“Structural Interpretation using Seismic sections and Rock physics analysis using wire line data of Ratana #1”.

Submitted By

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Dedication

Dedicated to our Parents for their support and fulfilling all our wishes, also dedicated to our teachers who have devoted all their efforts to guide us through the rocky course of life, especially to our supervisors for their continuous support and help.

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Praise to Allah, Lord of the worlds, The Beneficent, The Merciful, Who is the entire source of knowledge and wisdom endowed to mankind, who gave us courage and potential to pursue this goal. We believe that He never spoils any effort of good deeds. Blessings of Allah be upon Prophet Hazrat Muhammad (P.B.U.H), the city of knowledge and blessings for entire creature, who has guided his Ummah to seek knowledge from cradle to grave, and enabled us to win honour of life. Lots of thanks to my Allah Who gave us success in every step of my life.

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Abstract

The Ratana Condensate and gas Field is located in the north-western part of Potwar Basin, about 100km Southwest of Islamabad. Ratana is large; salt cored thrust bounded, east-west trending pop up structure. It is a sub thrust plays so there is total disharmony between surface and subsurface structure.

The purpose of study is to understand the subsurface structural trend and stratigraphy of the area. Seismic interpretation resulted in time and depth contour map, which helps to understand the subsurface structure for further exploration. Rock physics analysis is also applied in the area to understand the trends of elastic parameters at the reservoir (Lockhart) formation as well as to establish the relationships of elastic parameters and velocities. The relationships between the Vp, Vs, Porosity, Density, Vp/Vs and elastic parameters of Lockhart formation (proven reservoir) helps to understand the changes in trends and reasons for these changes.

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1 INTRODUCTION

1.1 Introduction

Ratana area is located in the north western part of the Potwar basin, about 100 km south west of Islamabad. Ratana is a large, salt cored, thrust bounded, east-west trending pop-up structure. It is sub thrust play so there is total disharmony between surface and subsurface structure (Sarfaraz U Siddiqui et.al) figure 1.1 and 1.2. The purpose of this research is to understand the structural style of Potwar basin emphasing the North western Potwar and calculating the rock Physics parameters using wire line data.

- To study the geology of the area.
- To delineate the subsurface target horizons in the project area.
- Seismic data interpretation to understand the structural and geology of the area.
- Integration of seismic and well data to gain more confidence on interpretation.
- Using the well data to understand the rock Physics Parameters in the reservoir section.
- Aim to establish the relationships between P-wave velocity (Vp), S-wave velocity (Vs), density, depth, porosity and elastic moduli etc for characterization of reservoir formation.

Director General Petroleum Concession (DGPC) granted the data for this research purpose. Base Map for the available seismic data is shown in (Figure 1.3). Following integrated geological and geophysical (seismic) data have been used for structural and stratigraphic interpretation of sub-surface horizons.

- Base map.
- Seismic cross-sections (04 seismic lines).
- Geological well data of Ratana-1.

1.2 Physiography of Area

1.2.1 General Physiography

The Potwar Plateau and the Salt Range region are located to the south of the hilly north and lies between the Indus River on the west and the Jhelum River on the East. Its northern boundary is formed by the Kala Chitta Range and the Margalla Hills and the southern boundary by the Salt Ranges. The Soan Basin is located between the northern and southern range.

The Kala-Chitta Range rises to an average height of 450-900m and extends for about 72km. Their western part is composed of sandstone and the eastern side of limestone. The ranges are cut by deep valleys. A few kilometers north of the eastern extremity of the Kala Chitta Range, the Margalla Hills appear and extend eastward into the Kurang River. They attain an average height of 900m with several peaks rising to over 1200m. The south-facing slope is steep. The main Potwar Plateau extends north of the Salt Range. It is an undulating area 300-600m high. Small hills of bare rocks rise steeply above the surface. A few large and high hills are also there. Khairi Murat is the largest and the most spectacular. It is about 39km long running southward from the neighborhood of Rawalpindi. It rises approximately to 1,000m. The Soan River dominates the topography. The Soan and other rivers have also produced large tracts of alluvial plains where agriculture is practiced.

The Salt Range has a steep face towards the South and slopes gently into the Potwar Plateau in the North. It extends from near the Jhelum River in the East and runs westward along a sinuous path up to Kalabagh where it crosses the Indus River and enters Bannu District. The Salt Range comprises parallel ranges and rises to an average height of 750-900m. Sakesar Peak (1,527m) is the highest point in the Salt Range. The Kala-Chitta and the Salt ranges are badly faulted. Rivers like the Khewra, the Makrachi, the Jarhanwala and the Jamsukh have cut the ranges deeply and have formed gorges. In some areas badland topography has developed. A number of beautiful solution lakes dot the region. The Uchchali, Khabeki and Kallar Kahar are some of the important lakes. The Potwar Plateau and the Salt Ranges are rich in minerals like rock salt, gypsum, limestone, coal and oil.

1.2.2 Drainage

It is difficult to divide the Potwar into physiographic areas that have any clear distinction. Most of the landscape patterns are controlled by the surface geology. In a very general way, however, one can distinguish the following main features:

i. Central Potwar area(Soan River)
ii. West-marginal area(Khushalgarh-Makhad)
iii. Hill tract areas(Khairi- Murat, Bakrala Ridge)

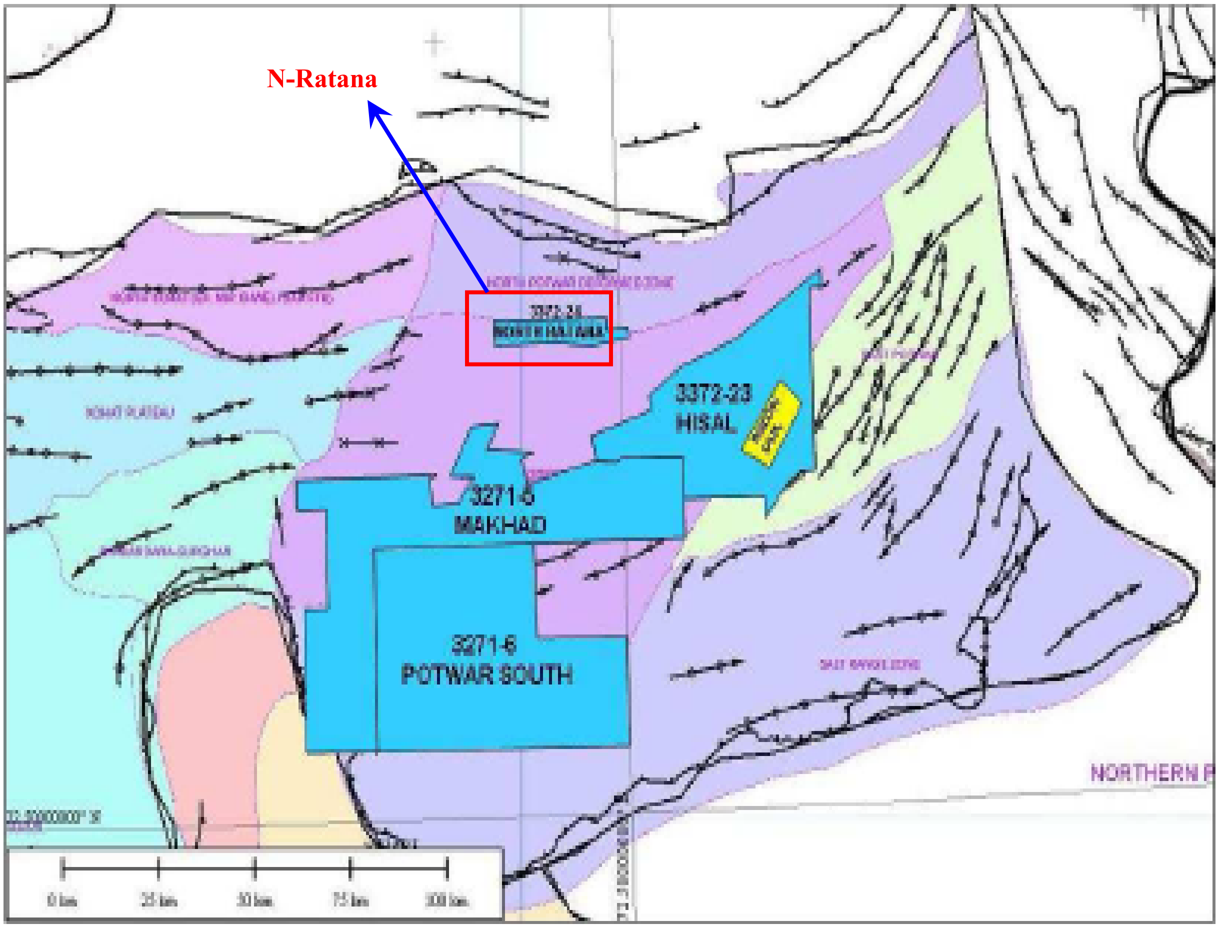

Figure 1.1: Showing North Ratana block (www.ppisonline.com).

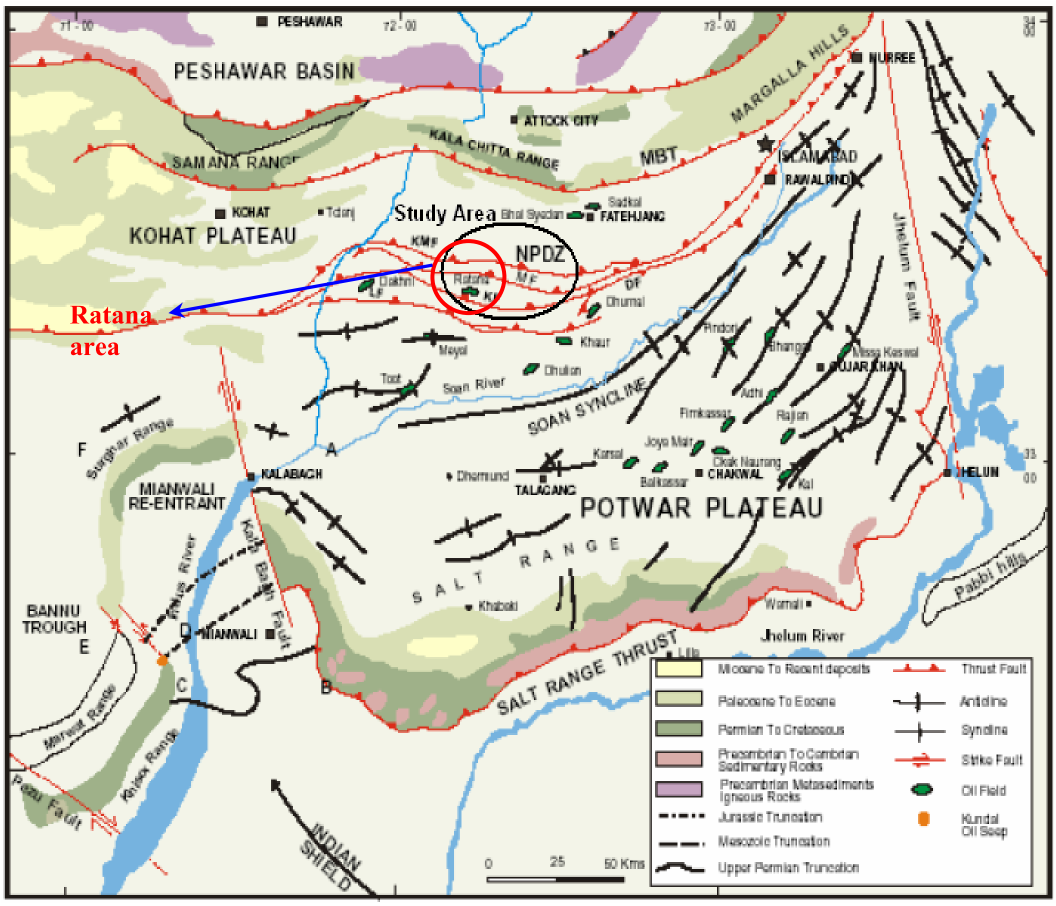

Figure 1.2: Structural and Stratigraphic Map of Upper Indus Basin, showing area under Study (Kadri, 1995).

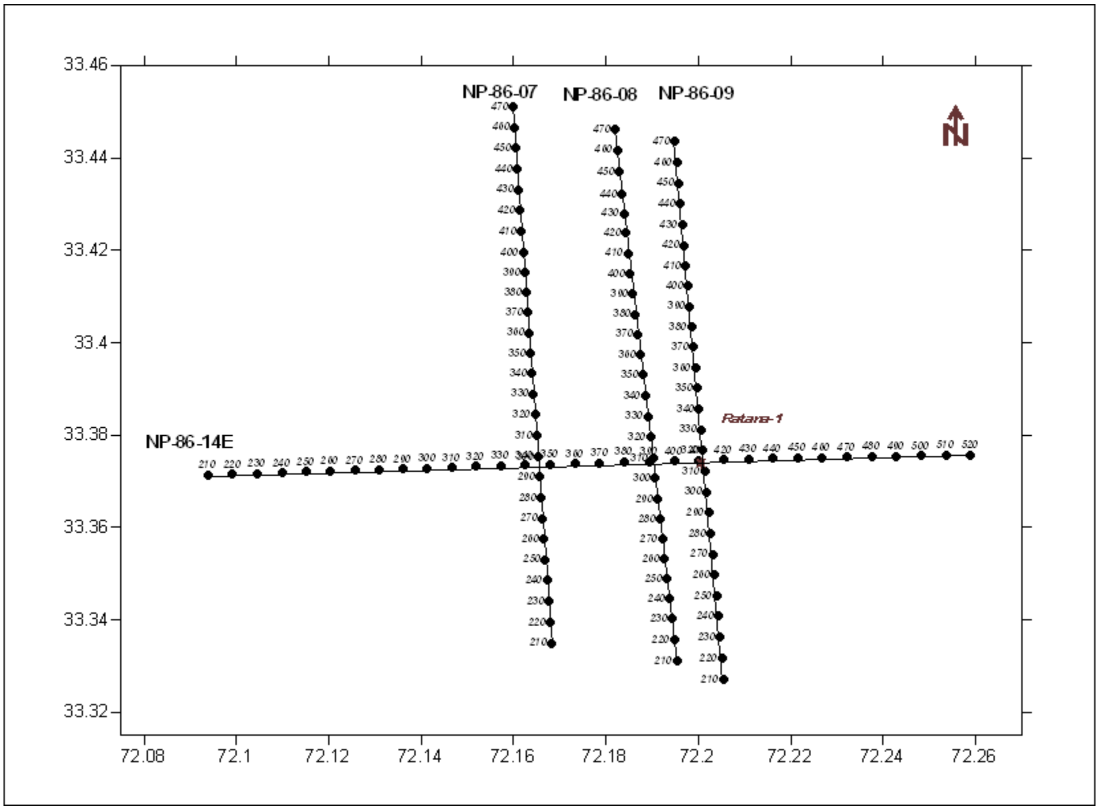

Figure 1.3: Base map of study area, showing position of Ratana#1 well.

2 Geology & Stratigraphy

2.1 Introduction

The studied area is a part of the Potwar plateau where the topography is undulating and characterized by a series of parallel ridges and valleys. Generally they trend in E-W direction. Geologically it forms part of the foreland zone of the NW Himalayan fold and thrust belt. This fore-land zone, comprising of Salt range, Potwar plateau/Kohat plateau and Hazara ranges, is an area bounded by the Salt range thrust in the south and the Panjal-Khairabad fault in the north. At its eastern end is the nearly N-S running left lateral Jhelum fault. (Kazmi & Jan, 1997)

2.2 Tectonic Setting

The collision of the Indian plate with Asia, which is continuing at a rate of 5 mm/a, has produced a remarkable variety of active fold-and-thrust wedges within Pakistan. These zones extend from the Kashmir fold-and-thrust belt in NE Pakistan, southwest ward through the Salt Range-Potwar Plateau fold belt, the Sulaiman fold belt, and the Makran accretionary wedge (Fig.2.1). This collision between the Indian and Eurasian plats began during the middle to late Eocene in association with Late Cretaceous-Cenozoic spreading along the Carlsberg-southeast Indian Ocean Ridge. Sea-floor reconstruction indicates that about 2000 km of convergence has occurred between India and Eurasia since the collision began. In northern Pakistan, the Himalayan ranges are divided into four major subdivisions. North of the Main Karakoram thrust lie the Karakoram Range and Hindukush, terranes of Gondwanaland affinity sutured to Eurasia (Turan block) in the Late Triassic-Middle Jurassic. South of the Main Karakoram thrust and north of the Main Mantle thrust lies the Kohistan block (Figure.2.1), a terrane believed to have been formed as an island arc, which docked with Eurasia in the Late Cretaceous to early Eocene. It is suggest that the Main Mantle Thrust locked approximately 15 Ma ago, subsequent to rapid uplift north of the fault between 30-15 Ma. During the early Miocene, deformation propagated southward nears the Main Boundary thrust, where unmetamorphosed lower Tertiary rocks are thrust over Neogene molasse. In the latest phase in Pakistan, thrusting transferred to the Salt Range thrust, where deformation as young as 0.4 Ma has been documented. In the Lesser Himalaya of northern Pakistan (Hill Ranges), detachments at upper crustal levels occur along a series of south-verging thrust (Shah &John 1998).

2.3 Sedimentary Basins

Basin is an area that is characterized by regional subsiding and in which sediments accumulate and preserved for a geologic time. Pakistan has three broad tectonic basins, Indus Basin, Peshawar Basin and Baluchistan Basin.

2.4 Indus Basin

Indus Basin is including the 25000 square Km of South-East of Pakistan. It includes the Thar-Cholistan desert and Indus Plain. It has 80% of Pakistan population. Tectonically it is much stable area as compare to other tectonic zone of Pakistan. It comprises of buried ridges, platform slop, zone of up warp and dawn warp. (Kazmi & Jan, 1997), Structurally Indus Basin divided into two main parts;

- Upper Indus Basin (in north)
- Lower Indus Basin (in south)

Lower Indus Basin is further divided into two parts;

- Central Indus Basin (in north)
- Southern Indus Basin (in south)

2.5 Upper Indus Basin

It is located in the northern Pakistan and separated from the lower Indus Basin by the Sargodha High. In its north MBT, while in east and west strike slip faults Jhelum and Kalabagh is located, Upper Indus basin is subdivided into Potwar and Kohat Basins along the Indus River. (Kazmi & Jan, 1997) (Figure 2.2).

2.6 Potwar Basin

2.6.1 Geology and Structure of Potwar Plateau

Potwar Plateau has undulating topography. It is characterized by a series of parallel ridges and valleys, generally trend in the E-W direction. Geologically, it forms part of the foreland zone of the NW Himalayan Fold-and-Thrust belt (Figure 2.3).

foreland zone comprising of Salt Range, Potwar Plateau, Kohat Plateau and Hazara ranges is an area bounded by the Salt Range Thrust in the south and the Panjal-Khairabad Fault in the north. At its eastern end is the nearly N–S running left-lateral Jhelum Fault (Kazmi and Jan).

In this zone of convergence, intense deformation has resulted in the formation of complex structures. The northern part of Potwar Plateau, also referred to as the Northern Potwar Deformed Zone (NPDZ), lies between the Main Boundary Thrust and the Soan Syncline. It is more intensely deformed than the southern Potwar and the Salt Range. Mostly E-W trending tight and complex folds with their southern limbs overturned with steep angle faults occur in NPDZ.

The MBT itself is represented by many high angle thrusts along which Eocene and older rocks have been thrusted over the molasses of the NPDZ. The NPDZ is considered to be a thin-skinned tectonic feature by most workers in which the basal decollement is in the Eocambrian Salt Range Formation. In this interpretation the Soan (Dhurnal) back thrust is a passive back thrust and the area bounded by it and the Khair-i-Murat Fault is a triangle zone of complex geology (e.g. Jadoon et al., 1999).

The area east of Indus River and north of the Salt range orocline forms the Potwar Plateau. Structurally the plateau comprises of

1. The northern folded zone
2. The platform zone

The plateau is covered by fluvial sediments ranging in age from Miocene to Pleistocene. The Siwalik rocks, however, are restricted to the platform zone. Fold structures in the region are generally oriented in a sublatitudional fashion. The structural complexities increase northward. The MBT, Salt Range thrust, Kurram and Khairi murat thrust faults and Jelum and Kalabagh wrench faults are the major faults of the Potwar area.

Potwar Plateau is characterized by east west trend, tight and complex folds overturned to the south and sheared by steep angle faults (Kazmi and Jan, 1997). The NPDZ is marked by east west-west trending and south vergent tight folds which imbricate style of south ward directed thrusts. In the south of the Soan Syncline axis the style of the folding is gentle and open with southward directed thrust.

The deformation style of NPDZ abruptly changes from east to west. The eastern NPDZ represents a buried thrust front with the development of foreland syncline on the back of the

Dhurnal Fault (DF), and passive roof duplex (triangle zone) and hinterland dipping imbricate stack farther north (Jaswal, 1990). Western NPDZ is characterized by compressed and faulted anticlines separated by large synclines, representing the emergent thrust front. Jadoon et al (1999) indicate structural variation in the triangle zone of Potwar plateau shows the presence of blind thrust of smaller lateral extent (about 10 km) and about 2 km of shortening on the west, the salt range/Potwar plateau thrust sheet appears to be abruptly truncated by the Kalabagh transpressional fault system. This fault extends 20 km north of the Indus river, before bending to the west along several north dipping reverse faults (McDougall, 1985).

The Potwar sub basin is fault-bounded basin, which is filled with thick syntectonic molasses sediment derived from the rising Himalayas. The present structural pattern in the Potwar sub basin is the response of the left and right lateral strike slip movements initiated during late Tertiary time along MBT, Jehlum and Kalabagh faults system in the east and west respectively (Iqbal and Manshoor, 2001). Khan and Ali (1994) also suggested that the western limb of Hazara Kashmir Syntax moves southward between Kalabagh right lateral strike slip fault and jehlum left lateral strike slip fault.

2.6.2 Tectonic Boundaries

Potwar Plateau is bounded on two sides by thrusts and two sides by strike slip faults. All these boundaries are tectonically controlled. Each of these boundaries is different from other in tectonic causes and effects. Northern and southern boundaries of Potwar Plateau are marked by MBT and SRT respectively, while eastern and western boundaries are marked by left lateral Jhelum Strike Slip Fault (JF) and right lateral Kalabagh Fault (KBF) with associated re-entrance. All Tectonic boundaries Potwar Plateau are visible (Figure 2.3).

The northern boundary of Potwar Plateau, marked by MBT is characterized by thrusting of older sedimentary strata (up to Jurassic) over the Siwalik molasse. The hill ranges of Margalla and Kalachitta have been developed as a result of thrusting on the MBT. Like other areas MBT in Potwar Plateau represents a zone of more or less parallel, east west trending thrusts which tend to merge into each other both towards Hazara - Kashmir Syntaxis (HKS) and Safadkoh in the west.

Salt range thrust (SRT) is a folded thrust, caused by the allochothonous movement of the covered sediments on a salt lubricated devolvement. It is documented to be active since 5.1 Ma.

It is one of the frontal thrust zones of the Himalayas. Maximum uplift on this thrust is documented from the central Salt Range; westwards the thrust merges into the Kalabagh Fault which is interpreted to be the western extension of the salt range thrust. In the east the Eocambrian salt reaches the surface only upto Jalalpur and further east the magnitude of thrust appears to diminish. This may in fact be due to transfer of deformation from SRT to the NE - SW, trending Domeli - Diljabba Thrust which ultimately merges into Jhelum Thrust. The north south trending Jhelum Fault may extends from Indus - Kohistan in the north to as far as south of Ravi River and may have been a long lived active feature of the Indian shield. Synsedimentary movement on this fault may have affected the Siwaliks sedimentation but lack of sediment logical data across the Jhelum Fault hinders the conclusiveness of this hypothesis.

Western boundary of Potwar Plateau is not very sharp. In its northern part the trusts of NPDZ are continued west wards into the Shakardara area in Kohat Plateau while in the southern part the KBF marks the western boundary of Potwar Plateau. Kalabagh fault has been documented to be a right lateral trench fault extending from Shakardara thrust complex in Kohat Plateau in the north to as far as 25 km south of Kalabagh town. Movement along Kalabagh fault may have resulted from either extensional release of stress in the direction perpendicular to the main stress or due to differential stress across the KBF.

2.6.3 Division of Potwar Plateau

The Potwar Plateau can be divided into following zones on the basis of intensity, type, trend and timing of the deformation (figure 2.3).

(1) Northern Potwar deformed zone (NPDZ).

(2) Soan syncline

(3) Eastern Potwar Plateau.

(4) Central Potwar Plateau.

(5) Western Potwar Plateau.

Potwar plateau is nearly undeformed south of Soan syncline, but is deformed on its northern and eastern margins.

2.6.4 Soan Syncline

It is an asymmetric with steeper northern flank and shallower southern flank. Axis of syncline lies a little south of and roughly parallel to the Soan River. Southward shifting of the axis of the syncline indicates that:

(i) The deformation is still going on and the river has no time to adjust its coarse accordingly

(ii) During this phase, uplift in the northern side of Potwar Plateau was more than its southern side.

Another evidence of rivers migration through time can be seen in the area just south of Dhulian anticline where two major southern tributaries of Soan River appear to adjust there coarses near Soan syncline, in response to the ongoing uplift.

The Soan syncline is not a true syncline. Its present configuration has resulted from deformation and rotation (more severe in eastern Potwar Plateau) of an initially broad syncline that develops in the south of NPDZ. The uplift along its northern (MBT) and southern (SRT) boarders not only caused deformation within the syncline but also change the slope of Potwar Plateau from NW-SE to NE-SW.

2.6.5 Eastern Potwar Plateau

The eastern Potwar represent strong deformation as compared to central and western Potwar. This difference may be related to lesser thickness of salt in the infra-Cambrian in the eastern area and very low dip of the basement (1°-1.5°) as compared to the central Potwar (2°-3°). Brittle deformation predominates over the ductile deformation whereas the fault propagated folds dominate over the other types. It is characterized by north-east south-west trending tight, crusted, faulted anticlines separated by broad synclines. Anticline represents folding phenomenon while synclines are not true folds and represents un-deformed area between anticlines. The structural style of the central, western and eastern parts of Potwar sub-basin shows a marked difference.

There are some north facing basement normal faults noted to exist beneath the Chak Beli Khan, Chak Naurang, Qazian and south of Bhaun structures. Apart from EW and NE ward trending normal offsets, a few north south trending basement faults with reverse offsets have also been recognized in the east Potwar Plateau. So the deformation of the east Potwar Plateau has largely been controlled by these basement faults. All major salt accumulations are along basement normal faults.

In eastern Potwar Plateau, major structures are parallel to sub parallel with each other and show a wavy trend (two of the thrusts i.e. Dilljabba and Riwat have resemblance in their wavy pattern). These structures are aligned in NE direction, changing to EW direction westward, and turning northwards near Jhelum fault in the east, the paleomagnetic studied have shown that originally the structural trends developed perpendicular to the transport direction and subsequently acquired the present alignment (northeast) because of the tectonic rotation as manifested by the strike slip nature of the left lateral Jhelum Strike-Slip Fault.

Tectonically, south east Potwar Plateau is less deformed than east Potwar Plateau. Anticlines are incipient and are farther from each other and there are big flat areas between different anticlines. The structures are generally maintaining NE trend as in the eastern Potwar Plateau.

Bhangali, Adhi and Misa Kaswal oil field are the well known structural traps created by tectonic forces in the eastern Potwar plateau.

2.6.6 Central Potwar Plateau

The most important feature of the central Potwar plateau is a large normal fault (throw = 1Km) in the basement beneath the northern flank of the salt range that causes the ramping of the entire section. This basement normal fault has been intercepted as being due to flexure of the Indian plate. Another important difference between eastern and central Potwar plateau is the lack of major deformation in the southern portion of central and western Potwar. The surface of the central Potwar plateau between the north flank of the salt range and the Margalla hills is essentially flat, while there is change in the basement slope being 1.3° in the front and underneath the Salt Range to 3.6° under the central and northern Potwar Plateau.

Southern Potwar plateau, although has been pushed at least 20 km southward (Baker, 1987; Leather, 1987), yet it has undergone almost no internal deformation, except broad, gently folded anticlines (Khan et al., 1986). This phenomena is due to the week evaporate layer and to the increase in the basement slop(1.9°-3.6°) in the Central Potwar as opposed to 0.6 °in the eastern Potwar Plateau.

Major structural features of central Potwar Plateau include a number of broad flat based synclines separated by somewhat narrow, sharp crested anticlines. The anticlines occur along the deeply eroded gorges and canyons. In central Potwar, structures are mainly fault bounded mostly by thrusts and back thrusts, while at some places; asymmetric anticlines are bound by a single fault. The axial lines of various anticlines and synclines show no particular parallelism.

2.6.7 Western Potwar Plateau

The western Potwar plateau is similar to the central Potwar plateau in all almost respect. There is, however, one difference between the two i.e. the lack of a large basement normal fault which acts as a ramp in the central Potwar plateau. Some sort of ramp exist, as indicated by the westward continuation of the Salt Range, but the basement looks to be gently folded rather that abruptly faulted(Leather, 1987).

Structurally it is much less deformed than rest of the Potwar Plateau; it is characterized by a series of gentle folds, incipient in nature having a general NE to EW trend with the exception of Dhadambar anticline, which is aligned in a NW direction parallel to the Kalabagh fault. Faulting predominates over folding in extension, distribution and intensity. Folding in southwest Potwar Plateau follows two trends, NW and NE which are the directions of the basement faulting. In this part, the Potwar Plateau is not only over-spilling southwards but also westwards onto the Kalabagh thrust due to uplift and room available. Important structures of western Potwar plateau are Ghabir, Khabakki, Dhadambar, and Jhatla.

2.6.8 Northern Potwar Deformed Zone (NPDZ)

It is bounded to the north by MBT, to the south by Soan Syncline; eastward all its thrusts merge into Kahairi-Murat thrust which ultimately dies out. Westward these thrust are continued in Shakardara area of Kohat Plateau. It represents severest and oldest phase of deformation within Potwar Plateau as it is marked by imbricate stack of thrust faults, tight isoclinals to overturned folds, vertical dips and thrust bounded ridges. Pariwali, Khaur, Dhulian, Ballkassar, Karsal structures are the prominent tectonic features of this area.

Dhulian and Khaur anticlines are oil and gas producing structures. The youngest oil producing formations (at Khaur) is Murree formation. However the presence of oil and gas suggest migration of oil from older formations to Murree formation through deep seated buried faults. The tectonic style of NPDZ resembles more to the north of MBT Himalayan zone. Almost all the fold axis and thrusts are aligned in E-W direction.

The area immediately north of NPDZ, between Khairi-Murat thrust and Murree fault, shows very less deformation and rocks of Murree formation are exposed in this zone. Further north of this zone the deformation style is similar to the NPDZ. The Siwaliks of NPDZ have been thrusted over from this zone of less deformation. The strata i.e. Siwaliks below NPDZ is not much deformed. Its deformation stage is yet alike Khaur, Dhulian structures and Southwest Potwar Plateau. The NPDZ structures are not true thrusts but are shear boundaries between isoclinals folds along which thrusting took place due to continuing stress. There is an aging of exposed formations in NPDZ from south to north which is quite compatible with the normal down cutting of an isoclinals fold stack by erosional surface.

Ratana area is located in the north western part of the Potwar basin, about 100 km south west of Islamabad. Ratana is a large, salt cored, thrust bounded, east-west trending pop-up structure (Sarfaraz U. Siddiqui et.al) (figure 2.4).

2.6.9 Stratigraphy of the Ratana Area

Stratigraphy of the Ratana is well established from the outcrop as well as from the wells drilled in the field area and the surrounding areas (fig 2.5). The stratigraphic succession drilled in the Ratana area can be subdivided into three major unconformity bounded sequences.

1. Neogene Molasse Sequence.
2. Paleogene marine carbonates and shales.
3. Jurassic Clastics.

In late Eocene, Himalayan orogenic movement caused uplift and deformation of the preexisting rocks. Thick molasse Sediments were rapidly deposited in the orogenic fore deep, covering potowar basin. In Ratana field area thick molasse section is represented by Chingi, Nagri, Kamlial, Murree fm of the Plio-miocene age.

Nagri Formation predominantly consist of argillaceous Sandstone interbedded with claystone and siltstone and was deposited in fluvial floodplain environments. The Chingi Formation is predominantly claystone with interbeds of sandstone and was deposited in the lacustrine environments with occasional fluvial influxes. Kamlial Formation is mainly composed of sandstone with interbeds of claystone and siltstone and was deposited in the fluvial environments. Murree fm is mainly composed of the claystone interbedded with sandstone siltstone and occasional stringers of limestone at the base and was deposited in the brackish water, estuarine and deltaic coastal plain environments. Post Himalayan orogenic Tectonic movement has contributed in the complex, shallow thrusting, repetition of the Molasse Section and frequent abnormal formation pressure encountered in the well.

The contact of Eocene with the overlying Murree Formation is unconformable and is represented by a thin conglomerate Bed. Eocene consists of Kohat, Mamikhel, Chorgali, and Nammal and Sakesar Formation. The Kohat formation is consist of Limestone and Claystone with subordinate shale and abundant forams and was deposited in the shallow marine to sublittoral environments. Mamikhel formation is predominantly clay and shale which are generally red to purplish brown and Gypsiferrous. Mamikhel plays the role of regional seal and it was deposited in the near shore environments. The underlying Chorgali formation is mainly composed of the limestone with thin bedded bluish grey shale and was deposited in the supratidal environments. The Sakesar Formation is dominantly limestone which is slightly dolomitised in the basal part and it was deposited in the Shallow marine environments. Nammal formation is interbedded argillaceous limestone and shale and was deposited in the Shallow marine quiet environment.

Paleocene sequence is represented by Dhakpass, Lockhart, Patala formations. The Patala formation in this part of Potwar Plateau is composed of mainly limestone and interbedded Shale. Patala Shale was deposited in the shallow marine, quiet lagoonal environments.

Lockhart formation is composed of the limestone and interbedded shales and was deposited in the shallow marine lagoonal environments. Dhak pass formation is dominantly sandstone interbedded with thin beds of the shale and was deposited in the very shallow, littoral to plaudal environments.

Underlying Mesozoic formation was deposited in the shallow marine environments, on a west northwest facing passive margin, after breakup of the Gondwana. Towards end of the cretaceous a significant uplift occurred and resulted in the stripping of the cretaceous through Permian rocks from east to west across the Potwar basin, forming erosional wedge.

As such in Ratana area, Cretaceous to late Jurassic rocks is missing. Paleocene rocks rests directly upon the Jurassic, data formation. In general data formation is generally composed of the predominant sandstone interbedded with the shale and occasionally dolomite. However in the Ratana field only upper part of the Datta formation is drilled so far it is predominantly sandstone with siliceous cement and very poor porosity. Productive Zone of Datta at the Dhulian, Meyal, and Toot are still to be penetrated in the Ratana Field. In the end of this chapter figure 2.5 is showing the stratigraphic column of the Ratana area.

2.6.10 Structural Configuration of Ratana

Ratana field is located in the Potwar Basin, Which structurally form the upper part of the over thrust sheet where developments of folds and faults are controlled by movement along a detachment zone in the salt bearing Salt range formation just above a rigid basement. Most of the structures of Potwar are caused by compressional forces from the north, but the salt has played a fundamental role in the kinematics of these structural features.

Ratana is located in the (NPDZ) Northern Potwar Deformed Zone (comprising of area north of soan syncline). The subsurface anticlinal feature of Ratana is not conformable to the two synclines at the surface. This disharmony between the subsurface and surface structure suggests the presence of detachment zone in the younger molasses deposits.
Both Tawin and Kanet synclines are separated by a high angle thrust fault known as “Tawin fault” which is an anomalous feature. The surface geological map (fig.2.8) and seismic dip lines (fig 2.9) show that the rocks are deformed by Kanet and Mianwala faults resulting in complex shallow thrusting and repetition of molasses section, which further confirmed the wells drilled in the area and dipmeter interpretation.

Ratana was one of the early revealed by seismic survey and was mapped at the prominent reflection, corresponding to the top of early Eocene Chorgali Limestone. Seismic lines (fig 2.9) show it as a large east west trending, salt cored, thrust fault bounded, fault anticline at the Eocene level. It appears several thrust faults steeply dipping towards the north and anticlinal turn over with south flank terminated by the thrust faults at a down dip position. In addition several small back thrusts are also present on the northern flank. The Ratana structure consists of one large anticline with two subsidiary highs.

After the discouraging production performance, it was decided to conduct 3D seismic survey with the objective to get an accurate structural picture of Ratana field and identify compartments if any and interpret fractured intervals (Sarfaraz U Siddiqui et.al).

2.7 Petroleum Geology

Kohat-Potwar Foldbelt is a prolific hydrocarbon province and have many proven petroleum systems.

2.7.1 Source Rocks

Source rock indicates that good oil-prone source potential exists in the Infra-Cambrian sediments of the Kohat-Potwar Basin with total organic carbon contents (TOC) ranging from 3.75% to 30%. Source potential, mainly for gas, is present in Permian sediments with TOC up to 6%. Paleocene sediments show oil and gas potential in the Kohat-Potwar Basin. TOC in the Paleocene (Patala) source rock ranges up to 10.73% with good hydrocarbon potential. The coal and coaly shales in Patala Formation also exhibit good source potential. In Ratana area the source rock is Mianwali Formation of Triassic age.

2.7.2 Reservoir Rocks

Petroleum plays with reservoirs ranging in age from Infra-Cambrian to Miocene are present in the Kohat-Potwar Foldbelt. The target reservoirs are clastics and carbonates of Infra-Cambrian, Lower Cambrian, clastics of Permian, clastics and carbonates of Lower to Middle Jurassic, clastics of Lower Cretaceous, carbonates of Upper Paleocene and Lower Eocene and clastics of Miocene.

In Ratana area carbonates of the Paleocene age are confirmed reservoirs. The Patala (Late Paleocene) is the primary proven reservoir in the Ratana field. In the Potwar area, the Patala formation is generally composed of shale, marl and limestone with rare coal seams. However at Ratana area it is limestone with some shale in its upper and lower part. The limestone is dark grey, brown to dark grayish brown, occasionally light brown and creamy, microcrystalline, micrite, dense, firm to hard, at places slightly to highly argillaceous, partly dolomitic and traces of forams.

The Lockhart formation (Early to Late Paleocene) is another primary potential reservoir in the Ratana field, where it is mainly limestone with subordinate shale. The Limestone is light brown to brownish grey, occasionally dark grey, microcrystalline, in parts chalky, firm, nodularity rubly and brecciated with traces of pyrites (Sarfraz U Siddiqui et. Al).

2.7.3 Seal Rocks

Thick layers of evaporites and shale have good sealing potential for Infra-Cambrian reservoir. Interbedded shale, siltstone and mudstone provide seal to Cambrian reservoirs. Limestone and intraformational shale are the potential seals for Mesozoic and Cenozoic reservoirs. Paleocene shales (Patala Formation) and Miocene shale are the regional seals in the area. In study area Mamikhel Formation of Eocene age and Murree Formation of Miocene age providing the seal to the hydrocarbon.

2.7.4 Trapping Mechanism

Both structural and stratigraphic traps are possible in the Kohat-Potwar. Eastern Potwar represents, thrusted and salt cored anticlines and local pop ups. While the Salt Range Zone exhibits thrusted anticlines. Northern Potwar represents Passive Roof Duplex geometry, where thrusted anticlines are the potential targets. Further north in the North Potwar Deformed Zone imbricated antiformal stacks are the main targets. The Kohat area has experienced very complex deformation style due to the development of multiple detachment levels, and compression as well as strike slips motion. The area is represented by antiformal stack and possibly flower structures, thrusted anticlines and pop-up, fault propagating folds etc. The Cretaceous and Jurassic truncations, thrusted anticlines and gentle fold could be the potential targets in Bannu Area.

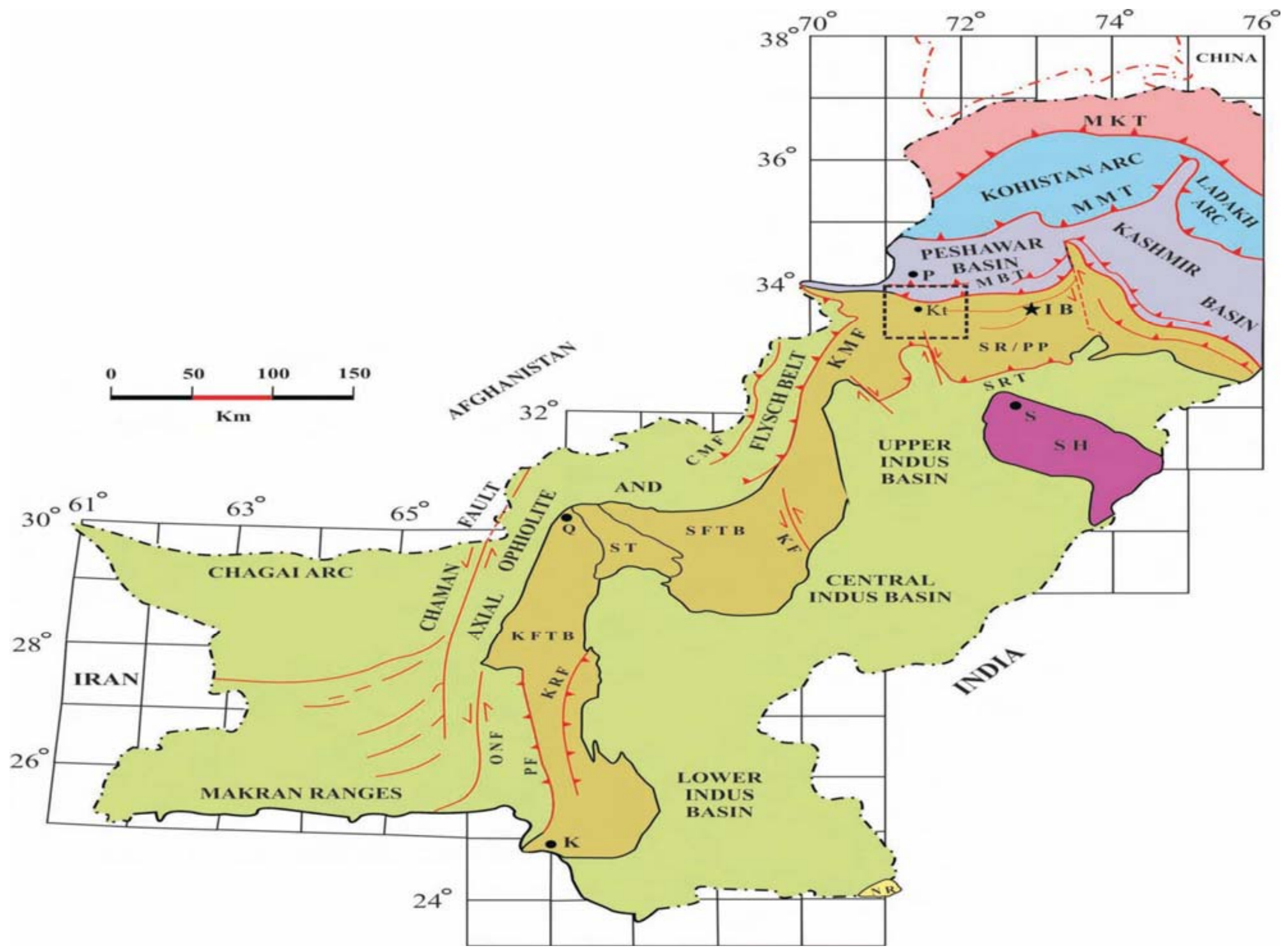

Figure 2.1 Generalized tectonic map of Pakistan (Davis & Lillie, 1994).

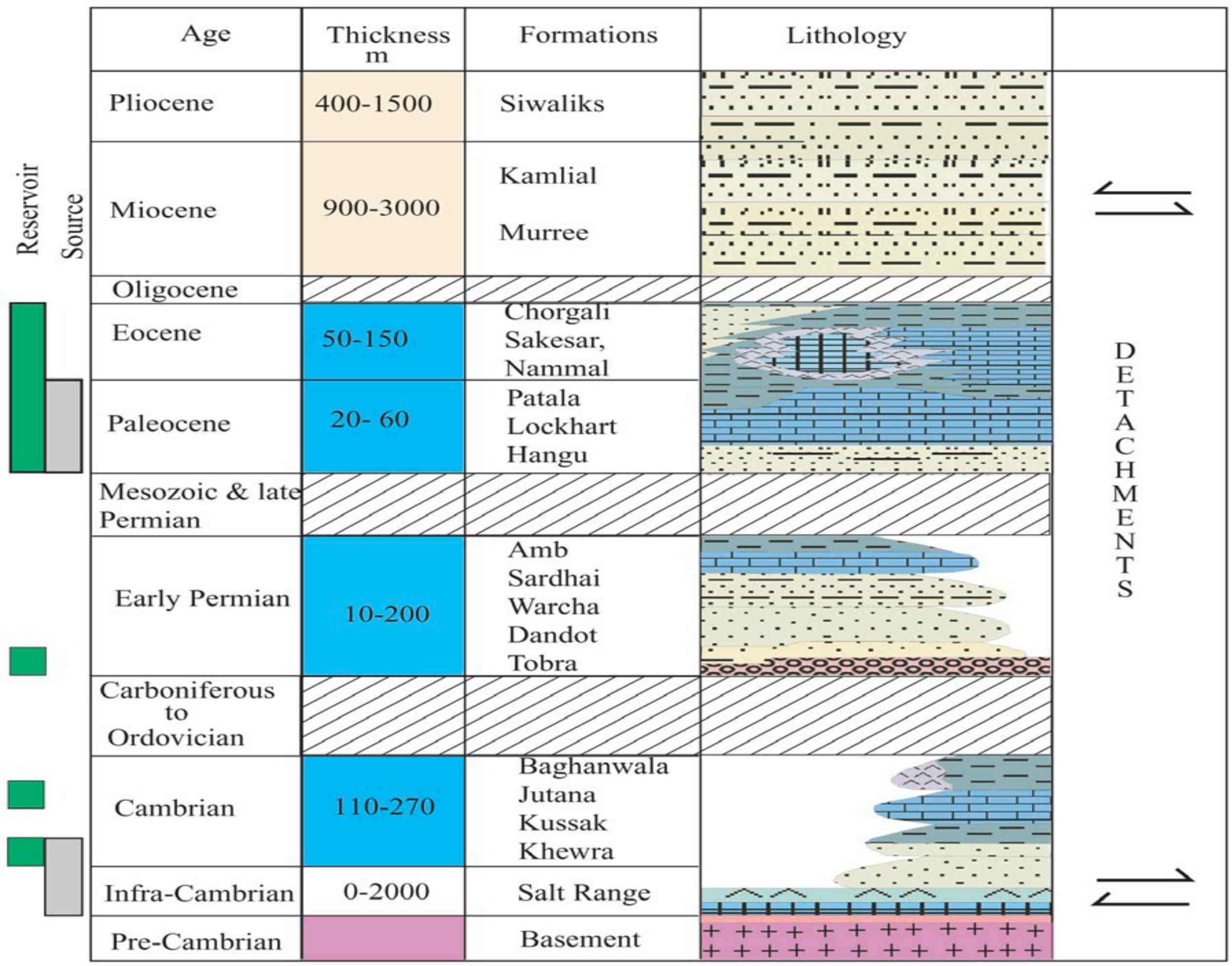

Figure 2.2: Stratigraphic Column of Upper Indus Basin. (Muhammad Aamir et al)

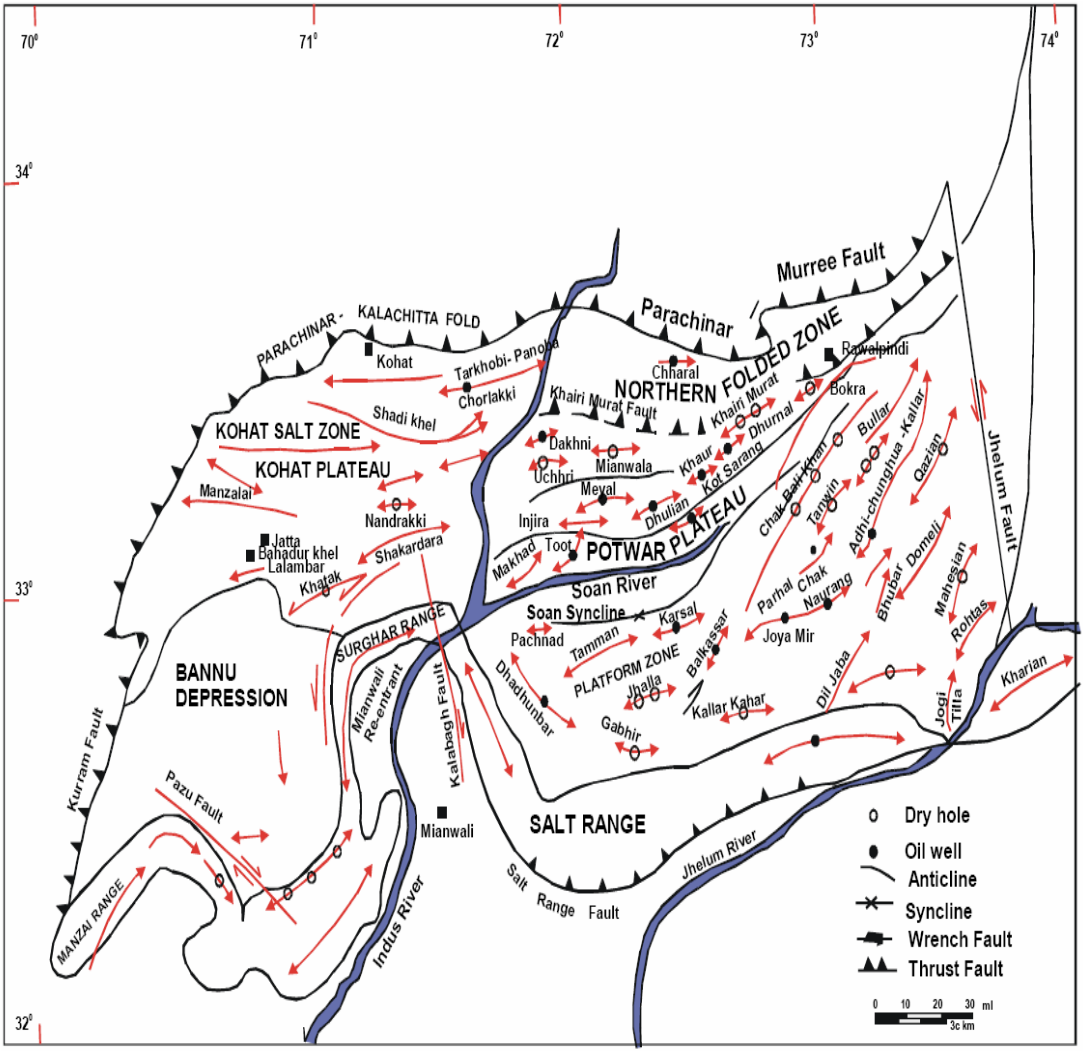

Figure 2.3: Tectonic division of Potwar Basin (Shami & Baig, 1998).

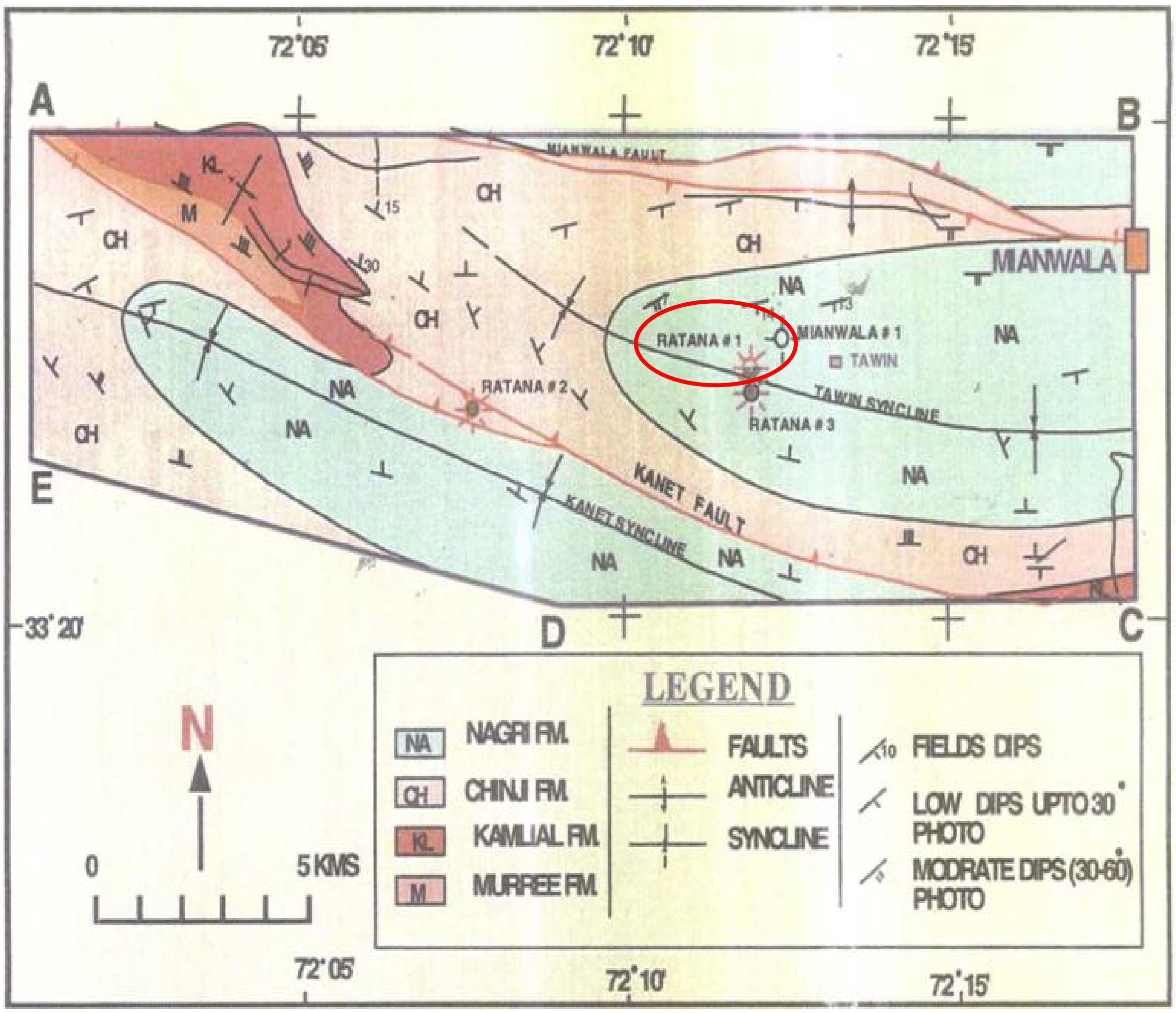

Figure 2.4: Surface Geological map of Ratana area (Sarfaraz U Siddiqui) et.al.

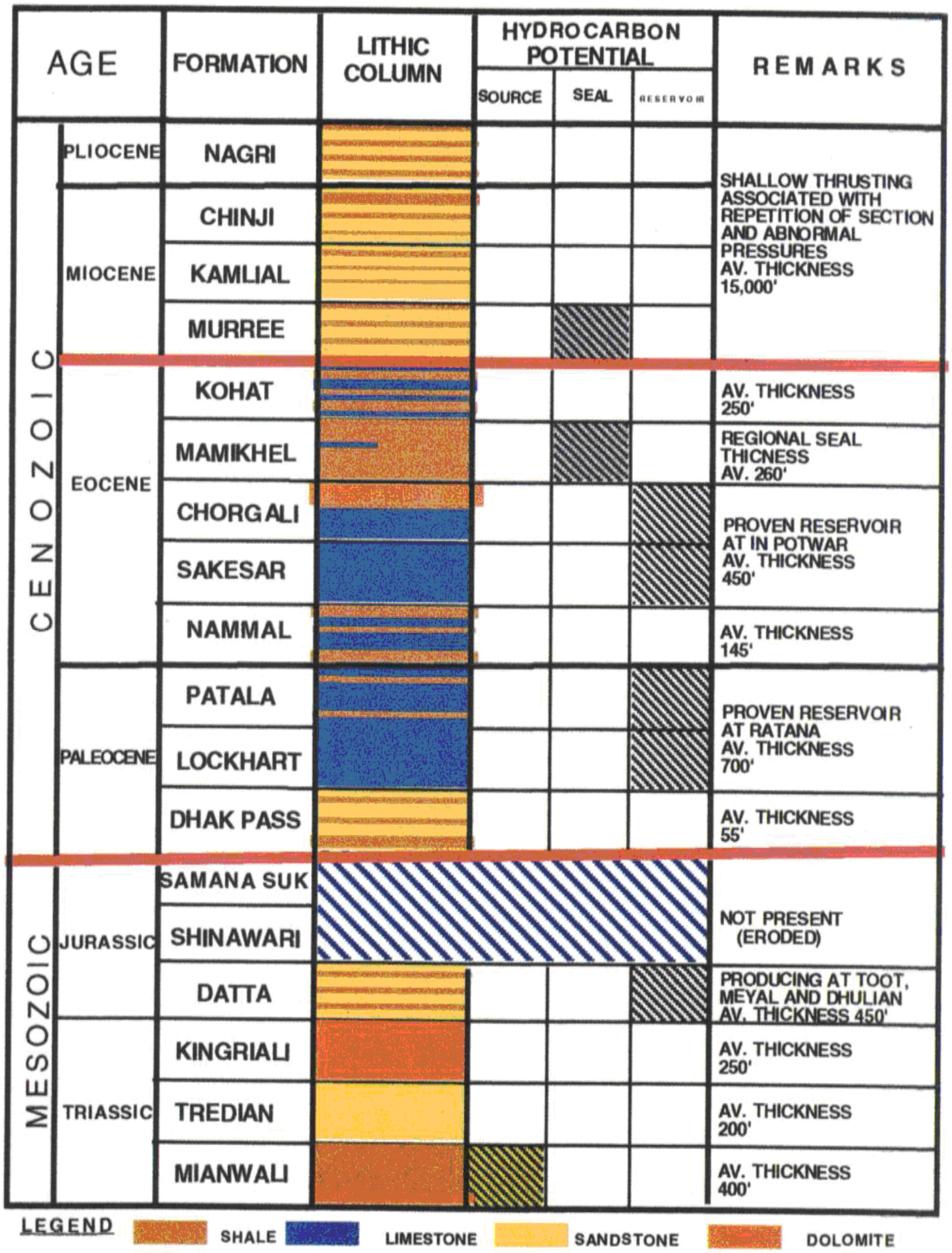

Figure 2.5: Generalized Stratigraphic Column of Ratana area & Petroleum play (Sarfaraz U Siddiqui)

3 Seismic Procedures

3.1 Seismic Acquisition

3.1.1 Introduction

Seismic investigation starts in the field with the acquisition of data. Acquiring seismic data costs much more than processing it. The primary objectives of good seismic acquisition should include the maximization of signal to noise ratios by taking advantage of means and opportunities that will not be available at the processing stage.

In seismic data acquisition some receivers are placed at different locations to detect vibrations produced by an energy source the receivers converts the mechanical vibrations into electric current that is transmitted to a recorder, the recorder is designed to preserve the information in a form that can be displayed and analysed. Acquisition essentially comprises of a source pattern, a detection spread and digital recording instruments.

3.1.2 Recording Parameters

There is a set of parameters which defines a given recording operation. These parameters are normally kept constant during a survey of given area. The most important parameters are following:

i. The initial (suppression) gain
ii. The filter setting
iii. The sampling period
iv. The recording density
v. The total recording time (i.e. record length)
vi. The trace-to-channel relationship
vii. The recording format

The observer must see to it that all these parameters are kept fixed during the recording of one complete seismic line, and it is advisable to keep them constant for the whole given area. Due to their importance in the processing stage, these parameters must be documented clearly for each seismic line. As recording parameters mentioned above were used for the seismic cross-sections in Ratana area of North Potwar.

3.1.3 Source

The wave put in to the earth by a vibroseis source is oscillatory rather than impulsive and persists for many seconds, the frequency changing slowly over the duration of the signal. The returned signals recorded in the field cannot be interpreted directly as is generally possible with the other sources. The recorded data must be processed by cross-correlation of the signals received by the geophones with the oscillatory source signal itself. Reflections and other seismic events related to the source signal give a greater degree of correlation with the generated waveform than with random noise.

3.1.4 Receivers

Receivers are the sensitive recording receiving instruments; they are primary elements of modern instrumental systems used to record seismic ground motions. In recent years, special-purpose digital computers have been put in to recording trucks and seismic ships to control the entire process in the field.

3.1.4.1 Geophone

The geophone is an electromechanical instrument which produces an electrical output which is linearly dependent on the vertical component of the motion of the ground in which it is planted. There are several types of geophones depending on the particular physical principle applied in functioning. The most commonly used type (the electromagnetic) operators on the principle of voltage generation due to differential movement of a coil in magnetic field. The generated voltage is proportional to the rate of change in the magnetic flux due to movement of one part relative to the other.

3.1.4.2 Geophone Interval

Geophone interval is distance between adjacent geophones within a group. It is sometimes used for group interval, the separation between the centres of adjacent geophone groups.

3.1.4.3 Group

The various geophones which collectively feed a single channel. The number of geophones may vary from one to several hundred. A large group is sometimes called a patch.

3.1.4.4 Group Interval

The horizontal distance between the centres of adjacent geophone groups is the group interval.

3.1.5 Recording Parameters of Seismic Line

The seismic reflection data acquisition of seismic lines NP-86 involves the following field parameters.

Date Recorded	January 1986
Party number	377

3.1.6 Energy Source

Table 3.1: Showing energy source parameters used in Acquisition

Type	Vibroseis	Vibrator point interval	50m 12sweeps/vp
Sweep length	12sec	Source Array	inline 4Vibrator/45.9m
Direction of recording	NW_____SE push trace no:96	Sweep Frequency	8___47 Hz Sweep length 12sec

3.1.7 Receivers Arrangements

Table 3.2: Showing the Receivers arrangements.

Fold of recording	48	Type split spread
No. of groups	96	Interval 50m
No. of receiver/group	36	Interval 2.8m
Receiver Array	inline	
Cable length	5000m	depth 0m
Near trace	48,49	Offset 150m
Far trace	1,96	Offset 2500m

3.1.8 Instrumentation

Table 3.3: Instrument used in data acquisition.

Geophones	SM- 4	
Natural frequency	10Hz	Damping 70%
Recording System	MDS-10	
Gain type	IFP	
Low-cut	Out	
High Cut	125 Hz	Slope 72db/octave
Recoding format	SEGB	
Recording length	12 sec	sweep 5 sec, listen
Sample Interval	2 ms	
Compression produces	negative number	

3.2 Seismic Data Processing

3.2.1 Introduction

Data processing is a sequence of operations, which are carried out according to the pre-defined program to extract useful information from a set of raw data as an input-output system (Al. Sadi, 1980). Processing may be schematically shown as:

Observational data ⇒ **Processing system** ⇒ **Useful Information**

3.2.1.1 Processing Sequence

The seismic data processing sequence can be broadly defined in five categories (Yilmaz, 2001).

i. Data Reduction
ii. Geometric Corrections
iii. Data Analysis and Parameter Optimization
iv. Data Refinement
v. Data Presentation

In figure 3.1 and 3.2 a systematic diagram is given that explains the stages involved in data processing.

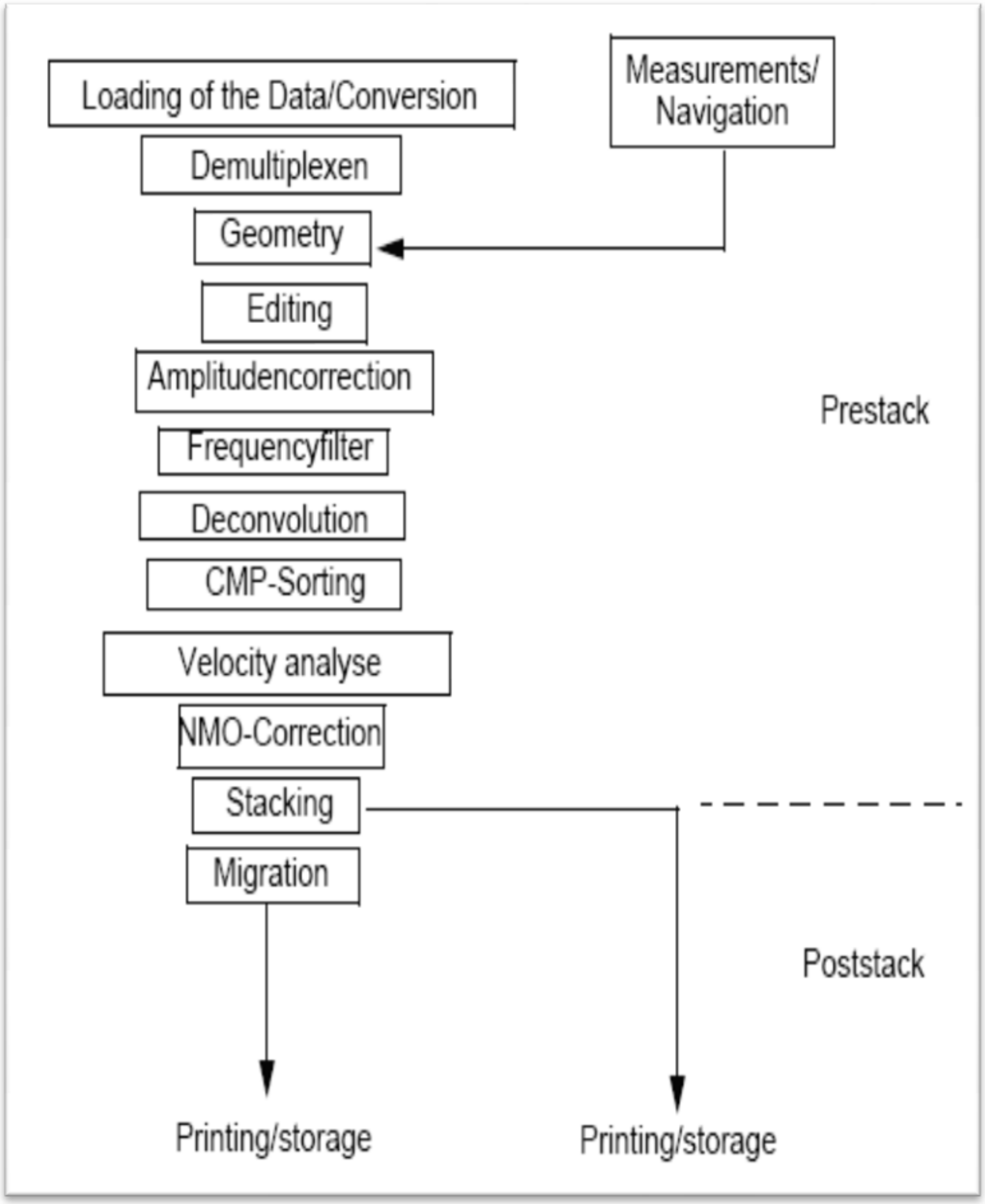

Figure 3.1: Diagram showing the various stages of seismic processing (modified from Rehman, 1989).

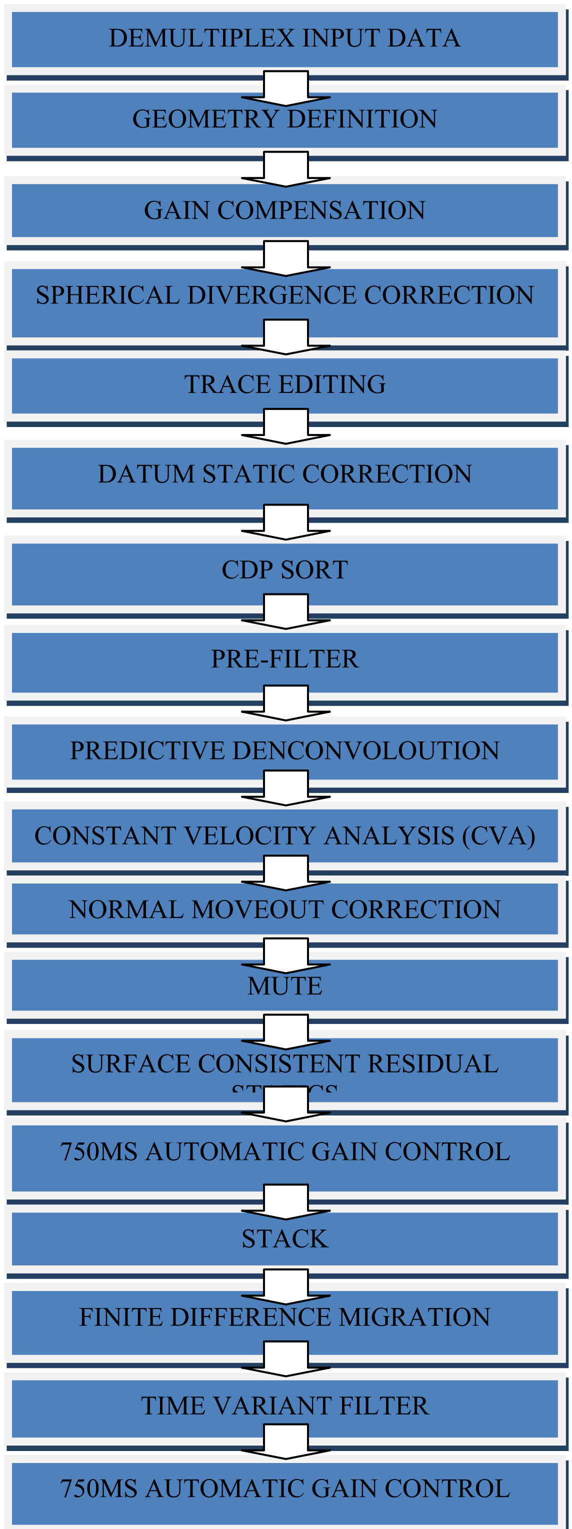

Figure 3.2: Processing sequence followed in the processing of available seismic data (adopted from seismic section).

3.3 Seismic Interpretation

3.3.1 Introduction

Interpretation method use in this chapter, involves determining the geologic significance of seismic data. This necessarily involves geologic terminology. Interpretation sometimes also includes data reduction, selecting events believed to be primary reflections, and locating the reflectors with which they are associated.

One can usually be consistent and still have a choice of interpretations, the more so when data is sparse. The objective of seismic interpretation is to discover hydrocarbon accumulations in the subsurface sedimentary rocks.

Interpretation can be also said as the transformation of seismic reflection data into a structural picture by the applications of corrections, migration and time depth conversion. (Dobrin and Savit 1988).The seismic reflection interpretation usually consists of identifying the reflectors and calculating their positions on the basis of geology of the survey area and then correlations with the wells data. The interpretation of reflection data requires the fitting of all geological and geophysical information into an integrated picture that is more complete and reliable then either source is likely to give alone. Ideally this integration would be accomplished most efficiently if a single person highly competent both in geophysics and geology will do it. However in actual practice such persons are very few and it is usually necessary for a geophysicist and geologist to collaborate at this stage of interpretation. For interpretation of seismic reflection data the area study as well as the experience is of vital importance.

In general the interpretation is of two types;

(1) Structural Analysis

(2) Stratigraphic Analysis.

3.3.2 Structural Interpretation

The main application of the structural analysis of the seismic sections is in the search for structural traps containing hydrocarbons. An initial interpretation of reflections displayed on seismic section may lack geological control at some point but the geological nature of the reflectors can be established by tracing reflection events back either to outcrop or to an existing borehole for stratigraphic control. Generally, the structural interpretation is carried out in units of two way reflection time rather than depth, and time structure maps are constructed to display the geometry of selected reflection events by means of contours of equal reflection time. Depth structural contour maps can be produced from time structure maps by converting the reflection time in to depths using appropriate mathematical expression involving velocity information. Time structural maps bear a close similarity to depth structural maps.

Interpreting the faults during structural interpretation is very important. Faults are often critical to accumulation of oil. They can be critical in either a positive or a negative way. A fault may form a seal by cutting of a structural and stratigraphic feature so the oil is trapped against the fault or faults may act as a migration path.

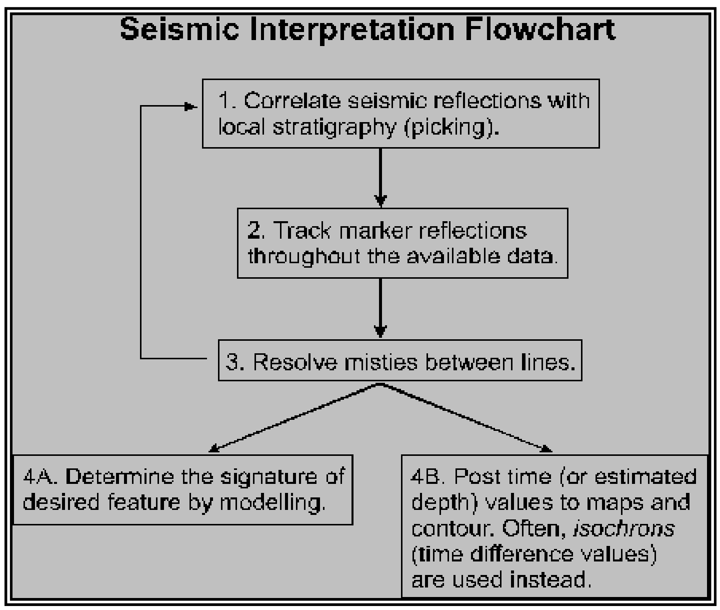

Figure 3.3: After (Dobrin&Savit, 1988) (Seismic data interpretation flowchart).

3.3.3 Stratigraphic Interpretation

Seismic stratigraphic interpretation involves the subdivision of seismic sections into its constituent sequences. Each sequence then can be analyzed in terms of the reflection events and their character to obtain insight into the depositional environments responsible for the sequence. Different types of reflection configuration are diagnostic of different sedimentary sequences on a regional scale for example parallel reflections characterize some shallow water shelf environments. While the oblique cross-bedded show the deeper water environment.

This method also facilitates for the identification of the major progradational sedimentary sequences, which offer the main potential for hydrocarbon generation and accumulation. Stratigraphic analysis therefore greatly enhances the chances of successfully locating hydrocarbon traps in sedimentary basin environments. Hydrocarbon accumulations are some time revealed directly on true amplitude seismic sections by localized zones of anomalous strong reflections known as bright spots. These high amplitude reflection events are attributable to the large reflection coefficients at the top and bottom of gas zones with in a hydrocarbon reservoir. In the absence of bright spots fluid interfaces may nevertheless be directly recognizable reflection events discordant to the local geological dip. (Keary. et al, 2002)

3.4 Interpretation procedures applied on the projected area

3.4.1 Collection and examination of Data

All the data relevant to the interpretation, including geologic, well data and etc. The relevant seismic data usually include seismic sections, a base map, and velocity and other data from the field or generated in processing. All possible approachable data is kept in order to improve the interpretation as well as to resolve many questions which arise as a result of interpretation.

Once all the data was collected next task was to examine the data for evidence of any mislocation or improper acquisition or processing. The header of the section was checked to see the processing sequence. Several things were read from it such as the type of array used, number of groups, number of channels and the interval between them.

3.4.2 Calculation of Interval Velocity

It is the average speed of a wave front between two point measured perpendiculars to the velocity layers (Zia Ur Rehman, 1989). It is calculated by using velocity functions available on the section with help of formula given below:

$$Vint= ((((Vrms_{n})^2 * T_n)-((Vrms_{n-1})^2*T_{n-1}))/(T_n-T_{n-1}))^{1/2}$$

Vrms=Root mean square velocity

Tn= two-way travel time of nth depth

Tn-1 = two-way travel time for n-1 depth

3.4.3 Calculation of Average Velocity

It is the ratio of vertical depth to the travel times of a wave from its source to that depth (Zia Ur Rehman, 1989). It is calculated by using velocity functions available on the section with help of formula given below:

$$Vavg= (((Vint_{n}*(Tn-T_{n-1})) + (Vavg_{n-1} * T_{n-1}))/Tn)$$

Tn= two-way travel time of nth depth

Tn-1 = two-way travel time for n-1 depth

Vint= Interval Velocity

As data was in time domain on seismic section, for the picking of horizon according to well data it was necessary to convert all seismic reading in the depth domain so that well data easily match with seismic data.

3.4.4 Depth Conversion

After calculation Vint and Vavg from velocity functions given on sections, The time domain data is converted in depth domain with help the given formula:

$$S= (V*T)/2$$

Where,

S=Depth of the reflector

T=Two-way time of the reflector road from the seismic section

V=Mean average velocity

A time section is actually a reproduction of an interpreted seismic section. It consists of two scales; horizontal scale and vertical scale. By interpolating method Vavg and depth value were calculated at every time slice so that correlation of well data with seismic data can easily be done.

3.4.5 Picking of Horizon

3.4.5.1 Methodology

Reflectors R1, R2 and R3 were picked on the seismic section on the basis of geological history and previous research papers of that area. Laterally on the basis of the well log data these reflectors were named as (fig 3.2-3.5)

R1= Chorgali Formation

R2= Lockhart Formation

R3= Datta Formation

3.4.6 Picking of Faults

3.4.6.1 Methodology

On the basis of previous studies, geological history and waves characteristics various faults were marked on the seismic sections and faults were correlated on basis of throw and dip direction, which are shown in the figures 3.5-3.8 at the end of this chapter.

3.4.7 Time and Depth Section

To understand the structure and stratigraphy of the area time and depth sections were made through different technologies (figure 3.9-3.16).

3.4.8 Time and Depth Contouring

Contour is defined as the line draw by joining the point of equal values. The time and depth values are used for the contouring of the Lockhart formation, which is proven reservoir in Ratana field (figure 3.17 & 3.18).

3.5 Description

From the interpretation and time and depth contouring of the Lockhart formation (shown in figures below) it is concluded that

- The subsurface structure is fault bounded anticline.
- There are many faults and presence of faults showing that the area is highly disturbed by tectonic activities.
- Anticlinal traps or fault traps are considered as the best for the accumulation of hydrocarbons and Lockhart is a proven reservoir in this area, so the top of the anticline may be the best location for drilling well.

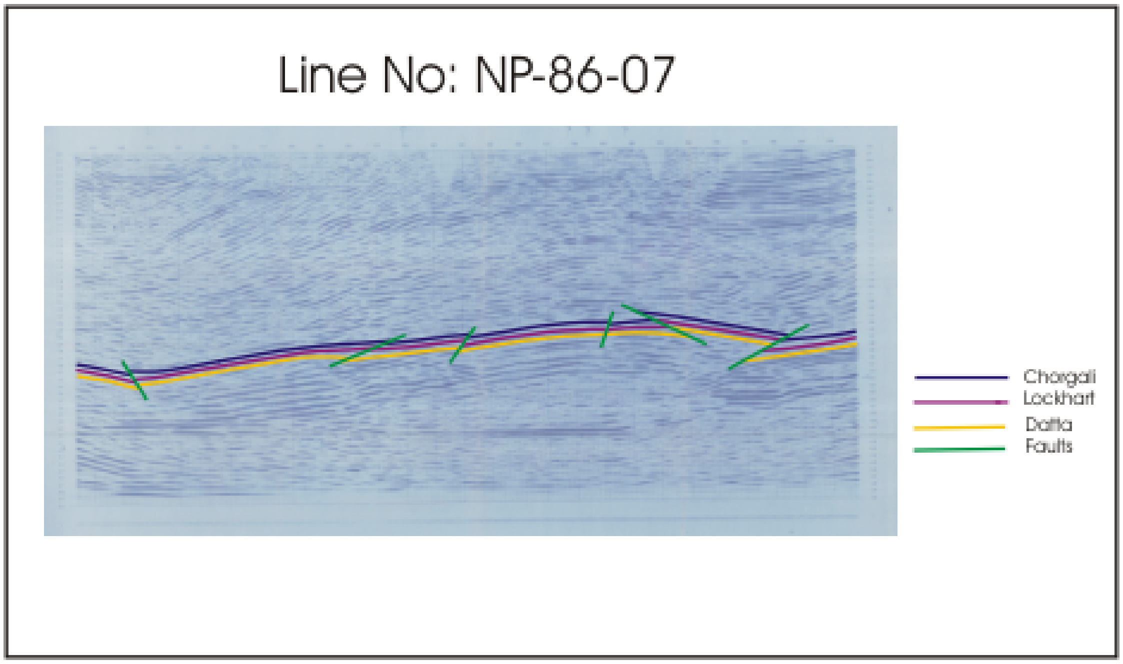

Figure 3.2: Faults and horizons on seismic line 07.

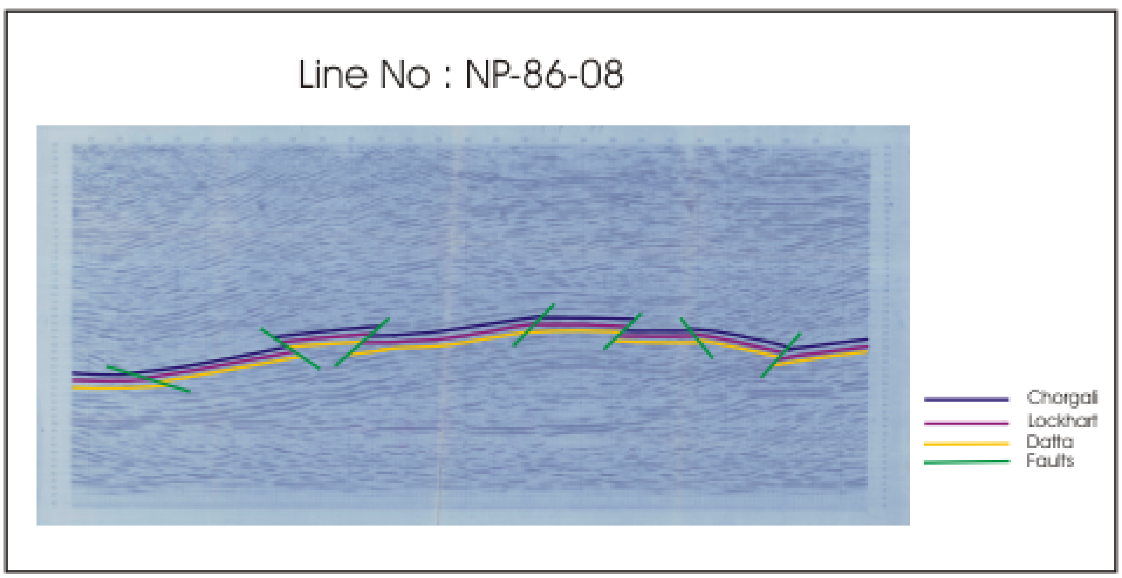

Figure 3.3: Faults and horizons on seismic line 08.

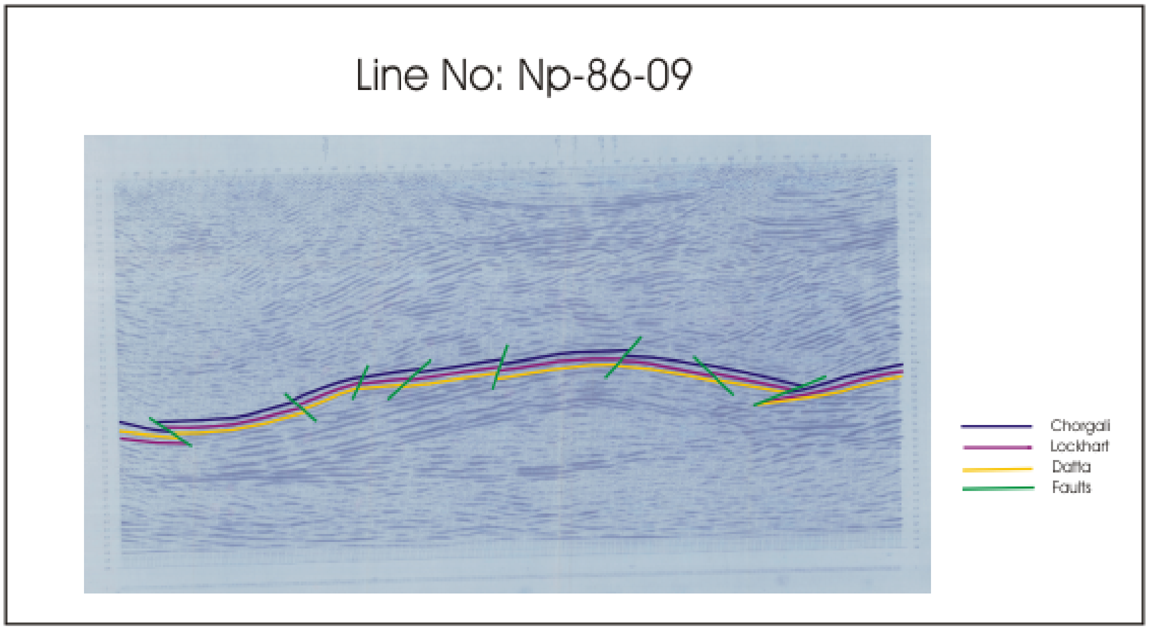

Figure 3.4: Faults and horizons on seismic line 09.

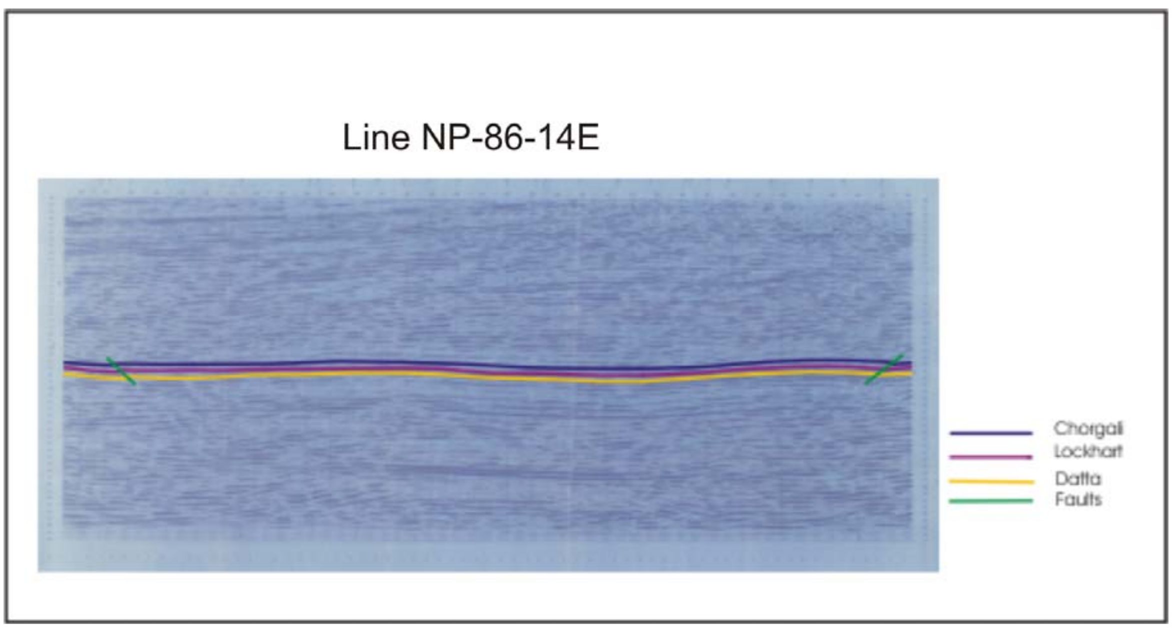

Figure 3.5: Faults and horizons on seismic line 14E.

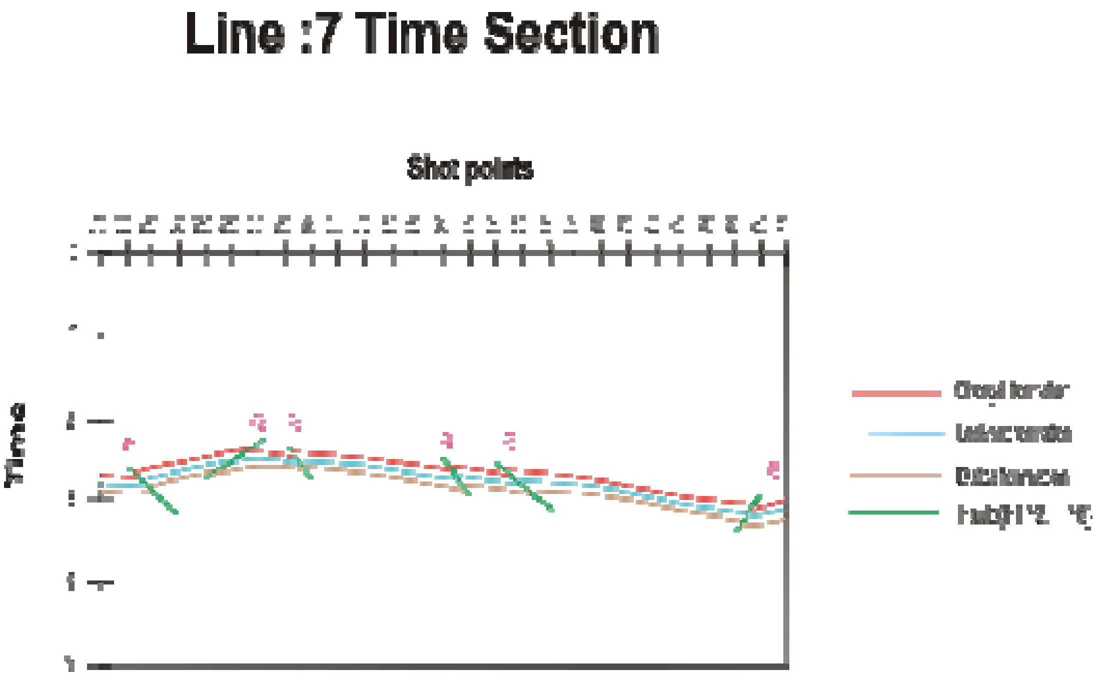

Figure 3.6: Time section of Np-86-07.

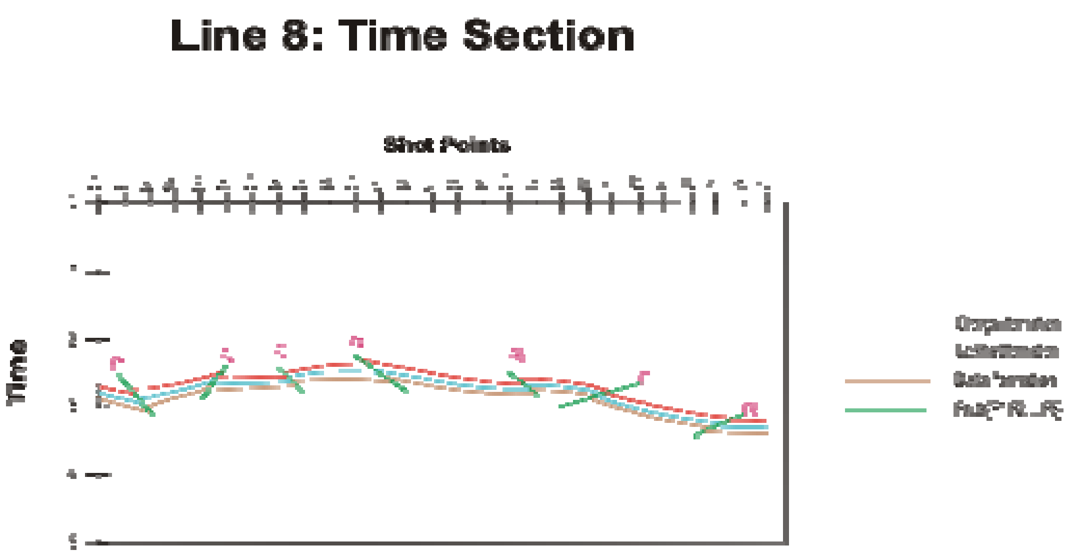

Figure 3.7: Time section of Np-86-08.

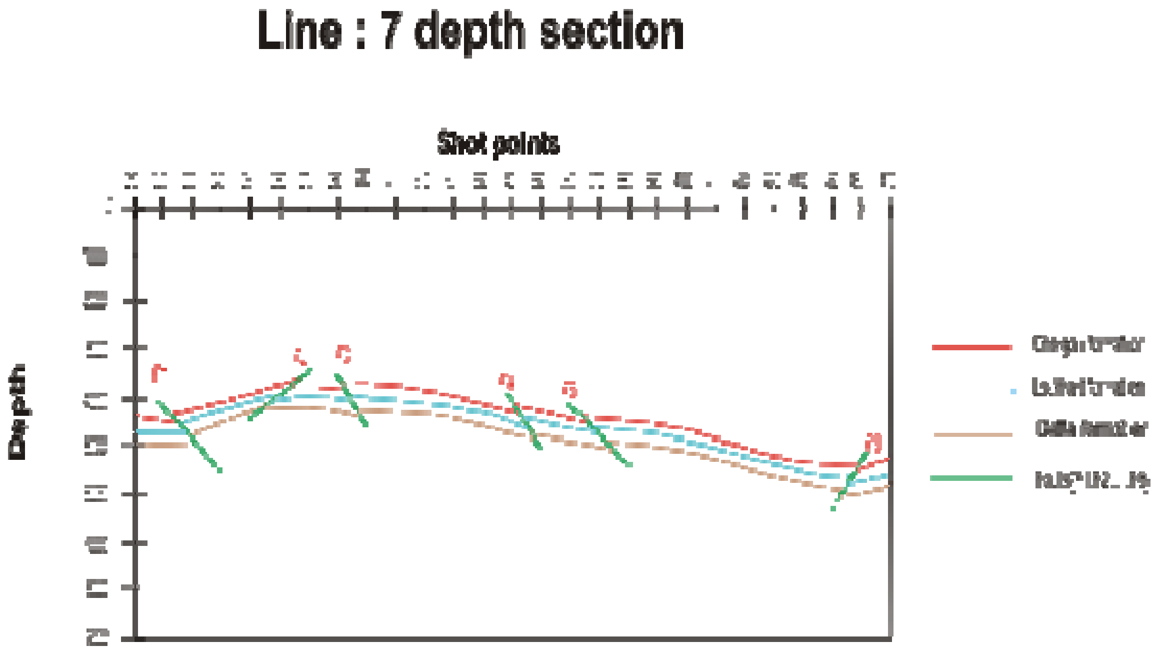

Figure 3.8: Depth section of Np-86-07.

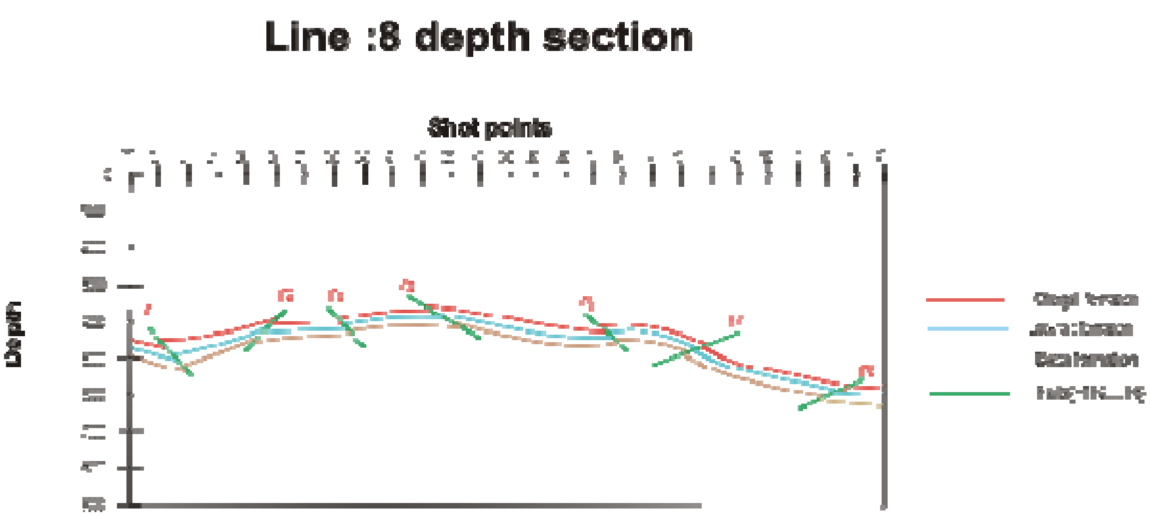

Figure 3.9: Depth section of Np-86-08.

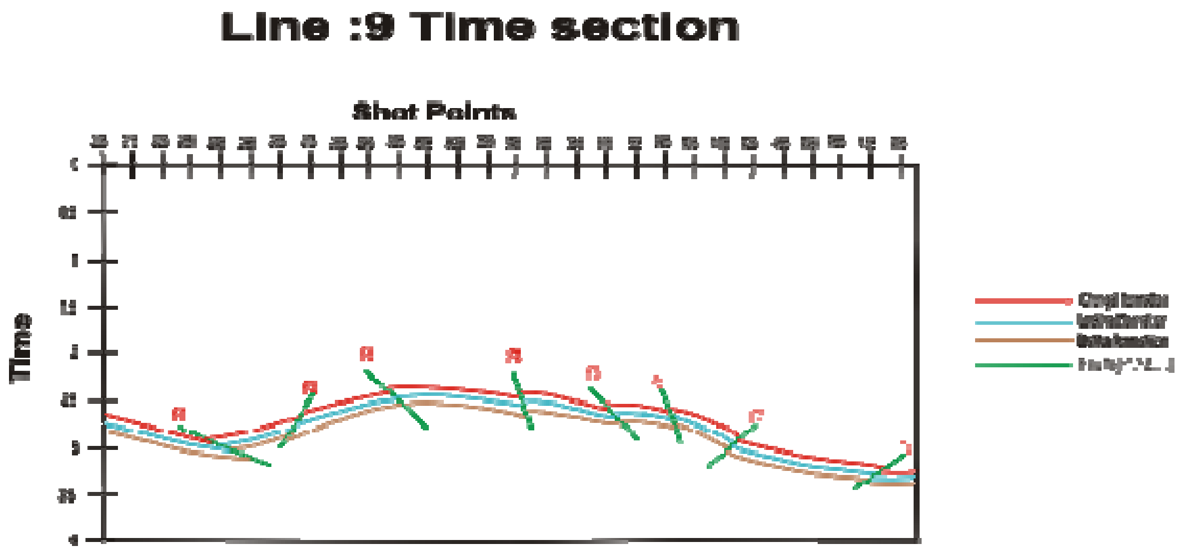

Figure 3.10: Time section of line NP-86-09.

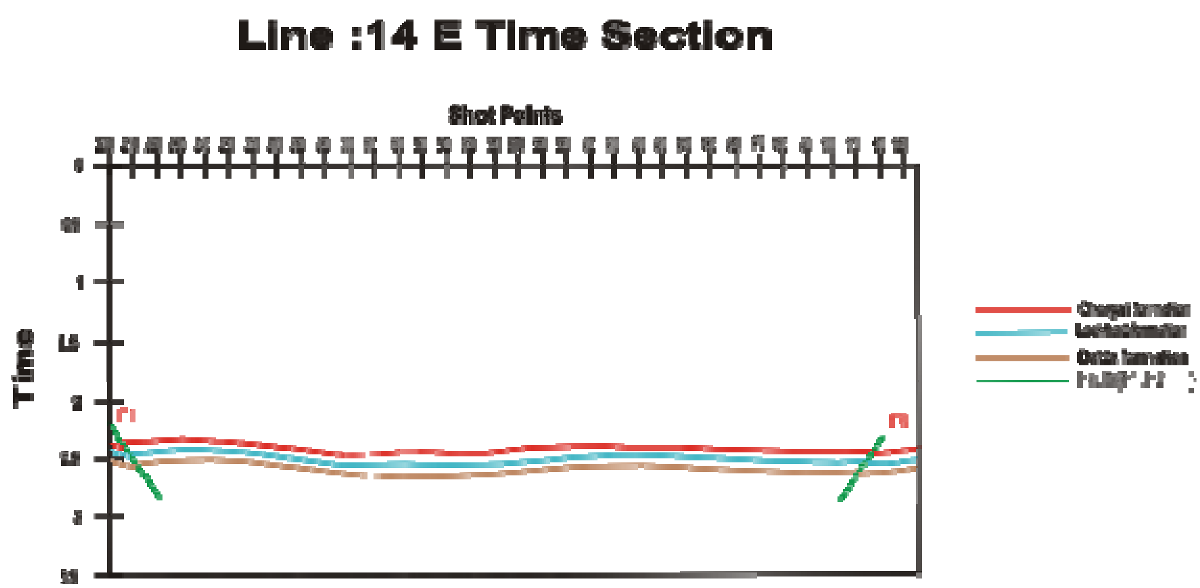

Figure 3.11: Time section of NP-86-14E.

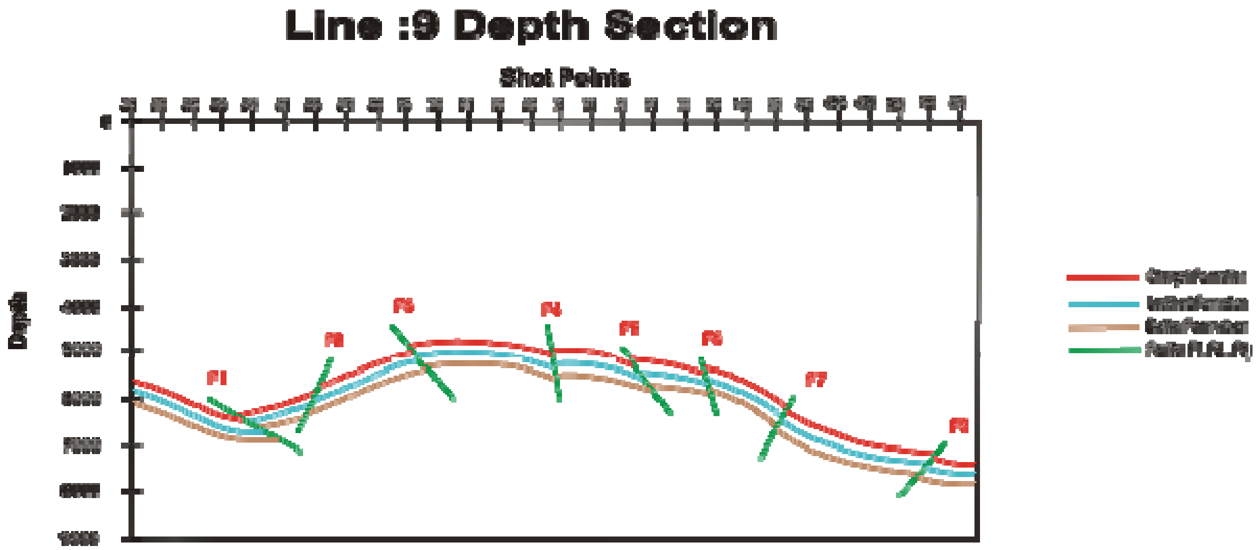

Figure 3.12: Depth section of NP-86-09.

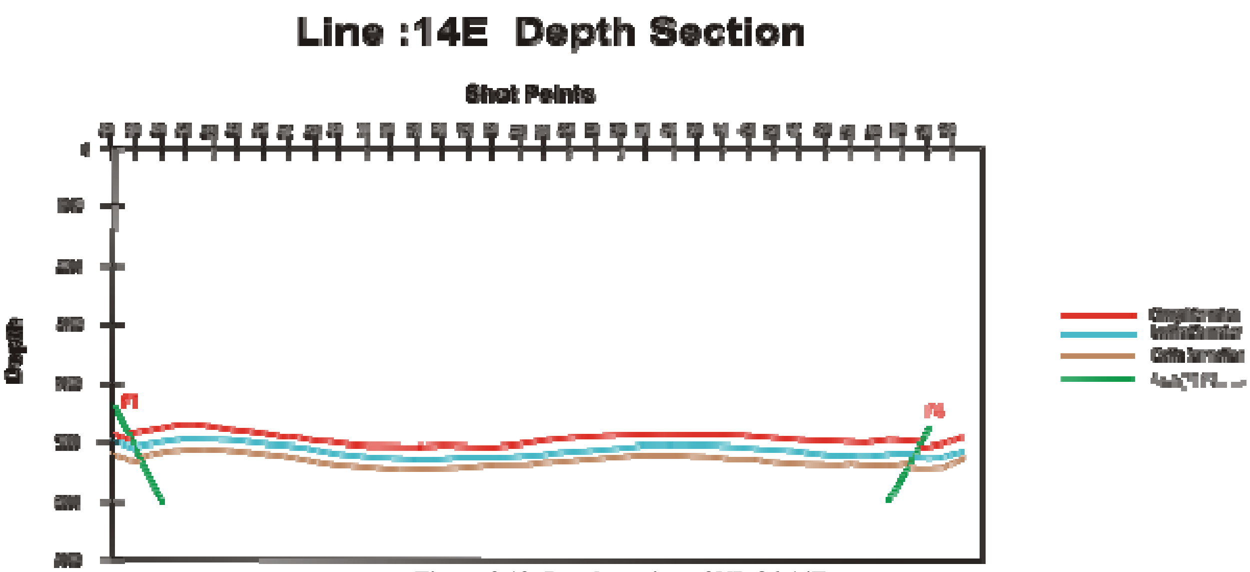

Figure 3.13: Depth section of NP-86-14E.

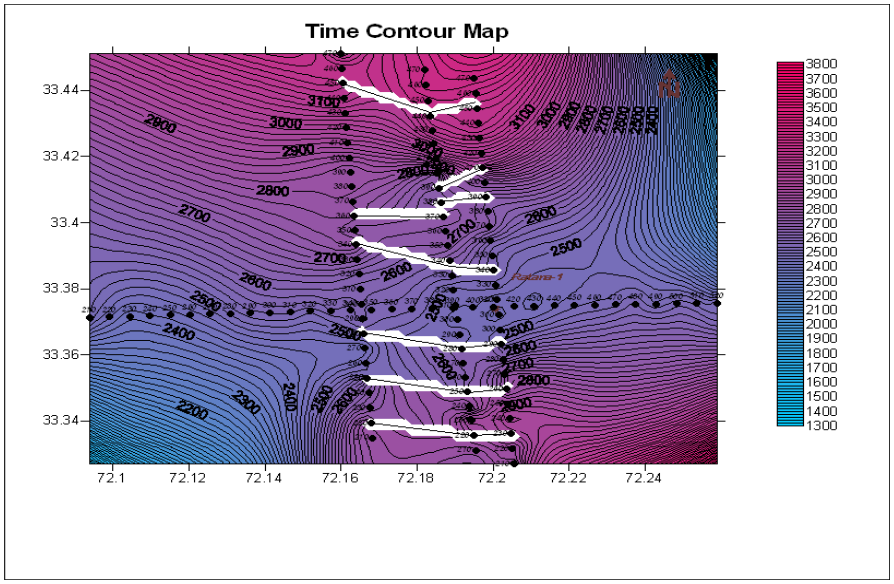

Figure 3.14: Time contouring of the Lockhart formation (Time=msec, interval=100msec

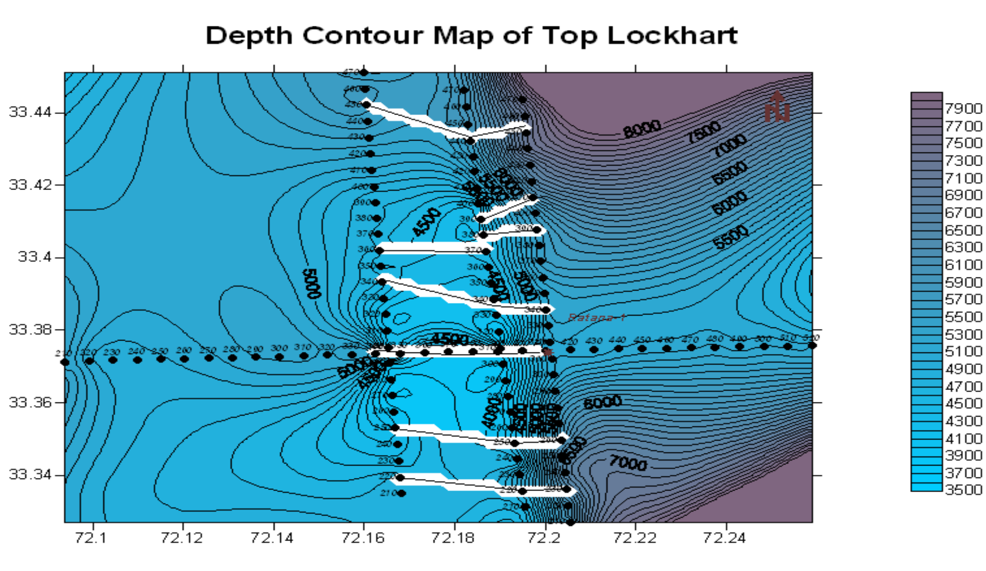

Figure 3.15: Depth contouring of Lockhart formation (depth=meter, interval=200m).

4 Well Log Interpretation & Rock physics

4.1 Well Log Introduction

Well logs or wire line logs are continuous recordings of well depth versus different petrophysical characteristics of the rocks through which the well is drilled. There are many types of well logs, depending upon the characteristics of the rock being measured. Open hole logs are created by remote sensing equipment lowered into a hole drilled with a rotary or percussion-drilling rig. Cased whole logs are run after the well is cased to assess the current state of the reservoir, to check the mechanical integrity of the casing, tubing, or cement, and to monitor fluid flow.

The two primary parameters determined from well logs measurements are porosity, and the fraction of pore space filled with hydrocarbons. The parameters of log interpretation are determined both directly or inferred indirectly, and are measured by one of three general types of logs: (1) electrical, (2) nuclear, and (3) acoustic or Sonic. The names refer to the sources used to obtain the measurements. The different sources create records (logs), which contain one, or more curves related to some property in the rock surrounding the well bore (Alger, R. P, 1980).

4.1.1 Rock Properties that affect Logging Measurements

- Porosity
- Permeability
- Water saturation:
- Resistivity

4.2 Log Interpretation

4.2.1 Basic Information Needed for the Log Interpretation

These are factors that should be known before the log interpretation;

4.2.1.1 Lithology

In quantitative log analysis, there are several reasons why it is important to know the lithology of a zone (i.e. sandstone, limestone, or dolomite). Porosity logs require a lithology or a matrix constant before a zone's porosity can be calculated.

4.2.1.2 Temperature of Formation

Formation temperature ($\mathbf{T_f}$) is also important in log analysis because the resistivity of the drilling mud ($\mathbf{R_m}$), the mud filtrate ($\mathbf{R_{mf}}$), and the formation water ($\mathbf{R_w}$) varies with temperature. The temperature of a formation is determined by knowing

1. Bottom hole temperature (BHT)
2. Total depth of the well (TD)
3. Surface temperature.

The following petrophysical parameters can be found

1. Volume of shale
2. Porosity of formation
3. Water saturation and hydrocarbon saturation
4. Lithology of formation

4.2.2 Calculation for the Porosity of Formation

Porosity of formation can be calculated form the following types of log data;

- Porosity from Sonic Log data.
- Porosity from Density Log data.
- Porosity from Neutron porosity Log data.

4.2.2.1 Porosity from Sonic Log Data

From Sonic Log data, I calculated the value of Δt each specific interval depth, then Wyllie formula was used for calculation of $Ø_{sonic}$ porosity.

Wyllie formula

Wyllie used the empirical time average relation for the calculation

$$Ø_{sonic} = (\Delta t_{log} - \Delta t_{ma}) / (\Delta t_f - \Delta t_{ma})$$

Where:

Øsonic = Sonic derived porosity

Δtma = Interval transit time of the matrix

Δtlog = Interval transit time of formation

Δtf = Interval transit time of the fluid in the well bore

(Fresh mud = 189; salt mud = 185)

The Wyllie formula for calculating sonic porosity has been used to determine porosity in consolidated sandstones and carbonates with intergranular porosity (grainstones) or intrecrystalline porosity (sucrosic dolomites). However, when sonic porosities of carbonates with vuggy or fracture porosity are calculated by the Wyllie formula, porosity values are too low. This has happened because the sonic log only records matrix porosity rather than vuggy or fracture secondary porosity. The percentage of vuggy or fracture secondary porosity has been calculated by subtracting sonic porosity from total porosity. Total porosity values are obtained from one of the nuclear logs (i.e. density or neutron).

Where a sonic log is used to determine porosity in unconsolidated sands, an empirical compaction factor or **Cp** should be added to the Wyllie et al equation:

$$Ø_{sonic} = (1/Cp) \times [(\Delta t_{log} - \Delta t_{ma}) / (\Delta t_f - \Delta t_{ma})]$$

Where:

Øsonic = Sonic derived porosity

Δtma = Interval transit time of the matrix (Shown in Table 4.1)

Δtlog = Interval transit time of formation

Δtf = Interval transit time of the fluid in the well bore

(Fresh mud = 189; salt mud = 185)

Cp = Compaction factor

The compaction factor is obtained from the following formula:

$$Cp = (\Delta tsh \times C) / 100$$

Where,

Cp = Compaction factor

Δtsh = Interval transit time for adjacent shale

C = Constant which is normally 1.0 (Hilchie, 1978)

The interval transit time (Δt) of a formation is increased due to the presence of hydrocarbons (i.e. hydrocarbon effect). If the effect of hydrocarbons is not corrected, the sonic derived porosity will be too high. Hilchie (1978) suggests the following empirical corrections for hydrocarbon effect:

$$Ø_{sonic} \times 0.7 \text{ (gas)}$$

$$Øsonic \times 0.9 \text{ (oil)}$$

Table 4.1: Interval transit times for Different Matrices. These constants are used in the Sonic Porosity Formula. (after Schlumberger, 1979)

Lithology	Δt_{ma}(µsec/ft) commonly used
Sandstone	55.5 to 51.0
Limestone	47.6
Dolomite	43.5
Anhydrite	50.0
Salt	67.0
Shale	167.5 - 62

4.2.2.2 Porosity from Density Log data

Formulation bulk density (Øb) is a function of matrix density, porosity, and density of the fluid in the pores (salt, mud, fresh mud, or hydrocarbons). The formula for calculating density porosity is:

$$Ø\,den = (\rho ma - \rho b) / (\rho ma - \rho f)$$

Where:

Ø den = Density derived porosity

ρma = Matrix density (Shown in Table. 4.2)

ρb = Formation bulk density

ρf = Fluid density (1.1 salt mud, 1.0 fresh mud, and 0.7 gas)

Table 4.2: Matrix densities of Common Lithologies. Constants presented here are used in the Density porosity Formula (after Schlumberger. 1972)

1. **Lithology**	**ρma (gm/cc)**
Sandstone	2.648
Limestone	2.710
Dolomite	2.876
Anhydrite	2.977
Salt	2.032
Shale	2.2 – 2.25

4.2.2.3 Porosity from Neutron Log

Neutron Logs are porosity logs that measure the hydrogen ion concentration in a formation. In a clean formation (shale free) where porosity is filled with fluid like water or oil the neutron log measures the liquid filled porosity.

Neutrons are created from a chemical source in the neutron logging tools. The chemical source may be the mixture of americium and beryllium which will continuously emit neutrons. These neutrons collide with the nuclei of the formation material and result in a neutron losing some of its energy. The max energy loss is a function of concentration of hydrogen in the formation. Whenever pores are filled with the gas rather than oil or water, neutron porosity will be lowered. This occurs because there is less concentration of hydrogen in the gas as compared to oil and gas. Neutron log responses vary, depending on:

- Difference in detector types.
- Spacing between source and detector.
- Lithology i-e sandstone, limestone and dolomite.

These variations in responses can be compensated by using the appropriate charts. If a formation is limestone and neutron log is recorded in apparent limestone porosity units then apparent porosity will be equal to true porosity. However, when the lithology of a formation is sandstone or dolomite, apparent porosity must be corrected to true porosity by using appropriate charts.

The combination of Neutron-Density log is not only used as a porosity device. It is also used as to determine the lithology and to detect the gas bearing zones. Therefore, porosity from a Neutron-Density Log can be calculated mathematically. The alternate method of determining the neutron-density porosity is to use the root mean square formula.

$$\mathbf{Ø_{N\text{-}D} = \sqrt{(Ø_N^2 + Ø_D^2/2)}}$$

Where

$Ø_{N\text{-}D}$ = Neutron-Density Porosity

$Ø_N$ = Neutron Porosity (Limestone units)

$Ø_D$ = Density Porosity (Limestone units)

Whenever N-D Porosity log records density porosity of less than 0.0, a common value is anhydrite. The following formula should be used to determine the N-D porosity:

$$\mathbf{Ø_{N\text{-}D} = (Ø_N^2 + Ø_D^2/2)}$$

Where

$Ø_{N\text{-}D}$ = Neutron-Density Porosity

$Ø_N$ = Neutron Porosity (Limestone units)

$Ø_D$ = Density Porosity (Limestone units)

Where an increase in density porosity occurs along with the decrease in neutron porosity in gas bearing zone, it is known as gas affect. Gas effect is created because of the gas in the pores. Gas in pores causes the density log to record high value while low in neutron log case. This is very important and helps to detect the gas zone.

4.3 Rock Physics

The term Rock physics contains the range of techniques that relate the geological properties (e.g. porosity, lithology, saturation) of a rock at certain physical conditions (e.g. pressure, temperature) with the corresponding elastic and seismic properties (e.g. elastic modulus, velocity, impedance). The techniques can be used for rock physics modeling, i.e. to predict the elastic (seismic) properties from the geology, or for rock physics inversion, i.e. to predict geology from elastic (seismic) observations.

Reservoir characterization, especially reservoir monitoring has become integral part of E&P strategy. The goal of reservoir characterization is to see how the hydrocarbons are distributed in the reservoir. Among the many parameters use to describe the reservoir, the main ones are porosity, fluid saturation and permeability. In the reservoir monitoring, the objective is to find out how reservoir change with time during production and enhanced recovery efforts. In both of these area rock physics play very important role.

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. The Rock Physicist seeks to establish relations between these material properties and the observed seismic response to develop a predictive theory, so that these properties may be detected seismically. Establishing relationships between seismic expression and physical rock properties therefore requires

- Knowledge about the elastic properties of the pore fluid and rock frame.
- Models for rock-fluid interactions. This is the domain of Rock Physics (Jan Dewar et.al, 05_May2001).

Rock Physics is a highly interdisciplinary field involving geology, geophysics, chemistry, Physics, acoustics, well logging, core analysis, petroleum, chemical and mechanical engineering (Yale, 1985).

4.4 Objectives

Rock Physics uses sonic logs, density logs, and also dipole (shear velocity) logs if available. Rock Physics aims to establish P-wave velocity (Vp), S-wave velocity (Vs), density, and their relationships to elastic moduli κ (bulk modulus) and μ (rigidity Modulus), porosity, pore fluid, temperature, pressure, etc. for given lithology and fluid types. Rock Physics talks about velocities and elastic parameters, because these are link between physical rock properties to seismic expressions.

Rock Physics may use information provided by the Petrophysicist, such as shale volume, saturation levels, and porosity in establishing relations between rock properties or in performing fluid substitution analyses. Rock Physics is the interest of Geophysicists (and maybe Physicists). Accurate relations between rock properties and seismic attributes can to put "flesh on the bones" of a seismic interpretation. That is, Rock physics which allows the interpreter to put "rock properties together with seismic horizon"(Peeters). Information about porosity, pore fill and lithology becomes available to argument the seismic interpretation (Jan Dewar et.al, 05_May2001).

4.5 Elastic Parameters

An elastic modulus, or modulus of elasticity, is the mathematical description of an object or substance's tendency to be deformed elastically (i.e., non-permanently) when a force is applied to it. The elastic modulus of an object is defined as the slope of its stress-strain curve in the elastic deformation region. Where lambda (λ) is the elastic modulus; stress is the force causing the deformation divided by the area to which the force is applied; and strain is the ratio of the change caused by the stress to the original state of the object. If stress is measured in Pascals, since strain is a unitless ratio, then the units of λ are Pascals as well. The three primary ones are:

4.5.1 Young's modulus

It describes the behaviour of the object (rod) that is pulled or compressed. It is often referred to simply as the elastic modulus or stretch modulus. It is denoted by E. The equation is given below:

$$\mathbf{E=Stress/Strain}$$

$$\mathbf{E= (F/A)/ (\Delta L/L)}$$

E= Young’s modulus.
F/A= Force per unit area applied to the end of object.
L= Original Length of the object.
ΔL= Change in the length of the object (R.J.Lillie.).

4.5.2 Shear modulus or modulus of rigidity

It describes the ability of material to resist shearing. It is denoted by G or μ.A material that shows strong resistance to shearing (ΔL=0) is very rigid (μ = ∞). A fluid on the other hand has no resistance to shearing (ΔL= ∞) and therefore lacks rigidity (μ =0).

$$\mathbf{\mu= Stress/ Strain}$$

$$\mathbf{\mu = (F/A)/ (\Delta L/L)}$$

μ=Shear Modulus.
F/A= Force per unit area applied to the end of object.
L= Original Length of the object.
ΔL= Change in the length of the object (R.J.Lillie.).

4.5.3 Bulk modulus

It describes the strain of material under certain type of stress. The bulk modulus or incompressibility describes the ability to resist being compressed. The bulk modulus is denoted by K and is stress divided by strain. The mathematically representation is given below.

$$\mathbf{K= Stress/ Strain}$$

$$K = \Delta P / (\Delta V/V)$$

ΔP= Change in pressure.

V= Original volume.

ΔV= Change in volume.

If a material under goes no volume change ($\Delta V=0$) when subjected to compressive stress (ΔP), the material is said to be incompressible ($K = \infty$). Conversely, materials that are easy to compress (K very small) undergo large changes in volume (large =ΔV) when subjected to relatively small compressive stresses (small ΔP) (R.J.Lillie. Whole earth geophysics).

Homogeneous and isotropic (similar in all directions) materials (solids) have their (linear) elastic properties fully described by two elastic moduli, and one may choose any pair. Fluids are special in that they cannot support shear stress, meaning that the shear modulus is always zero. This also implies that Young's modulus is always zero. Three other elastic moduli are Poisson's ratio, Lamé's first parameter, and P-wave modulus.

4.5.4 Poisson's ratio

Poisson's ratio is named after Siméon Poisson, is the ratio between transverse strain to the longitudinal strain and it is unit less. When a rod is compressed or stretch under some stress then there will be change in its length and also its width will be change according to applied stress. It is represented by υ or σ and its simplest formula is mention below.

$$\upsilon \text{ or } \sigma = (\Delta W/W)/(\Delta L/L)$$

υ or σ = Poisson Ration.

W= Original Width.

ΔW= Change in width.

L= Original Length of the object.

$\Delta L/L$= Change in the length of the object (R.J.Lillie.).

4.5.5 Lamé's constant

It is denoted by λ and illustrates the relationship four constant describe above and represented as:

$$\lambda = K-(2\mu/3)$$

$$\lambda = (\upsilon E/ (1+\upsilon)(1-2\upsilon))$$

4.6 Well Logs

As it is already mention that logs used for rock physics are named as below:

- Sonic log
- Density log
- Neutron log

Sonic log did not run in Ratana#1 while remaining four logs were available. All these logs were rectified manually to use the for reservoir characterization integrated with rock physics.

4.7 Formulas

The formulas which were used in this technique for calculating the elastic parameters are listed below:

$$\sigma = (Vs^2-0.5*Vp^2)/ (Vs^2-Vp^2)$$

$$K=\rho*(Vp^2-4/3\ Vs^2)$$

$$\mu = \rho * (Vs)^2$$

$$E = 2*\mu(1+\sigma)$$

Where

Vp = P wave velocity

Vs = S wave velocity

σ = Poisson ratio

K= Bulk Modulus

μ = Sheer Modulus

E = Young Modulus

ρ = Density

4.8 Calculation of Vp

Due to unavailability of sonic log the velocity of primary waves were calculated through density log using the relation given below:

$$\rho = 0.31(Vp^{1/4})$$

Where density is in gm/cm^3 and P-wave velocity is in m/s. (Ahmed Naveed, page79).

4.9 Calculation of Vs

The value of shear wave velocity was calculated from the relation given below:

Vs=Vp/1.9 (for limestone case)

Vs=0.862*Vp-1.172 (for sandstone case)

The first equation is Pickett (1963) empirical relation for limestone derived from laboratory core data. The second equation is the famous “mudrock line” of Castagna et al (1985), which was derived from in situ data. According to the book the values will be in km/sec so we had converted first the Vp value in km/sec so that to obtain desire value. (Gary Mavko et al).

4.10 Description

- The **Depth vs Vp** plot (Figure 4.1) is representing that in Lockhart formation velocities of primary waves (Vp) lies in a certain range, with change in depth there is no variation in Vp but at the end primary waves suddenly drops down with increase of depth and shows some change from its continuous trend. From this sudden variation it is concluded that at the bottom of the formation there is something special due to which velocity of primary waves has been slow down. It may be due to the presence of secondary porosity in that portion which is filled by fluids or it may be due to the presence of the transitional zone.

- The **Depth vs Vs** (Figure 4.2) relationship is showing same trend like the depth vs Vp graph but the difference is that secondary velocities are lower than Vp velocities. From the start of the formation secondary velocities are lying in certain range with no major variations but just near to the end of Lockhart formation, sudden variation has been noted providing some positive information that there may be presence of secondary porosity or fractures.

- In **Vp vs Density** (Figure 4.3) velocity of primary waves is continuously increasing with increase in density of Lockhart formation.

- In the light of **Vs vs Density** (Figure 4.4) relation it is clear that with increase in density of Lockhart formation, secondary velocity Vs also showing increase in trend.

- **Porosity versus density** plot (Figure 4.5) shows disharmony between derived result and general relationship of porosity and density. In initial portion of formation there are very minute signatures of porosity while with increase in density (2.67 to 2.75 gm/cm3); sudden abnormality in graph has been record. Cluster of porosity signatures at 2.67gm/cm3 to 2.75gm/cm3 density has been observe which may be due to the development of secondary porosities due to tectonic activities or other factors like dissolving of limestone in fluid. In general there is inverse relation between density and porosity.

- In general porosity is decreasing due to increase in depth because overburden pressure effect reduces the pore spaces in the formation. While **Depth versus Porosity** plot (Figure 4.6) is showing some variation in its trend. According to graph initially porosity is showing consistency with minute variations but with increase in depth slightly or abrupt changes has been observe. In the start of Lockhart porosity is low as moving toward the center of formation there is increase in porosity and after that again porosity fall down. Between the centre and the end of the Lockhart there is little consistency in porosity with low value depth. Near to end of formation is again porosity increase and reach to its maximum. It is concluded from the graph that in the Lockhart formation secondary porosities have been develop due to tectonic effect or dissolving in fluids like vuggy porosity etc.

- From the **Depth versus Density** plot (Figure 4.7), it is apparent that density of the formation from the top to 5170 depth approx is lying in certain range with slightly ups and down, after that decline in the density of Lockhart formation with increase in depth is recorded which is against the natural phenomena. This may be due to the presence of secondary porosities or transitional zone.

- **Vp versus Vs** plot (Figure 4.8) is creating the difference between the P-wave velocity and S-wave velocity. It is proving that Vs are always slower than the Vp due difference in wave properties.

- In the light of **Vs versus Porosity** plot (Figure 4.9), it is clearly observed that in the low porosity zone the Vs values are very prominent as moving toward the high porosity zone the S-wave velocities signature starts decreasing and few marks of Vs are recorded. This trend strengthens this belief that Vs decreases in liquid and gases media due to zero rigidity value.

- In the plot of **Vp versus Porosity** (Figure 4.10), the Value of Vp is high at the lower Porosities. By the increase of the porosity the Vp value is decreasing with increase of porosity which indicates the presence of fluids (liquid or gases) in these portions.

- The **Depth vs Bulk modulus** (Figure 4.11) is representing the ability to resist being compressed due the change in overburden because of increase in depth. The values of K are lying in very high values range and showing very minute ups and down with increase in depth. But near to end of formation bulk modulus fall down, this may be due to generation of secondary porosities or weakening of that portion due to dissolving in fluids or fracturing.

- The **Depth vs Young Modulus** plot (Figure 4.12) is representing the ability to resist being stretched due the change in overburden because of increase in depth. The values of E are lying in very high values range and showing very minute ups and down with increase in depth. But near to end of formation young modulus fall down, this may be due to generation of secondary porosities.

- The **Depth vs Shear Modulus** (Figure 4.13) are representing the ability to resist being sheared due the change in overburden because of increase in depth or due to shearing forces acting on it. The values of μ are lying in very high values range and showing very minute ups and down with increase in depth. But near to end of formation shear modulus fall down, this may be due to generation of secondary porosities or weakening of that portion due to shearing forces.

- In the light of **Depth vs Poisson Ratio** plot (Figure 4.14), it is concluded initially high values show changes in transverse strain and the longitudinal strain due to the acting of different forces on it. The values of υ are lying in very high values range and showing very minute ups and down with increase in depth. But near to end of formation there is decline in its reading, this may be due to generation of secondary porosities or weakening of that portion due to dissolving in fluids.

- **Vp vs Vp/Vs** plot (Figure 4.15) is showing linear pattern and there is no such variation in it.

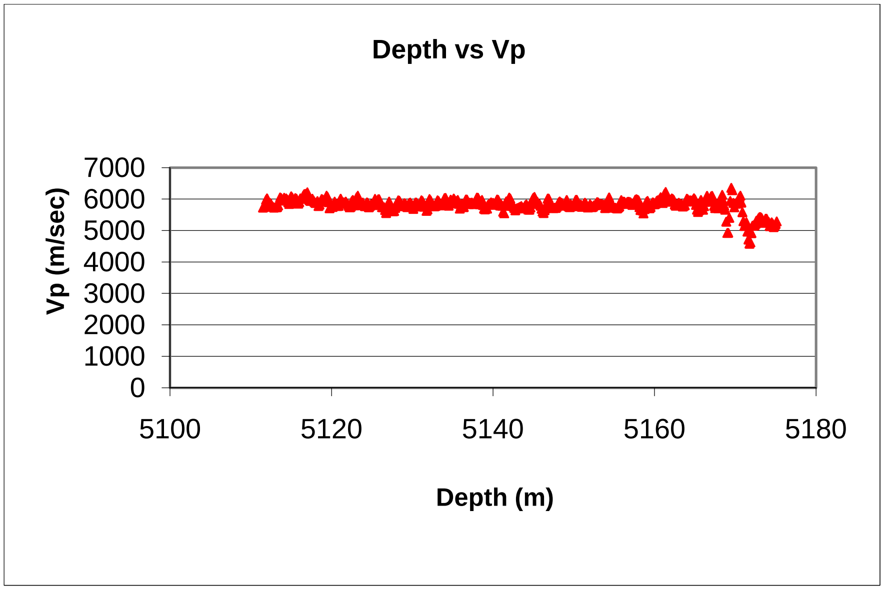

Figure 4.1: Representation of Depth vs Vp plot.

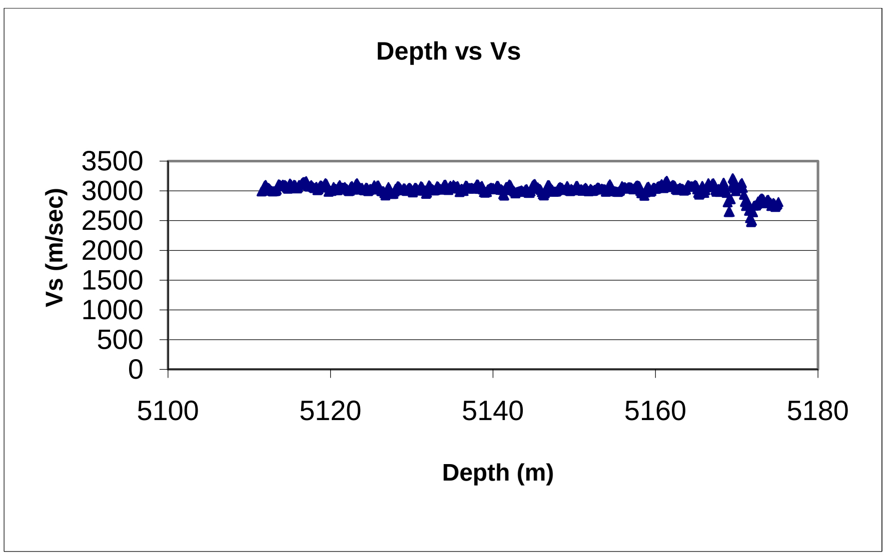

Figure 4.2: Showing the plot of Depth vs. Vs.

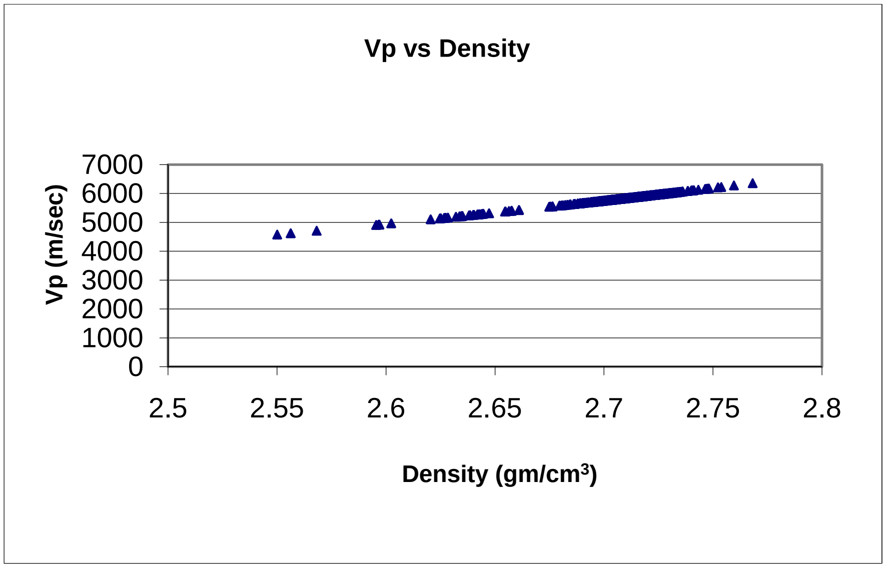

Figure 4.3: Vp vs Density Plot.

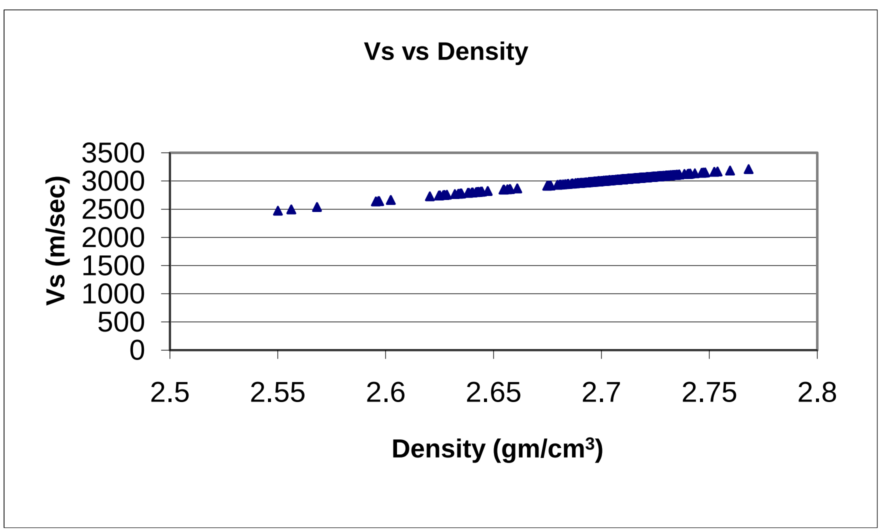

Figure 4.4: Graphical representation of Vs vs Density.

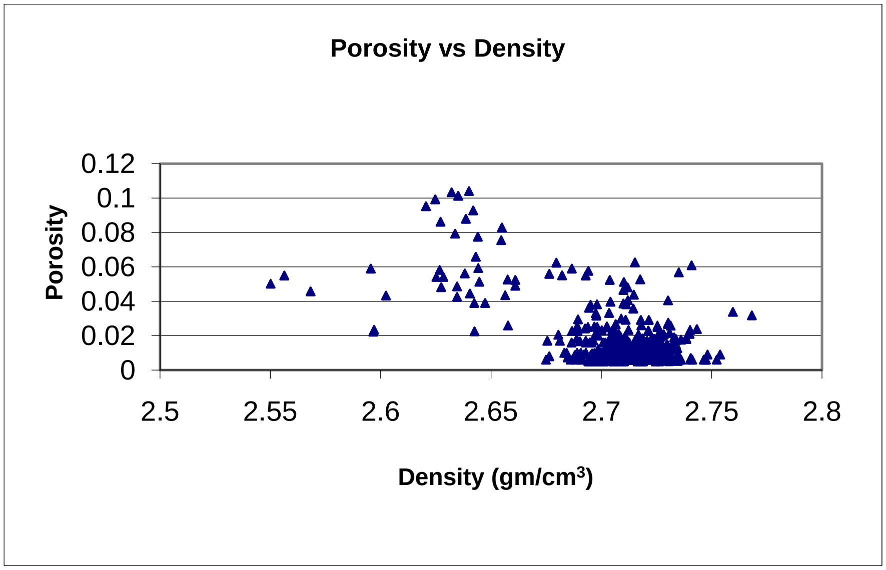

Figure 4.5: Representation of Porosity vs Density plot.

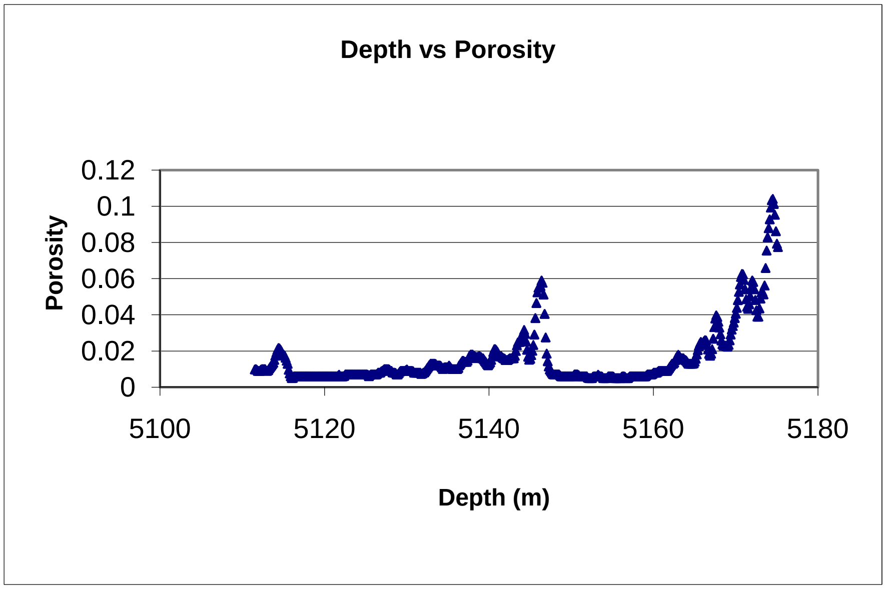

Figure 4.6: Depth vs Porosity plot.

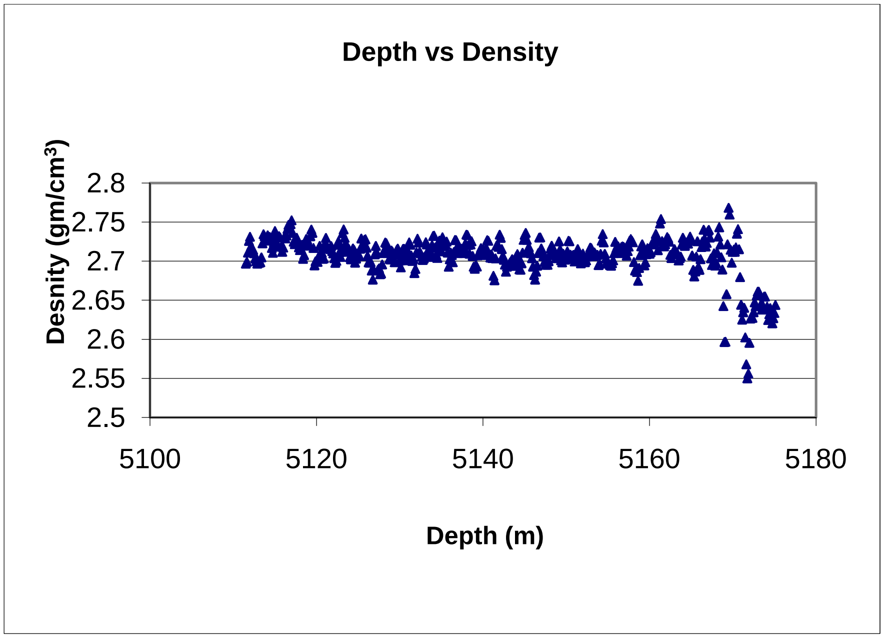

Figure 4.7: Plot representation of Depth vs Density.

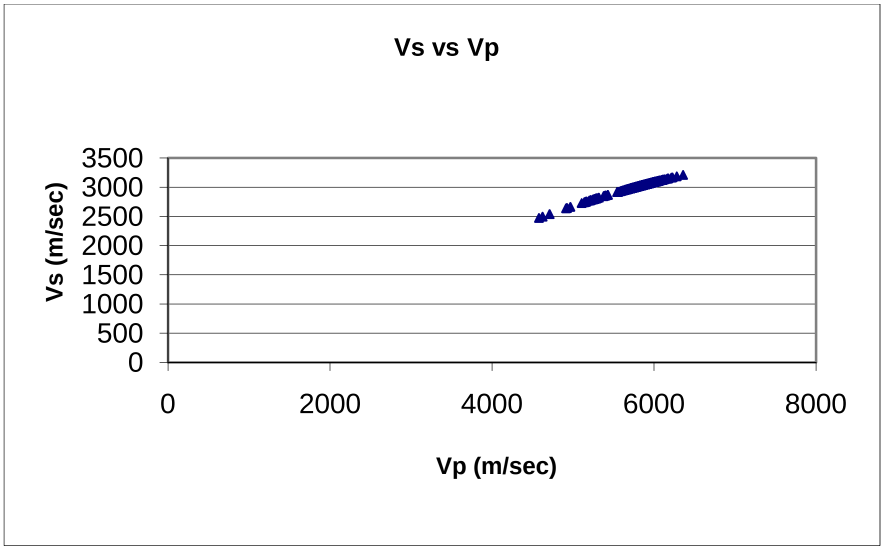

Figure 4.8: Showing Vs vs Vp plot.

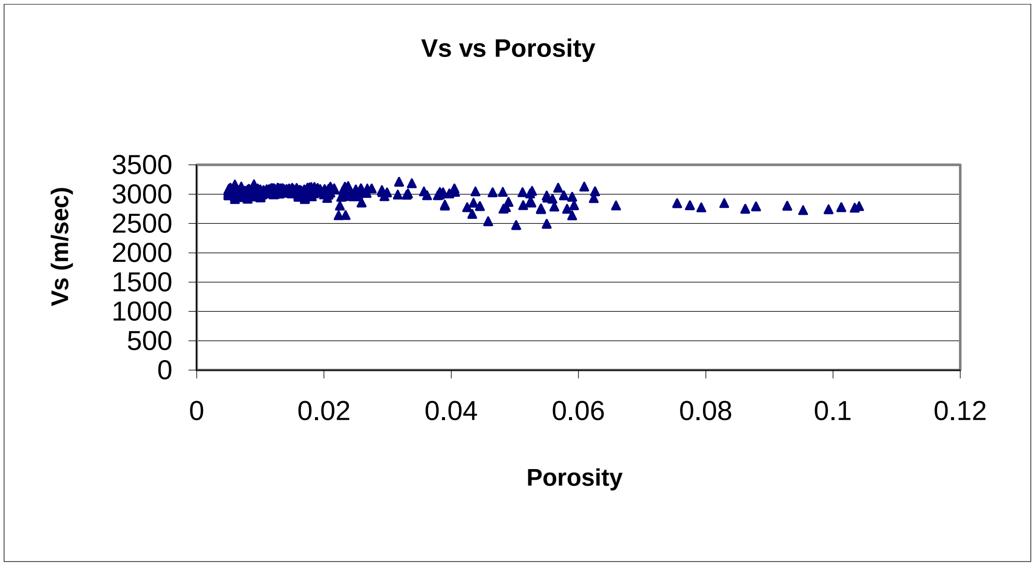

Figure 4.9: Showing Vs vs Porosity plot.

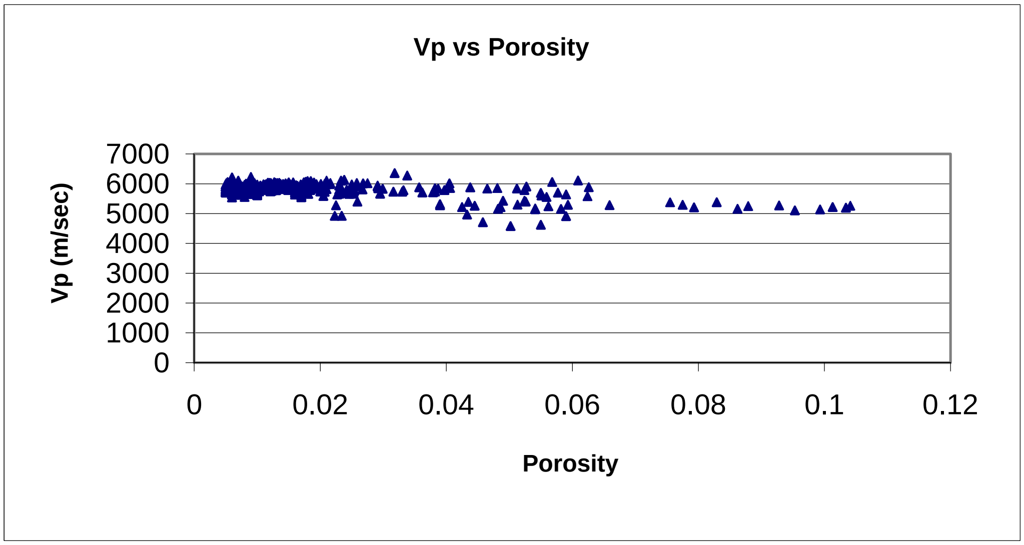

Figure 4.10: Plot of Vp vs Porosity.

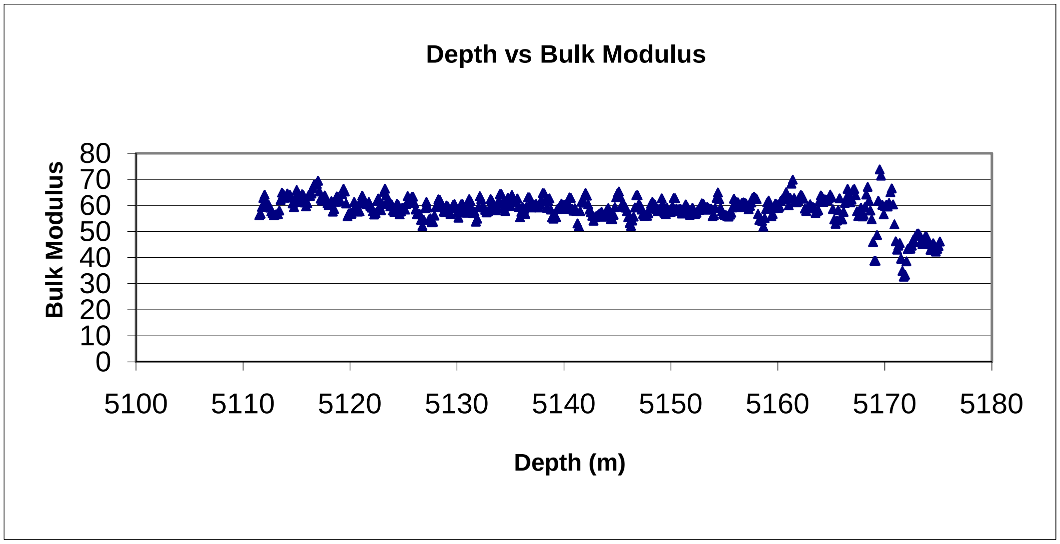

Figure 4.11: Plot of Depth vs Bulk modulus.

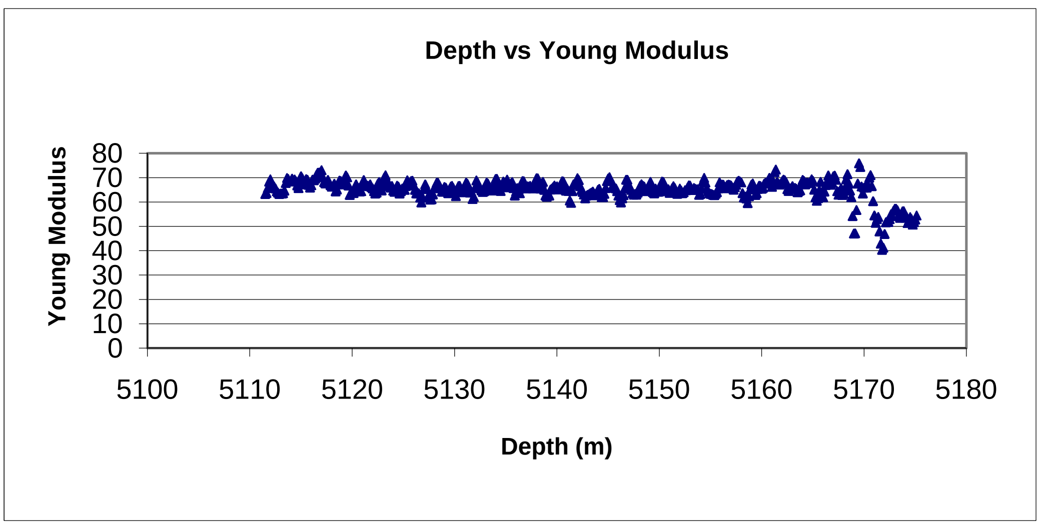

Figure 4.12: Showing plot of Depth vs Young's Modulus.

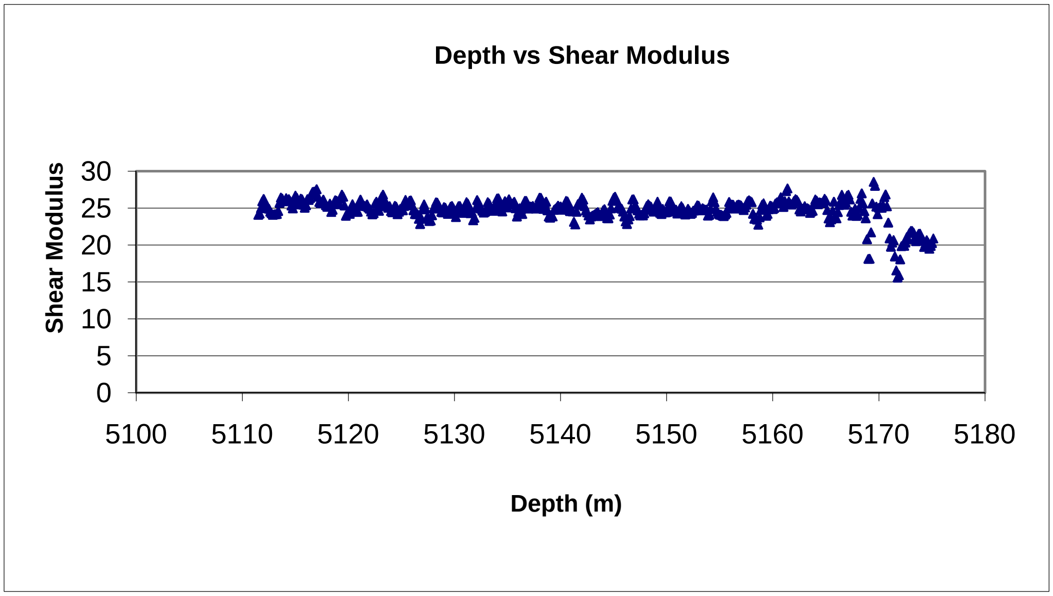

Figure 4.13: Depth vs Shear Modulus plot.

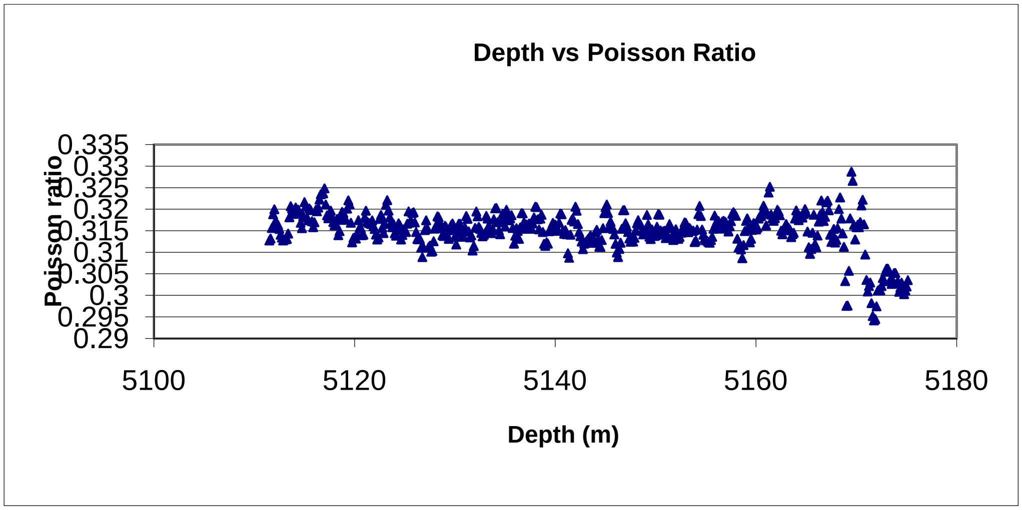

Figure 4.14: Showing plot of Depth vs Poisson Ratio.

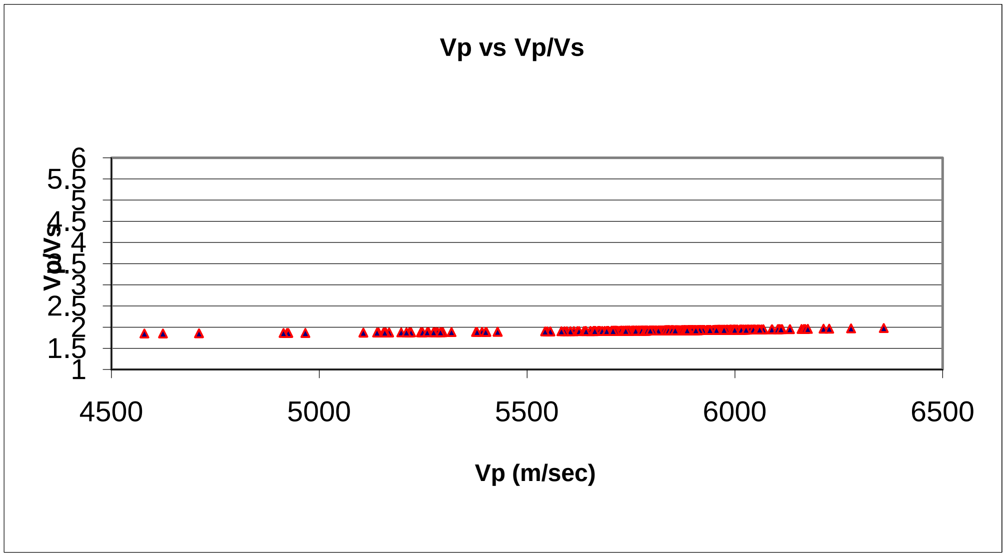

Figure 4.15: Plot of Vp vs Vp/Vs

Conclusion

On the basis of 2D seismic interpretation and Rock physics analysis of the area using Seismic lines and Wire line data of Ratana #1, it is concluded that:

- Ratana area in an anticlinal structure with lots of faults in it due the tectonic effect.
- The interpreted geology on seismic sections namely Chorgali (Proven reservoir in Potwar), Lockhart (Proven reservoir in Ratana) and Datta formation which is also proven reservoir having faults.
- The relationships between Vp, VS, Porosity, Density, Depth, Vp/Vs and Elastic Parameters help us to understand the changes in Lockhart formation occurred due to overburden, tectonic activities, transition zones, increase in depth, porosity and due to the presence of fluids in the porosities.
- As the porosity evaporites is very low or can say that there is no primary porosity in limestone. The plots are showing some variations which are totally against the general trends or concept, So in the light of these graphical trends it is apparent that there is something special in the Lockhart formation.
- The variations in the plots may be due to the generation of secondary porosities, fractures and transition zones etc. The variations in the velocities graph are giving the clue about the presence of the Hydrocarbons (oil & gas) in secondary porosity or fracture of Lockhart formation.
- Previous studies about the Lockhart formation as reservoir, decreasing of seismic velocities in the fluids or in that portion of Lockhart formation where sudden increase in porosity with increase in depth or density is occurring strengthen our idea about the contribution of Lockhart formation as reservoir.

Rock Physics is a very broad field which is used for reservoir characterization, as seismic attributes etc. Due to the availability of limited data for students, detail work can’t be possible but for the better result of production and the exploration of new reservoirs Rock Physics can be help us to achieve the goal more efficiently.

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Appendixes

Depth (m)	NPHI.V/V	RHOB.G/CC	Vp(km/s)	Vp(m/s)	Vs(km/s)
5111.50932	0.0098	2.6968	5.727276926	5727.276926	2.98954708
5111.634318	0.01	2.6991	5.746840258	5746.840258	2.99709703
5111.759317	0.0096	2.711	5.848860928	5848.860928	3.035786985
5111.884315	0.009	2.7259	5.978509218	5978.509218	3.083302389
5112.009314	0.009	2.7312	6.025141347	6025.141347	3.099940696
5112.134312	0.009	2.7189	5.917335091	5917.335091	3.061112786
5112.259311	0.0097	2.7163	5.894733279	5894.733279	3.052810321
5112.384309	0.01	2.7145	5.879123843	5879.123843	3.047043604
5112.509308	0.01	2.71	5.840235881	5840.235881	3.032560358
5112.634306	0.01	2.7034	5.783549574	5783.549574	3.011150405
5112.759305	0.01	2.7001	5.755361669	5755.361669	3.000372481
5112.884303	0.0092	2.6968	5.727276926	5727.276926	2.98954708
5113.009302	0.009	2.6979	5.73662706	5736.62706	2.993160769
5113.1343	0.0094	2.6981	5.738328314	5738.328314	2.993817244
5113.259298	0.0103	2.6986	5.742583103	5742.583103	2.995457678
5113.384297	0.0111	2.7048	5.795539307	5795.539307	3.015708303
5113.509295	0.0119	2.7228	5.951359598	5951.359598	3.073505253
5113.634294	0.0127	2.7344	6.053428347	6053.428347	3.109916918

Vs(m/s)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson Ratio
2989.54708	24.10235805	56.32314984	0.312745644
2997.09703	24.24491031	56.81439634	0.313201908
3035.786985	24.9845831	59.42829366	0.315629589
3083.302389	25.9144597	62.87806538	0.3188211
3099.940696	26.24582779	64.15448188	0.319995096
3061.112786	25.47721179	61.2322724	0.317301326
3052.810321	25.31496762	60.63237745	0.316745975
3047.043604	25.20270665	60.22063288	0.31636445
3032.560358	24.9223045	59.20390311	0.315421341
3011.150405	24.51180014	57.74483124	0.314066299
3000.372481	24.30693478	57.02937348	0.313401613
2989.54708	24.10235805	56.32314984	0.312745644
2993.160769	24.17051682	56.55753865	0.312963324
2993.817244	24.18291298	56.60026401	0.313003007
2995.457678	24.21390821	56.70722477	0.313102357
3015.708303	24.59879432	58.05117612	0.314350892
3073.505253	25.72075196	62.14364887	0.318143676
3109.916918	26.4459772	64.93803634	0.320713413

Young Modulus (GPa)	Vs(km/s) Pickett	Vp/Vs	RHOB.kg/m3
63.28053105	3.014356277	1.91576743	2696.8
63.67692497	3.024652768	1.917468871	2699.1
65.74091359	3.078347857	1.926637461	2711
68.35307247	3.146583799	1.938995422	2725.9
69.28872797	3.171127025	1.943631165	2731.2
67.12232976	3.11438689	1.933066667	2718.9
66.66676342	3.102491199	1.930920253	2716.3
66.35189416	3.094275707	1.929451825	2714.5
65.56666239	3.073808358	1.925843245	2710
64.420261	3.04397346	1.920710957	2703.4
63.84953469	3.02913772	1.918215724	2700.1
63.28053105	3.014356277	1.91576743	2696.8
63.47000422	3.0192774	1.916578328	2697.9
63.50447493	3.020172797	1.916726322	2698.1
63.59067989	3.02241216	1.917097059	2698.6
64.6628945	3.050283846	1.921783782	2704.8
67.8072931	3.132294526	1.936342745	2722.8
69.85511358	3.18601492	1.946491983	2734.4