INTEGRATED SEISMIC INTERPETATION, PETROPHYSICAL ANALYSIS AND ROCK PHYSICS MODELLING OF DANDHI AREA, RAHIM YAR KHAN

QUAID-I-AZAM UNIVERSITY

ISLAMABAD

BY

FARMAN ULLAH

BS (GEOPHYSICS)

2016-2020

DEPARTMENT OF EARTH SCIENCE

QUAID-I-AZAM UNIVERSTY ISLAMABAD, PAKISTAN

“In the Name of ALLAH, the Most Merciful & Mighty”

“PAY THANKS TO ALLAH EVERY MOMENT AND GO TO EXPLORE THE HIDDEN TREASURES, ITS ALL FOR YOUR BENEFIT”

(AL-QURAN).

DEDICATED

TO

My parents, brothers and sisters

And loving, caring and sweet friends

And all those who helped me in this work

ACKNOWLEDGMENT

In the name of **Allah**, The Most Gracious and the Most Merciful, Beneficent Alhamdulillah. I bear witness that Holy Prophet **Muhammad (PBUH)** is the last messenger, whose life is perfect model for the whole mankind till the Day of Judgement. I am thankful to Allah for the strengths and His blessing in completing this thesis.

Special appreciation goes to my supervisor **Dr. Shazia Asim** for her supervision and constant support. Her positive criticism, encouragement, motivation and suggestions throughout the experimental and thesis work have contributed in the success of this research. I express my sincerest appreciation to **Mr. Raja Hammad Khalid** for his guidance in the preparation of this thesis and his assistance in any way that I may have asked.

I also wish to thank the whole faculty of my department for providing me with an academic base, which has enabled me to take up this study I pay my thanks to the employees of clerical office who helped me a lot. Also thankful to DGPC and LMKR for providing the data.

I would like to express my appreciation to of my whole family, especially my parents for their support and help without which I was unable to reach at this stage. I also wish to thank the whole faculty of my department for providing me with an academic base, which has enabled me to take up this study.

I sincerely thank to all my **friends** especially Mr. Ahmed Rafeh, Mr. Asmad Hussain, and Mr. Jamal Abdul Nasir for their endless love, care and moral support during my study.

I am extremely thankful to all my teachers for their endless love, prayers and encouragement and my special appreciation to those who indirectly contributed in this research.

FARMAN ULLAH

BS (GEOPHYSICS)

(2016-2020)

ABSTRACT

The dissertation work includes seismic data interpretation, Petrophysical analysis using well logs data; for the identification of possible prospect zones. Facies modeling for the confirmation of lithology's and Rock Physics to find out the rock physical properties.

Two-dimensional seismic data interpretation has been carried out in Central Indus Basin, Dandhi area to confirm the reservoir characteristics of Sui Main Limestone Formation. Time and Depth contour maps of Sui Main Limestone Formation, Ghazij Formation and Upper Ranikot Formation confirm that the area is tectonically stable.

Petrophysical analysis of well Sabzal-01 is carried out for Sui Main Limestone Formation in order to depict the probable hydrocarbon producing zones. The results suggest that Sui Main Limestone's marked zone having VSH 11%, PHIE 8%, SW 67% and H.C Saturation 33%.

Facies modeling is done for the confirmation of lithology's for this purpose different cross plots has been generated which gives the result that we have pure limestone, and carbonaceous shale (limy shale) but didn't get pure shale in our reservoir. Rock Physics describes a reservoir rock by physical properties such as porosity, rigidity, compressibility, properties that will affect how seismic waves physically travel through the rocks. This prepare links between seismic and properties of reservoir (petrophysics) more quantitatively. Different plots of elastic modulus with reservoir depth show low values in productive zones which also confirm our Petrophysical results.

Contents

CHAPTER 01

INTRODUCTION

1.1 Introduction to Hydrocarbon Exploration

Hydrocarbon industry plays a vital role in the economy of any country. As the demand for energy increases with the revolution of time, exploration industry determine to discover new hydrocarbon reserves and make production better. Major sources of energy from hydrocarbon prospective are coal, natural gas and oil.

Pakistan is blessed by Almighty Allah with variety of natural resources. Hydrocarbon industry plays a vital role in the economy of our country. Hydrocarbon exploration began in the late nineteenth century in our region from the regime of British Empire. Most of the rocks in Pakistan are sedimentary and are rich in the production of hydrocarbon. The major discovery up to date is in Sui in 1952 (Kadri, 1995).

The exploration companies searches for structural and stratigraphic traps for hydrocarbon exploration. The exploration industry become advance with the passage of time and technology advancement. Many of the techniques and methods like magnetic, gravity, resistivity, seismic etc have been designed. Seismic reflection technique is the most useful for deep hydrocarbon exploration. Investigation of earth's interior include the geophysical methods, involves taking measurements at or near the earth surface for variations of physical properties of earth's subsurface.

1.2 Exploration History of Pakistan

In Pakistan the first exploratory well was drilled by Punjab Government near an oil seepage at Kundal(Khisor Range,NWFP) in 1866. In 1912 Attock Oil Company (AOC) of U.K was formed. AOC discovered first commercial oil discovery at Khaur (North Potwar, Punjab) in 1915 in Miocene and Eocene reservoirs and had a production of 4 million barrels of oil upto 1990. In 1952 PPL discovered large reserves of natural gas in Sui Main Limestone of early Eocene age, with original gas reserves estimated as 8.624 trillion cubic feet (TCF). During 1956-59, thirty five exploratory wells were drilled.

The Central and Southern Indus Basins had been regarded as gas prone until 1981. The first natural gas discovery in Punjab Platform was made by OGDC at Nandpur in 1984 followed by Panjpir(1985) in Cretaceous/Jurassic reservoirs (Kadri, 1995).

The petroleum exploration initiated in Central Indus Basin in 1983.Later on 420 seismic lines have been acquired in 1990, 1992 and 1994 by OGDCL (Oil and Gas Development Cooperation Limited). Twenty five gas producing wells have been drilled in this basin to the date. Most of the wells have been drilled in Sui Main Limestone as it is the most producing gas reservoir (Ali et al, 2005).

1.3 Introduction to Study area

Figure 1.1 Map of Pakistan showing study area (www.png.com)

The study area as shown in Figure 1.1 is Dhandi which is located in Rahim Yar Khan District of Punjab province. Geographically this area lies in UTM (Universal Transverse Mercator) Zone 42N in the world Geodetic System.

- Longitude 069^0 57'' 39.15'
- Latitude 028^0 5'' 30.624'

Geologically the area lies in Central Indus Basin (Punjab Platform). Central Indus Basin is bounded by Sukker Rift in south, Sargodha High in the north, Subsidiary Zone of Indian Plate in the east. Sargodha High and Sukker uplift separates this basin from upper and Lower Indus Basin respectively. (Kazmi & Jan, 1997).

Limestone of Eocene age is the main gas producing reservoir in Central Indus Basin (Kadri, 1995).

1.4 Data Format

The data for dissertation was provided by LMKR (Land Mark Resources) through university request, is with the approval of DGPC (Directorate General of Petroleum Concession) Pakistan.

The data for the dissertation consists of following files;

- SEG-Y(Seismic)
- LAS file(Well data)
- Navigation file

1.5 Data Description

The data includes seismic and well data for interpretation.

1.5.1 Seismic Data

The 2D seismic reflection survey was performed by OGDCL in 1984 and processed by OGDCL. Base map shows six seismic lines including four dip lines and two strike lines. The description of lines is shown below:

Sr.	Line Name	Nature of Line	Orientation	SP Range
1	846-DAN-201	Dip	NE-SW	152-373
2	846-DAN-205	Strike	NW-SE	161-444
3	846-DAN-211	Dip	NE-SW	148-336
4	846-DAN-245	Strike	NW-SE	190-510
5	846-DAN-246	Dip	NE-SW	153-375
6	846-DAN-248	Dip	NE-SW	149-368

1.5.2 Well Data

The well data includes the following files;

- SABZAL-01.las
- SABZAL-01.txt

These files stores information about log runs in the well and formation tops of the well. SABZAL-01 lies on the line 846-DAN-205.

Technical Well Data

The technical well data is presented in the table below:

Well Bore Name SABZAL-01			
Operator	OGDCL	**Province**	Punjab
Type	Exploratory	**Status**	Abandoned
Latitude	028.091844	**Longitude**	069.960875
Start depth(m)	289.0118	**End depth(m)**	3640.5925

Total Depth	3631.0000	Depth Ref. Elev.(m)	78.8200 KB

Formation Tops

Formation Name	Top (m) (MD)	Thickness (m)
SIWALIK	0.0	693.0
DRAZINDA	693.0	44.0
PIRKOH	737.0	90.0
SIRKI	827.0	67.0
HABIB RAHI	894.0	109.0
GHAZIJ	1003.0	324.0
SUI MAIN LIMESTONE	1327.0	286.0
UPPER RANIKOT	1613.0	67.0
LOWER RANIKOT	1680.0	43.0
PAB	1723.0	322.0
PARH	2045.0	503.0
UPPER GORU	2548.0	407.0
LOWER GORU	2955.0	430.0
SEMBAR	3385.0	------

1.6 Objectives

The dissertation was performed to fulfill the following objectives:

- To study the reservoir formations and structures of the subsurface geology.

- ❖ Conversion of time sections to depth section and Confirmation of depth section by correlation with Synthetic seismogram and formation tops.
- ❖ To generate time, depth and velocity contour map of selected reflectors.
- ❖ To estimate the hydrocarbon saturation, effective porosities and total porosities.

1.7 Methodology

The basic work flow followed to achieve the objectives of dissertation is as follow;

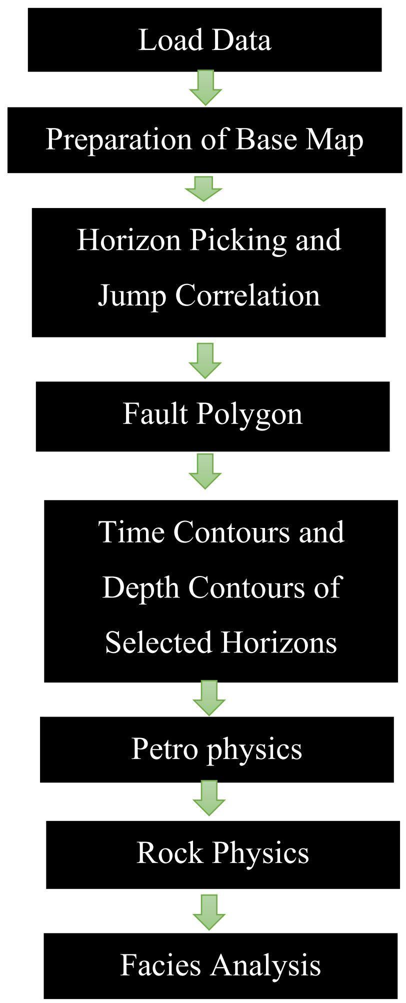


Figure 1.3 Workflow of dissertation

CHAPTER 02

GENERAL GEOLOGY AND STRATIGARPHY OF AREA

2.1 Central Indus Basin

The basin is separated from Upper Indus Basin by Sargodha High and Pezu Uplift in north. It is bounded by Indian Shield in the east, marginal zone of Indian Plate in west and Sukkur Rift in the South.(Asim et al, 2014)

Central Indus Basin is subdivided into three tectonic divisions as shown in figure 2.1:

- Punjab plateform
- Sulaiman depression.
- **Su**laiman fold belt (Kadri, 1995)

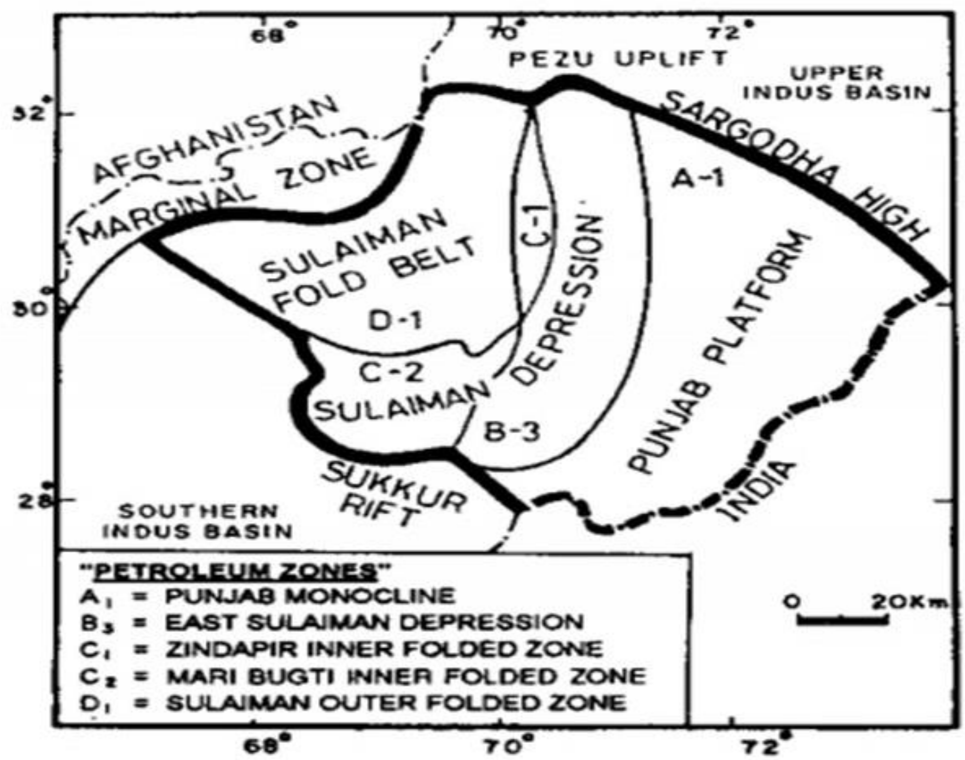


Figure 2.1 Central Indus Basin and sub division into petroleum zones (modified after Kadri, 1995)

2.2 Punjab Platform

The Punjab platform is tectonically, the least affected area because of its greater distance from collision zone(Asim et al,2014). This unit shows no surface outcrops of sedimentary rocks. Tectonically, it is a broad monocline dipping gently towards Sulaiman Depression(Kadri, 1995).

2.3 Sulaiman Foredeep

Sulaiman Fore deep is also known as Sulaiman Depression. The depression was formed as a result of two plate's collision. The western flank of depression includes Zindapir Inner Folded zone while in south there is Mari Bugti Inner Folded zone and it merges to Punjab Platform in the east. This depression is longitudinally oriented area of subsidence; it becomes accurate and takes up a transverse orientation along its southern rim. (Kadri, 1995).

2.4 Sulaiman Fold Belt

This is major tectonic feature in the proximity of collision zone and therefore contains a large number of disturbed anticlinal features. Asim et al, (2014) describes that there are some large anticlines with in Kirthar and Sulaiman belts especially along eastern margins, that are clearly detachments. The Sulaiman anticlines have broken limbs that are as result of steeply dipping faults classified as flower structures. The possible reservoirs are Ranikot Formation, Pab Formation and Lower Goru Formation. It is separated from khuzdar Block and Hazara Blocks by Kirthar Basement Fault and Sulaiman Basement faults respectively. (Raza et al, 2009).

2.5 Stratigraphy of the study area

The study area is located in Central Indus Basin. For this study well SABZAL-01 has been selected which has been drilled upto Cretaceous age rocks. The stratigraphic column Central Indus Basin is represented in figure 2.2.

2.5.1 Cretaceous

Sembar Formation, Goru Formation, Parh Formation and Pab formations are drilled.

Sembar Formation

Sembar Formation is composed mainly of clastic rocks, primarily shales followed by sandstone sand siltstone with minor limestone. The upper contact is conformable with Goru Formation. Numerous good source rock determination have been reported from Sembar(Kadri, 1995).

Goru Formation

Goru Formation is subdivide into Upper Goru and Lower Goru on the basis of lithology and petroleum system. The Upper Goru is mainly consist of Shales and the lower Goru is mainly sandstone. The lower contact is conformable with Sembar Formtion and upper contact with Parh Formation is transitional (Shah, 1977). The petroleum potential of Lower Goru sands is very good (Kadri, 1995).

Parh Limestone

Parh Formation is mainly composed of limestone with minor argillaceous content. No oil or gas has been reported from Parh Formation and no surface seeps are known. The argillaceous content and compact nature of limestone of the parh formation results in a low primary porosity (Kadri, 1995).

Mughal Kot /Fort Munro Formation

The Mughal Formation is a very heterogeneous unit. It is dark gray, calcareous mudstones with scattered intercalations of quartzose sandstone and argillaceous limestone. A dark limestone, often sandy, at the top of the Formation is widely distributed and has been called Fort Munro Limestone Member (Shah, 1977)

PAB Formation

PAB formation is composed of sandstone of cretaceous age. In some fields of Central Indus Basin PAB sandstone forms petroleum reservoir (Kadri, 1995).

2.5.2 Paleocene

Ranikot Formation of Paleocene age is encountered in the SABZAL-01. Ranikot Formation is subdivided into Upper Ranikot and Lower Ranikot. Lower Ranikot is composed of sandstone and Upper Ranikot is composed of Limestone (Shah,1977). It lies Pab sandstone unconformably. It is correlated with Dungan Formation.

2.5.3 Eocene

Sui Main Limestone, Ghazij, Habib Rahi Formation, Sirki, Pirkoh and Drazinda are encountered in SABZAL-01.

Sui Main Limestone

Sui Main Limestone is composed of limestone. The Formtion is fossiliferous making it a good reservoir rock in the central Indus Basin. The limestone of this formation is reported as main potential for hydrocarbon because it is buildup on a stable platform, while timely gas entrapment is responsible for preservation of porosity(Kadri, 1995)

Habib Rahi Formation

Habib Rahi Formation of Eocene age is composed of limestone. It is highly fossiliferous like Sui Main Limestone as result it has a reservoir potential (Shah, 1977).

Sirki Formation

The formation is composed of shales mainly (Shah, 1977).

Pirkoh Formation

The formation is composed of limestone. The abundant faunal content is foraminifera (Shah, 1977).

Drazinda Formation

Drazinda is composed of shales. The formation is highly fossiliferous (Shah, 1977).

2.5.4 Post Eocene

Siwalik Group is encountered in the well. The Siwalik group is composed of sandstones with alternating bands of argillaceous material (Kadri, 1995).

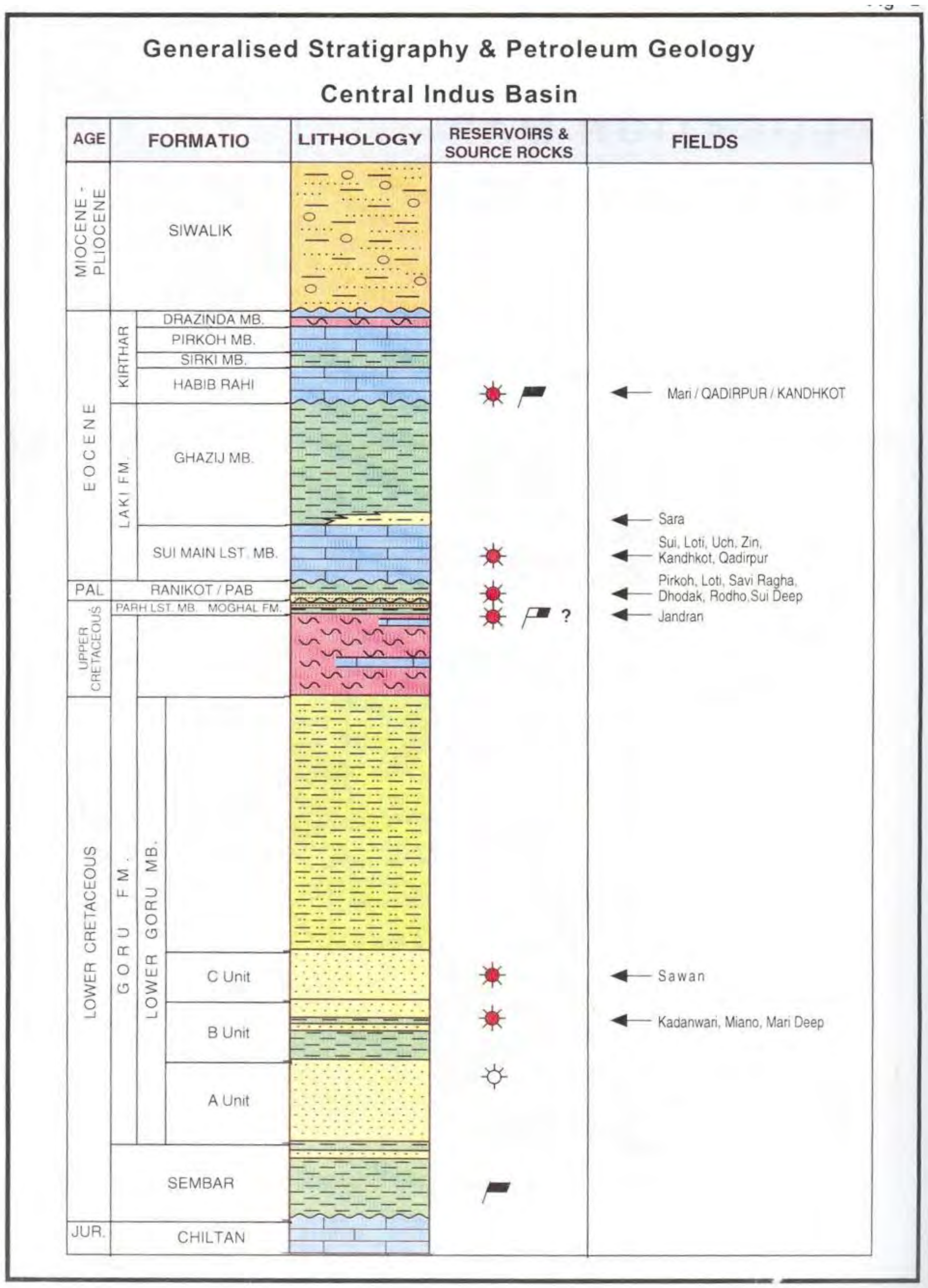


Figure- 2.3 Stratigraphy and depositional environment of Indus Basin (Khan et al, 1999)

2.6 Petroleum System of Study Area

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

2.6.1 Source rocks

Source rock is the productive rocks for hydrocarbons. They also initiated the conversion of organic compound into oil and gas form. Sembar shales is proven to be th3e source rock of the project area. Other potential source rocks are shales of Goru, Ranikot, Sirki, and Pab Formation (Kadri, 1995).

2.6.2 Reservoir Rocks

The rocks that contain the hydrocarbons have the porosity as well as permeability is called reservoir rock. The major reservoir rock of the project area is Sui Main Limestone of Eocene age. Habib Rahi Formations and Lower Goru sandstones are also thought to be secondary reservoir of prospect area (Kadri, 1995)

2.6.3 Seal rock

The rocks that act as a cap rock and used to seal the hydrocarbons are called Seal rocks. These should be impermeable. The following formations act as seal rock in the middle and upper Indus basin, Ghazij Shale acting as a seal rock for Sui Main Limestone, Ranikot formation and Sirki Shale acting as a seal rock for Habib Rahi Formation (Kadri, 1995).

CHAPTER 03

SEISMIC INTERPRETATION

3.1 Seismic Interpretation

This chapter deals with the structural Interpretation of 2D seismic data of Dandhi Area. Seismic interpretation is the transformation of the seismic reflection data in to a Geological image by the application of corrections, migration and time to depth conversion(Yilmaz, 2001). The seismic reflection data interpretation usually involves calculating the position and identifying geologically hidden interfaces or sharp transition zone formed seismic pulses return to ground surface by reflection. The impact of varying geological condition is brightened along the profiles to transform the irregular recorded travel time in to acceptable sub surface models(Badly, 1985). This is very important for confident approximation of the depth and geometry of the bed rock or target horizons.

3.2Work Procedure

The workflow of seismic interpretation begins by loading Navigation File and SEG-Y Data in software. Also loading well in software. Then integrating well data to seismic data to obtain synthetic seismogram and mark the horizons of interest on Well line and on other lines from control line. Marking of faults on discontinuities present. In the last step generate Time-depth contour maps of marked horizons. The schematic work flow has been shown in the figure 3.2.

3.3 Base Map

Base map shows all the survey lines of an area which are acquired according to their location. After loading the Navigation file and Seismic data (SEG Y), Base map is generated. For completion of this dissertation the assigned lines are.

- O-846-DAN-201(Dip line).
- O-846-DAN-205(Strike line).
- O-846-DAN-211(Dip line).

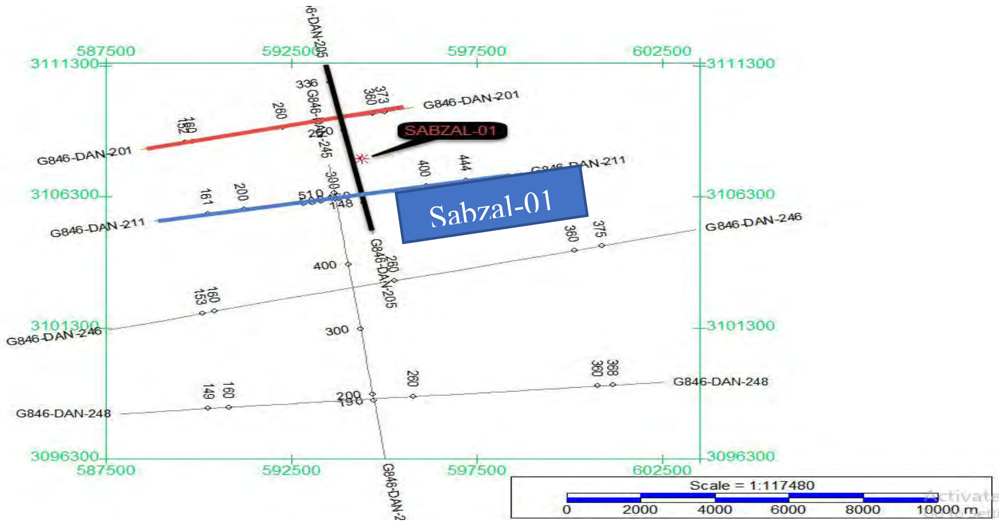


Figure 3.1 Base Map of Dhandi Area

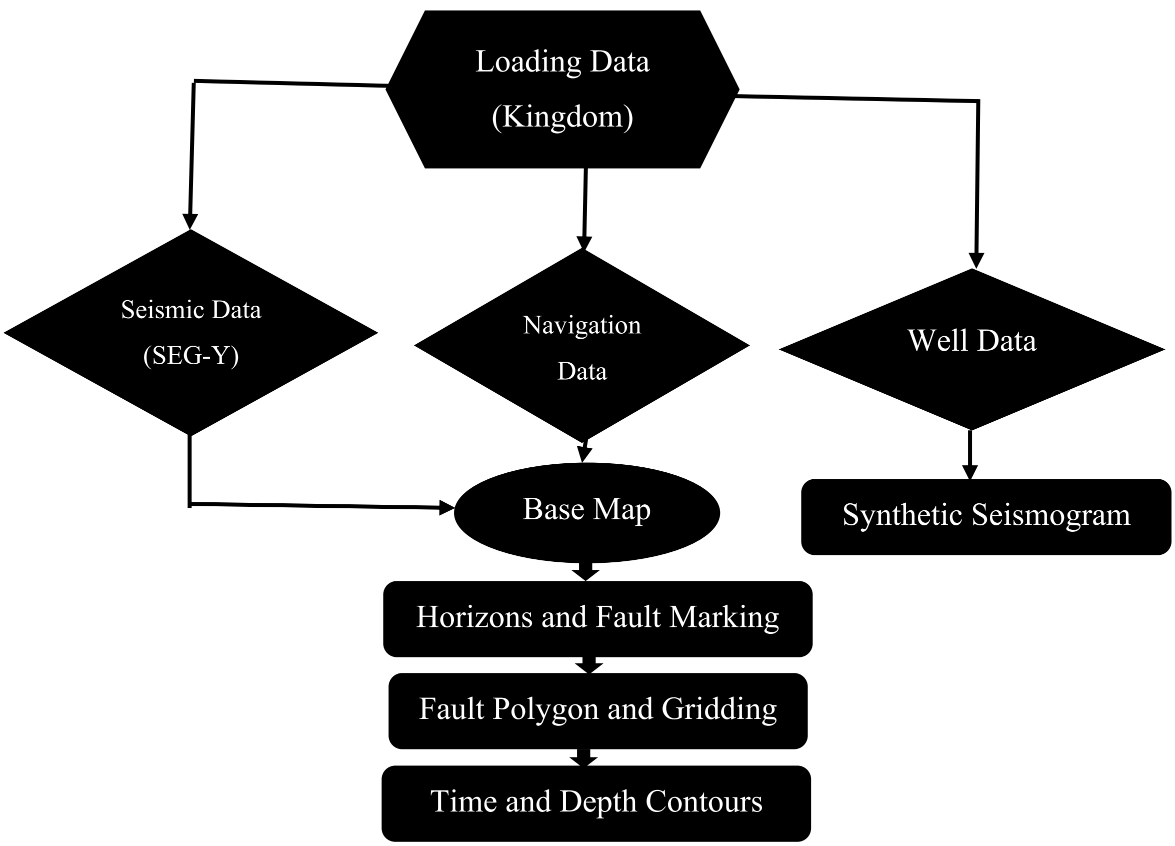


Figure 3.2 Work Flow adopted for the seismic data interpretation

3.4 Time to Depth Conversion

The seismic data is in time domain while the well log data is in depth domain. The bridge between time and depth is velocity. The velocity technique uses input data from variety of sources such as Seismic-to-well tie, check shot survey, Vertical Seismic Profile (VSP), and integrated sonic log. The following procedure is to be adopted for Time-Depth conversion:

- Compute thickness of each formation top by subtracting the top value of one formation from the top value of next successive formation.
- Convert sonic log into interval velocity i.e

  $V_{int} = \frac{1}{DT}$

  DT = Sonic log
- Divide the thickness by interval velocity to compute delta time.

Formation	Depth(H)	Thickness	V(int)	Delta time	D.time*V(int)	V(avg)	Twt
Siwaliks	0	693	2317.366	0.299046417	692.9999701	2317.366	0
Drazinda	693	44	2181.59	0.020168776	44	2308.787	0.600315
Pirkoh	737	90	3730.419	0.024125976	90	2408.683	0.611953
Sirki	827	67	4008.053	0.016716346	67	2482.937	0.666147
Habib Rahi	894	109	3648.277	0.029877117	109	2572.226	0.695118
Ghazij	1003	324	2360.175	0.137277974	324	2517.011	0.796977
SML*	1327	186	4145.73	0.044865442	186	2644.744	1.0035
U. Ranikot	1613	67	3055.86	0.021925085	67	2659.919	1.212819
L. Ranikot	1680	43	3706.436	0.011601442	43	2679.966	1.253747
Pab	1723	322	3523.515	0.091386011	322	2790.568	1.234874
Parh	2045	503	4275.712	0.11764122	503	3005.039	1.361047
Upper Goru	2548	407	3750.713	0.108512693	407	3092.69	1.647756
Lower Goru	2955	430	4063.431	0.105821913	430	3192.524	1.8512
Sembar	3385	354	4341.693	0.081535023	354	3276.898	2.065978

*SML= Sui Main Limestone

- Compute average velocity from interval velocity by using the equation:

$V_{avg} = \sum_{i=1}^{n} \frac{v_{i\Delta t_i}}{\Delta t_i}$

Where v_i = interval velocity of i^{th} layer

Δt_i = delta time

- ❖ In the last step, divide depth by average velocity and multiply the result by 2 to get two way time.

3.5 Synthetic Seismogram

Synthetic seismogram is a seismic trace created from sonic and density logs and is used to compare original seismic data collected near the well location (Onajite, 2014).

The primary well data required to generate synthetic seismic trace is sonic log and density log. The following procedure is adopted to generate synthetic seismogram:

- ❖ Multiply sonic and density log to obtain acoustic impedance log.

$$Z = \rho \text{ x v}$$

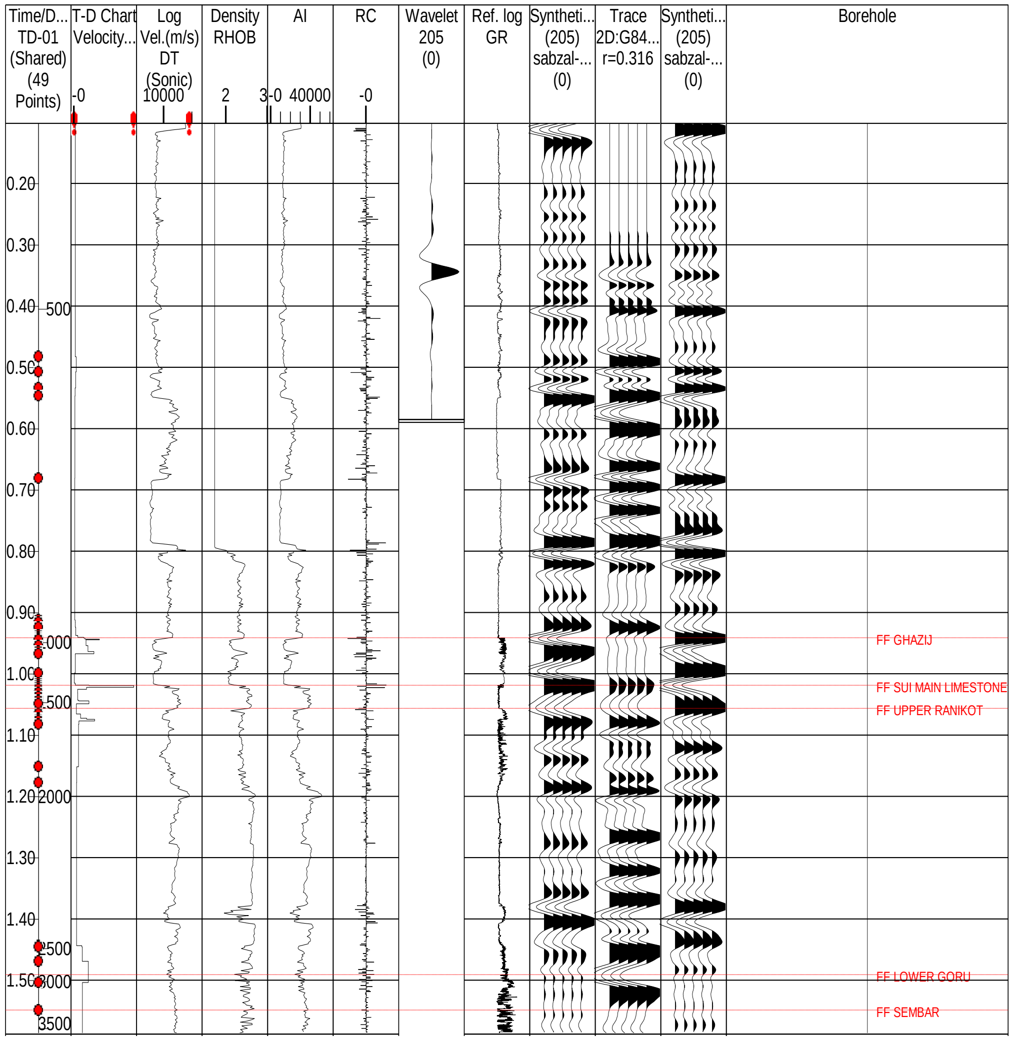
Where Z = Acoustic impedance, $\rho =$ density log and v = sonic log.

- ❖ Now compute reflection coefficient for each interface using Zeoppritz Equation:

$$R_i = \frac{Z_{i+1} - Z_i}{Z_{i+1} + Z_i}$$

- ❖ In the last step convolve source wavelet with the reflection coefficient to compute seismic trace.

$$S(t) = S(w) * RC$$



FORMATION	DEPTH (Elev. Ref)	DEPTH (TVDSeis)	AVG VEL	TIME TO TOP	TIME THICKNESS	INT VEL	THICKNESS
FF GHAZIJ	1003.0	924.2	1963.7	0.94127	0.07747	8364.1	324.0
FF SUI MAIN LIMESTONE	1327.0	1248.2	2450.5	1.01874	0.03765	15192.7	286.0
FF UPPER RANIKOT	1613.0	1534.2	2904.6	1.05639	0.43448	6177.5	1342.0
FF LOWER GORU	2955.0	2876.2	3858.4	1.49087	0.05783	14871.9	430.0
FF SEMBAR	3385.0	3306.2	4269.6	1.54870			

Figure 2.3 Synthetic Seismogram of Sabzal-01

Where S(t) = Synthetic seismic trace, S(w) = source wavelet and RC = Reflection coefficient.

3.6 Marking and identification of seismic horizons:

To distinguish different Horizons on seismic sections is an important query in the interpretation of seismic data, which may be structural or Stratigraphic. For this purpose the seismic data is correlated with well Top data and already known geology of area (Dobrin and savit 1988).

The first step of Seismic data interpretation is to mark the horizons on the seismic sections. A horizon is defined as "an interface or boundary between two rock units (formations)". Those reflectors are selected which are real, show strong character ,continuity and can be followed throughout the seismic line and also can be correlated at tie points of other seismic lines of the area (Badely, 1985). Five horizons are marked on the Seismic lines. These horizons were marked through the same steps and all the sections are correlated at their respective tie points. The reflectors are strong enough to be picked because of contrast in acoustic impedance that is ultimately caused by changes in lithology. Normally the VSP data is used for naming the marked horizons. But in this study due to the unavailability of VSP data the identification of Horizons has been done by using the depths of the formations from the well top data of Sabzal-01 and also depths can be calculated by using interval and average velocities derived during processing of seismic data. In this study five horizons are marked on seismic lines O-846-DAN-201, O-846-DAN-205 and O-846-DAN-211.

3.7 Seismic Tie

After marking horizons on a seismic section the next step is to tie the seismic section with the other intersecting seismic lines of the area. In this study horizons on the seismic line O-846-DAN-205 are marked first because it is nearer to the well Sabzal-01. The tie points of the lines are confirmed from the base map, where tie points of the lines have been mentioned. At the tie point of both Intersecting seismic lines have same horizons at the same time. If the horizon does not have same time then there may be mistie that may be removed later on, Taking seismic line O-846-DAN-205 as a reference line, all other seismic sections used in the study are marked. Seismic Interpretation

To develop complete interpretation there is a need for congregation of all the relevant seismic and well data and this would be helpful in providing the accurate results. The basic aim of seismic data interpretation is to construct a geological model. In the first step the prominent reflector are picked and correlated with the well tops of Sabzal-01 and the reflectors are identified. Also the lines are correlated with the synthetic seismogram of these wells. The nearest line to the well Sabzal-01 is O-846-DAN-205 so first of all this line is interpreted. Using tie of seismic lines from O-846-DAN-205 the other lines used in the study are marked. Five horizons are marked on all the seismic lines used in the study, with the help of well data all these horizons were named and ages were assigned to Horizons. The detail of marked Horizons with specific color assigned is given as under Horizon 1 is Ghazij Shales of Eocene age (golden color), Horizon 2 is the Sui

Main Limestone of Eocene age (Light green), Horizon 3 is the Upper Ranikot Shales (Tomato color), Horizon 4 is Lower Goru of Cretaceous age (pink), Horizon 5 is Sembar shale of Cretaceous age (Dark blue). The horizons were marked with a specific color scheme as color of each reflector is mentioned above. Throughout the study color scheme is kept constant for each horizon. The direction of deposition is east to west in the study area so the EW trending lines are dip lines. The NS trending lines are strike lines and on strike lines. The base map of the lines used for the study along with the well location is shown in figure 3.1.

3.8 Interpreted Seismic Sections

3.8.1 Interpretation of Strike line DAN-205

Line DAN-205 is a strike line which is NW-SE oriented and is the major control line. Ghazij, Sui Main Limestone, Upper Ranikot, Lower Goru and Sembar are marked on this line which are straight and continuous showing the area is tectonically stable.

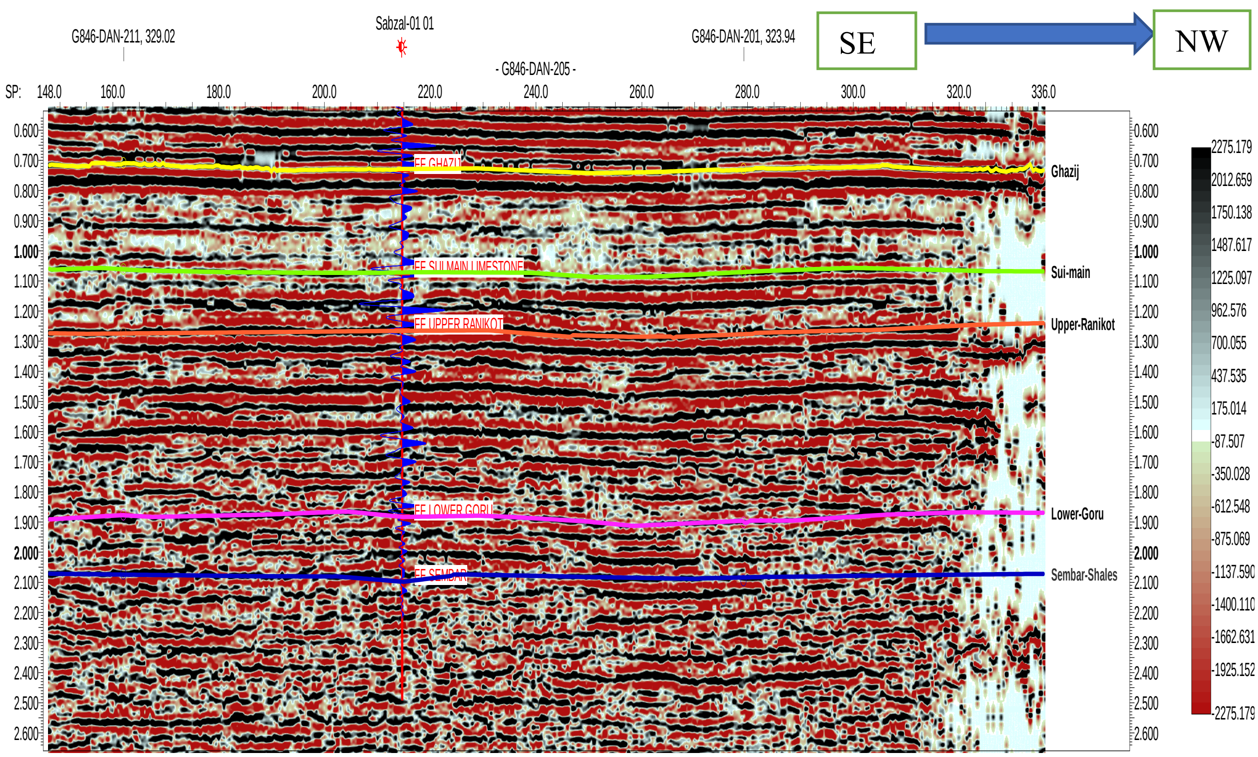


Figure 3.3 Interpreted Seismic Section DAN-205

3.8.2 Interpretation of Dip line DAN-201

Line DAN-201 is a dip line which is SW-NE oriented and is the major control line. Ghazij, Sui Main Limestone, Upper Ranikot, Lower Goru and Sembar are marked on this line which are straight and continuous showing the area is tectonically stable. No major discontinuity is observed.

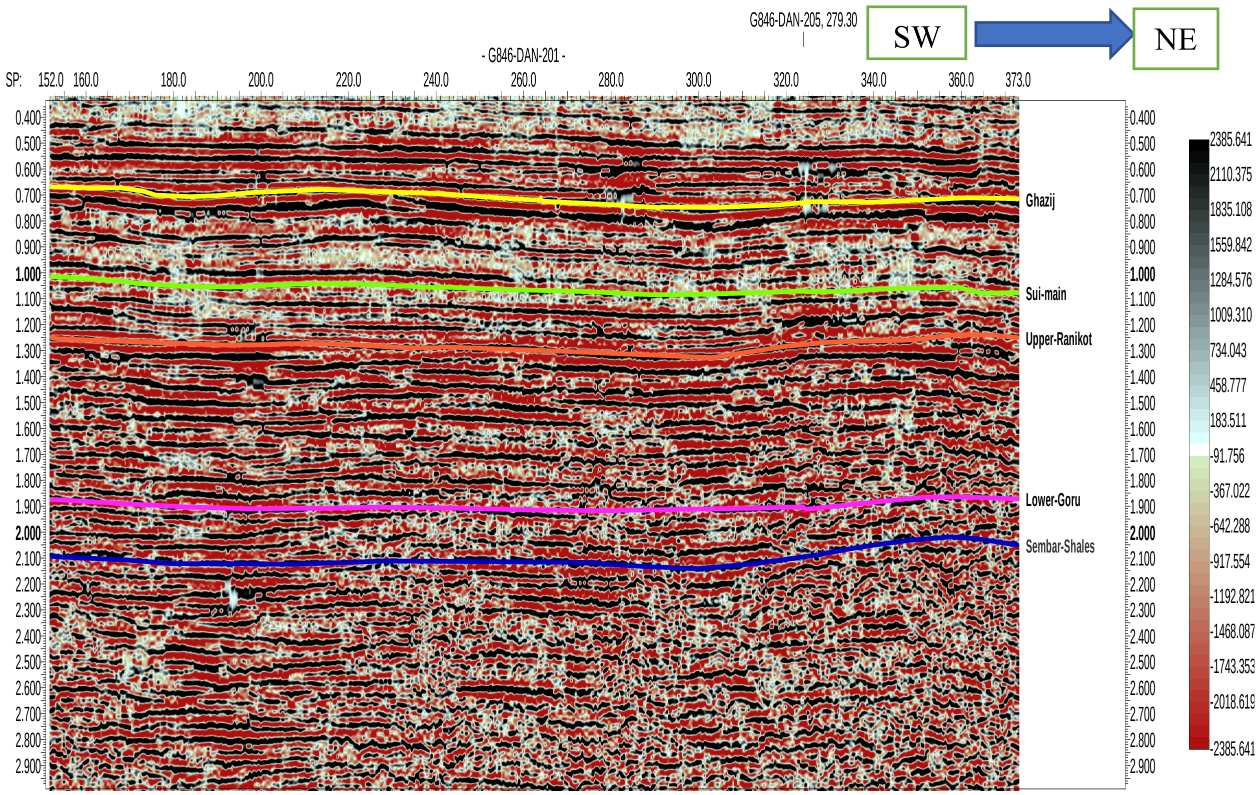


Figure 3.4 Interpreted Seismic Section DAN-201

3.8.3 Interpretation of Dip Line DAN-211

Line DAN-211 is a Dip line which is SW-NE oriented and is the major control line. Ghazij, Sui Main Limestone, Upper Ranikot, Lower Goru and Sembar are marked on this line which are straight and continuous showing the area is tectonically stable.

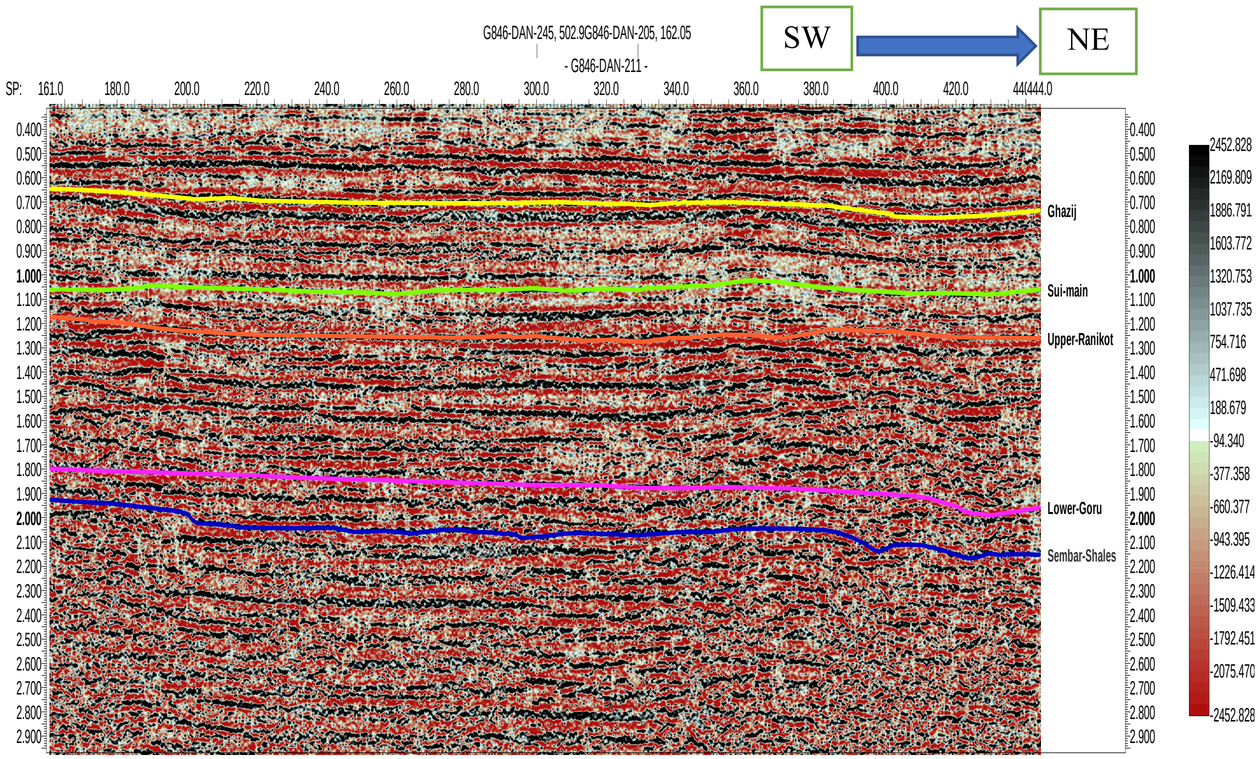


Fig 3.7 Interpreted Seismic Section DAN-211

3.9 Contour Maps

A map prepared by seismic time of horizons at every seismic line is intended to show the structure in the subsurface. Obviously it doesn't show structure directly but it gives us the idea of subsurface structure as well as the distribution of horizon in subsurface. The time and depth contour maps are limited to the specific area so basically it is a local study of the area. In this study, time contour maps are generated. Two-way travel time of the seismic waves is plotted against the Northings and Eastings (X and Y's) and the contours of time are calculated. The time contour maps for the reservoir formations of the area with respect to time. The details of these time contour maps is given as under.

3.9.1 Time and Depth Contour Map of Ghazij Formation

Time and depth contour map of Ghazij Formation is shown in figure 3.8 and 3.9. Time and Depth variation is given through color bar. Red color shows the lowest values i.e shallowest part while the dark blue and black color is showing deeper parts. It is clear that Ghazij is deepening NW-SE direction as the time is increasing and Ghazij formation is shallowing towards NE-SW direction because time is decreasing. Hence the red color is showing low time values and it is a good indicator for hydrocarbon.

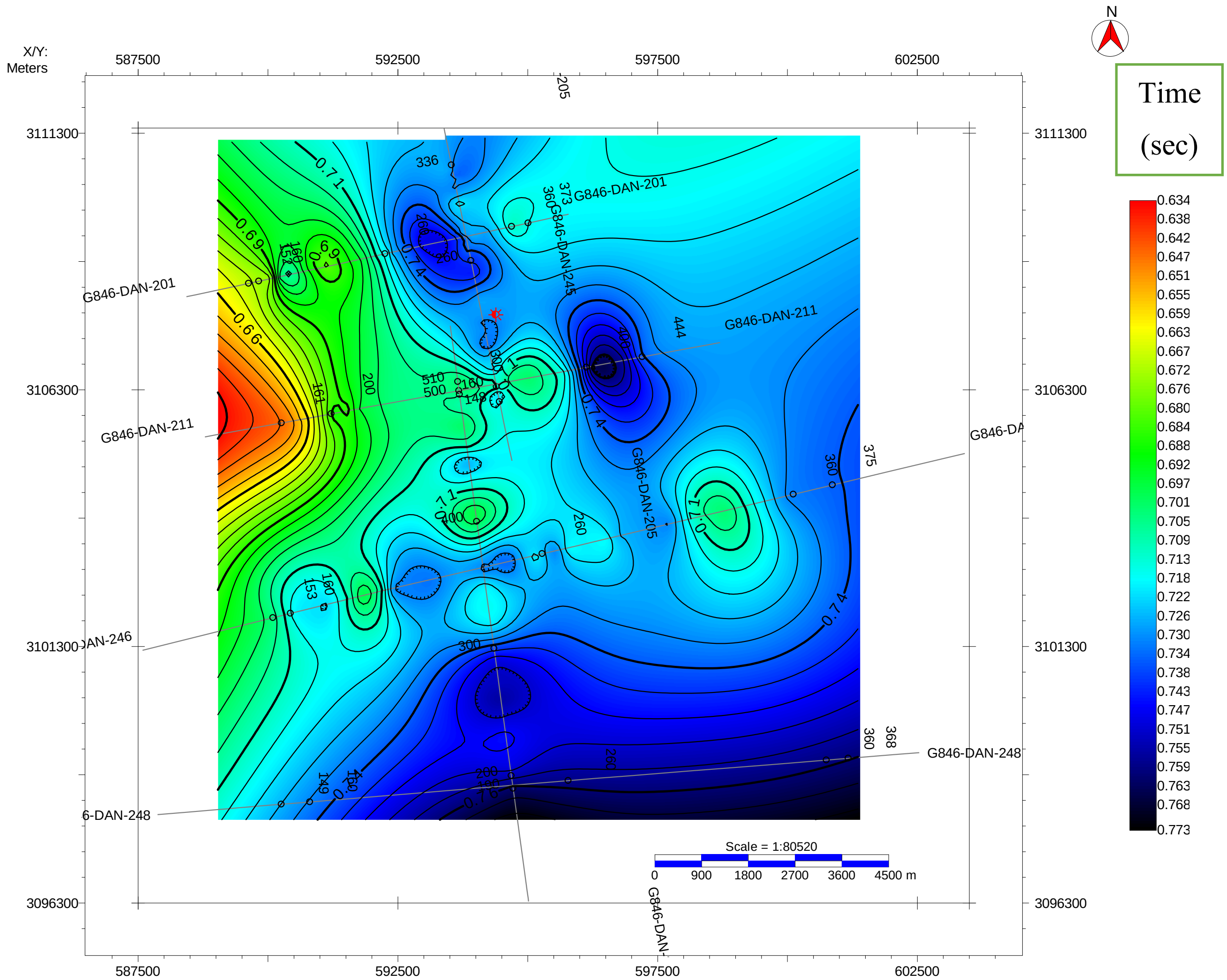


Figure 3.8 Time contour map of Ghazij

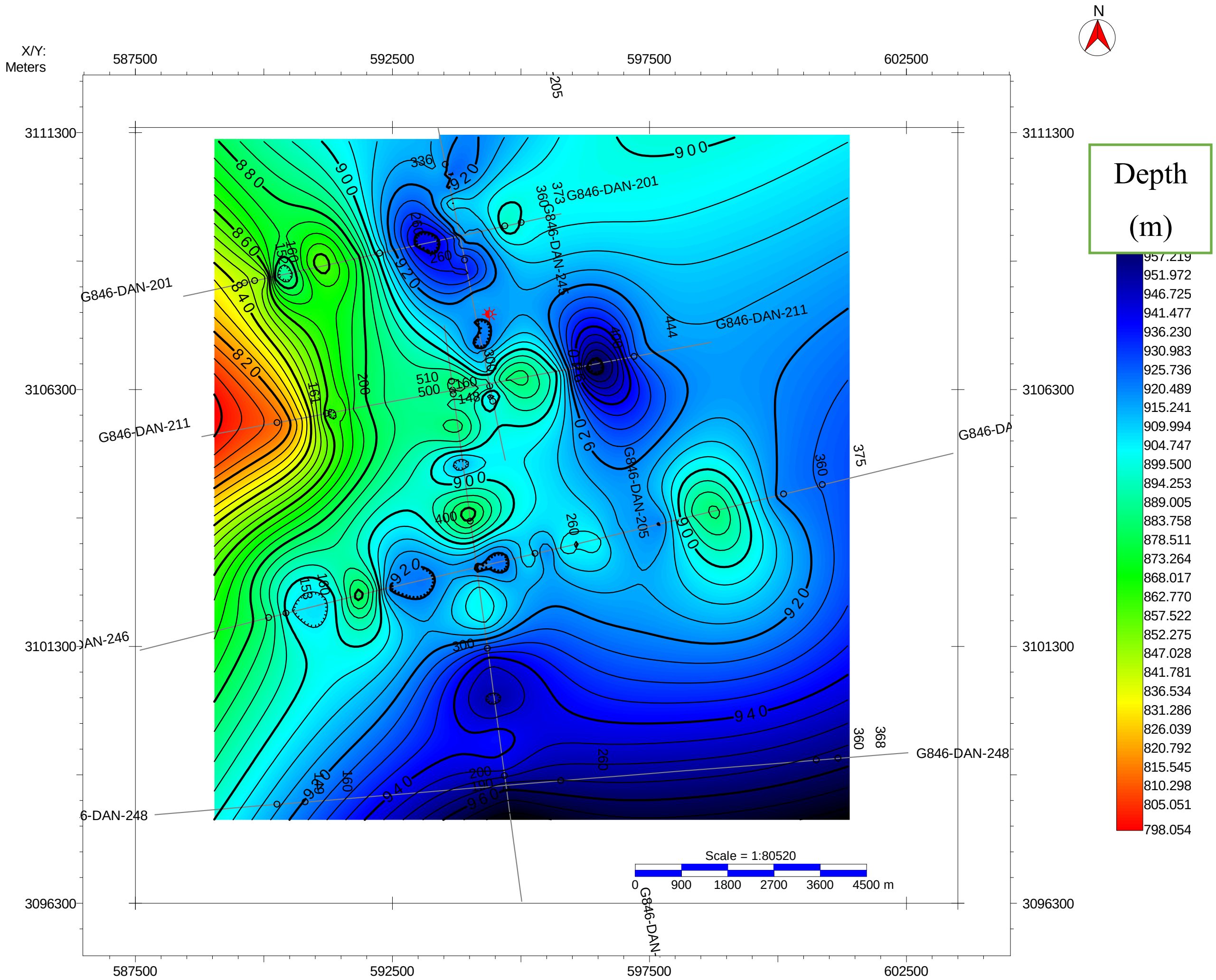


Figure 3.9: Depth contour map of Ghazij formation

3.9.2.Time And Depth Contour Map of Sui Main Limestone

Time and depth contour map of Sui Main Limestone formation are shown in figure 3.10 and 3.11. Time and Depth variation is given through color bar. Red color shows the lowest values i.e shallowest part while the dark blue and black color is showing deeper parts. It is clear that Sui Main Limestone is deepening NW-SE direction as the time is increasing and Sui Main Limestone formation is shallowing towards NE-SW direction because time is decreasing. Hence the red color is showing low time values and it is a good indicator for hydrocarbon.

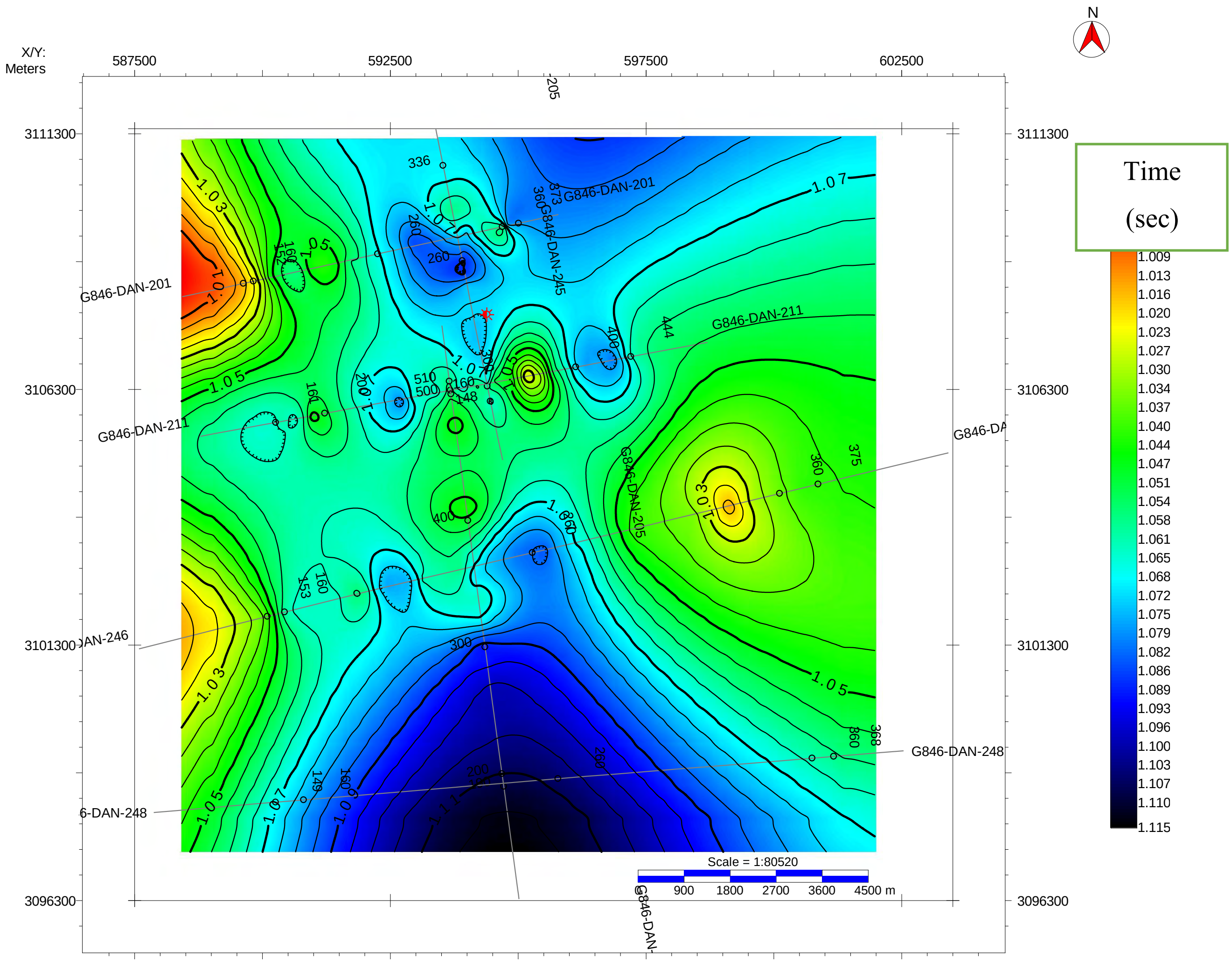


Figure 3.10 Time contour map of Sui Main Limestone

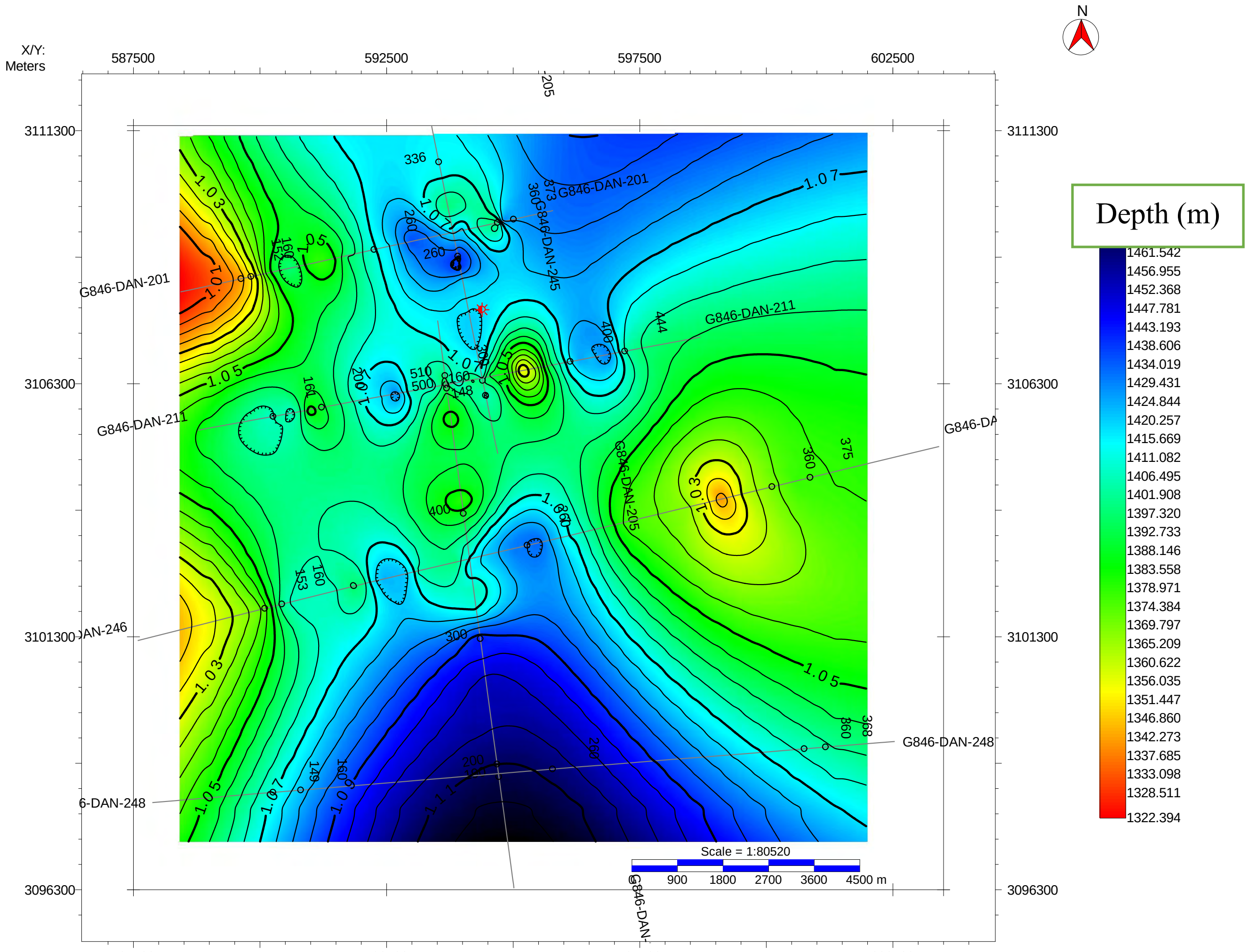


Figure 3.11 Depth Contour Map of Sui Main Limestone

3.9.3.Time and Depth Contour Map of Upper Ranikot Formation

Time and depth contour map of Ranikot formation is shown in figure 3.12 and 3.13. Time and Depth variation is given through color bar. Red color shows the lowest values i.e shallowest part while the dark blue and black color is showing deeper parts. It is clear that Upper Ranikot is deepening NW-SE direction as the time is increasing and Upper Ranikot formation is shallowing towards NE-SW direction because time is decreasing. Hence the red color is showing low time values and it is a good indicator for hydrocarbon.

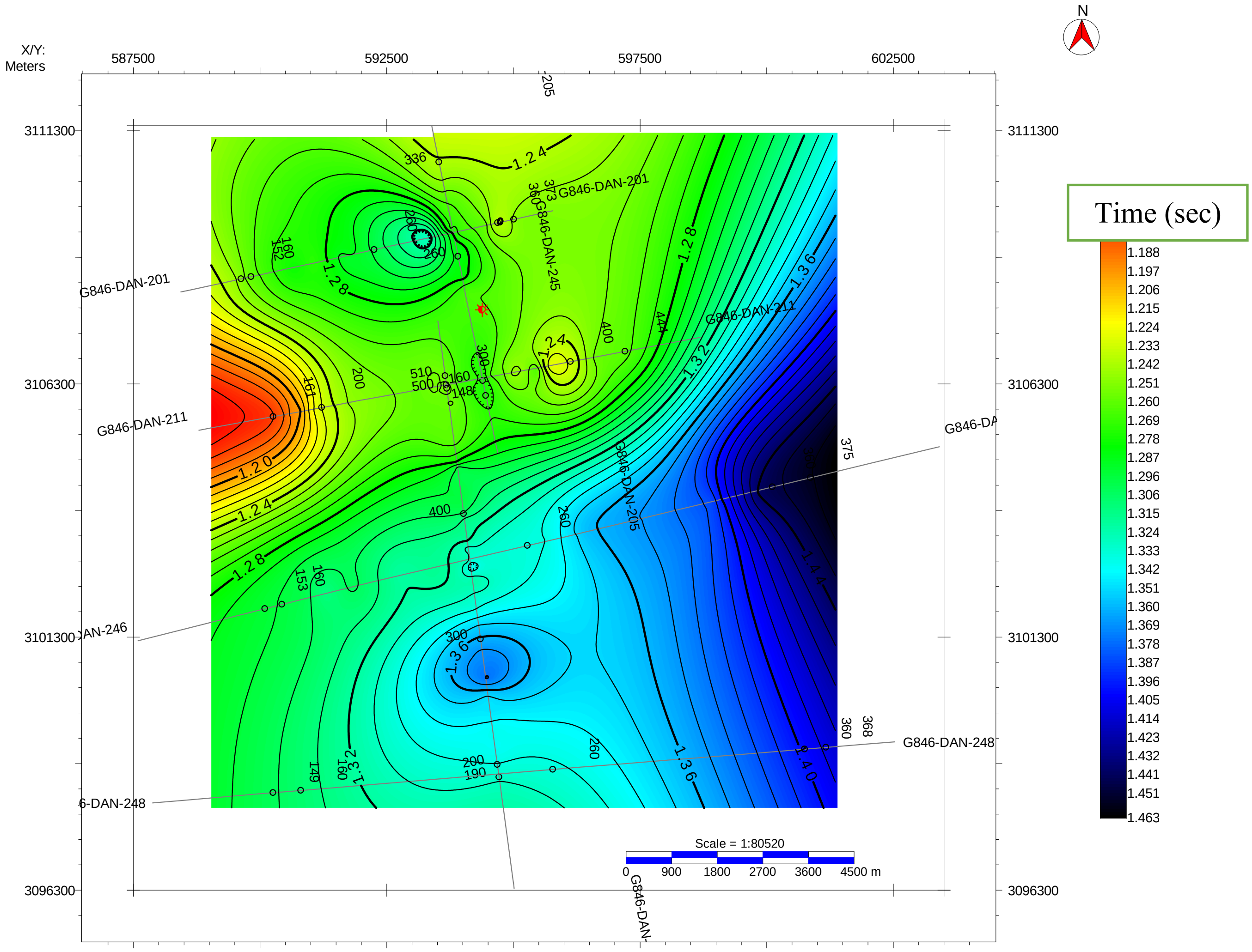


Figure 3.12 Time Contour map of Upper Ranikot

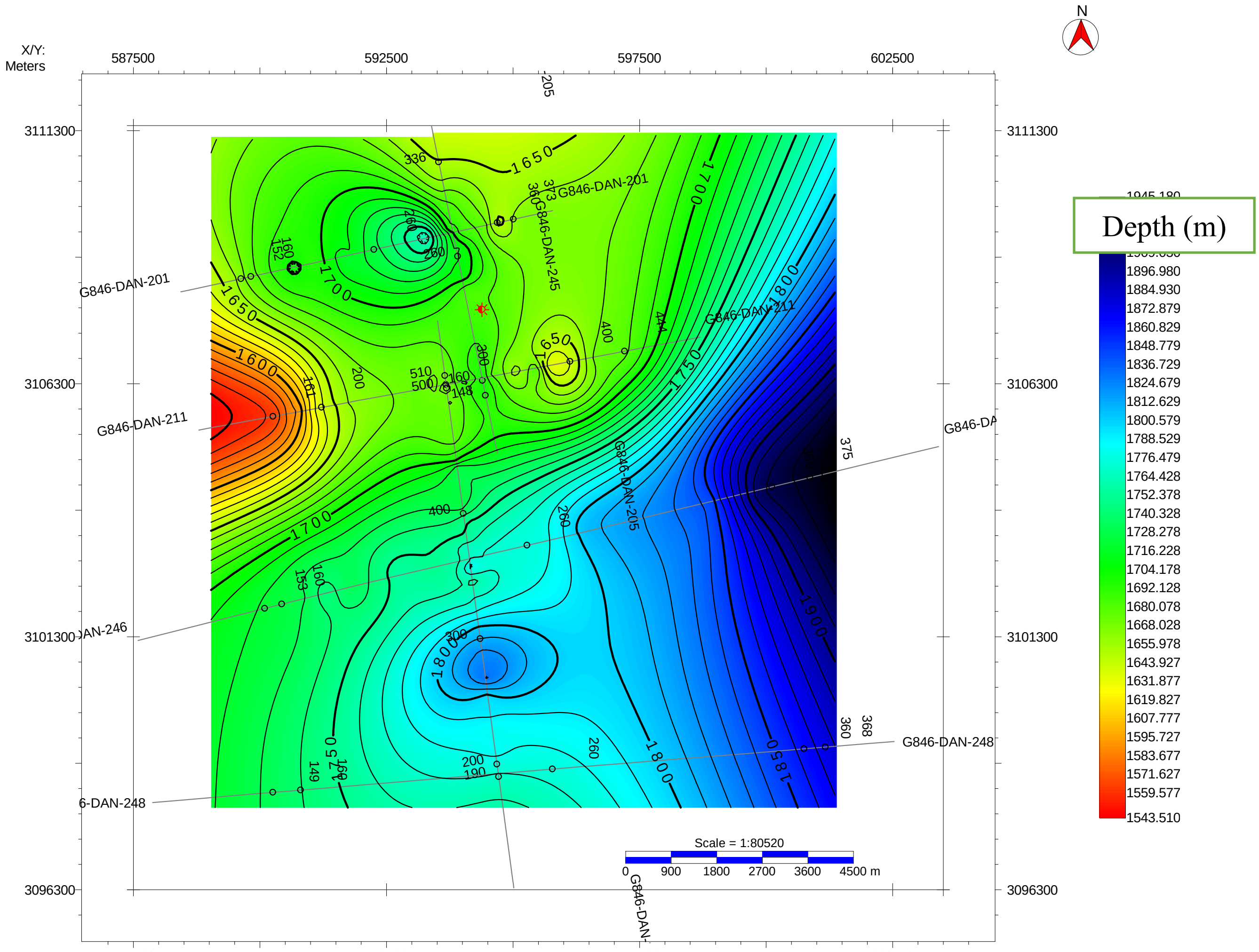


Figure 3.13 Depth contour map of Ranikot formation

3.9.4 Time and Depth Contour Map of Lower Goru

Time and depth contour map of Lower Goru formation is shown in figure 3.14 and 3.15. Time and Depth variation is given through color bar. Red color shows the lowest values i.e shallowest part while the dark blue and black color is showing deeper parts. It is clear that Lower Goru is deepening NW-SE direction as the time is increasing and Murree formation is shallowing towards NE-SW direction because time is decreasing. Hence the red color is showing low time values and it is a good indicator for hydrocarbon.

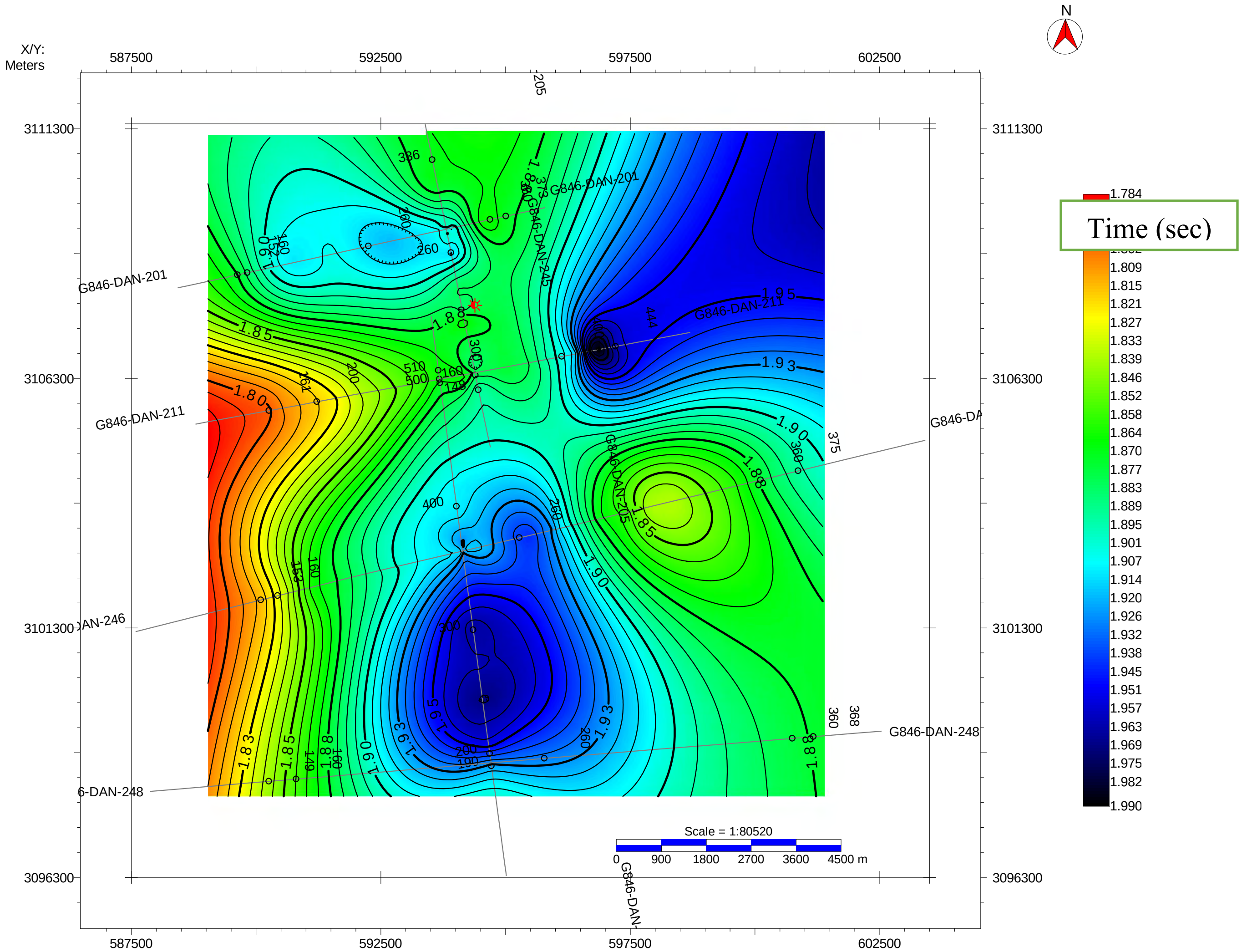


Figure 3.14 Time Contour Map of Lower Goru

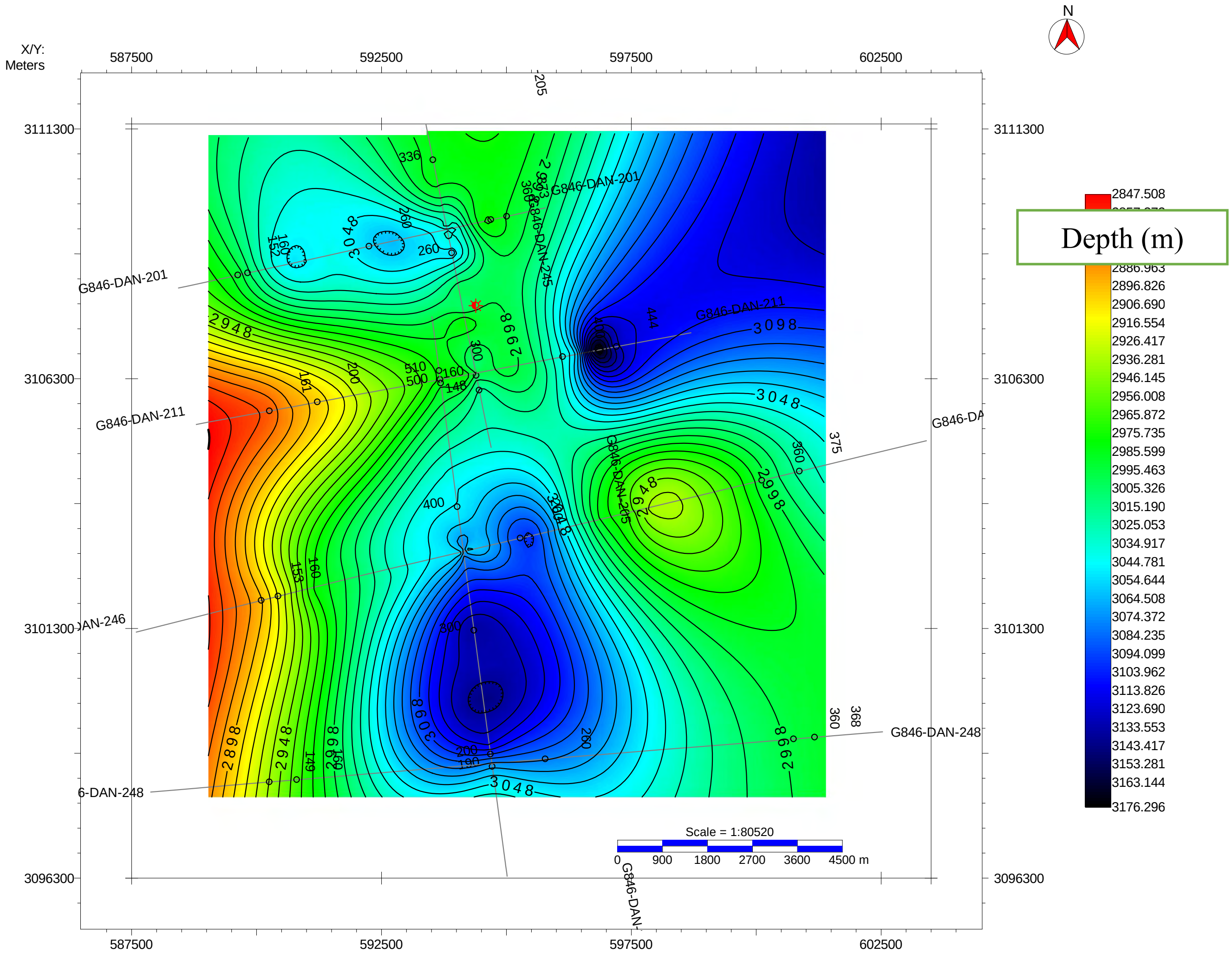


Figure 3.15 Depth contour map of Lower Goru

3.9.5 Time Contour Map of Sembar

Time and depth contour map of Sembar formation is shown in figure 3.16 and 3.17. Time and Depth variation is given through color bar. Red color shows the lowest values i.e shallowest part while the dark blue and black color is showing deeper parts. It is clear that Sembar is deepening NW-SE direction as the time is increasing and Sembar formation is shallowing towards NE-SW direction because time is decreasing. Hence the red color is showing low time values and it is a good indicator for hydrocarbon.

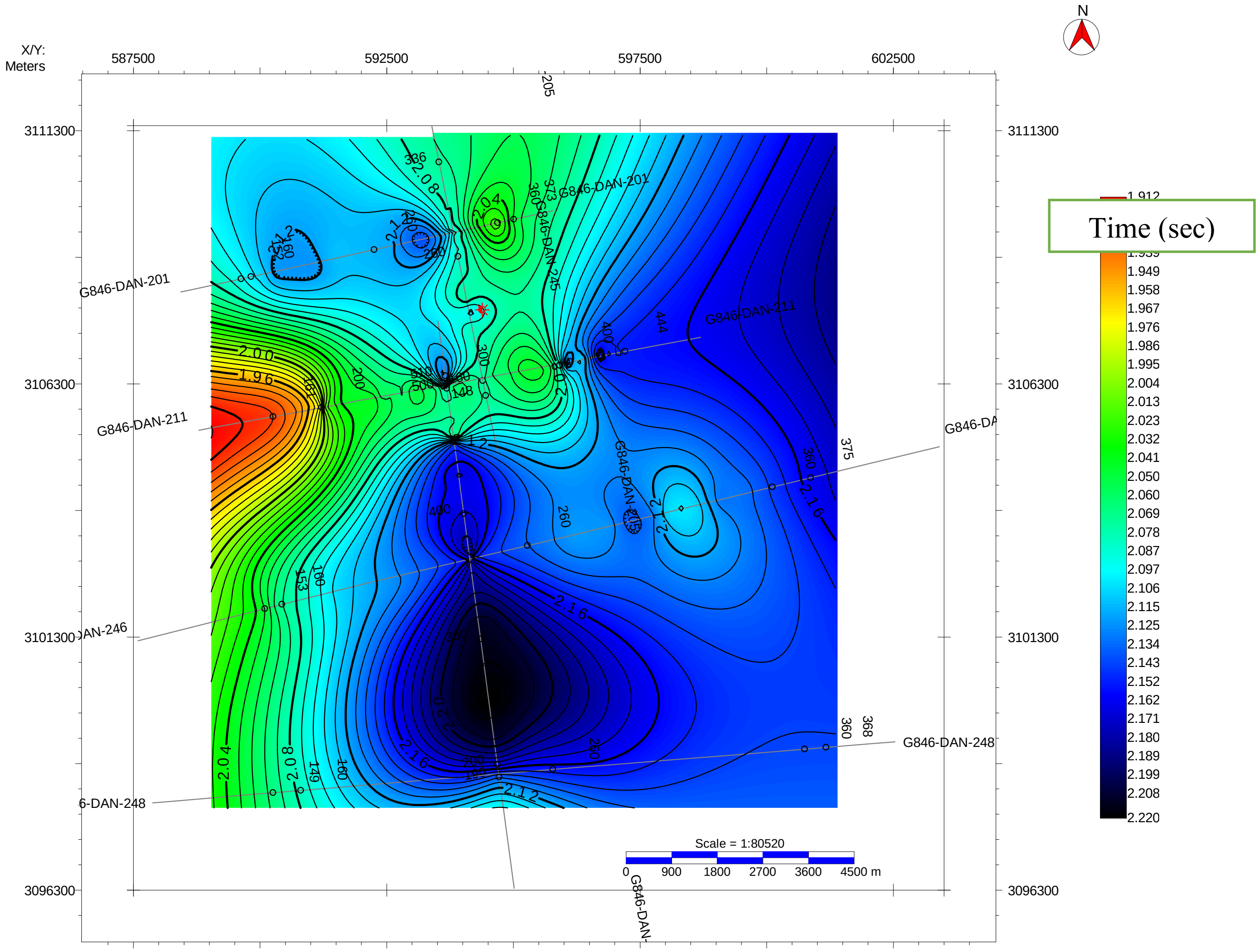


Figure 3.16 Time contour map of sembar Shale

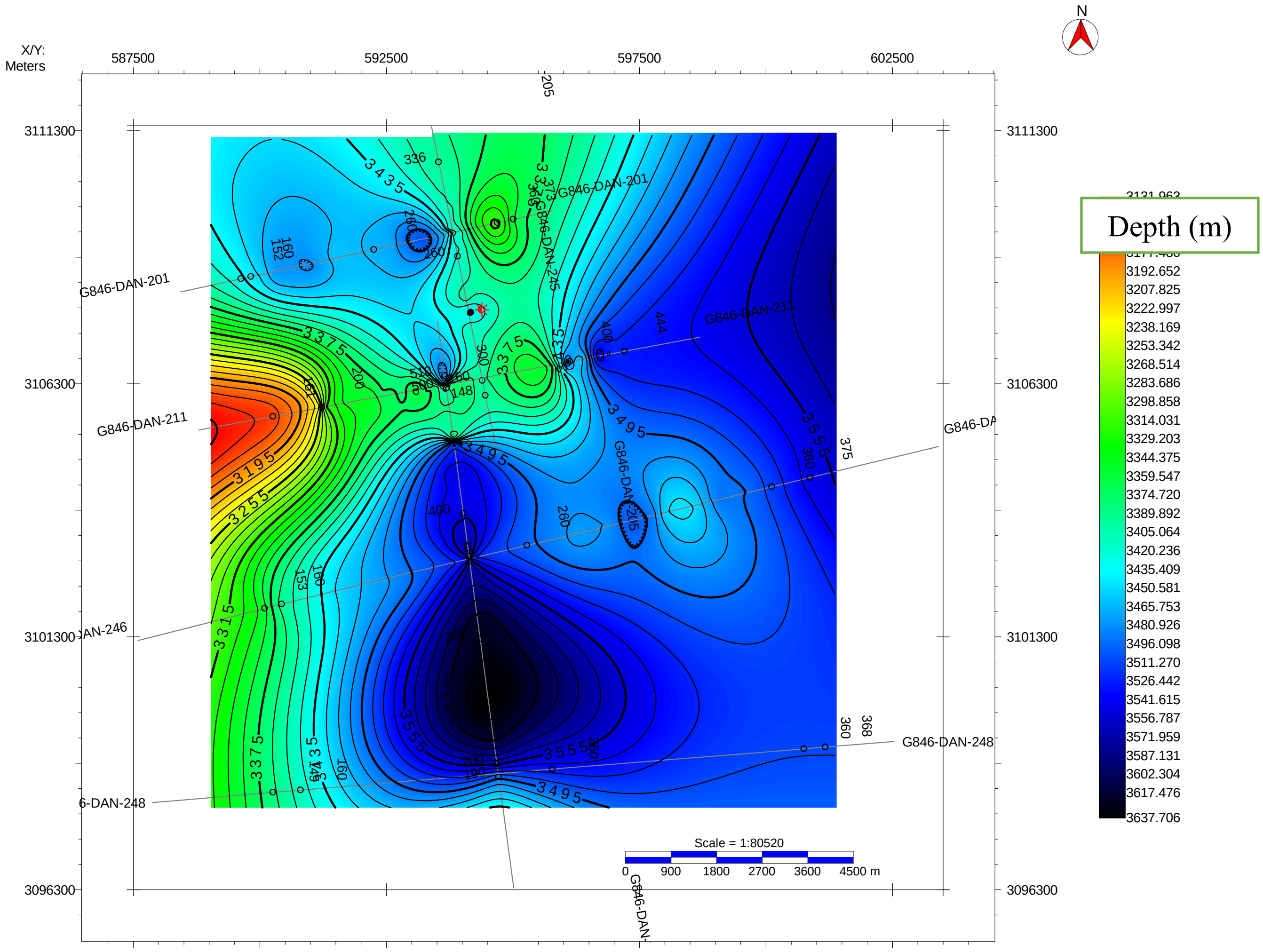


Figure 3.17 Depth contour map of sembar shale

CHAPTER 04

PETROPHYSICS

4.1 Petro physical Analysis

Electrical well logging was introduced to the oil and gas industry over half a century ago and since then, many improved and additional logging tools and devices have been developed and have been put in general use. The art of interpretation of the data advanced along with the advancements in well logging science. Today, the detailed analysis of a carefully chosen suite of wire-line services provides a method of inferring or deriving accurate values for the following:

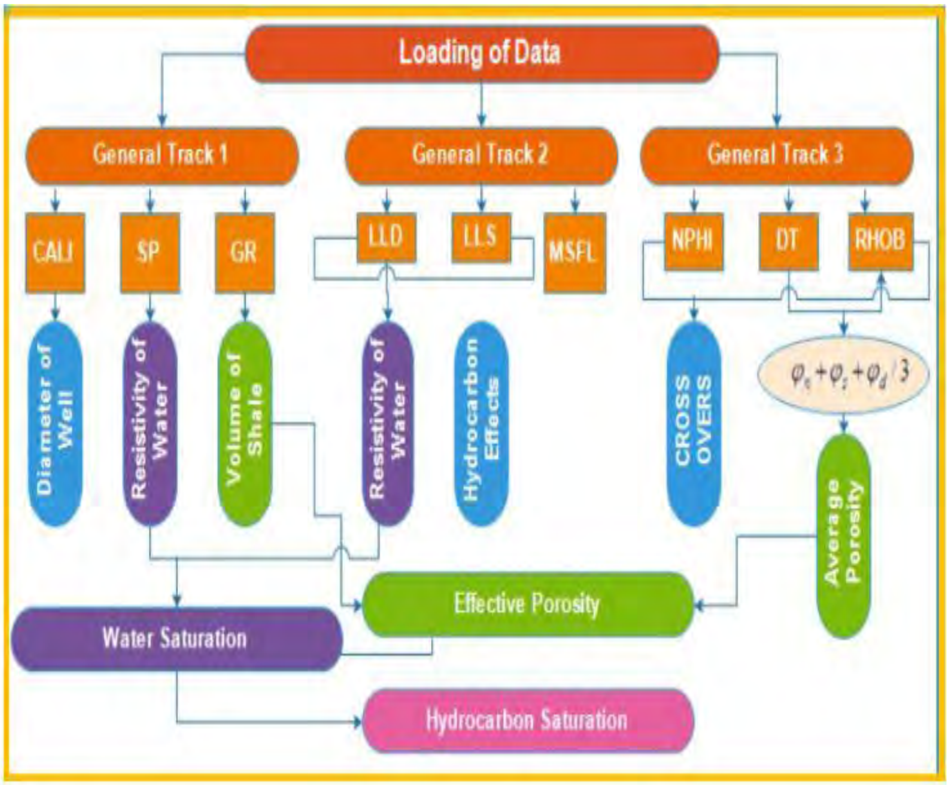
- ❖ Hydrocarbons and water saturations
- ❖ Permeability index
- ❖ Porosity
- ❖ Lithology of the reservoir rock.

The petrophysical analysis was carried out by using the following wireline logs of Sabzal_01 issued by DGPC:

- ❖ Density log
- ❖ Neutron log
- ❖ Resistivity logs
- ❖ Spontaneous Potential log
- ❖ Gamma Ray log
- ❖ Neutron Porosity log
- ❖ Caliper log

4.2 Log Curves

The log data of Sabzal_01 was available in Logging ASCII Standard (LAS) format. The log curves along with some parameters given in the LAS file header are used to calculate all basic and advance parameters. The methodology adopted for this work is given in Fig 4.1 and each analysis step is discussed in the proceeding sub-sections.



4.1 Flowchart of scheme used for Petrophysical Analysis

4.3 Calculation of the Volume of Shale

The source formations are commonly shally with higher radioactive content and are therefore indicated by a higher Gamma Ray value. On the other hand, it is also assumed that the radioactive material is not present in other formations which are termed as clean formations. This creates a contrast between shale and other formations.

Gamma Ray log is used to calculate the volume of shale. The maximum value of gamma ray corresponds to the 100% shale and lowest value corresponds to 0% shale i.e clean formation. The volume of shale can be computed from below formula:

$$\text{Volume of Shale (Vsh)} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}}$$

GR_{log} = LLD log.

GR_{min} = Minimum Value of GR log

GR_{max} = Maximum value of GR log.

4.4 Porosity

Porosity is the ratio of void space in a rock to the total volume of rock. Porosity is very important for reservoir rocks, as well as source rock to accumulate hydrocarbons.

$$\text{Porosity} = \frac{\text{Volume of void space}}{\text{Total volume of rock}}$$

Porosity can be calculated from various ways, some of them are mentioned below:

- Neutron Porosity (Log derived porosity).
- Density Porosity.
- Total Porosity(Average porosity)
- Effective porosity

4.4.1 Neutron Porosity

The porosity is calculated from the amount of hydrogen present in the formation. The porosity is mathematically given by the following formula:

$$\text{Log}_{10}\emptyset = aN + B$$

Where;

$\emptyset$ = true porosity.

a , B = constants.

N = Neutron tool reading.

The neutron log porosity is valid only for clean formations either water filled pores of oil filled pores. However in case of gas, the hydrogen index gets lowered as a result of density drop. The presence of gas makes neutron porosity too low (Rider, 2002).

4.4.2 Density Porosity

Density porosity calculated from formation/Bulk density log. The porosity can be calculated mathematically using the following relationship:

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

Where;

ρ_{ma} = Matrix density.

ρ_f = Fluid Density.

ρ_b = Density log.

4.4.3 Total Porosity

The total porosity is the sum of neutron porosity and density porosity divided by 2.

PHIT = (PHID + NPHI) / 2.00.

PHIT = Total porosity.

4.4.4 Effective Porosity

Effective porosity is the percentage of interconnected pores with respect to bulk volume of rock. It is important in hydrocarbon prospect as represents interconnected pores suitable for recoverable hydrocarbons. It is given by following relationship:

$$PHIE = \frac{(NPHI + PHID)}{2(1 - V_{SH})}$$

PHIE = Effective Porosity.

4.5 Water Saturation

Water saturation is the percentage of pore volume in rock that is occupied by water of formation. To calculate saturation of water in the formation, a mathematical equation was developed by Archie shown below. All the parameters of Archie equation can be calculated from resistivity and spontaneous potential logs. The resistivity of water is calculated by Spontaneous potential log.

The steps are discussed below

1. Pick SSP from S-P log by using formula given by (Rider, 1996)

$$SSP = SPclean - SPshale$$

SSP = Static spontaneous potential.

SP Clean= Spontaneous potential for sand.

SP shale= Spontaneous potential for shale.

2. Determine the Formation temperature TF against the depth (d) using formula shown in equation given by (Rider, 1996).

$$T_f = \frac{d(BHT - T_S)}{T_D + T_S}$$

D=Depth of Formation.

Tf = Borehole temperature.

Ts = Temperature at surface.

TD = Temperature at depth.

3. Resistivity of the mud filtrate is calculated 0.48Ωm at surface temperature by using This relation.

$$Rmf = Rmf((T\_s+6.67))/((T\_f+6.67)).$$

Where,

Ts = Surface temperature

Rmfe = Resistivity of mud filtrate equivalent.

Tf = Formation temperature.

4. Now resistivity of the mud equivalent (Rmfeq) is calculated by using Schlumberger Chart shown in figure (4.1).

5. Rweq (Water equivalent resistivity) is determined from the SSP (Static spontaneous Potential)

$$SSP = -K \log R_{mfe}/R_{we} .$$

$$K = 65 + 0.24*T°C.$$

6. This is the last step in this step the value of the resistivity of the water (Rw) is obtained against the value of the Rwq (Resistivity of the water equivalent) and Formation temperature.

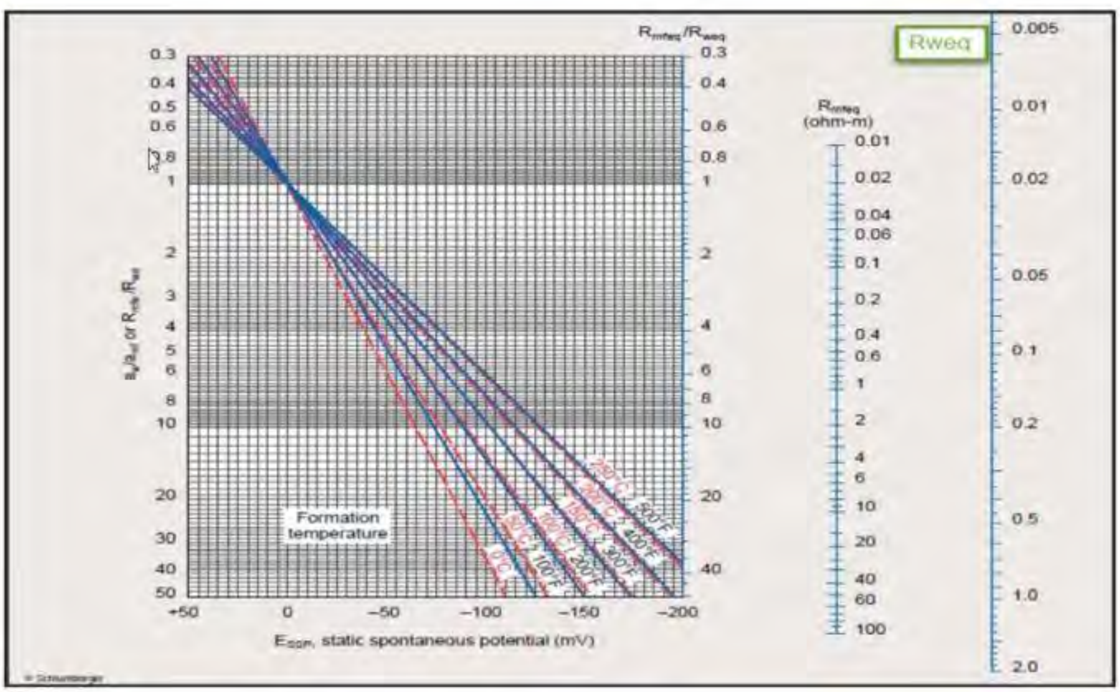


Figure 4.1 Determination of Rwq from SP chart (Schlumberger, 1989)

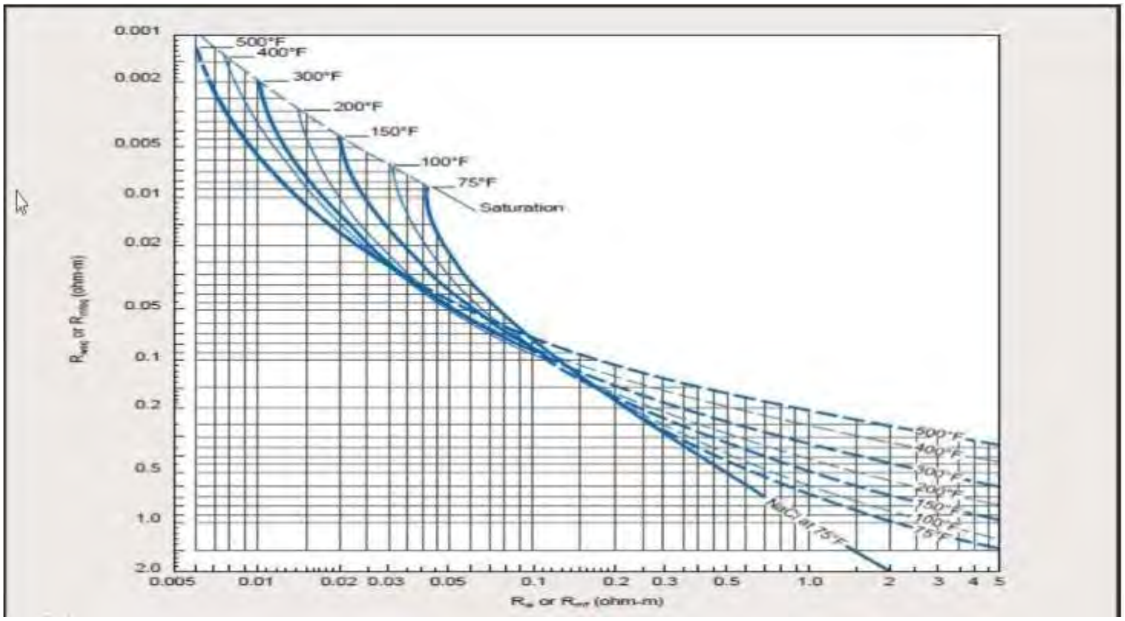


Figure 4.2 Determination of Rw from SP chart (Schlumberger, 1989)

7. After calculating all these parameters, Archie equation is used for calculating saturation of water stated below:

$$S_w = \sqrt[n]{\frac{a \times R_w}{LLD \times PHIE^m}}$$

m = Cementation factor dependent on rock type (usually 1.8 to 3)

a = constant also dependent on rock type.

n = constant (usually equals to 2).

4.6 Hydrocarbon Saturation

The fraction of pore spaces containing hydrocarbons is known as hydrocarbon saturation. The saturation of hydrocarbons is percentage of pore volume occupied by hydrocarbon.

$$S_H + S_W = 1$$

Where, S_H = Hydrocarbon saturation and S_w = Water saturation.

4.7 Interpretation of Sui Main Limestone Formation

- Volume of Shale = 10.8%.
- Effective Porosity = 8.2%.
- Water Saturation = 67%.
- Hydrocarbon Saturation = 33%

4.7.1 Petrophysical Analysis of Zone of Interest

Only one main zone of interest is marked. Depth range of Zone of interest varies from 1575m to 1582m in well Sabzal-01 .This is only one pay zone in which high net pay is expected. These zones bear low value of the GR, high porosity and the greater value of the resistivity.

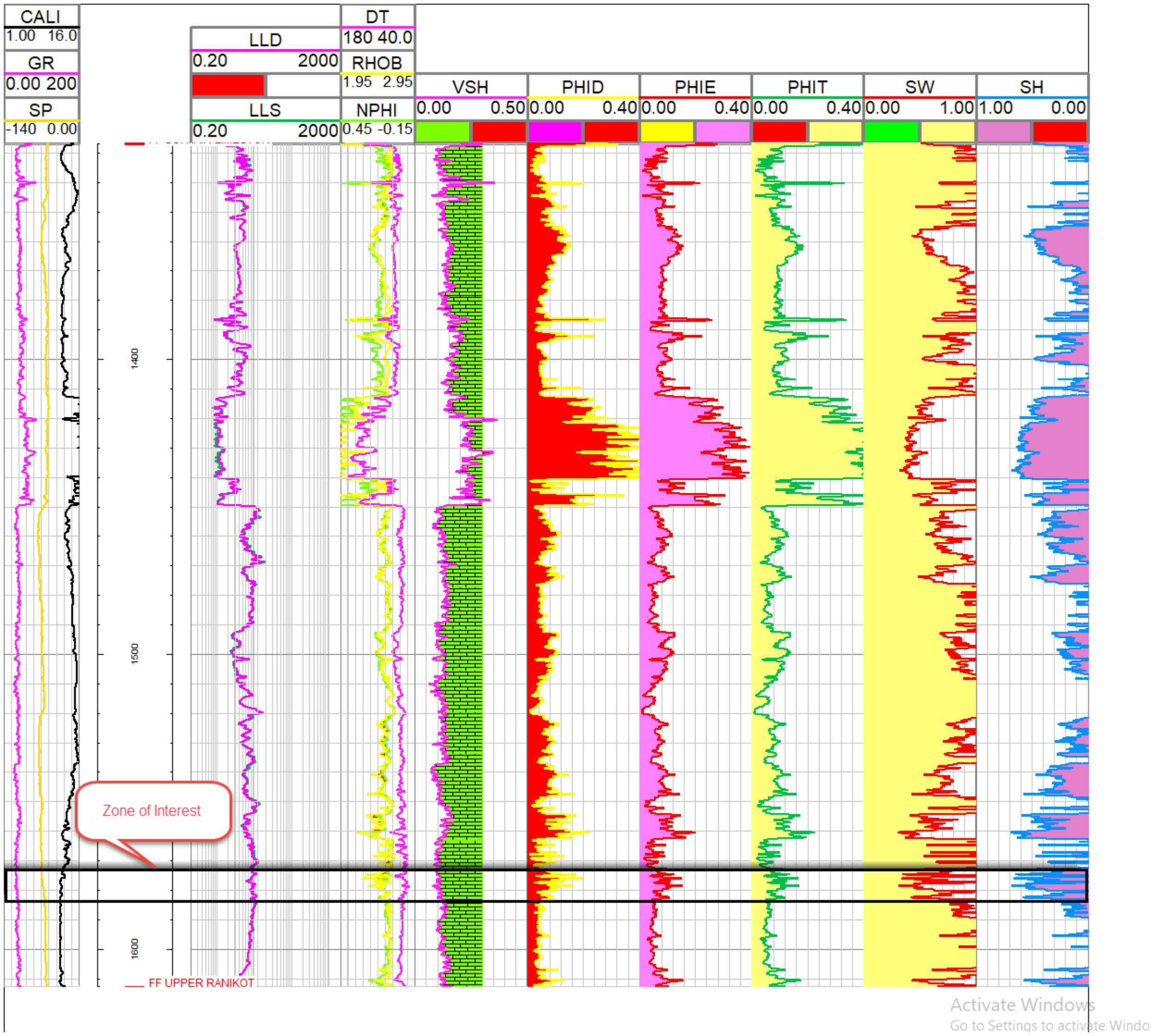


Figure 4.2 Petrophysical Analysis of Sui Main Limestone

CHAPTER 05

ROCK PHYSICS

5.1 Introduction

Quantitative Seismic Interpretation shows how rock physics can be functional to predict different parameters of reservoir, such as pore fluids and lithologies, from seismically resulting attributes. It demonstrates how the multidisciplinary combination of rock physics models with seismic data, sedimentological information and stochastic techniques can lead to more powerful results than can be obtained from a single technique. This provides an integrated methodology and practical tools for quantitative interpretation, characterization of reservoirs in the subsurface and assessment of uncertainty, using seismic and well-log data. The aim, in preparing Quantitative Seismic Interpretation, is to aid illustrate the potent role that rock physics can play in integrating both the data and expertise of geology and geophysics for characterization of reservoir (Avseth et al., 2005).

The objective for this research is to prepare links between seismic and properties of reservoir more quantitatively. The Quantitative Seismic Interpretation includes the use of any seismic attribute for which there are specific models and relates them to different rock properties. This technique introduces primary rock physics relations, which help to quantify the fluid properties and geophysical signatures of rock. Since rock properties are outcome of geologic processes, the geologic trends of various seismic signatures are quantified.

One of the main use of rock physics is for extrapolation. At a well location having good data quality, we can estimate the porosity, lithology, permeability and fluids from logs, cores and cuttings. But we have no idea what is happening as moving away from the well. But by using rock physics, we can extrapolate to geologically probable conditions that might be present away from the well, by knowing how the seismic signatures might change. This is very useful when we have to understand the facies and seismic signatures of fluids that are not represented in the well.

Rock Physics describes a reservoir rock by physical properties such as porosity, rigidity, compressibility, properties that will affect how seismic waves physically travel through the rocks. Rock physics or engineering parameters have been computed using velocity data derived from the velocity functions. In the real earth velocity varies laterally as well as vertically. Thus instead of using a regional averaged velocity function which only shows a vertical mean trend of the velocity with depth, velocity of DT log was used. The RMS and average velocities are not the true representative of a particular subsurface layer as they provide a vertically summed effect of all overlying layers rock properties.

5.2 Elastic Rock Properties

5.2.1 P-Wave and S-Wave Velocity

Sonic travel time of compressional wave is generally used as porosity tool for given lithology. VP-VS relations are keys to the determination of lithology from Seismic and Sonic log data as well as for direct seismic identification of pore fluids using e.g. AVO analysis with passage of time as the waves go deeper, its values are decreasing. Introducing shear wave travel time is very helpful in determining mechanical rock properties. It is found that compressional wave is sensitive to the saturating fluid type. The use of the ratio of compressional wave velocity to shear wave velocity, Vp/Vs, is a good tool in identifying fluid type.

Lower values of P-wave and S-wave velocities show the shaly material or fluid substitution and higher values consolidated material. Seismic velocity increases with depth due to compaction of rocks, because of overburden pressure of rocks. S-wave velocity is best indicator of fluids, as these waves can't pass through fluids.

From DT log, which has trainset time in μs/ft, we have calculated P-wave velocity in m/s using below formula

$$V_p = \frac{10^6}{3.28 \times DT}$$

5.2.2 S-wave velocity

S-Wave velocity in m/s has been calculated from P-wave velocity using formula. Castagna suggests a different formulas for Vs depend upon the lithology but it is not reliable for reservoir characterization. I use the formula given by Castagna in 1993 for limestone.

$$Vs = \frac{V_p}{1.9}$$

5.2.3 Density

A very important property of a rock is density. The density of the material directly affects the P wave velocities passing through it. Lower values of density show the shaly material or fluid substitution and higher values consolidated material.

$$\boldsymbol{\rho} = 0.31 \times (V_p)^{0.25}$$

5.2.4 Bulk Modulus

The bulk modulus (K) of a substance measures the substance's resistance to uniform compression. It is the ratio of volume stress to volume strain. It describes the material's response to uniform pressure. For a fluid, only the bulk modulus is meaningful. Bulk Modulus will be low where greater the volume of shale in other words the density would be high. Lower values show the shaly material or fluid substitution and higher values consolidated material.

$$K = \boldsymbol{\rho}\ ({V_P}^2 - \frac{4}{3}{V_S}^2)$$

5.2.4 Young Modulus

Young's modulus or modulus of elasticity (E) is a measure of the stiffness of an isotropic elastic material. It is the ratio of the uniaxial stress over the uniaxial strain in the range of stress in which Hooke's Law holds. It describes the material's response to linear strain. Young Modulus will be high where greater the volume of shale because it is linear strain. Lower values show the shaly material or fluid substitution and higher values consolidated material.

$$E = \frac{9K\mu}{3K+\mu}$$

5.2.5 Shear Modulus

Shear modulus or modulus of rigidity (μ) is defined as the ratio of shear stress to the shear strain (angle of deformation). Lower values show the shaly material and higher values stiffer material. Shear Modulus is good indicator of fluid presence, because fluids have zero value of Shear Modulus.

$$\mu = V_s^2 \times \rho$$

5.2.6 Poisson ratio (σ)

The ratio of the transverse strain (relative contraction strain normal to the applied stress) to the longitudinal strain (relative extension strain in the direction of the applied stress).

σ = Transverse Strain /Longitudinal Strain

Standard value for a limestone is 0.18-0.33GPa

5.2.7 Vp/Vs Ratio

It is the ratio between the primary wave velocities to the secondary wave velocity and calculated simply by dividing by Vp by Vs. Lower values of P-wave and S-wave velocity ratio show the shaly material and higher values stiffer material.

5.2.8 Acoustic Impedance (Z)

Acoustic impedance is the product of primary wave velocity and density of the rock.

Mathematically it can be written and calculated by the formula:

$$Z = Vp \times \rho$$

5.2.9 Shear Impedance

Shear impedance is the product of the secondary wave velocity and density. Mathematically it can be written calculated by the formula

$$\text{Shear impedance} = {V_S}^2 \times \rho$$

5.3 Results And Discussion

The rock physics parameter computed from P-wave velocity are shown in figure 5.1

Rock Properties in Sui

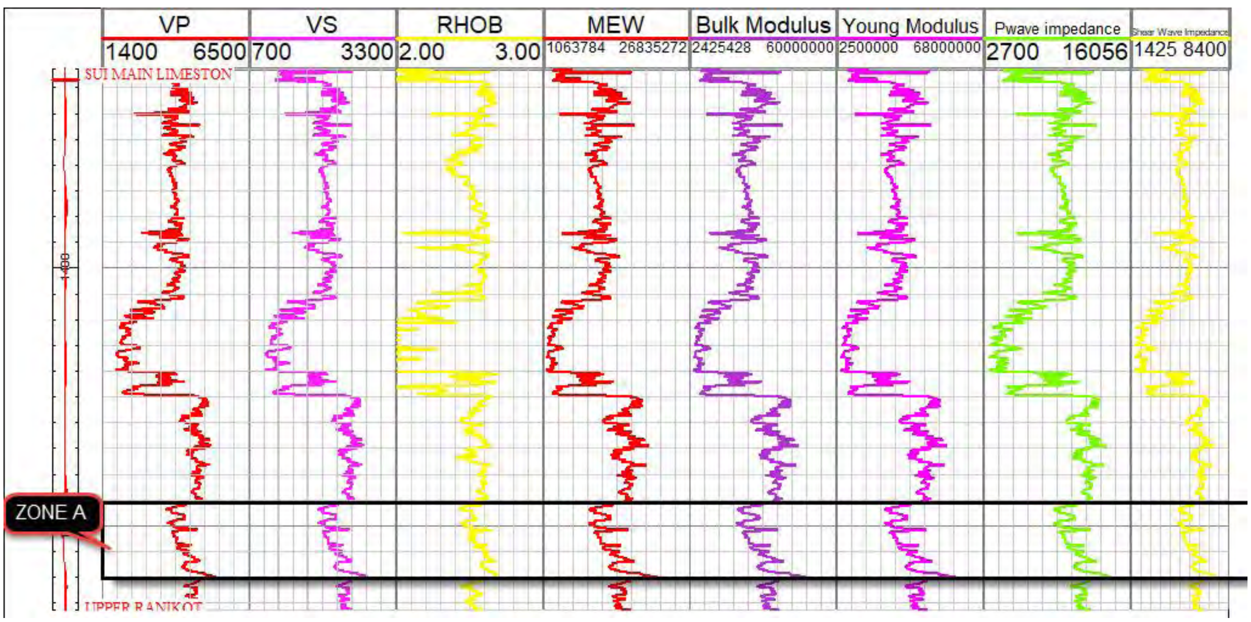


Figure 5.1 Elastic Properties of Sui Main Limestone

In the presence of hydrocarbon density and velocity can decrease and this is what happening in our zone of interest and this can be confirmed from the results of the Vp, Vs and density which decrease in our prospect zone.

The moduli (young, bulk and shear modulus) decrease in the perspective zone which indicate the presence of hydrocarbon; hence they give an idea about the presence of hydrocarbons.

P-impedance and S-impedance decrease in our area of interest hence indicating the presence of hydrocarbons present here.

CHAPTER 06

FACIES MODELING

6.1 Introduction

In geology, a facie is a body of rock with specified characteristics. Generally, the facies is distinctive rock unit that form under certain condition of the sedimentation that reveals the environmental process.

The differentiation between the shale and sand has been constantly challenged for the geoscientist. In this process the key challenge is identifying the facies, from logging and core data, and degree to which the shale content affects the reservoir properties. This gives the main indication about the productive zone in the reservoir (Kurniawan, 2005). This problem lead us towards the cross plots which provide us the relationship between the reservoir properties and log response (Naji et al., 2010).

These facies are related to the certain depositional environment. Basically, the depositional environment is specific type of place where the facies are deposit, Such as the Glaciers, Lakes, Abyssal plain, Sea bottom, Stream and Delta etc. The different types of the environment are shown in the below figure 6.1

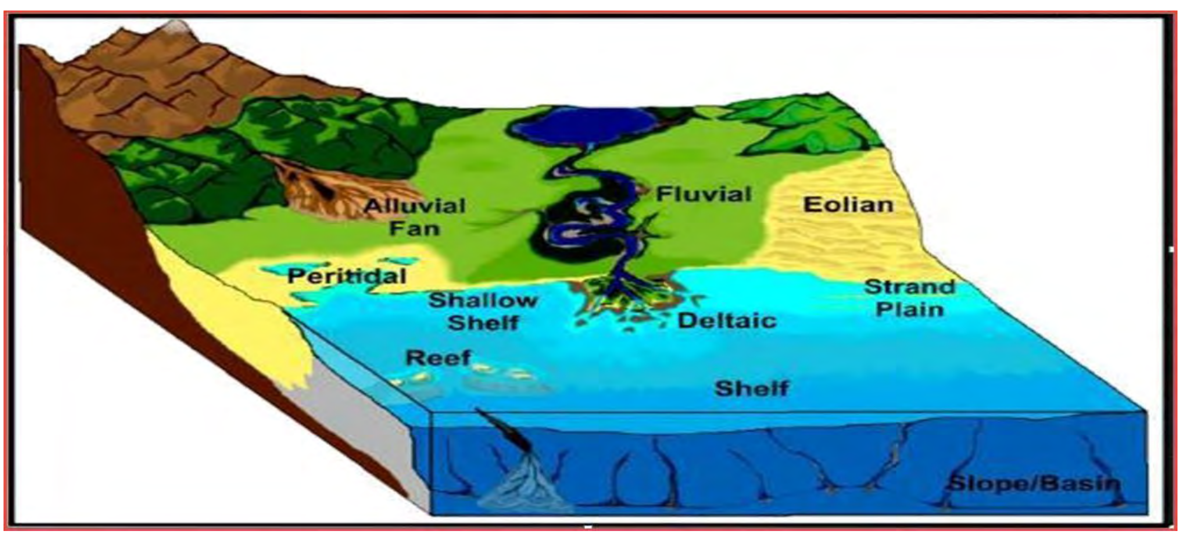


Figure 6.1 Diagram of major depositional environments

6.2 Sedimentary Facies

The sedimentary facies can be differentiated from each other on the basis of the change in the depositional environment. Sedimentary facies are defined as a really restricted, three-dimensional bodies of rock or sediment that are distinguished from other bodies by their lithology, sedimentary structures, geometry, fossil content, and other attributes. Lithofacies are defined solely on the basis of their lithology. Similarly, biofacies are defined based on their fossil content. Sedimentary facies analysis is based on the concept that facies transitions occur more commonly than would be expected if sedimentation processes were random.

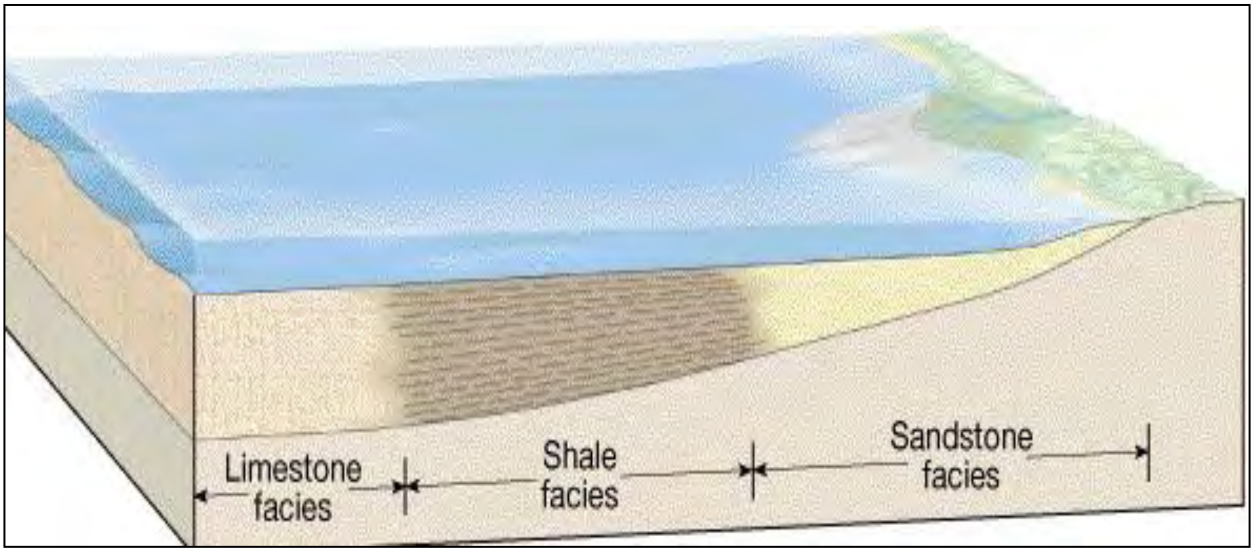


Figure 6.2 Sediment deposited in a different depositional environment.

The characteristics of the rock unit come from the depositional environment and from the original composition. Sedimentary facies reflect their depositional environment, each facies being a distinct kind of sediment for that area or environment.

6.3 Walther's Law of Facies

Walther's Law of Facies, or simply Walther's Law, states that the vertical succession of facies reflects lateral changes in environment. Conversely, it states that when a depositional environment "migrates" laterally, sediments of one depositional environment come to lie on top of another. A classic example of this law is the vertical stratigraphic succession that typifies marine transgressions and regressions. However, the law is not applicable where the contact between different lithologies is non-conformable (Lucia 1995).

6.3.1 Transgression

A marine transgression is a geologic event during which sea level rises relative to the land and the shoreline moves toward higher ground, resulting in flooding.

6.3.2 Regression

A marine regression is a geologic event during which sea level falls relative to the land and the shoreline moves toward lower ground and exposes former sea bottom.

6.4 Facies Analysis

Fundamental to all subsurface geologic studies is an analysis of depositional facies. Development of a facies classification scheme is a particular challenging interplay between capturing enough information for environmental interpretation. A good understanding of paleoecology always strengthens the interpretation and such studies should be included as part of all depositional facies studies. Depositional textures in turn affect porosity-permeability in carbonates. The vertical and lateral organization of facies is an exercise essential to sequence stratigraphic interpretations (Lucia, 1995)

6.5 Facies Analysis of Sui Main Limestone

For the facies analysis of the Sui Main Limestone zone we generate cross plots of DT vs NPHI and LLD vs RHOB from the log data of the Sabzal-01. These cross plots helped us to identify the major lithology of the Sui Main Limestone that there is limestone while also have limy shale present here.

6.6 DT vs NPHI Cross plot

A cross plot between DT vs NPHI is generated with log data, by keeping Gamma ray log as reference at Z axis. Major reservoir rock of our area lies between depth ranges of (1327-1613) meters. DT log is associated with lower values of the gamma ray logs indicate clean formation i.e. limestone. Due to compactness of limestone we have lower values of DT. NPHI log also have same trend in limestone. The polygon is drawn and labeled. The group of points is thick in the limestone polygon. It is therefore interpreted that the reservoir is mainly composed of limestone.

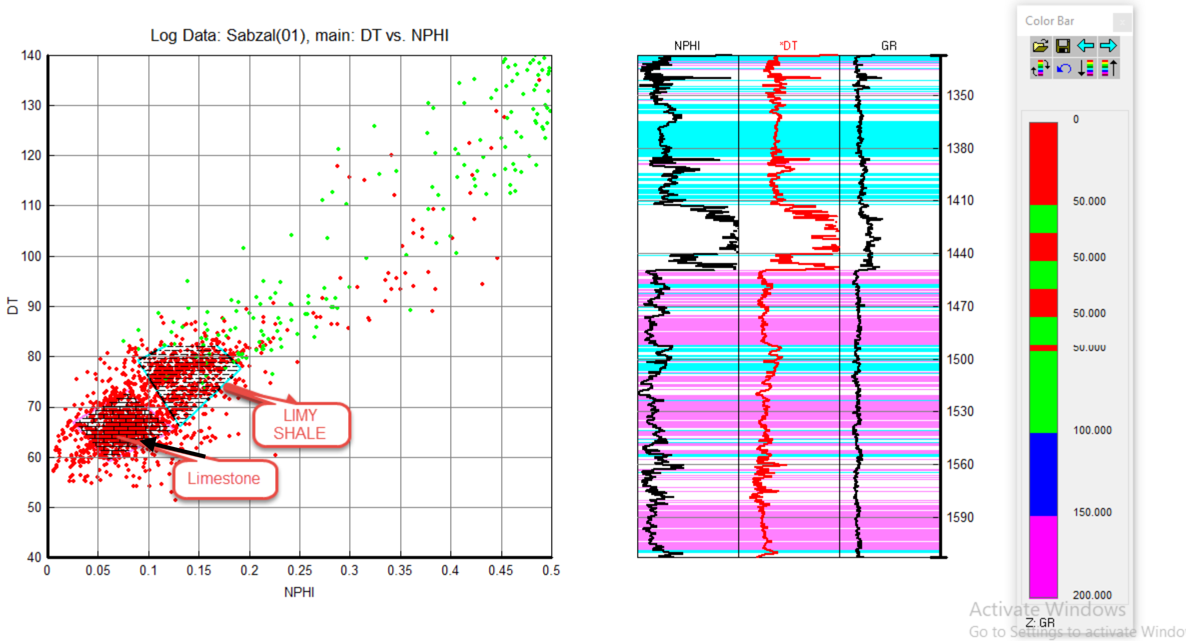


Figure 6.3 NPHI vs Dt cross plot for Sui Main Limestone

Polygon that is designed around a cluster point shows the limestone. We categorized it as a limestone because limestone does not show radioactive behavior and their general value of GR ranges from 10-40 API. DT value of limestone ranges from 47 us/ft- 65 us/ft in our study that matches with the standard range of transient time for limestone. Higher values of DT associated with higher gamma ray values indicate shale but in our reservoir zone we have calcareous shale (limy shale) instead of pure shale. It is also evident from the fact that DT log values increased in the second polygon which we have designated as calcareous shale.

6.7 LLD vs RHOB Cross plot

A cross plot between LLD vs RHOB is generated with log data, by keeping Gamma ray log as reference at Z axis. Major reservoir rocks of our area lie between depth ranges of (1327- 1613) meters.

Since resistivity and density of limestone is higher than shale so limestone facies are marked at higher values as shown in figure 6.4. Since density of shale is highly variable and if the concentration of organic contents is lower in shale, the density of limestone and shale can overlap so Gamma log is used as reference log for further separation of facies. The light green color shows the shale while the red color shows the limestone.

High resistivity values corresponding to low gamma rays value as compare to sandstone indicate limestone.so, the polygon that is designed at the top of cross plot indicate limestone by showing high resistivity values associated with low GR values(Generally radioactivity of limestone ranges from 10-40 API) .

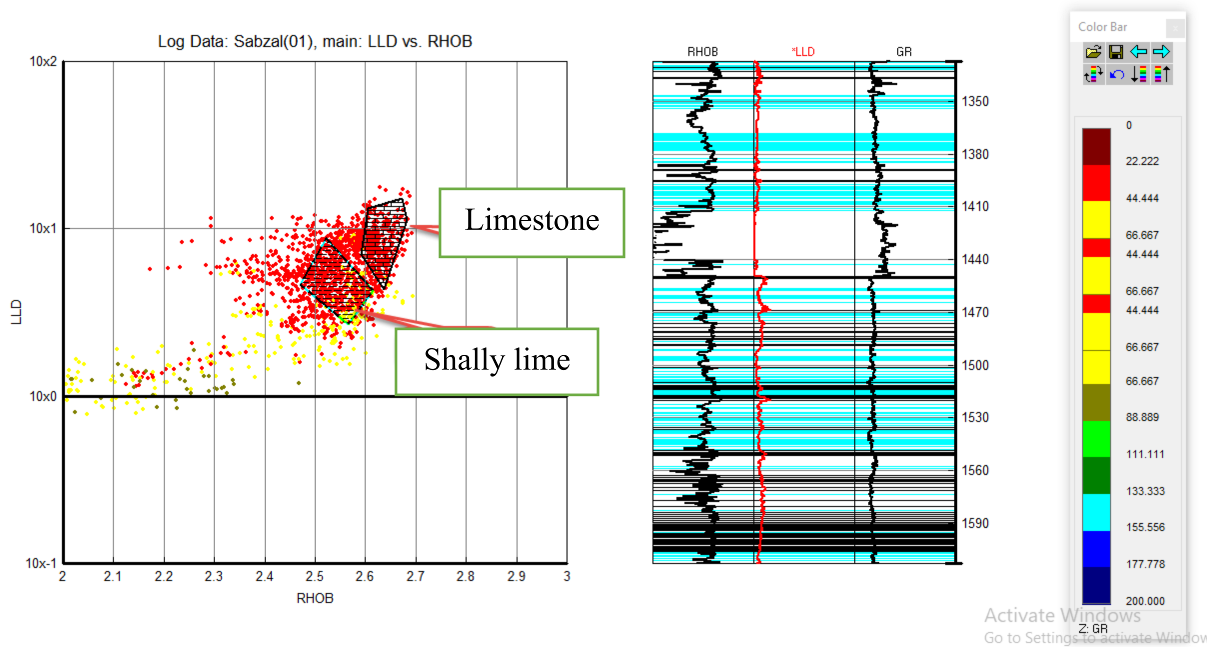


Figure 6.4 LLD vs RHOB cross plot for Sui Main Limestone

Conclusions

- Seismic data interpretation of Dandhi area indicates that it is tectonically stable area
- There is no regional fault in the area as the reflectors are straight and continuous throughout the seismic section.
- The Synthetic trace, generated via well data, confirms the marking of right seismic sections. The Depths are further confirmed by correlation with Synthetic Seismogram Generated from Sonic Log & Formation Tops of well Sabzal-01.
- Petrophysical analysis shows Only One prospective zone in Sui Main Limestone from 1575-1582 m having 11% shale volume, 8.2% Effective porosity, 67% Water Saturation and 33% Hydrocarbon Saturation.
- Petrophysical analysis shows that Sui Main Limestone formation should have good reservoir potential and will be economical for future prospective.
- The results of Rock Physics Parameters mark the presence of reservoir zone marked from petrophysical results due to drop the drop in elastic values at the marked zone from petrophysics.
- Facies analysis shows that reservoir rocks are mainly comprised of limestone with minor shaly limestones packages.

References

- Ali, A., Ahmad, Z., & Akhtar, G. (2005). *Structural Interpretation of Seismic Profiles integrated with Reservoir Characteristics of Qadirpur Area*. *15*, 25–34.
- Asim, S., Qureshi, S. N., Mirza, Q., Saleem, U., Ali, S., & Haroon, M. (2014). Structural and Stratigraphical Interpretation of Seismic Profiles along Safed Koh Trend (Eastern Part of Sulaiman Fold Belt), Pakistan. *Universal Journal of Engineering Science*, *2*(2014), 77–92.
- Asquith, G. B., Krygowski, D., & Gibson, C. R. (2004). Basic well log analysis (Vol. 16).
- Badley, Michael E., and Bruce Gibson (1985). "Practical Seismic Interpretation by Michael E. Badley." The Journal of the Acoustical Society of America 82.3 (1987):
- Castagna, J.P., Batzle, M.L., and Eastwood, R.L., 1985, Relationships between compressional-wave and shear-wave velocities in clastic silicate rocks. Geophysics, V.50, pp. 571-581.
- Dobrin, M. B., & Savit, C. H. (1988). Introduction to Geophysics Prospecting.
- Kadri, I. B. (1995). Petroleum geology of Pakistan. Pakistan Petroleum Limited.
- Kazmi, A. H., and R. A. Rana. "Tectonics map of Pakistan at a scale of 1: 200,000." Geological Survey of Pakistan, Quetta (1982).
- Kazmi, Ali H., and M. Qasim Jan. Geology and tectonics of Pakistan. Graphic Publishers, 1997.
- Kearey, P & Brooks M. (1984), Introduction to Geophysical Exploration‖, Blackwell Scientific Publications, Oxford, (P. 1-98).
- Lucia, F. J. (1995). Rock-fabric/petrophysical classification of carbonate pore space for reservoir characterization. AAPG bulletin, 79(9), 1275-1300. Tulsa: American association of petroleum geologists.
- Mavko, G, Mukerji, T, & Dvorkin, J. (2009). The rock physics handbook: Tools for seismic analysis of porous media. Cambridge university press.
- Onajite, E. (2014). *Seismic Data Analysis Techniques in Hydrocarbon Exploration*. Elsevier. http://elsevier.com/lcate/permissions

- Raza, H.A. & Ahmed, R., 1990, Hydrocarbon Potential of Pakistan. Journal. Canada-Pakistan Cooperation Ottawa. 4 (1): 9-27.
- Rider M. H. (1996). The Geological Interpretation of Well Logs
- Robinson ES, & Coruh, C, (1988), ―Basic Exploration Geophysics‖, John Wiley & Sons, New York, (p. 25-70)
- Shah, S.M.I, (1977). "Stratigraphy of Pakistan", Mem.12, Geological Survey of Pakistan, Quetta.
- Siddiqui, N. K. (2004). Sui Main limestone: Regional geology and the analysis of original pressures of a closed-system reservoir in central Pakistan. *American Association of Petroleum Geologists Bulletin*, *88*(7), 1007–1035.
- Telford e, (2004) ―Applied Geophysics‖, Cambridge University Press, London, (p. 860).
- Yilmaz, Ö, 2001, Seismic Data Analysis — Processing, Inversion, and Interpretation of Seismic Data Volume I. SEG, Investigations in Geophysics, 1000 p.