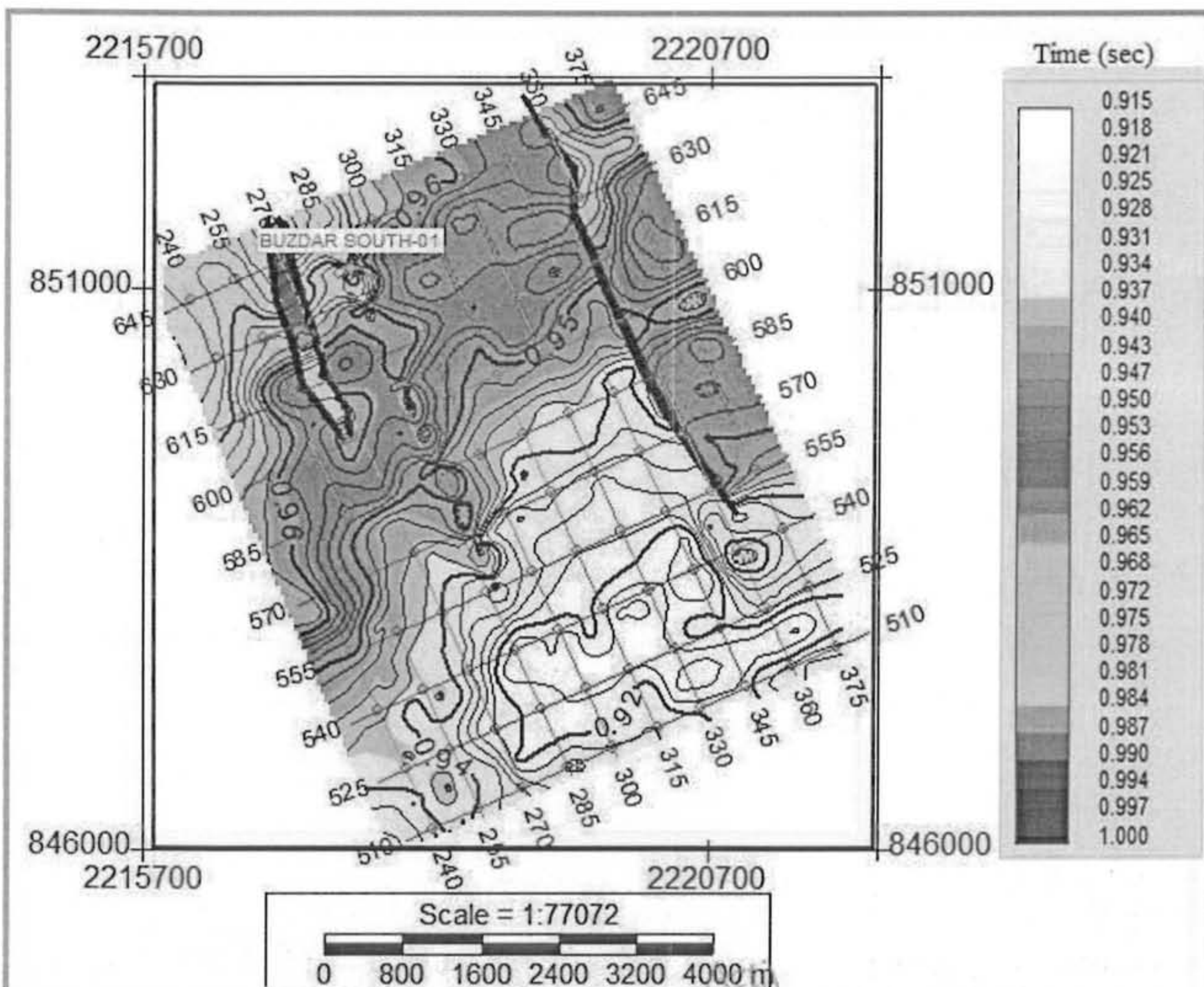

Figure 3.5: Time-contour map Of Lower Goru formation

3.3.5.2 Depth Contour map

Depth contour map shows the horizon depth variation. Depth contour maps have been created by using shared time-depth chart.

Depth contour map of lower goru formation is displayed in Fig 3.6. It can easily be interpreted that horizon is forming a horst and graben structures, as central portion between fault polygons is deepest in depth than the surrounding area. It also be noted that that there is no change in pattern of time and depth contours because variation is same either with time or with depth.

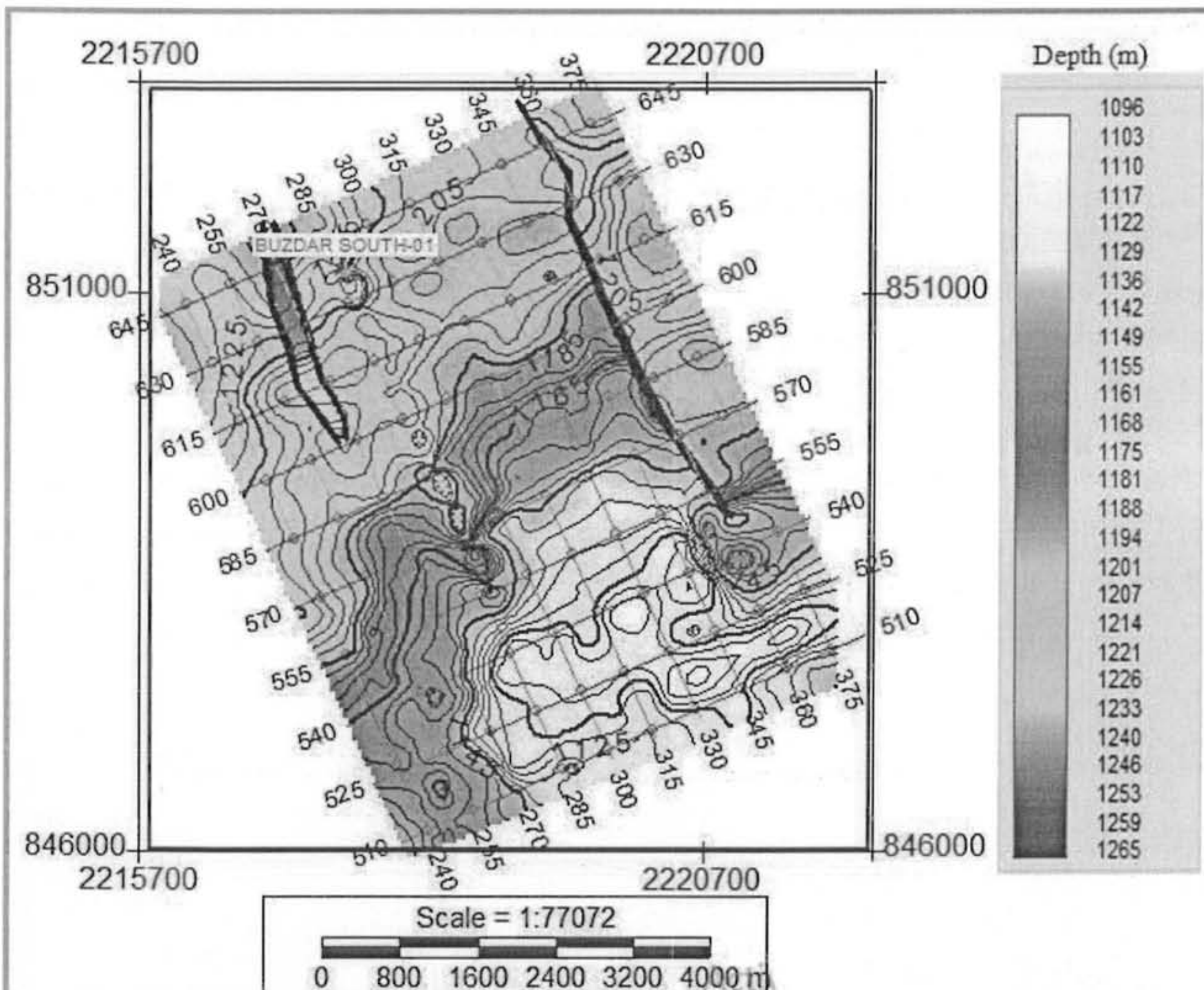

Figure 3.6: Lower Goru formation's depth contour map

Chapter 4

Petrophysics

4.1 Introduction

The physical properties of the rocks are analyzed through Petrophysics and their interaction with fluid content (Archie, 1950). It discusses the pore system, pore geometry, incorporation of fluid and its flow within the reservoir. The evaluation of reservoir hydrocarbon potential, its quality, hydrocarbon rich source, seal description and aquifers is done by petrophysics. Lithology, density, velocity, permeability and resistivity are the physical properties. Petrophysical tools helps to calculate the contact of fluid with physical properties to evaluate the lithology, porosity, volume of shale, water and hydrocarbon saturation within rock matrix (Rider, 2002).

The application of petrophysical relations of limestone to field is tough than sandstones due to the non-uniformity and dense limestone accumulation. It makes well logging interpretation burdensome (Archie, 1952). Lower Goru is the potential reservoir in the study area. With the help of petrophysics one can relate the fluid and matrix properties within the reservoir (Asquith et al., 2004). Figure 4.1 shows the well log interpretation workflow,

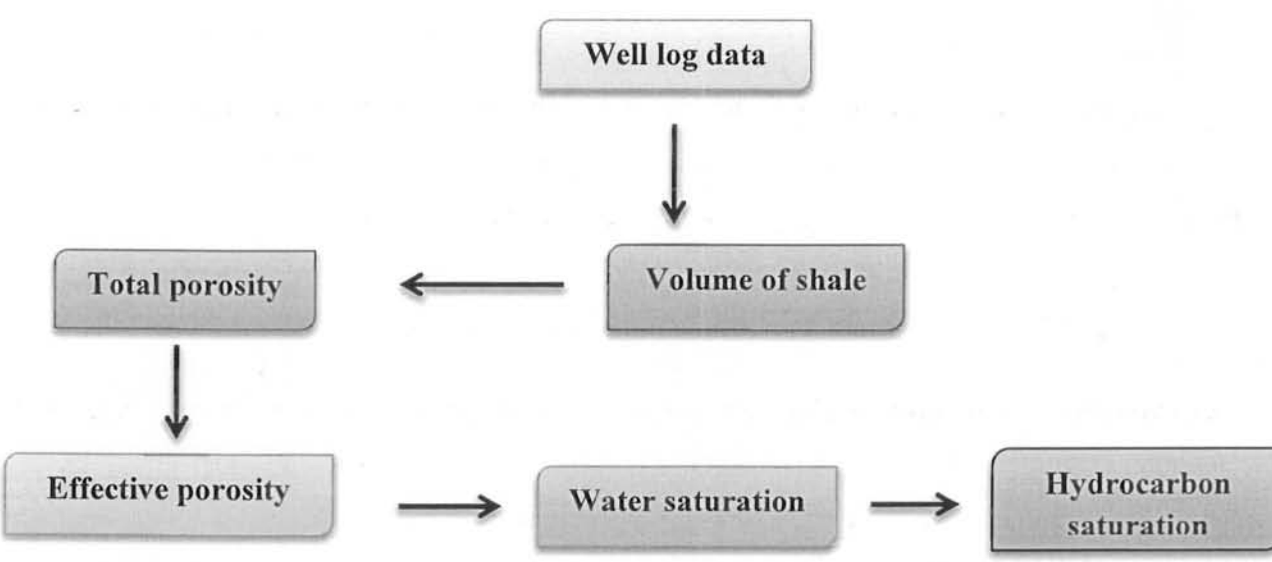

Figure 4.1: Well log interpretation workflow

4.2 Petrophysical analysis

A thorough petrophysical study has been done for the Badin area. Well log data of Buzdar South-01 is used for this purpose. To find the effective properties various logs are used like Caliper, Density *(RHOB),* Gamma Ray (*GR*) log, Spontaneous Potential *(SP)* log, shallow resistivity *(LLS)* log, latero log deep *(LLD),* Neutron and Sonic logs (Zemke et al, 2010). Following parameters are calculated from these logs;

- Volume of shale (V_{sh})
- Effective porosity (φ_{eff})
- Total Porosity (φ_T)
- Water saturation (S_w)
- Hydrocarbon saturation (S_h)

The geophysical logs are categorized into the following three different tracks;

- Lithology track
- Resistivity track
- Porosity track

4.3 Lithology track

Caliper log is used to estimate the bore size and geometry. By describing different conditions of log pattern caliper log identifies the lithology. The variation in the diameter of borehole is due to the formation of mudcake and washout which effects the log measurements (Bjorlykke et al, 2010). If the caliper log shows straight response then it means there is clean reservoir formation.

GR log finds the radioactivity in rock formation. GR log also finds the lithology (i.e shale ,non-shale) to calculate the V_{sh} (Rider, 2002). Volume of shale can be computed by the following formula,

$$V_{sh} = \frac{GR\ log - Grmin}{GR\ max - GRmin}\ , \qquad (4.1)$$

where, $GR\ max$ is the maximum value of GR log, $GRmin$ is the minimum value and $GR\ log$ is the gamma ray log.

Spectral Gamma ray log (SGR) records the response of each radioactive element (U, Th and K) whereas bulk gamma ray log gives the combined response of each element. It measures the radiation in units of 'counts' or API. The interpretation of $GR\ log$ is based on the lows and highs of the count rates of radiation. It means that a rock formation having fine layered material e.g clay or shale indicates relatively a high GR values than that from sand/limestone (Schlumberger, 1974).

SP log provides information that defines the reservoir and non-reservoir rocks unit lithology in the subsurface. Clay and/or shale are fine grained formations having low permeability so no current flows and hence have low SP values. Whereas, limestone, sandstone and dolomite have high SP values as they are permeable and course grained formations. SP log also used to calculate resistivity of water (Rw) (Schlumberger, 1974).

4.4 Resistivity track

Resistivity track generally displayed the following three logs;

- Latero log Deep
- Microspherically focused log
- Latero log shallow

LLD have greater depth of penetration as compared to *LLS*. It is incorporated in measuring the resistivity of mud filtrate (Rmf), whereas LLS has less depth of penetration. It is used to measure the resistivity of fluids present in invaded zone.

The presence of hydrocarbons is detected by the crossplot between the *LLD* and *LLS* of resistivity logs. Along with resistivity logs, other log responses are also important because sometimes both log responses (*LLD* and *LLS*) show zero crossplot between them but hydrocarbons may be present.

4.5 Porosity track

There are three logs which calculate the porosity information namely;

- Neutron porosity log *(NPHI)*
- Density log *(RHOB)*
- Sonic log *(DT)*

NPHI ***(*φ_N*)*** measures the hydrogen index and directly estimates the porosity. If the pore spaces have high hydrogen atoms then the $\varphi_N$value is high which is vice versa in case of hydrocarbons.

DT gives the measure of an interval transit time of compressional sound wave travel long through the rock strata in the subsurface. This log is both lithology as well as porosity dependant (George and Gibson,1982) .Sonic log uses an equation to calculate the porosity ,

$$\varphi_S = \frac{\Delta T_{log} - \Delta T_{mat}}{\Delta T_f - \Delta T_{mat}}, \qquad (4.2)$$

where, ΔT_{log} the interval-transit-time for sonic log, ΔT_{mat} is interval transit time for matrix and ΔT_f fluid's interval transit time.

RHOB used to calculate the density of rock formation. This log helps in lithology identification and quantitative measure of Total Organic Content (TOC). DT log uses the formula for calculating density,

$$\varphi_D = \frac{\rho_m}{\rho_m} - \frac{\rho_{log}}{\rho_f}, \qquad (4.3)$$

where, ρ_m is the density of matrix, ρ_{log} is the density from density log andρ_f is the density of the fluid.

4.6 Average Porosity

Average porosity is calculated by adding neutron porosity and density porosity values. It is calculated by

$$\varphi_T = \frac{\varphi_N + \varphi_D}{2}, \qquad (4.4)$$

where, φ_T is total porosity, φ_D is Density porosity and φ_N is neutron porosity (NPHI).

4.7 Effective porosity

The porosity of the interconnected pores is known as the effective porosity (PHIE). When the pores are interconnected the hydrocarbons accumulate.it is calculated by the following formula,

$$\varphi_{eff} = \varphi_T + V_{sh} \,, \tag{4.5}$$

4.8 Water Saturation

Reservoir rock composed of water saturation accompanying hydrocarbon saturation. The resistivity of water (Rw) for the well Buzdar South-01 is 0.03 ohm.m. Water saturation is estimated from the archie's formula given below

$$S_w = \sqrt[n]{\frac{F \times R_w}{R_t}} \quad , \tag{4.6}$$

where, R_w is the resistivity of water , R_t is the formation resistivity, n is the saturation component, F is the formation factor which is calculated using:

$$F = \frac{a}{\varphi^m} \,, \tag{4.7}$$

where, a is tortuosity factor, m is the cementation factor, φ is the effective porosity.

4.9 Hydrocarbon Saturation

The porous rock fraction filled with hydrocarbon is called hydrocarbon saturation. It is calculated by the formula,

$$S_h = 1 - S_w \,, \tag{4.8}$$

where, S_h is the hydrocarbon saturation and S_w is the water saturation.

4.10 Petrophysical analysis

In petrophysical analysis, the analysis of the physical properties of the rock and fluid present inside the rock is accomplished (Asquith et al., 2004). The thorough understanding of fluid, its identification and quantification in reservoir rocks is given by petrophysical analysis (Ali et al., 2014). The potential zones where hydrocarbons are present is known as the prospect. So the petrophysics is one of the fundamental approaches for the reservoir characterization (Cosgrove et al., 1998).

To extract the vital results or to identify the prospect and non-prospect zones the petrophysical results are integrated with rock physics. On account of the petrophysical results the reservoir is described (Daniel, 2003).

4.11 The petrophysical interpretation of the well Buzdar South-01

Petrophysical interpretation of the well Buzdar South-01 is performed by using the kingdom software. The Zone-01 is marked from depth 1255m to 1297m. The thickness of the one is 42 m. The petrophysical analysis shows that the value of GR is low that indicates the presence of sand in the area. Porosity and Resistivity are the best hydrocarbon indicators. Cross over of these two logs is a good indicator for prospective hydrocarbon zone. The separation between LLD and LLS is observed so that resistivity contrast is present. The zone shows high response of hydrocarbon saturation.

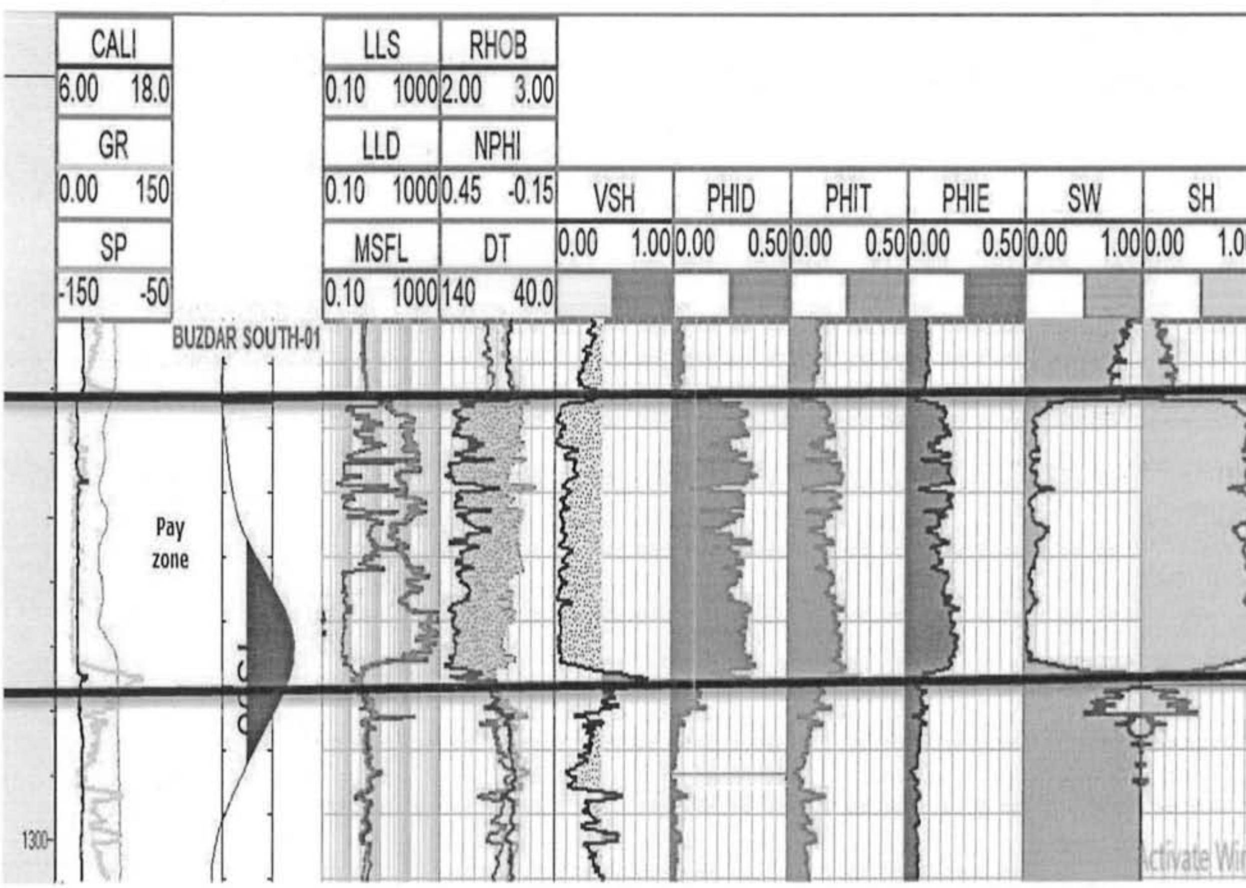

Figure 4.2: Petrophysical analysis of Buzdar South-01

4.12 Statistical analysis of petrophysical result

The table 4.1 shows the results of petrophysical analysis,

Zone	PHID (%)	PHIT (%)	PHIE (%)	Sw (%)	Shc (%)	Thickness (m)
01	27 %	18 %	16 %	9%	91 %	42 m

Table 4.1: Petrophysical results

Chapter 5

Fluid Substitution and AVO analysis

5.1 Introduction

The Rock Physics deals with the study of rock's physical properties (e.g. the velocity of P-wave (Vp), velocity of S-wave (Vs) and density (ρ)) and built mathematical links with their seismic responses. The mentioned properties are measured for any type of the underlying rocks and is then related with the rock's elastic moduli (i.e. bulk modulus K and shear modulus μ),porosity, fluid present in the pores, and with the temperature and pressure of that rock (Castagna et al., 2014)

Rock physics is used together with AVO analysis in order to make the quantitative interpretation, and precise hydrocarbon detection and allows us to identify the possible lithology. Seismic amplitudes at interface are effected by the difference of the physical properties just above and below the interfaces (Zhang and Brown, 2001). The dissimilarity in the seismic reflection amplitude due to angle obtained from the subsurface interfaces is contingent to the changes faced by both compressional/shear wave velocity and density (Poster and Buchan, 1991). However such changes are linked with the changes in, pore fluid contact, lithology, rock's porosity and pore pressure which effects the way the seismic waves propagate in the subsurface (Gregory, 1977; Castagna, 1993).

The exact and accurate interpretation necessitates how the seismic data and subsurface lithology are related together, other than the resolution of seismic and well data (Mavko et al., 2009). To demonstrate an appropriate association between underlying geology and seismic data using logs and a robust rock physics based approach is convened. Rock physics modeling acts as an upscaler for quantification. When porosity and water saturation changes it affects the seismic velocity, therefore, it allows us to see the effect of important parameters in seismic, as the density parameter remains unchanged over the same pack of lithology. Firstly, the model is developed for effective dry properties at the reservoir level using methods of T-matrix, Differential Effective Medium (DEM), NIA approximation and Backus averaging.

The goal as an exploration geophysicist is to identify the zones with economical quantity of hydrocarbons and it needs an improved complex model rather than a basic approach as subsurface geology is hetrogeneous, therefore, instead of dry pores or fractures, fluid is assumed in the dry porous media. Gassmann is used (for isotropic scenario) and Brown and Koringa is employed (for anisotropic scenario) and Woods equation caters for effective fluid properties. Figure 5.1 shows the rock physics workflow.

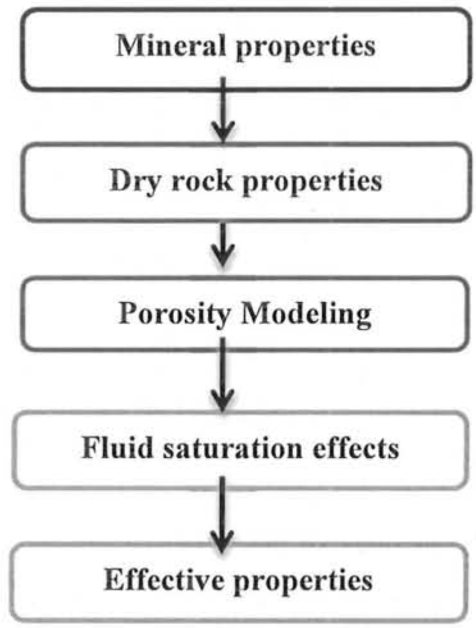

Figure 5.1: Workflow of Rock physics modeling

Petrophysical analysis is carried out to find the properties which helps in analyzing the different reservoir scenarios using Gassmann fluid substitution method at different saturation levels. AVO gathers were generated at different reservoir scenarios to predict the in-situ hydrocarbon bearing condition.

5.2 Fluid substitution approach

The method of fluid substitution is a pertinent part of rock physics analysis that offers a means for fluid identification and for quantification within a reservoir by using Gassmann equation. The estimation of the effect of the pore fluid on the elastic properties, the Gassmann fluid substitution approach was employed to model different scenarios and to make consistent estimates of Vp, Vs and density ρ, porosity and also get an indication of the sensitivity of the seismic response to the presence of gas or brine in the reservoir rock (Sule, 2014). By altering fluids percentage as compared to in-situ conditions new reservoir characterization were estimated because the fluids are substituted, and the response of the logs will be changed because of the changing rock density. For the identification and estimation of fluid, rock physics uses the best tool such as fluid substitution for catering this need. In fluid substitution technique Gassman equation plays the key role for the reservoir quantification and identification (Gassman, 1951).

The Gassman equation is used to evaluate the bulk modulus of an existing fluid which is saturated in a porous medium by finding the existing known moduli of the solid rock matrix, the pore fluid and also the framework. In the above three parameters the solid matrix refers the minerals which the rock is made of, frame refer to the skeleton of the rock and pore fluid represent the solution consisting of water, oil, gas or the combination of all these three fluids. There are few fundamental assumptions for the Gassman equation which are simply mention below.

1. The rock must be macroscopically homogeneous. Rock means matrix and frame both.
2. The pores inside the rock sample must be connected to one another.
3. Pores of the sample rock must be filled up from fluid such as (water, oil or gas or the mixture of any of these three fluids)
4. The rock system must be in undrained condition.
5. It should be kept in mind that the fluids which are present in the pores are not in such contact with the solid portion which may soften the rock or harden the rock.

5.2.1 Gassmann Equation

Gassmann equation is generally used to find the bulk modulus of a saturated rock. Thus to use the gassmann equation for the fluid substitution first observe the general Gassman equation which is given in the below equation (5.1)

$$K_{sat} = K_{frame} + \frac{\left(1-\frac{K_{frame}}{K_{matrix}}\right)^2}{\frac{\varphi}{K_{fl}}+\frac{(1-\varphi)}{K_{matrix}}+\frac{K_{frame}}{K^2{}_{matrix}}}, \tag{5.1}$$

where, φ is the porosity, $K_{sat}$is the bulk modulus of rock with fluids, K_{frame} is the bulk modulus of dry rock frames, K_{matrix} is the bulk modulus of mineral matrix(grain), K_{fl} bulk modulus of pore fluids (Gassmann, 1951).

In Gassmann equation shear modulus is constant because it is independent for the fluids. By using the wire line log's data such as velocity and density can be used to find out the shear modulus and bulk modulus first then vp and vs are estimated from the logs such as (DT4P and DT4S).

$$K_{sat} = \rho\left(Vp^2 - \frac{4}{3}Vs^2\right), \tag{5.2}$$

$$\mu = \rho Vs^2\ , \tag{5.3}$$

Now for a given reservoir situation and for the fluid type, we first estimate the saturated bulk modulus for which the bulk modulus of the matrix, frame and fluid present in the rock should be known. Bulk modulus, density and mineral properties are vital properties for fluid substitution therefore we study the following parameters.

- Matrix properties
- Pore fluid properties
- Frame properties

5.2.1.1 Matrix properties

For the estimation of bulk modulus of minerals the composition of the rock's mineral should be known. Three basic methods are well known to find the rock's mineral composition i.e. core sample/cuttings, laboratory data and lithology must be assumed (Kumar, 2006).

If the core data is available then the matrix properties can be easily determined from laboratory but due to limitation of core data, matrix properties were found from the available wireline log data (Smith et al., 2003). Nevertheless, the volume of shale is mostly determined by using log data (Gamma Log). Once the dominant mineral composition is estimated, then mineral matrix properties can be calculated by applying Voigt Ruess Hill (VRH) method (Hill, 1952). If there is no core and log data then it is anticipated that the lithology consists dominantly of quartz and clay mineral. In this research it was assumed that the lithology is composed of quartz and clay minerals while the other compositions are not being considered here.

For the estimation of $(K_{matrix})V_{sh}$, K_{cl} (Bulk Modulus of clay) and K_{qtz} (Bulk Modulus of quartz) are required which are put forward by Voigt-Ru1ess-Hill equation.

$$K_{matrix} = \frac{1}{2}\left(V_{cl}K_{cl} + V_{qtz}K_{qtz}\right) + \left\{\frac{V_{cl}}{K_{cl}} + \frac{V_{qtz}}{K_{qtz}}\right\}, \tag{5.4}$$

$$V_{qtz} = 1 - V_{cl} \quad , \tag{5.5}$$

where, V_{cl} is the volume of clay, V_{qtz} is the volume of quartz

Density of mineral is,

$$\rho_{matrix} = V_{cl}\rho_{cl} + V_{qtz}\rho_{qtz} \quad , \tag{5.6}$$

where, ρ_{cl} is the density of clay and ρ_{qtz} is the density of quartz.

5.2.1.2 Pore fluid properties

By taking average of the values of fluid types the bulk modulus and density of the pore fluid type i.e. oil, gas or brine can be determined. Thus here we have to estimate the properties for every fluid. Such properties are,

- Bulk modulus and density of brine
- Bulk modulus and density of oil
- Bulk modulus and density of oil

5.2.4.3 Matrix or frame properties

Frame bulk modulus can be estimated from the lab measurements, empirical formulas or wireline log data. The value of K_{frame}can be estimated by rewriting the Gassmann equation (Zhu & McMechan, 1990)

$$K_{frame} = \frac{K_{sat}\left(\frac{\varphi K_{matrix}}{K_{fl}}+1-\varphi\right)-K_{matrix}}{\frac{\varphi K_{matrix}}{K_{fl}}+\frac{K_{sat}}{K_{matrix}}-1-\varphi}, \tag{5.7}$$

K_{sat} and K_{matrix} are found from equations 5.2 and 5.4.

where , $\frac{1}{K_{fl}} = \frac{WS}{K_{brine}} + \frac{HS}{K_{hyc}}$, (5.8)

Here , WS is the water saturation and HS is the hydrocarbon saturation and is given by

$$HS = 1 - WS \tag{5.9}$$

In case of gas as hydrocarbon

$K_{hyc} = K_{gas}$; $\rho_{hyc} = \rho_{gas}$,

where,

K_{hyc} and K_{gas} are the bulk modulus of hydrocarbon and gas respectively.

ρ_{hyc} and ρ_{gas} are densities of hydrocarbon and gas repectively.

5.3 Log responses on fluid substitution

On different scenarios, the theory of Gassmann equation, the responses of different logs in the reservoir zone and change in synthetic seismogram are evaluated. There is no change in the behavior of logs at in-situ condition while some changes occur by changing the fluid percentage e.g 30%, 40%, 50%, 60%,70%, 80% and 100% in the zone of interest. The Vp, Vs and density of the rock fomation changes. The log responses shown below from Fig 5.2 to 5.8.

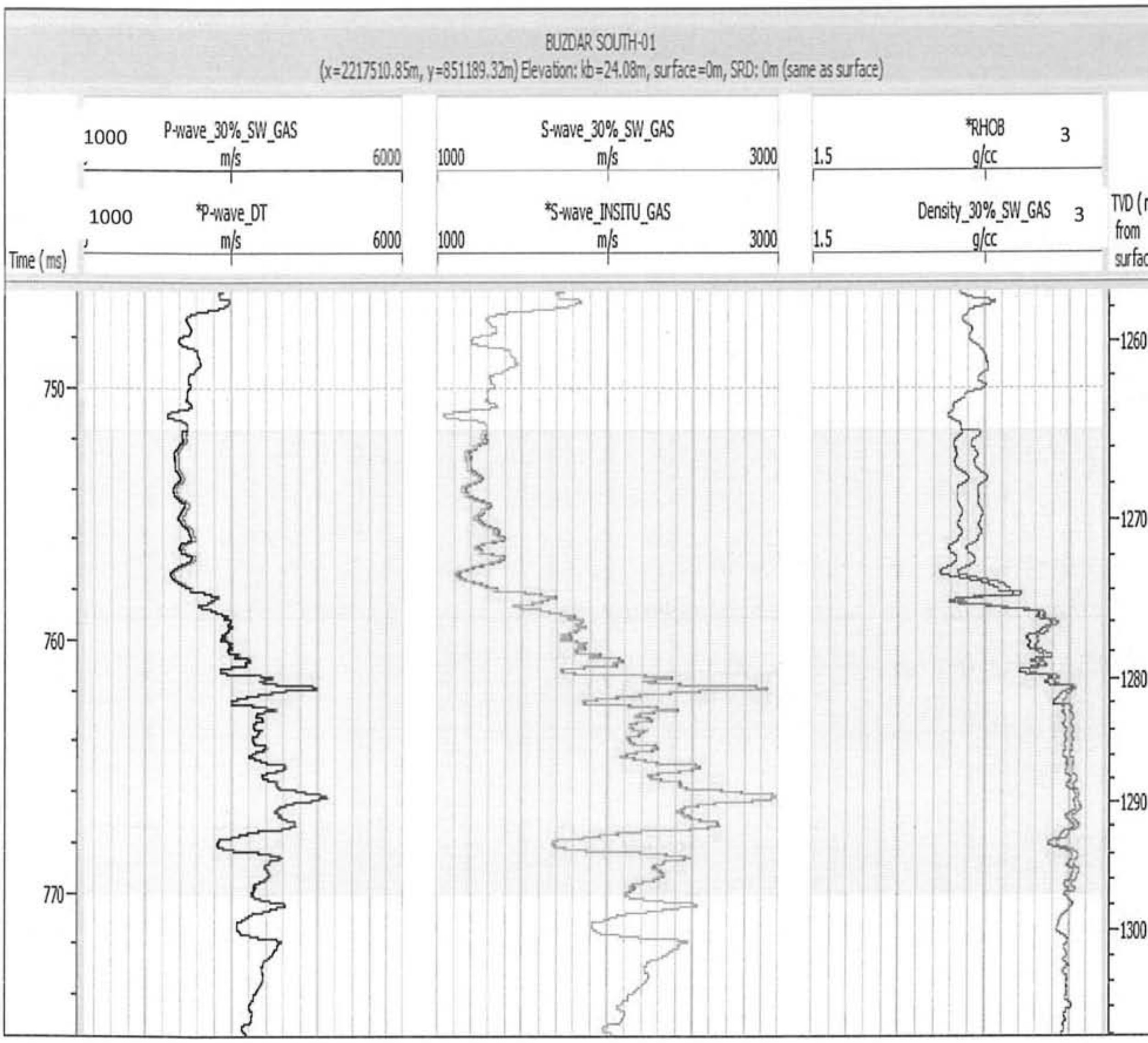

Figure 5.2: Log response in the reservoir zone comparing 30% fluid substitution with in-situ condition (9%)

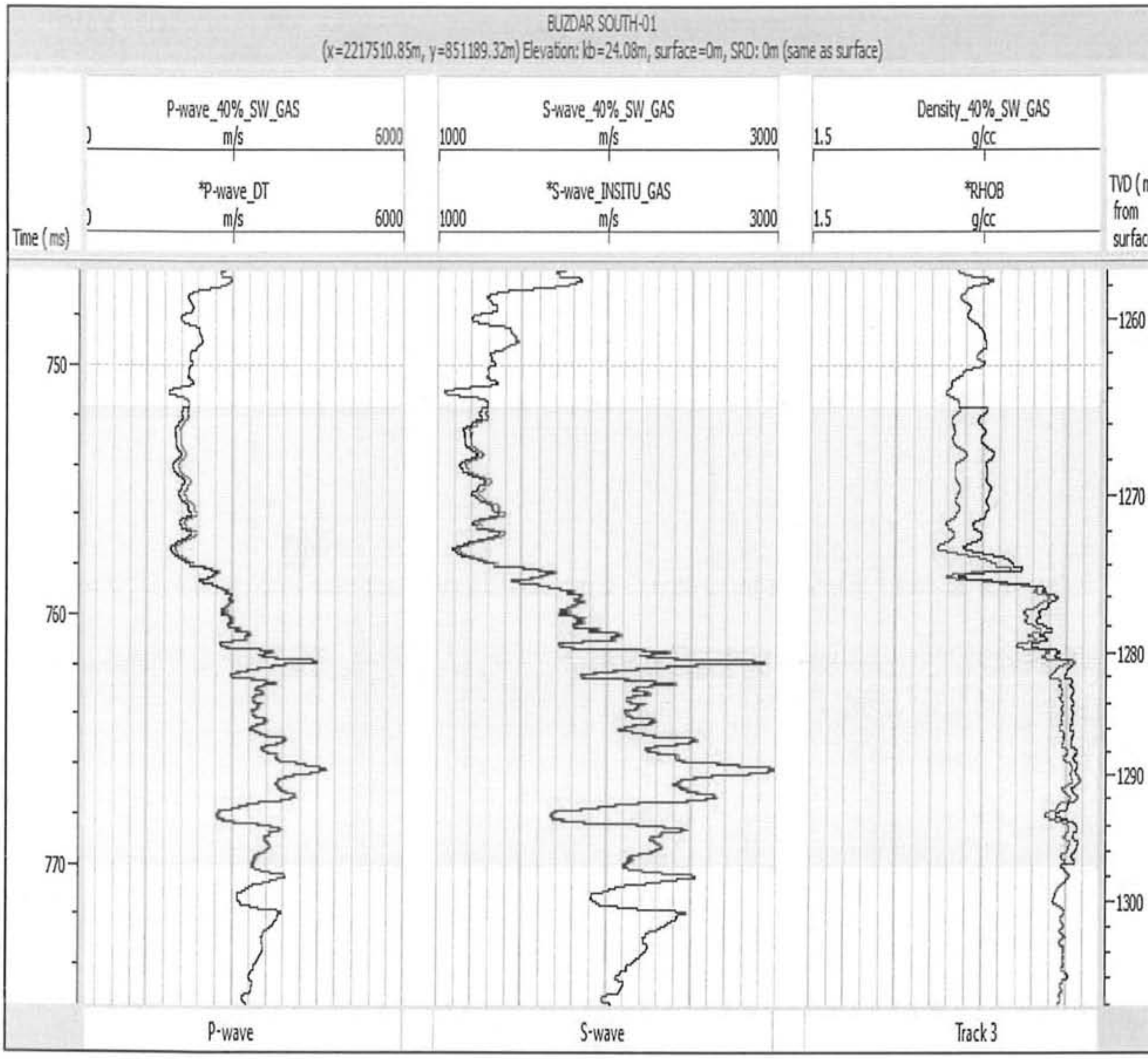

Figure 5.3: Log response in the reservoir zone comparing 40% fluid substitution with in-situ condition (9%)

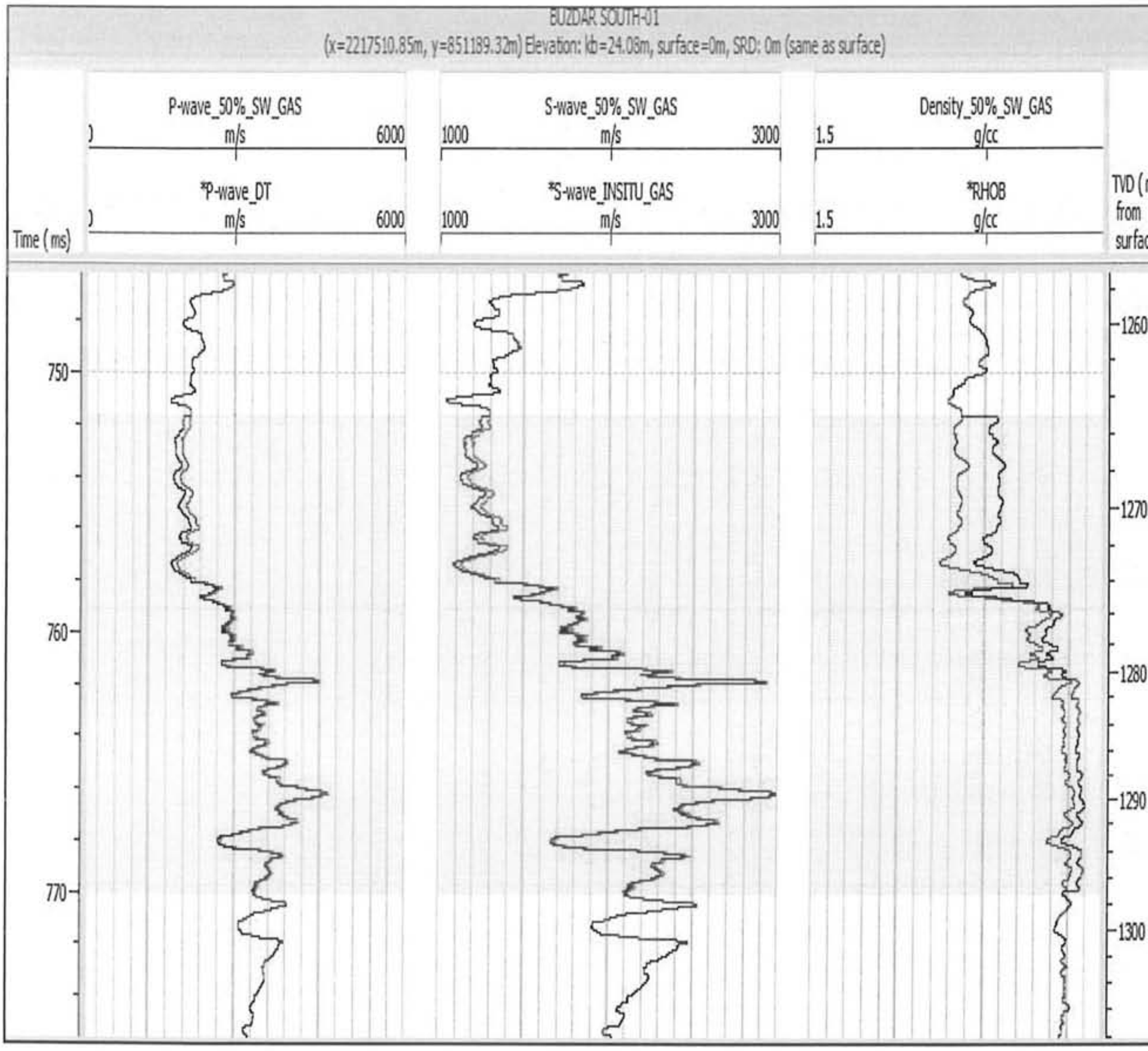

Figure 5.4: Log response in the reservoir zone comparing 50% fluid substitution with in-situ condition (9%)

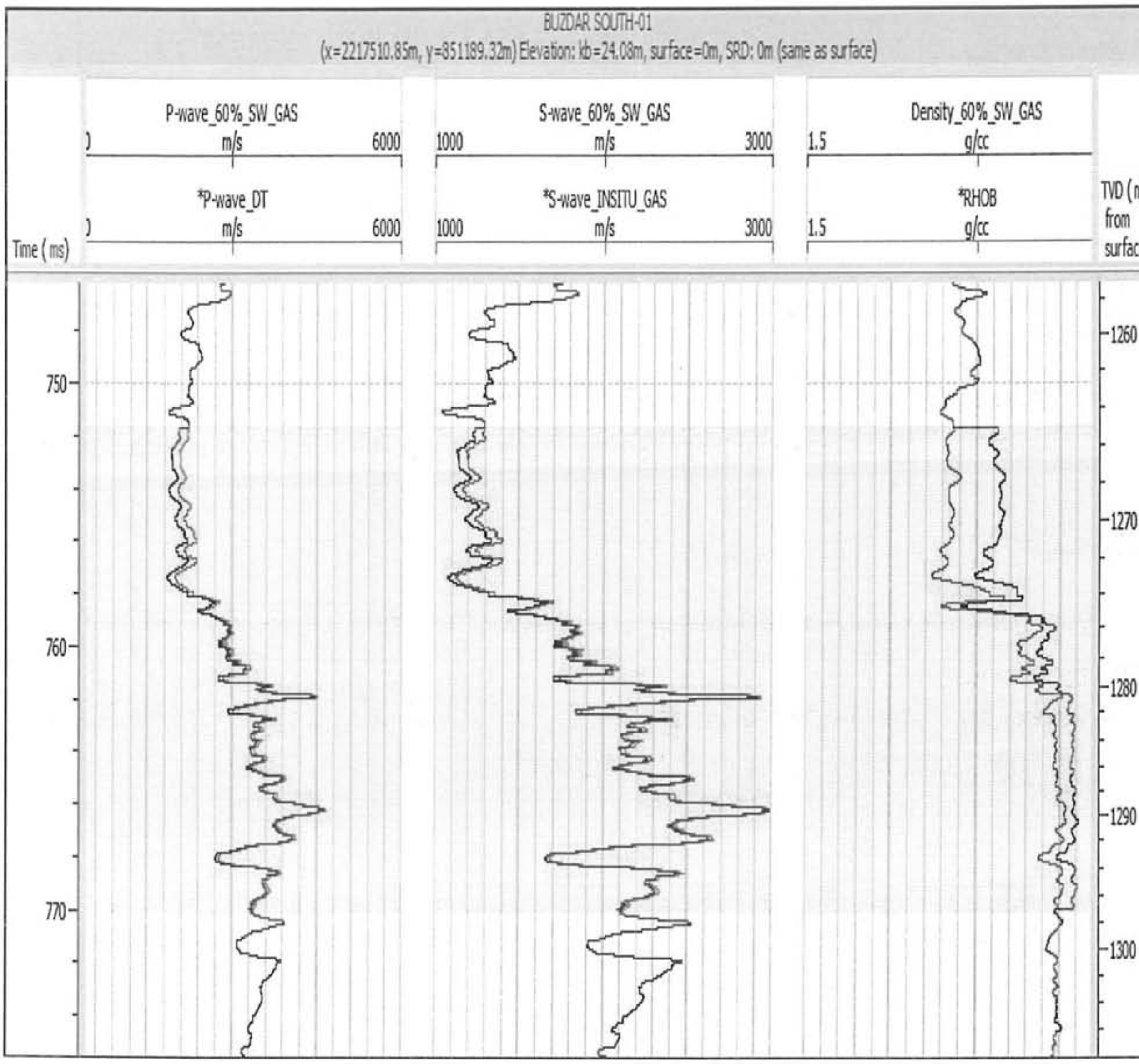

Figure 5.5: Log response in the reservoir zone comparing 60% fluid substitution with in-situ condition (9%)

Gassmann's fluid substitution has been used and the results show the log responses at different saturation levels. With increasing saturation from 30% to 100% compared to insitu underestimates the values of Vp and Vs. Whereas the density of the rock formation increases with each increasing saturation level due to replacement of gas with water. According to the Vp equation in relation with the moduli, the gas substitution with water will enhance the density values therefore decreasing velocity. The bulk modulus also increases due to a greater resistance of water to compressibility as compared to gas. This also causes an decrease in Vp values. The variation for Vs values is comparatively less as there is no change on the shear modulus and the only affecting factor is density.

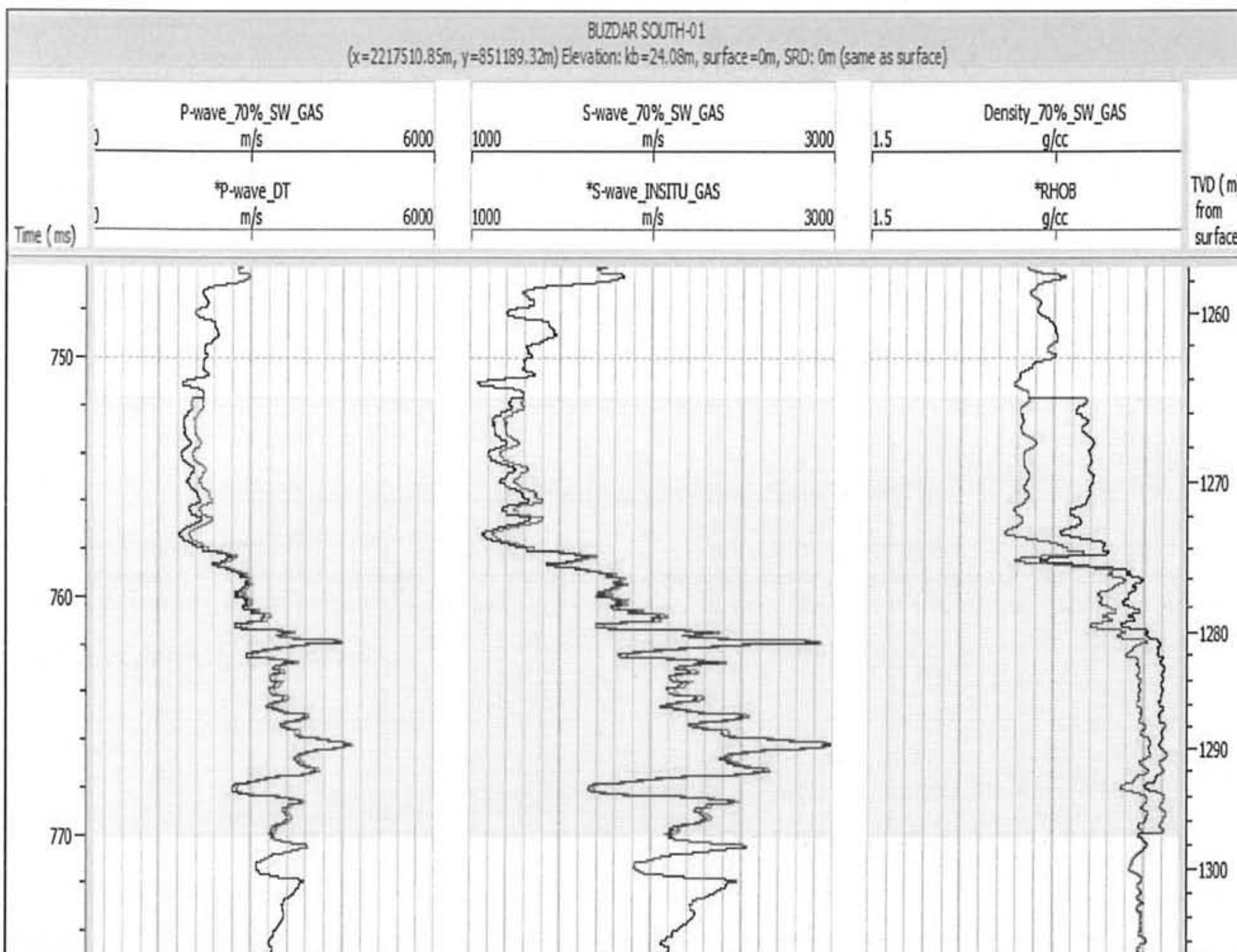

Figure 5.6: Log response in the reservoir zone comparing 70% fluid substitution with in-situ condition (9%)

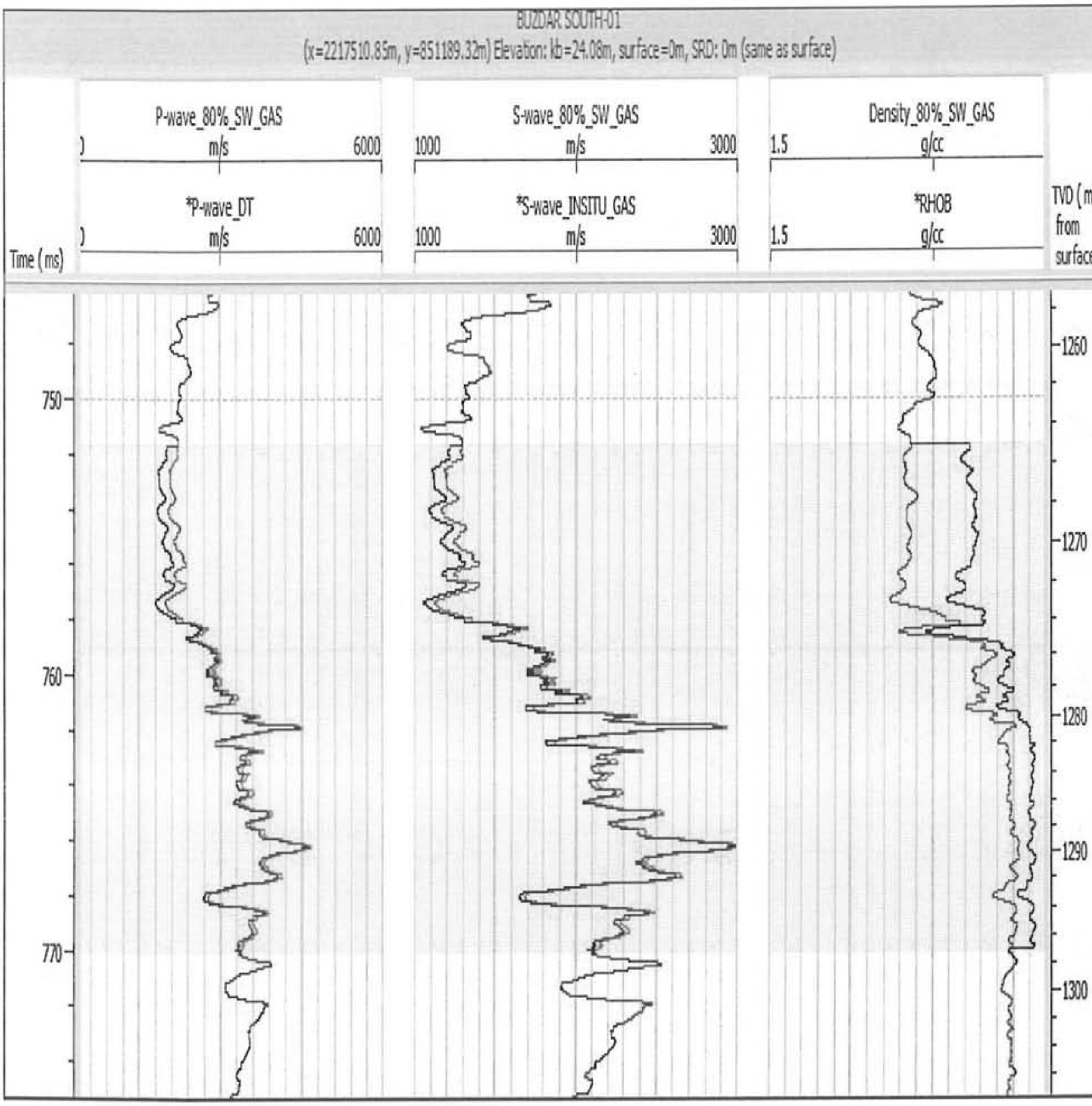

Figure 5.7: Log response in the reservoir zone comparing 80% fluid substitution with in-situ condition (9%)

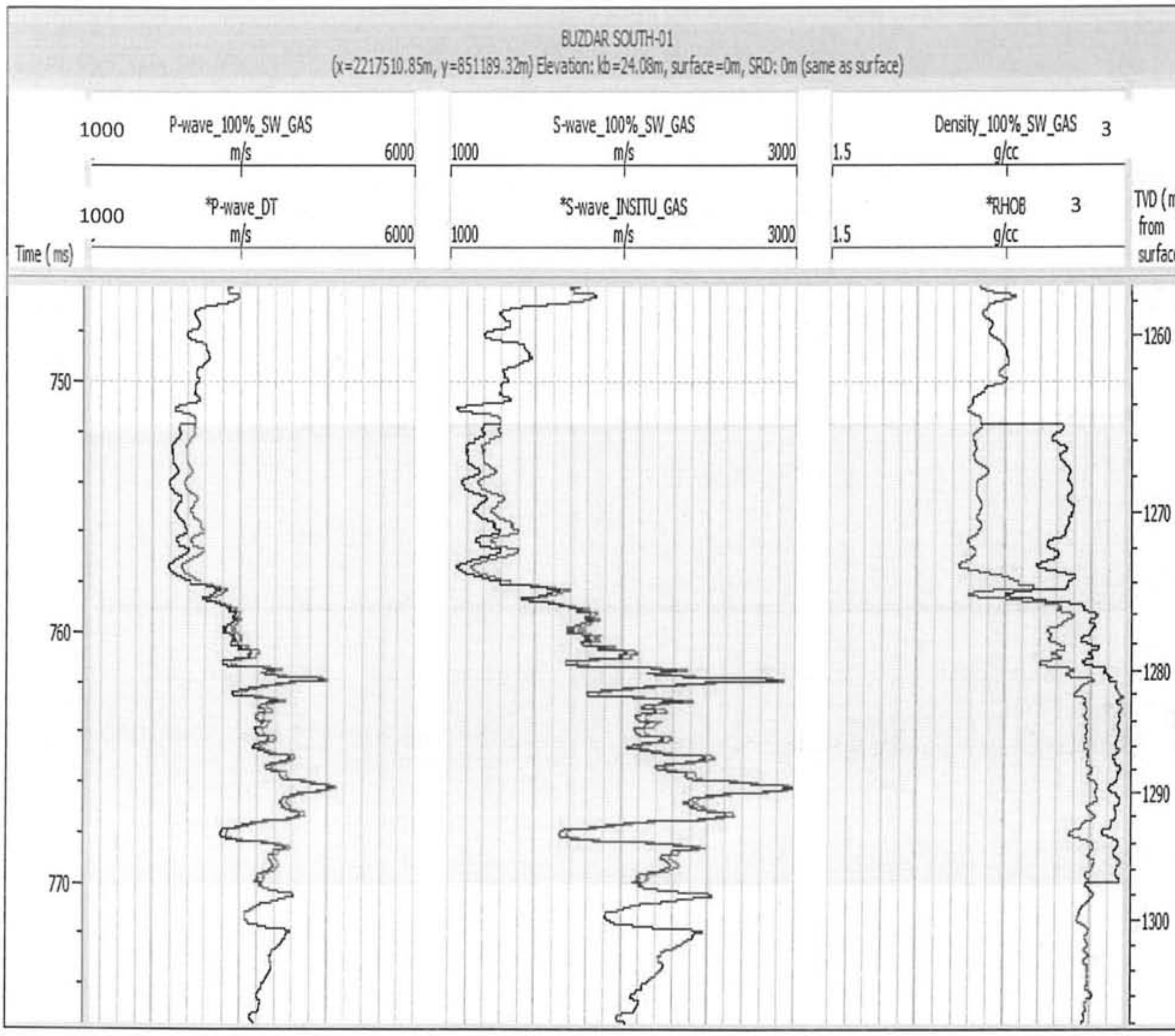

Figure 5.8: Log response in the reservoir zone comparing 100% fluid substitution with in-situ condition (9%)

5.4 AVO Modeling

Amplitude Variation with Offset (AVO) modeling is a technique by which geoscientist endeavors to estimate the density, velocity, thicknesses, porosity, lithology, and fluid content of the reservoir rock that have a pronounced effects on the seismic responses. AVO anomalies can be identified mostly on the pre-stack seismic data/angle gathers showing significant variation in amplitude caused by the presence of fluid (oil, gas or brine) with altering properties inside a reservoir rock (Batzle et al., 2001).

AVO analysis is the characteristic tool to differentiate the type of hydrocarbons present and for the classification of AVO classes and its modeling through cross plots which allows the extracted attributes to further confirm the pay or non-pay zone of different reservoir intervals (Castagna, 1997; Castagna et al., 1998; Chopra et al., 2003; Chopra et al., 2014)

The AVO attributes of intercept and gradient which can be extracted from (CDP) gathers of the given pre-stack seismic data or can be calculated using different mathematical relations developed by (Castagna and Smith, 1994) and when these attributes are cross plotted in the form of amplitude versus angle can be used for AVO sands classification. AVO amplitude anomalies can be treated as a function of the P-wave velocity, Swave velocity, density, and the seismic wave incident angle. The first three parameters of the AVO are function of rock fluid properties which are extracted using different rock physics templates (Mavko et al., 2009).

Zoeppritz equations are the fundamental equations which can be used for AVO analysis in the isotropic media that explain the change in the reflection coefficient for plane elastic-waves to be a function of seismic wave incidence angle (Zoeppritz, 1919). The zoeppritz approximation were very complex in terms of solution so many geophysicists (Aki and Richards 1980; Shuey 1985; (Smith & Gidlow, 1987) have applied linear approximations of the Zoeppritz equations.

A simpler form of it, which parameterized it in terms of the P-wave-velocity, S-wave-velocity and density by assuming a weak layer contrasts proposed by (Aki and Richards, 1980); (Wang, 1999). Another approximation that is proposed by Aki & Richards describe the variation of amplitude as a function of different incident angles ranges (i.e. near, mid, and far angles; (Shuey, 1985)

5.4.1 Sand Classification

(Rutherford & Williams, 1989) proposed classification for reflection coefficient versus impedance of the interface between shale and gas prone sand layers. This classification is defined for gas sand reservoirs. Three classes of sands were proposed based on AVO characteristics and are mentioned below,

- **Class 1**

Class 1 sands having high impedance. It is marked when normal angel of incidence reflection coefficient of P-wave is positive and its acoustic impedance is also positive.

- **Class 2**

Class 2 sands have close to zero impedance. It occurs when the reflection coefficient is very low and offset phase will be minimum or moderate. Such type of sand is condensed. Reflectivity changes may occur from near to far offset.

- **Class 3**

Class 3 has sands with low impedance. It is estimated when reflection coefficient is negative with offset increase.

5.4.2 Crossplotting

The synchronous and significant evaluation of two attributes is provided by using crossplotting in AVO analysis. To better acknowledge the AVO analysis in a clear and instinctive way, crossplotting is the best tool. It basically uses the intercept and gradient. Other attributes are also used as an indicators of AVO anomaly (Castagna and Smith, 1994; (Goodway et al., 1996)). For simple interpretation, and lithologies and type of fluids to group together, the kind of attributes used must be suitable. The basic purpose of AVO is to encapsulate the change of amplitude on the gathers (Chopra et al., 2014)

5.4.3 AVO responses for different fluid substitution scenarios

Primary intercepts and gradient crossplots used for identification of pay zones for the area. Synthetic gathers shows the relationship between known wireline log data in depth domain and seismic data in time domain (Thomas et al, 2012). So according to the AVO gradient analysis carried out in this research work, the sand is classified as Class1 by interpreted curves shown below from Fig 5.9 to 5.24.

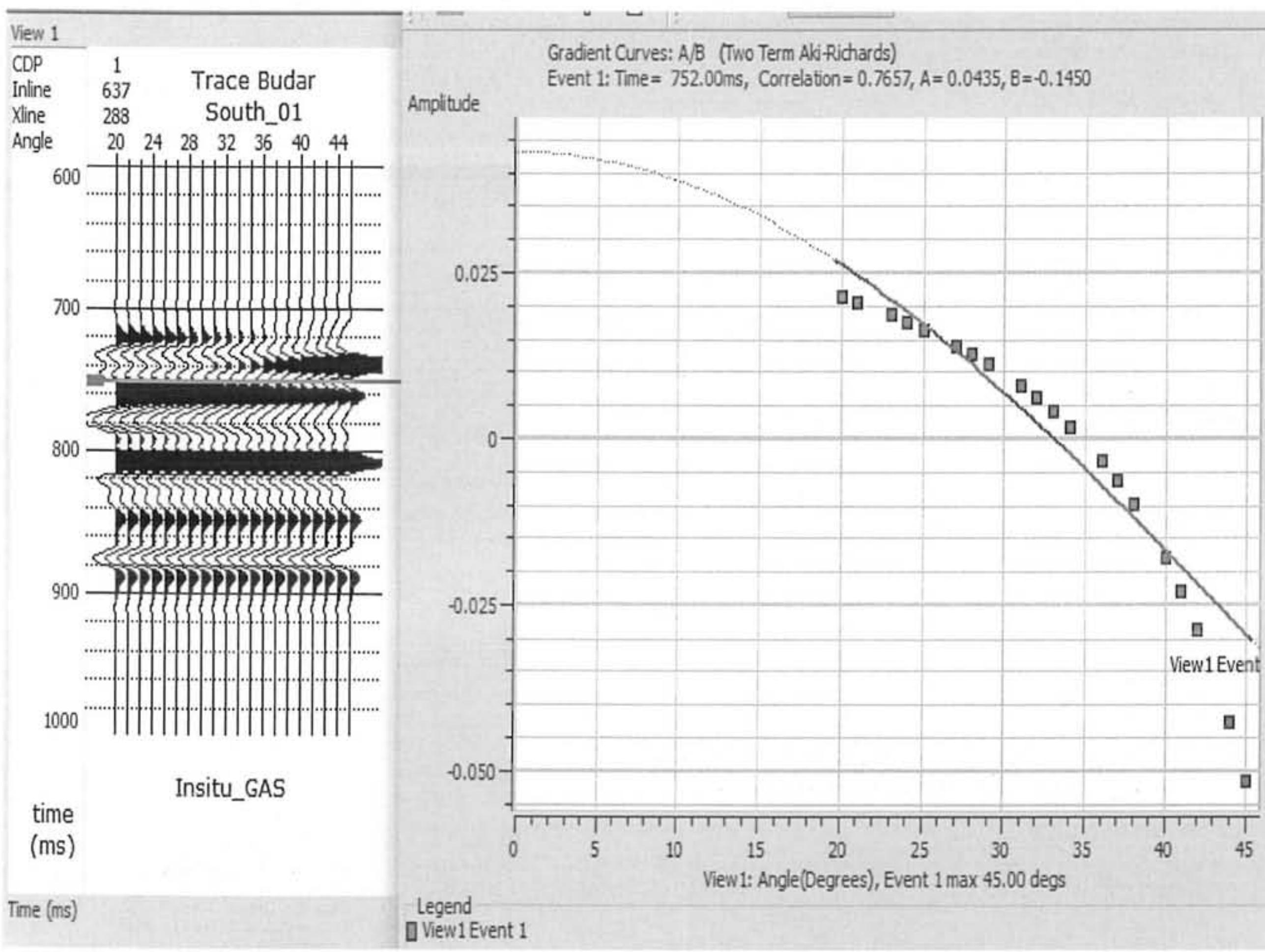

Figure 5.9: Classification of sands on the basis of curve at in-situ condition (9% Sw)

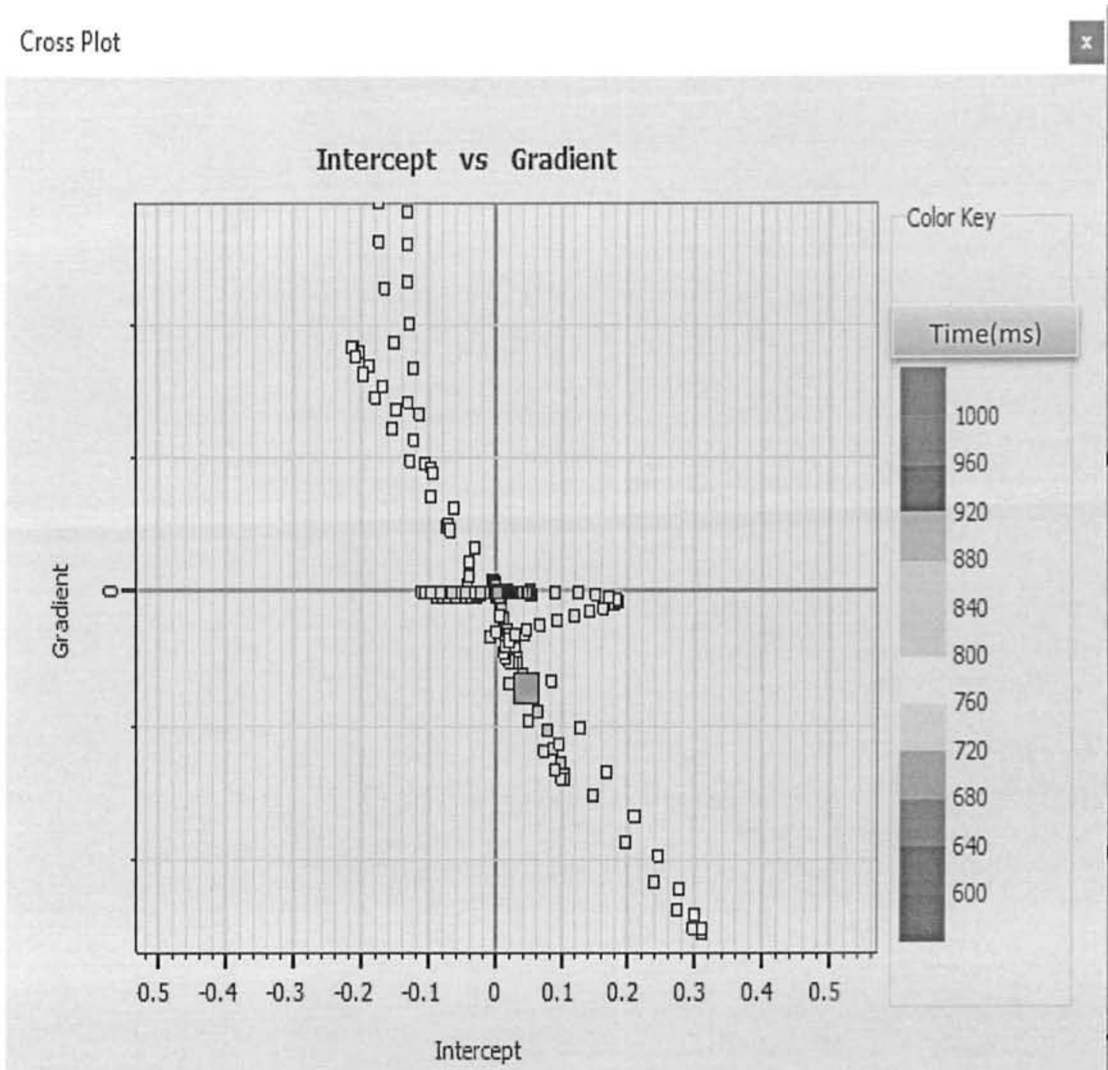

Figure 5.10: At 9% Sw

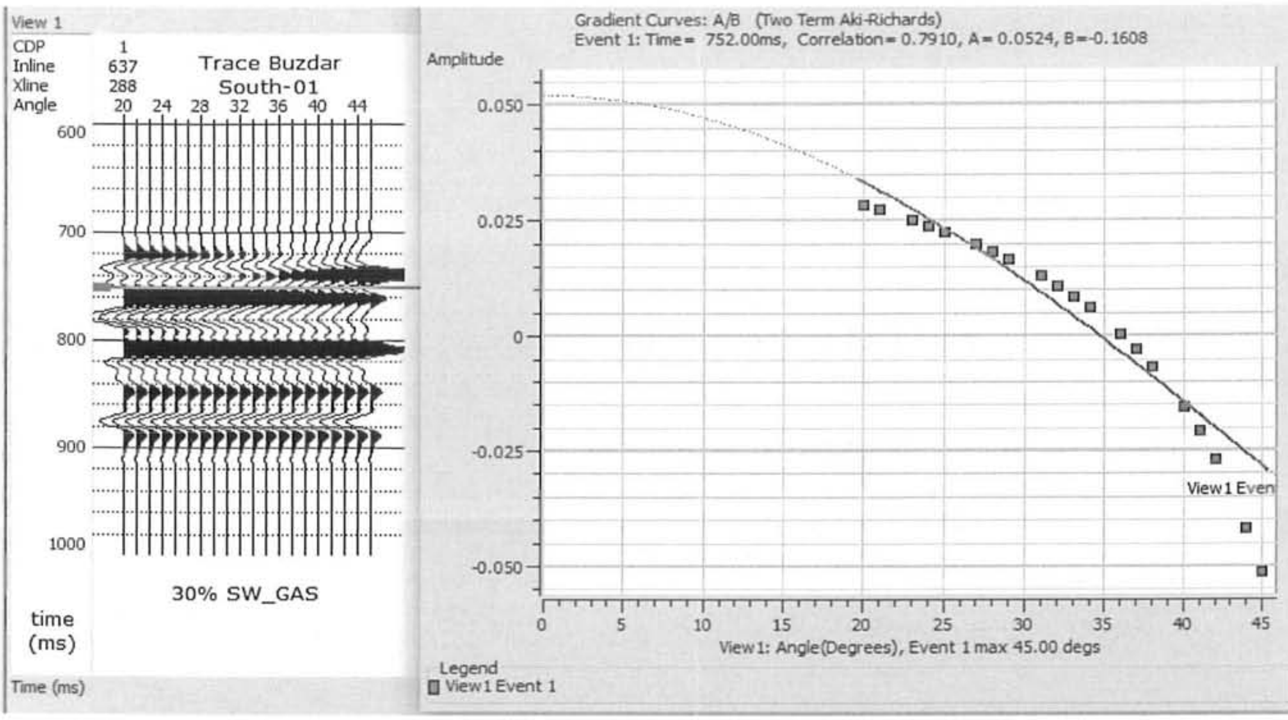

Figure 5.11: Classification of sands based on curve at (30% Sw)

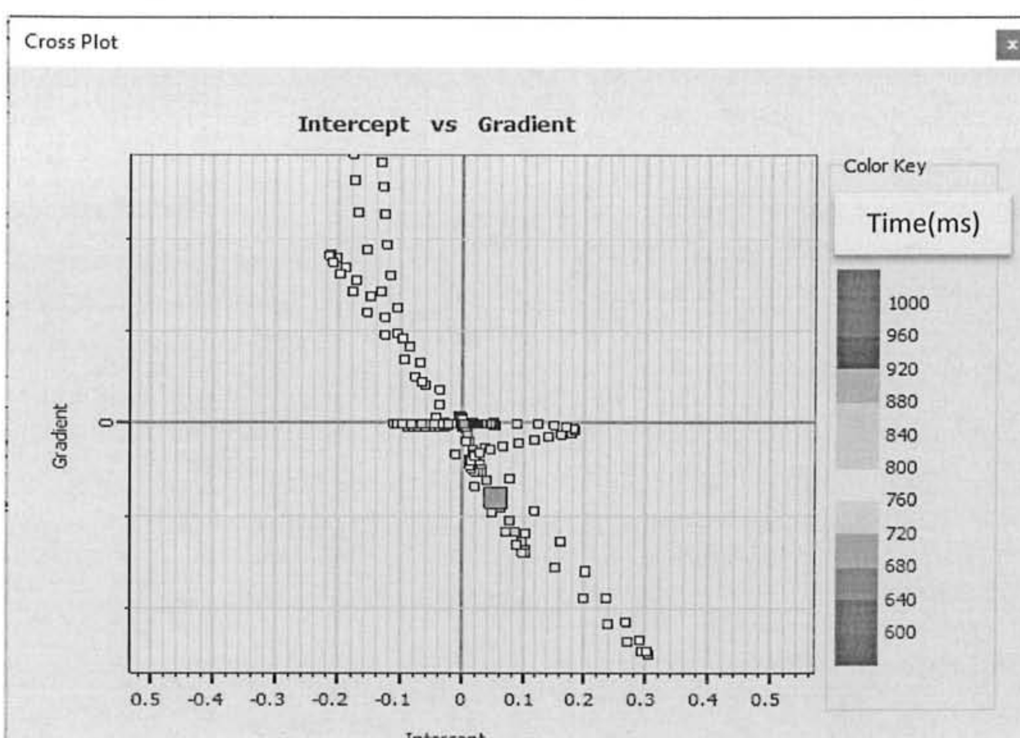

Figure 5.12: At 30% Sw

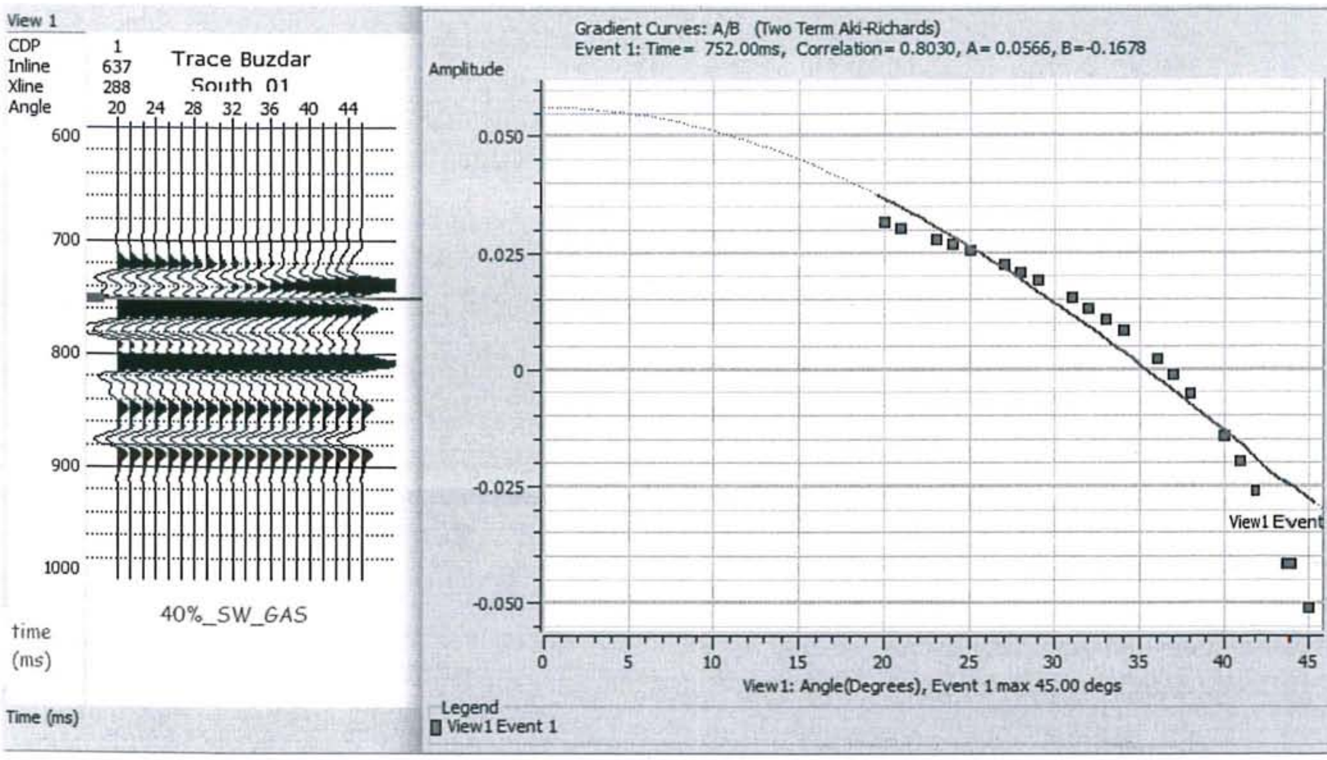

Figure 5.13: Classification of sands on the basis of curve at (40% Sw)

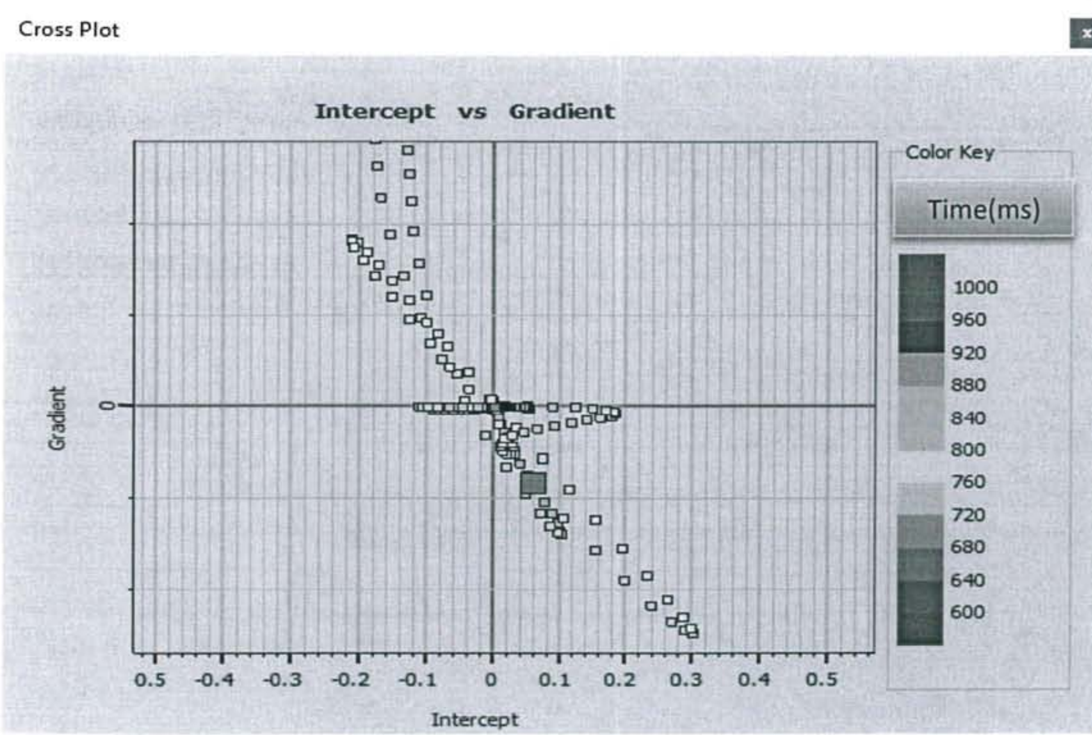

Figure 5.14: At 40% Sw

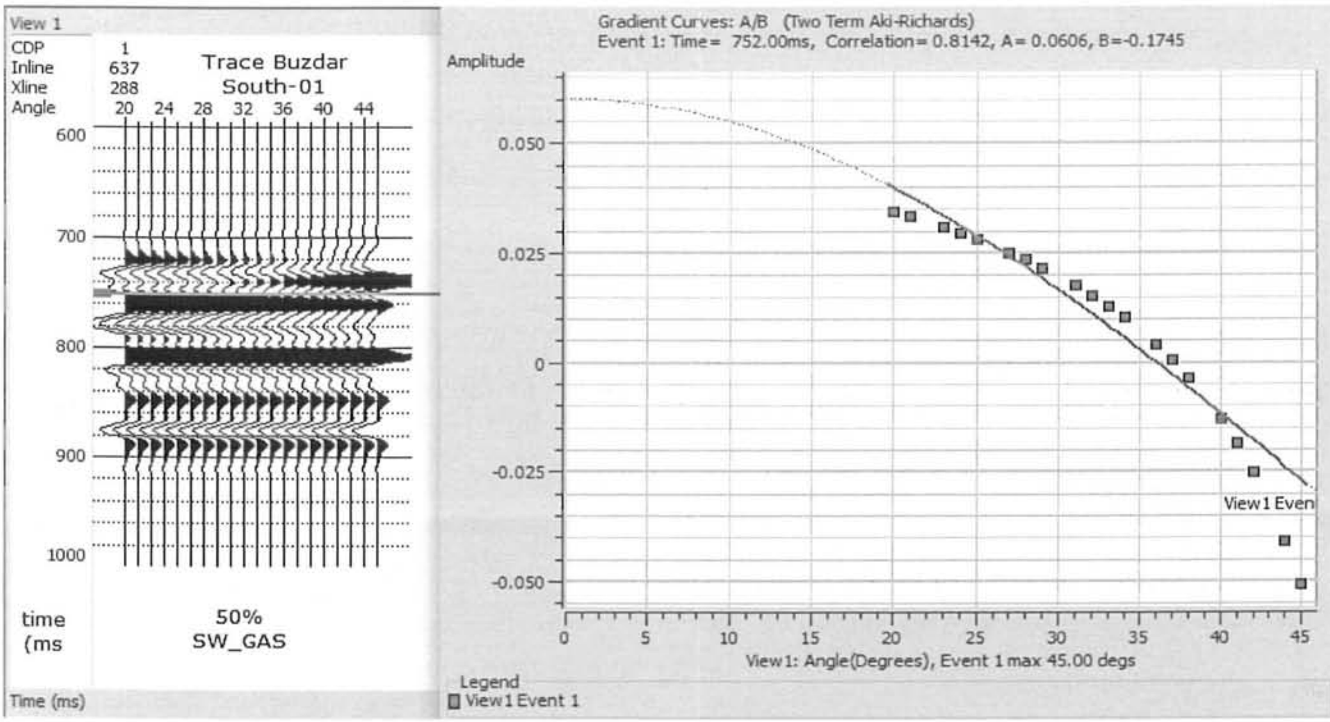

Figure 5.15: Classification of sands on the basis of curve at (50% Sw)

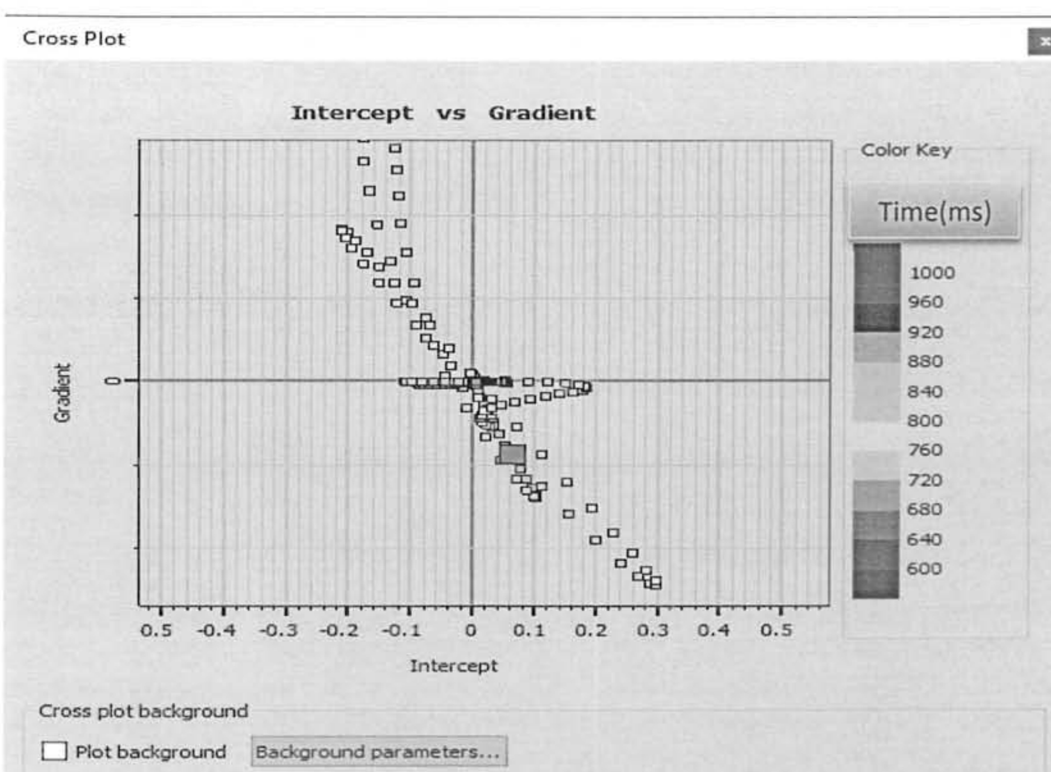

Figure 5.16: At 50% Sw

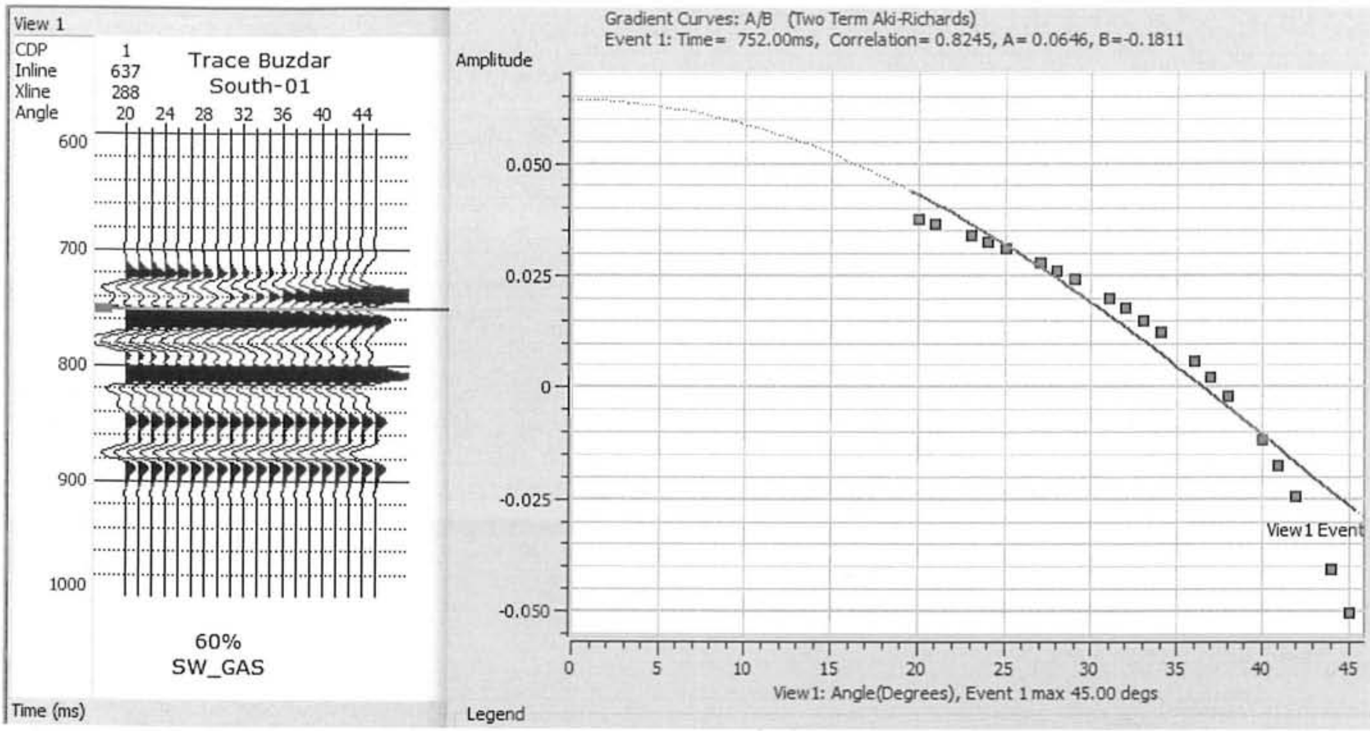

Figure 5.17: Classification of sands on the basis of curve at (60% Sw)

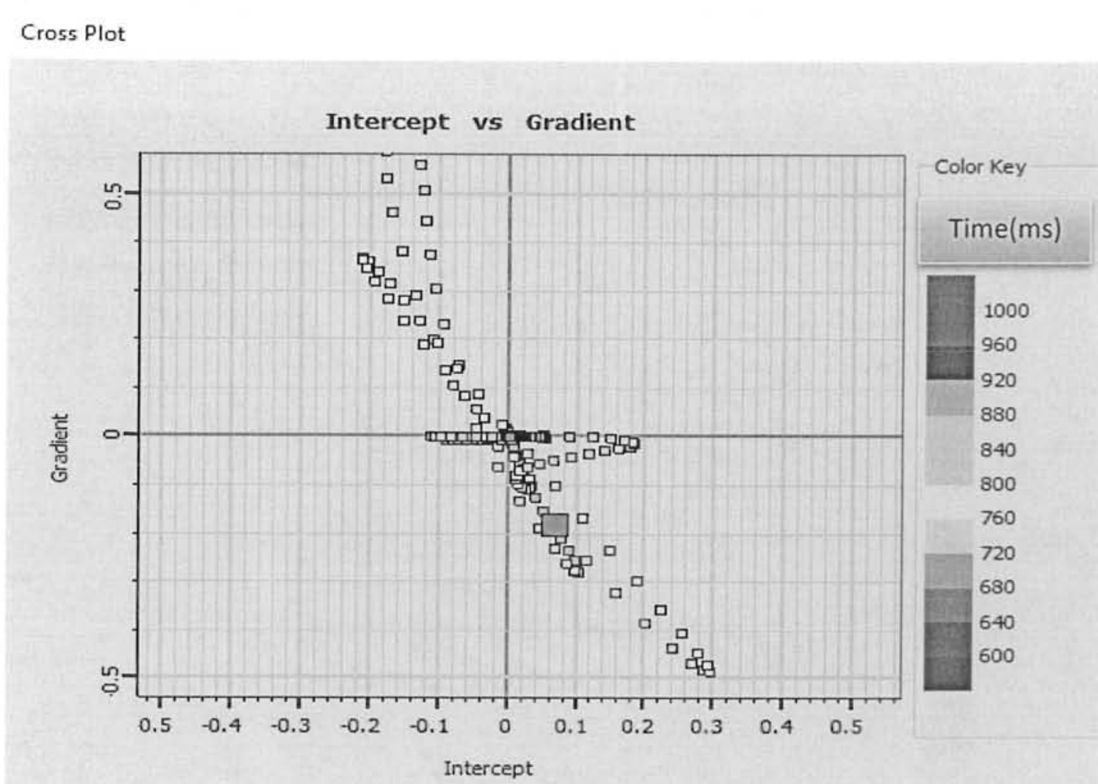

Figure 5.18: At 60% Sw

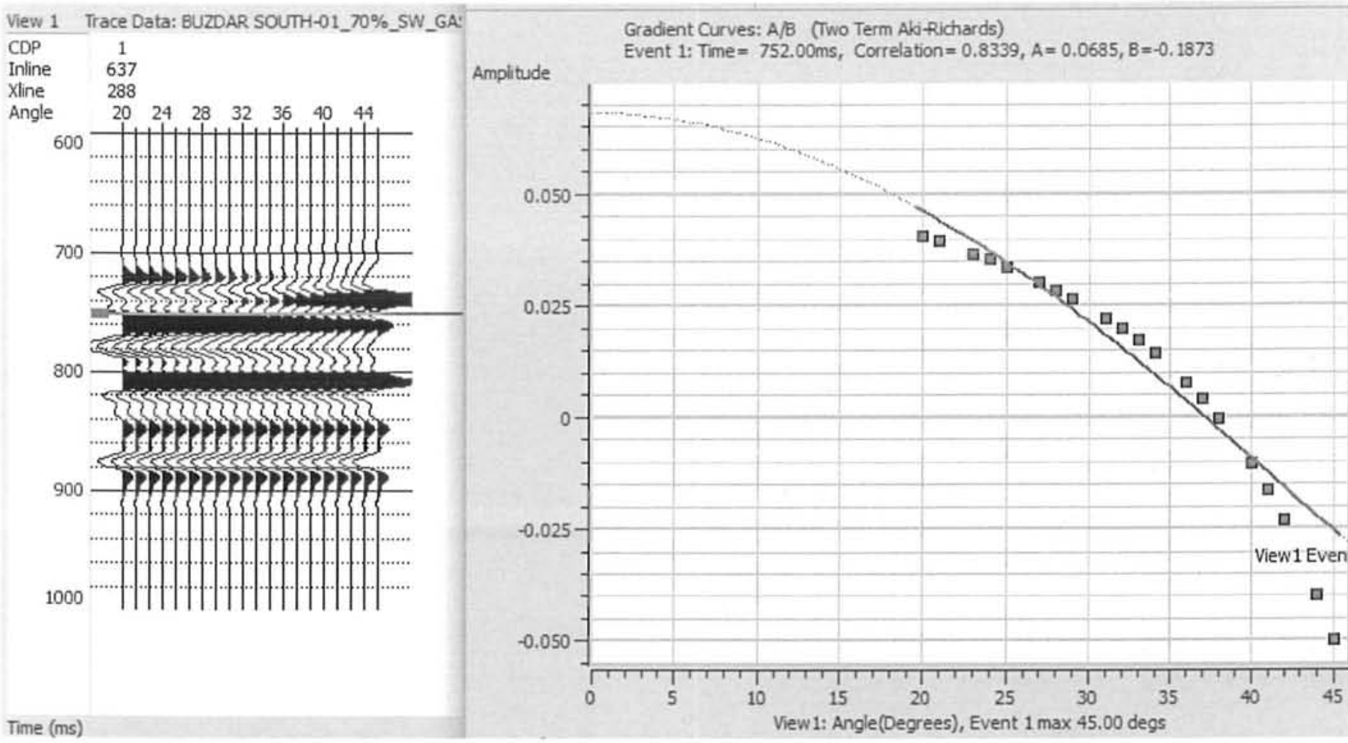

Figure 5.19: Classification of sands on the basis of curve at (70% Sw)

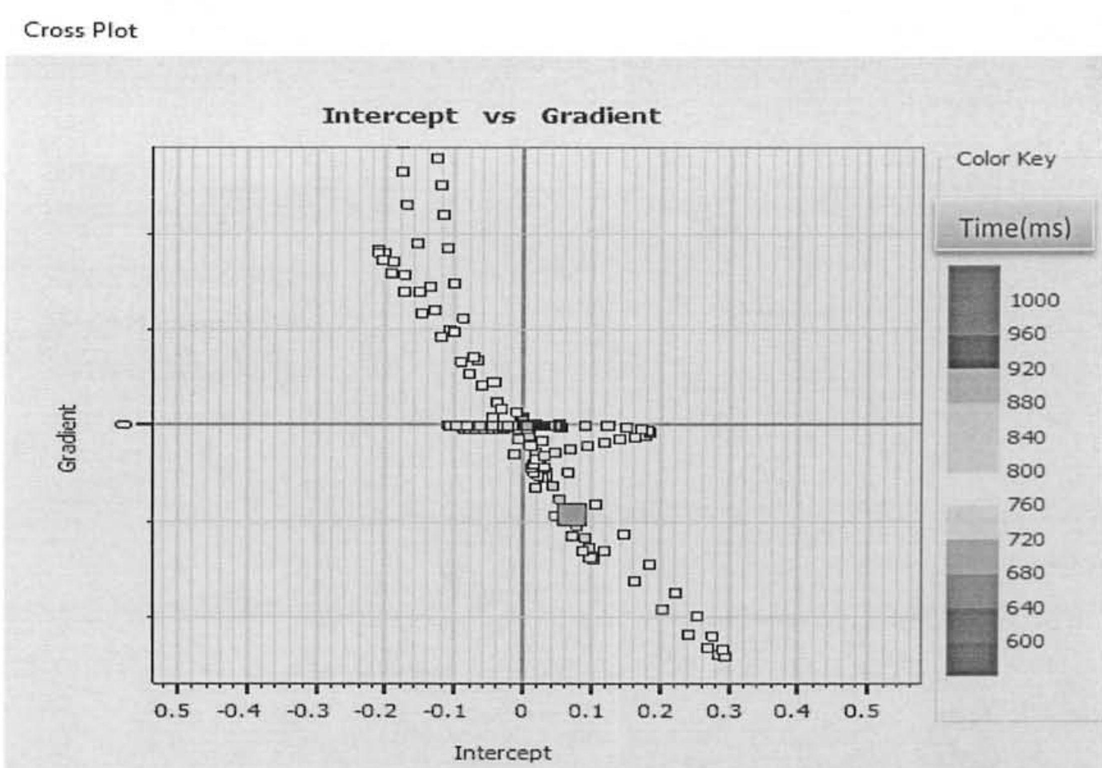

Figure 5.20: At 70% Sw

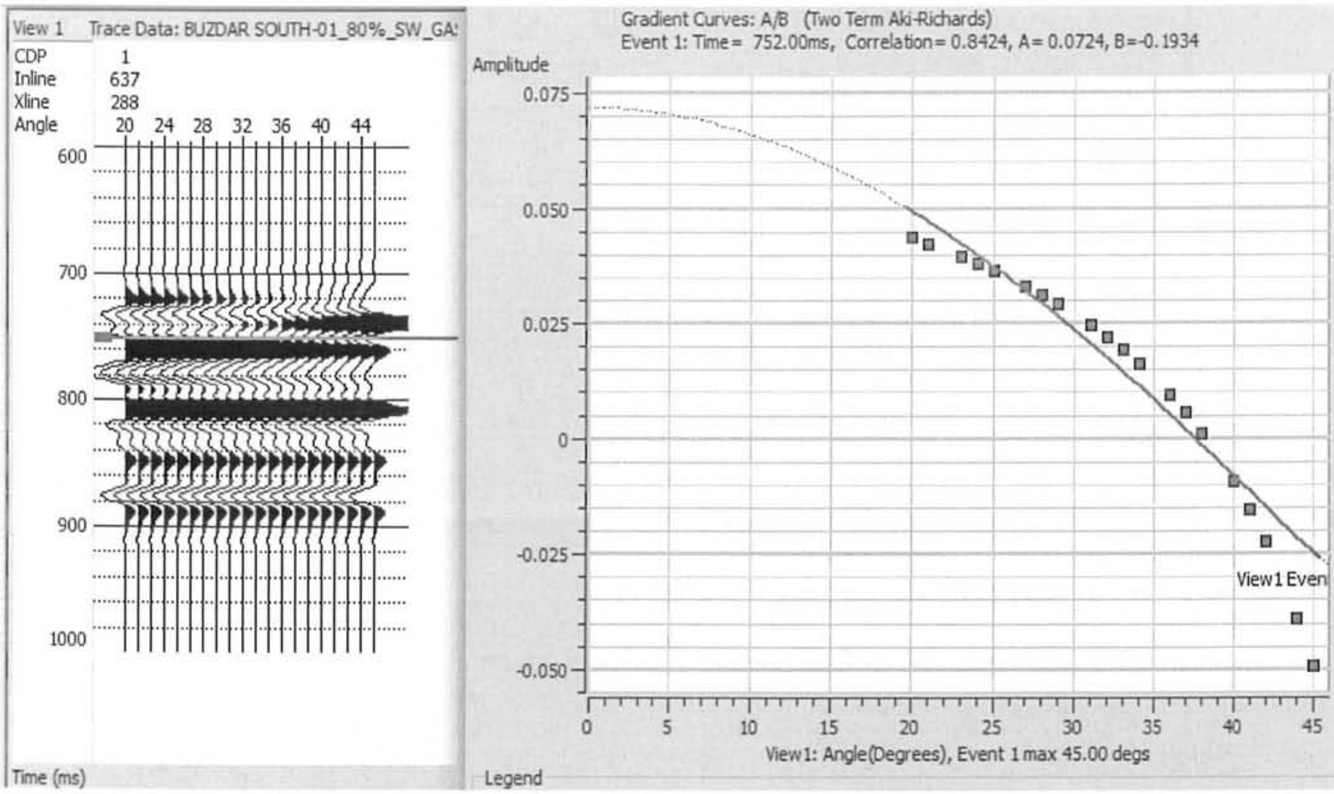

Figure 5.21: Classification of sands on the basis of curve at (80% Sw)

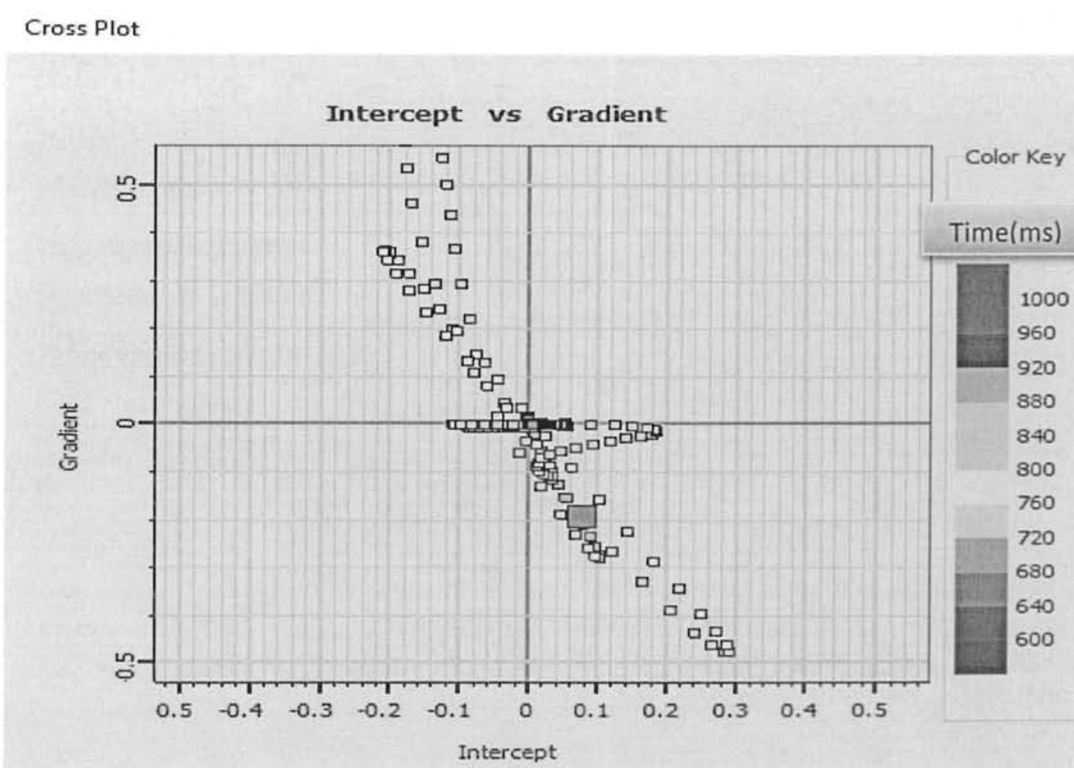

Figure 5.22: At 80% Sw

According to the cross plot results, the sands under observation are classified as Class 1 sand according to the Rutherford and Williams's classification of gas sands. Sands of this class usually show high impedance than the encased shale. Sands which are deltaic or fluvial deposits are usually classified as Class1 sand (Rutherford and Williams, 1989).

The high impedance contrast results in higher RC value at intercept which decease with angle thus have a negative gradient.

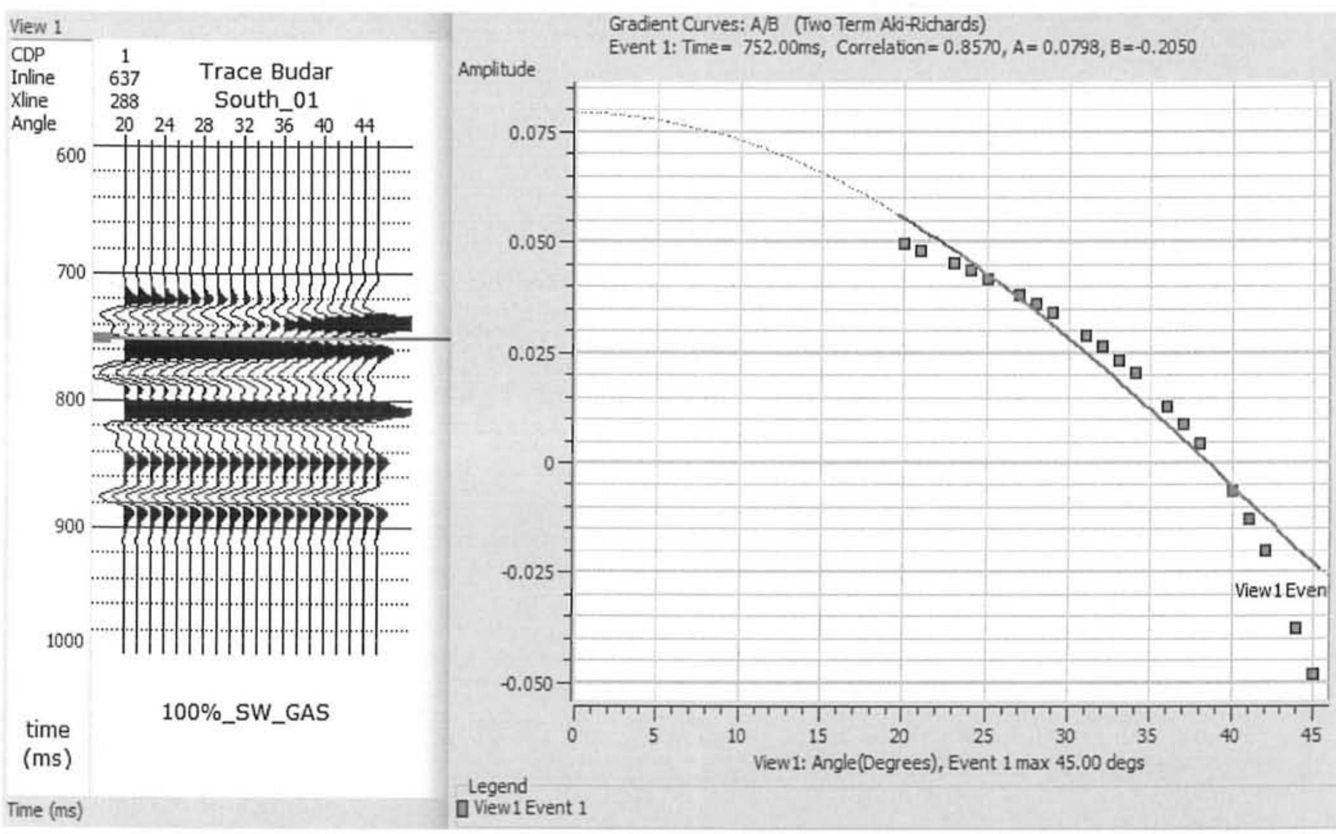

Figure 5.23: Classification of sands on the basis of curve at (100% Sw)

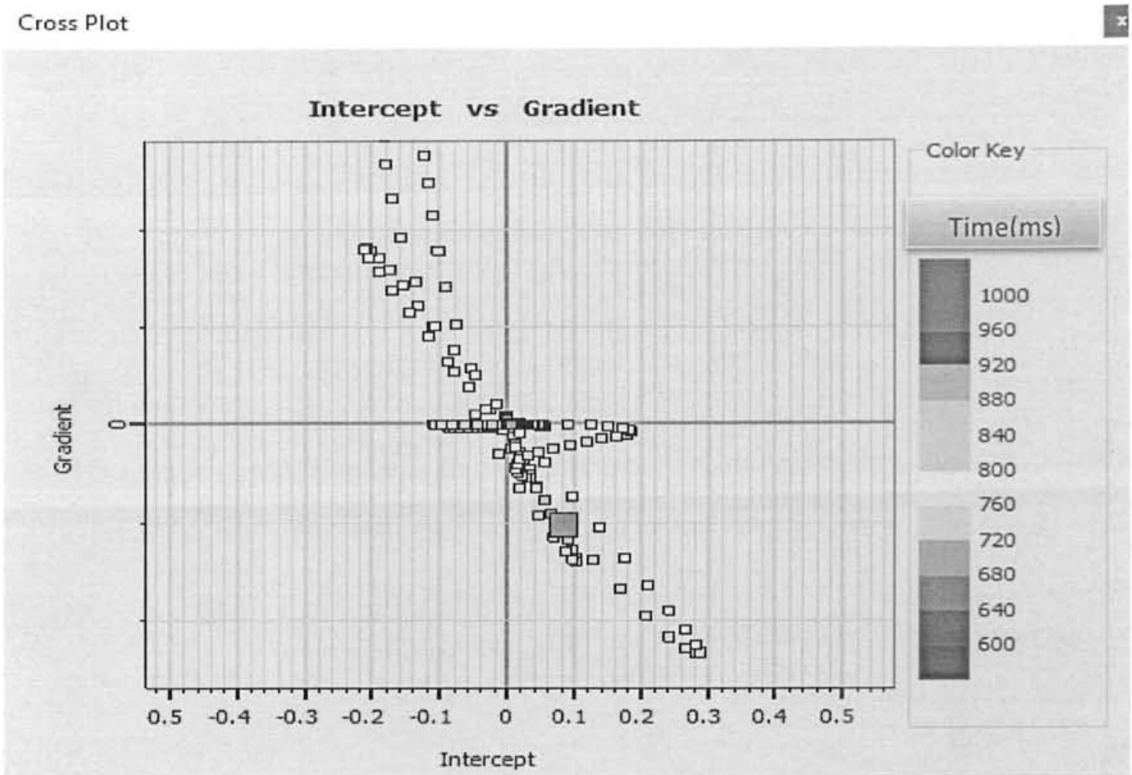

Figure 5.24: At 100% Sw

AVO primary attributes (intercept and gradient) cross-plot identifies pay zones of gas in Lower Goru formation. With increasing saturation from 30% to 100% the intercept values increases. At 30% water saturation the value of intercept is 0.02 and at 100%, it is 0.05. Whereas angle increases and reflection coefficient decreases at each increasing saturation. So the quantitative interpretation of the reservoir in Badin area shows the effect of fluids and amplitude variation with angle which can effectively separate the gas rich gathers in sand hosted formations.

Chapter 6
Discussion and Conclusions

For the economic growth of any country hydrocarbons play a vital role. The basic goal of the geophysicists is to find the hydrocarbon deposits (oil or gas) beneath the earth's surface. Various techniques are applied by the geophysicists to explore hydrocarbons. The geophysical methods like seismic method and well logging are of fundamental importance regarding this aspect.

A proper understanding of reservoir framework is required to give solutions about hydrocarbon exploration. In this study, seismic interpretation, petrophysical analysis and AVO modeling are used to characterize the Badin area of Lower Indus basin, Pakistan. Interpretation of 3D cube of Badin block with time and depth contour mapping using fault polygon orientation and demarcation of Upper Goru and Lower Goru formations. The interpretation was done by correlating the seismic data with Buzdar South – 01 well. Seismic interpretation confirms that normal faulting is present in the study area.The study area encompasses horst and graben structures formed under the influence of extensional regime. The shales within the Lower Goru formation act as a source rock for the above residing sand reservoir layers. With the low permeability shale dominated Upper Goru formation lying just above the reservoir, a systematic petroleum play is fashioned.

Estimation of reservoir properties within any area is essential and is done through a well drilled in the area. In petrophysical analysis fluid's behavior is tested and volume of shale, water saturation, porosity and hydrocarbon saturation by using well log data Petrophysical analysis concluded that Lower goru is a potential reservoir. Zone of interest marked through investigation of las files from Buzdar South – 01 well demonstrates presence of 18% total porosity and effective porosity reaching an average of 16%. The hydrocarbon saturation quantified within a potential zone of 42 meters averaged out to be 91%.

Zoeprittz equation gives P wave reflection coefficient and transmission coefficient using elastic parameters as an input. The equation gives good results but the mathmetical formulation was very complex. The calculation is also time consuming. Many researchers develop mathematical equations that approximate the Zoeprittz equation. One such approximation is Gassmann's fluid substitution approach. This approximation is comparatively simpler and gives valid results.

Reservoir analysis done through substitution of fluid delineates the reservoir potential upon evaluation of the behavioral change in the elastic parameters under the influence of the substitution. Gassmann equation used for that matter resulted in underestimation in Vp and Vs for a comparative increase in the saturation levels from 30% to 100% with respect to the insitu condition while the density show a comparative increase. There is progression in the underestimation of Vp and Vs.

Categorization of fluid filled sands, based on their reflectivity, entails information particularly regarding presence of gas within the reservoir pockets. An AVO analysis carried out over simulated multi scenarios via fluid substitution is efficient in mining that information. AVO crossplot results for the interest zone classify the existing sands into Class I based upon their high reflectivity intercept values for each fluid scenario, decreasing reflectivity with angle and a negative gradient. The intercept value at 50% saturation is 0.032 and as soon as the saturation level rises from 50% to 100% the intercept value becomes 0.05. This increment indicates the presence of gas in the reservoir.

The synthetic results upon correlating with prestack data within the domain of geostatistical setting give us the information about real subsurface situation from our model. The model with best correlation can then be applied to the whole cube as an inversion template to obtain the desired reservoir parameters like porosity, water saturation etc. AVO therefore provides an advantage in terms of inverting for a parameter to obtain distribution that required parameter through the seismic cube making it an efficient inversion tool.

On the basis of the techniques applied on Badin area the following conclusions have been executed:

- Seismic interpretation confirms that mostly normal faulting prevails in the study area. The geometries of horst and graben is favorable for hydrocarbon accumulation and are marked with NW-SE trend.

- Petrophysical evaluation of well Buzdar South-01 proves that Lower Goru is a potential reservoir having 16% effective porosity and 91% hydrocarbon.

- Gassmann's fluid substitution has been used and gathers are analyzed at different saturation levels showing that intercept values are increasing for each fluid scenario decreasing reflectivity with angle and a negative gradient. There is decrease in Vp and Vs whereas density increase as the saturation level increases.

- AVO primary attributes (intercept and gradient) crossplotting identify pay zones of gas in Lower goru formation. The sands of Lower goru is classified as Class 1 according to Rutherford and Williams sand classification. The intercept value increases after each increasing saturation.

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