3D SEISMIC STRUCTURAL INTERPRETATION AND SUB-SURFACE MODELING OF RAJIAN AREA, EASTERN POTWAR BASIN, PAKISTAN

By

Malik Khayyam Hussain

(01-262212-007)

Department of Earth and Environmental Sciences

Bahria University, Islamabad Pakistan

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A thesis submitted to Bahria University, Islamabad in partial fulfillment of the requirement for the degree of MS in Geology

Malik Khayyam Hussain

(01-262212-007)

Department of Earth and Environmental Sciences

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DEDICATIONS

With profound appreciation, I dedicate this research to my parents and teachers, whose belief in my potential has been unwavering. Your encouragement has been the wind beneath my wings, propelling me towards academic success.

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ABSTRACT

The present study aims to carry out seismic structural interpretation to map and model the subsurface geometries present in the Rajian area eastern potwar sub basin. To achieve this objective 2D and 3D seismic data along with the well tops were acquired followed by the seismic interpretation. Creation of TWT and depth contour maps.

Seismic interpretation confirms presence a duplex zone bounded by SRT as sole thrust from the bottom and a back thrust F4 as a roof thrust from the top and presence of three imbricated fault sheets along F2, F3 whereas all these sheets also folded to form multiple stacking patterns providing positive geometries for the accumulation of hydrocarbons.

Structural restoration was performed on move to understand the subsequent development of this deformation which shows sequential development as in sequence thrusting. Where, main displacement were being transferred along basal decollement SRT and divided along imbrication F1, F2 and F3 to the roof thrust F4 which dip towards south creating a stacked geometry and a passive roof duplex with maximum shortening at Eocene level.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

In 1868, the first drilling operation was carried in Pakistan in Kundal situated near Mianwali in expedition of survey hydrocarbons. Afterwards, in 1915 with means of drill "Khaur-01" first oil discovery was made in Pakistan. In Pakistan most of the rocks are rich in petroliferous content and are sedimentary. Objective of petroleum companies is to recognize stratigraphic and structural traps in areas with higher potential for hydrocarbon accumulation. In Pakistan, such formations are present in regions having stronger faulting and folding, i.e the Potwar area. (Ahmad et al. 2021)

Oil and gas exploration companies' main goal is to find locations with significant hydrocarbon accumulations that are trapped in stratigraphic and structural traps. These types of formations have founded in regions with high level of folding and faulting in Pakistan, such as the Potwar region. (Shami and Baig, 2002).

Seismic interpretation's primary focus is to accurately characterize between formations of subterranean geological and lithology. Rocks that contain hydrocarbons can be distinguished from rocks that do not by using seismic data analysis. On the other hand, identifying non-payable and payable gas and oil intervals only by interpreting seismic data is challenging. (Muhammad et al., 2021).

1.2 Location of Study Area

Rajian Field and Gujar Khan, which is around 60 kilometers southeast of Islamabad, is the location which is being studied. Gujjar Khan is located in Pakistan's north, in the western lower Himalayas. The Potwar sub-basin which is known as the most established oil region in the world and is famous for its substantial oil and petroleum gas deposits; first oil discovery was made in Khaur during the period of 1914. In the basin, approximately 150 wells were drilled. The majority of them were abandoned, primarily due to excessive water weight in molasses stocks (Kadri 1995).

Area of Study Location Geographically, Rajian has a boundary with Rawalpindi and Islamabad at north side, and Jhelum and Gujrat are to the west (Figure 1.1). The construction of the M2 highway has made it quite accessible.

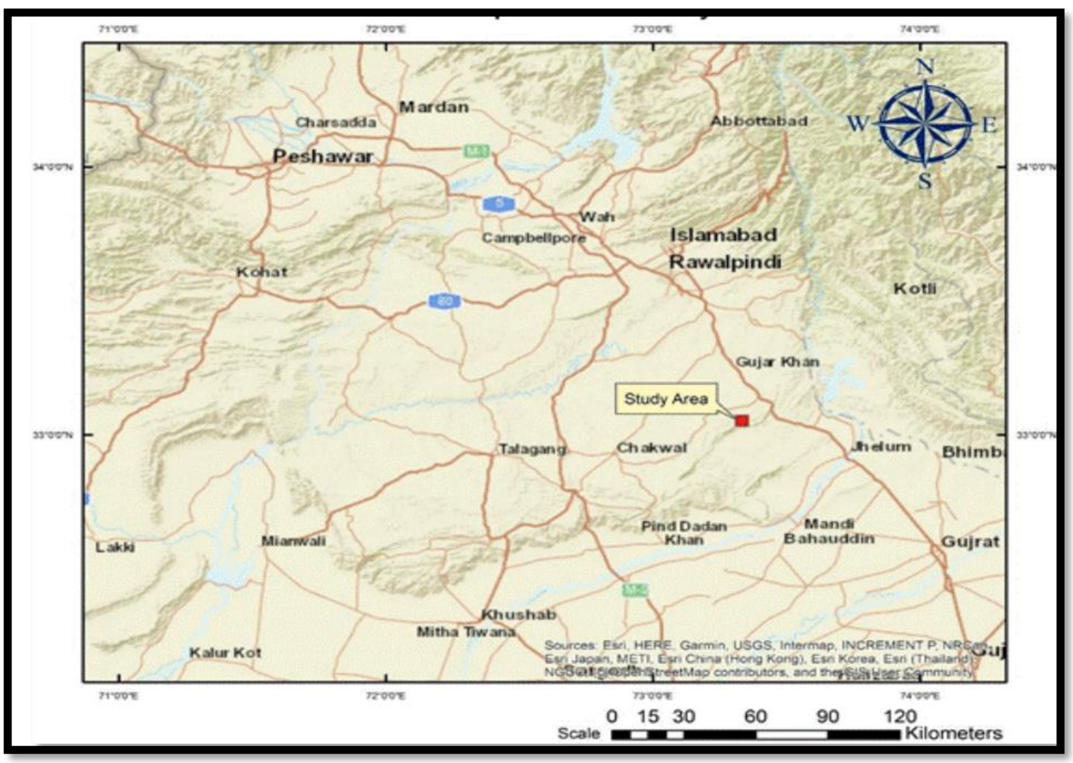


Figure 1.1 Study area map of Rajian (Geo-referenced map from Arc GIS software)

1.3 Literature review

The research area has undergone substantial distortion as evidenced by reverse thrusts and thrusts, generating triangle belt inside the sub-surface, according to seismic interpretation provided by 2D seismic data. These formations have a final trend situated in southeast- northwest (SE-NW), indicating specific region i.e. under compressional regime (Ahmed et al., 2021).

The Southern Potwar region has highly developed fault-related folds that can create and accumulate hydrocarbon. Concerning hydrocarbon exploration of the Potwar Basin, the 200-500m thick Cambrian to Eocene platform series is regarded as the main source and reservoir rocks (Ali et al., 2021). There have been approximately 150 exploratory wells sunk in the surface, due to this most of these wells are not ready for functioning due to the presence of heavy-weight water in molasses reservoirs (Ahmad et al., 2021).

One of the salt Range thrust encircles Potwar in southern region. The Domeli Thrust Fault in eastern Potwar is the second significant thrust. It is anticipated that the Domeli Thrust will be a inclined to headland thrust with important shortening. The Domeli Thrust situated in east limits Potwar (Qureshi et al., 2021). Domeli back thrust can easily be seen in eastern Potwar. Domeli back thrust is one of largest obstruct in any Potwar sub-district. A fault-limited anticline makes up the structure that exists in the Rajian region. The separation level existing in Precambrian salt is also compensated by some other fundamental structural flaws.

The Himalayan Orogenic Belt was created as a result of the Indian and Eurasian Plates colliding. Sedimentary record was separated apart from basement by subduction of the Indian Plate. A large arrangement of thrusts and nappes has been imbricated within the sedimentary succession (Riaz et al., 2019).

From the Paleocene to the Pleistocene, the Kohat-Potwar foreland basin contains a deformed sedimentary history.Salt Range Thrust forms its southern border and Main Boundary Thrust forms the northern border. Jhelum Fault forms the eastern

Indus River and Kalabagh Fault form the western side. The western region of the Kalabagh fault in between the MBT and SRT region is called as Kohat Sub-Basin. Region between Jhelum fault and Kalabagh fault is called sub-basin of Pothwar. Khisor Range lies below the Surghar Range, which is the range that causes a bend to the west of the Kalabagh Fault. Khisor and Surghar mountains are known as the Trans-Indus Ranges, while in between Jhelum and Indus river ranges are known as the Cis-Indus range (Hussain et al., 2018). In their 2018 study, Craig et al. concentrated on the Precambrian and Cambrian sequence's hydrocarbon potential in the eastern Potwar sub-basin.

Eastern Potwar is the study area revolves in eastern Potwar. When compared to other areas of the Potwar Area, Eastern Potwar has a very functional framework which is made up of lower directional thrust faults that are clearly visible shortenings. In the research area, faulted structures and thrust belts were well noticeable. As we go to some extent of east-west (E-W) trending folds are seen to be existing in the focal district of Eastern Potwar, where the majority of folds have a NE-SW direction. Here, you can find triangular zones, popup structures, and imbricate thrusts. Hydrocarbon (HC) traps with restricted faults were created in the region as a result of over-thrusting (Jadoon et al., 2015).

A comprehensive structural interpretation over three regional cross-sections of SRPP, seismic data and borehole were re-checked (Moghal et al., 2007). Seismic data based on interpretational cross-sections give a broader results of formations to south of Soan Syncline.

In particular, regional seismic lines shows general structural design of region in 2D. They also provide fresh structural interpretation. Basic Model of triangular zone was created in 3D as a result of the investigation, together with interpretations of all the major fault planes and analyses of base surface i.e. beneath the south-eastern and eastern Potwar region (Aamir & Siddiqui, 2006).

Geoscientists have been aware of the connection between thrusts of Dil Jabba and Domeli since late 1980s. When researchers hypothesized that Domeli fault turnover polarity to southwest, they gave it a name Dil Jabba Thrust. Based on surface geological knowledge, inaccurate assumptions have previously been made. Superficial geology cannot accurately depict system of “Domeli-Dil Jabba” thrust by itself. Structural details and modelling demonstrate that faults in Domeli and Dil Jabba are separate when they are applied to regional maps. Famous Salt Range thrust is thought to be the forerunner of the Dil Jabba Thrust. Domeli Thrust is predominant in northeastern region while Dil Jabba Thrust is predominant in southwestern region. Both the forward and back thrusts are roughly equal in intensity. We suggest that Domeli Thrust i.e. in northern region is not connected with southward-dipping Dil Jabba Thrust's back thrust that is showing triangular zone geometry (Aamir & Siddiqui, 2006).

In the 1980s and 1990s, several studies were conducted using seismic and borehole data to identify the general structural geometry and the deformation style (Lillie et al., 1987). The Pothwar Plateau and salt range were known by thin-skinned deformation (Jadoon et al., 1997).

The Siwaliks Group of Neogene sedimentary rocks contains the Foreland Basin (Potwar Plateau). The Salt Range and the Potwar Plateau, which preserved all the major deformation stages connected to the construction of the Himalayan frontal foreland basin during the Neogene, are associated with the Himalayan deformation front migration southward (Baker et al., 1988)

Numerous authors speculate that in salt range beginning of thrusting of the Potwar region may have started at around 5 to 6 Ma (Burbank & Beck, 1989) or 2 to 2.5 Ma (Baker et al., 1988).

One of oldest and highly established oil zone, the Potwar Basin, has a lot of triangular zones. Southern Potwar Platform Zone (SPPZ), which is less deformed, and Northern Potwar Deformed region, which is more deformed, are separated by the Soan syncline (NPDZ). The first ever oil was found in Khaur, and Potwar sub-basin which is famous because of having sizable deposits of petroleum and oil gas. This is known as most established oil basin in the world (1914).

1.4 Problem Statement

Rajian area is located in Eastern Potwar and has a complex subsurface structural framework which is being controlled by several low angle faults forming a complex duplex sheet. The hydrocarbon potential of these sheets are yet to be evolved.

1.5 Objectives

The main objective of research work is to model and mapping of the sub-surface structural framework which will eventually help to understand the following:

i. To carry out seismic data interpretation to delineate subsurface geometries and their structural trends. (See chapter 4)
ii. Mapping of thrust sheets where possible. (See chapter 4)
iii. Nature of displacement and Linkage of the main faults along them. (See chapter 5)
iv. The degree of lateral deformation and restoration are used to determine the degree of deformation. (See chapter 5)

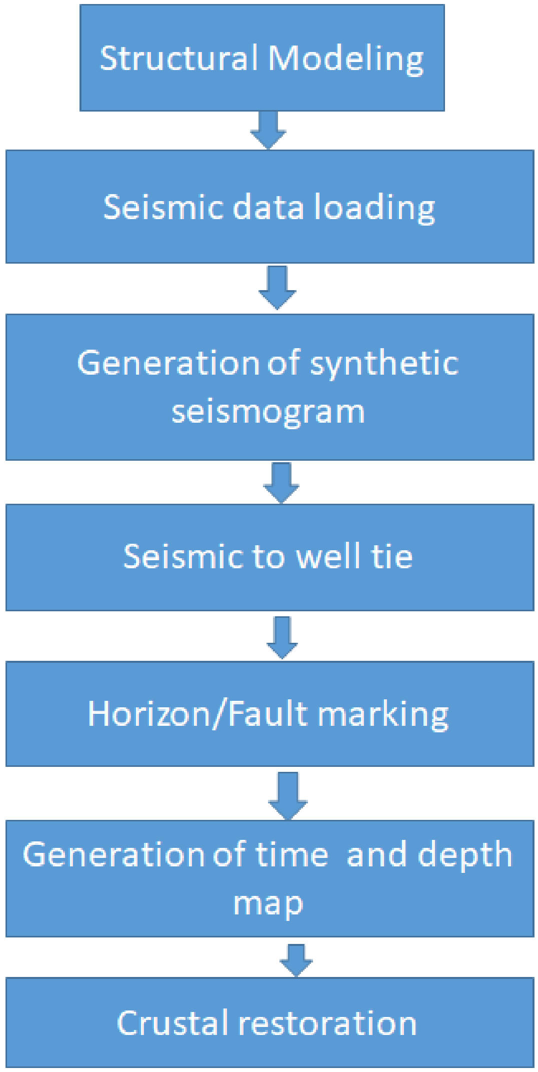
1.6 Data used

The Directorate General of Petroleum Concession authorized LMKR to supply the Data (DGPC). Twelve square kilometer of the region was covered by a 3D SEG-Y seismic cube acquisition. The oil-well data was also made available in las file format.

In order to perform the 3D seismic structural interpretation of Rajian Area and the interpretation of seismic lines by using Petrel/Move software/Decision Space, 2D and 3D accessible seismic data and oil-well data is required.

Seismic Data	**Well Data**
• 3D seismic cube of Rajian area • Following seismic lines are given for 2D seismic interpretation 1. GO-925-GJN-10 2. GO-925-GJN-11 3. GO-925-GJN-8 4. GO-932-GJN-13 5. GO-942-GJN-51 6. GO-942-GJN-50	• Complete log suits of Rajian-01, Daiwal-01 and Rajian-3A wells

1.7 Methodology



1.8 Expected outcome

i. Mapping of the subsurface geometries will help to establish number of separated stratigraphic sequences (especially Paleocene and Eocene)

ii. Fault modeling will help to understand the geometries, displacement, migration routes, entrapment and closure of the structural traps present in the study area.

iii. Crustal Restoration estimation will help to identify possible episodes of deformation as well amount of crustal shortening in the study area.

CHAPTER 2

REGIONAL GEOLOGY AND TECTONICS

2.1 Introduction

The geology of the Rajian area is dominated by sedimentary rocks, including sandstones, shales, and limestones. These rocks were deposited during the Paleozoic and Mesozoic eras, and they are now exposed at the surface due to uplift and erosion. (Khan et al., 1986)

Triangle zone plays are common in the Potwar area of Pakistan. The Potwar Basin (Figure 1) is one of the oldest oil provinces. It is located in the western foothills of the Himalayas in northern Pakistan. It includes the Potwar Plateau, the Salt Range, and the Jhelum Plain. The Khairi Murat thrust-Dhurnal backthrust triangle zone in the Northern Potwar deformed zone (NPDZ) and the Joya Mair triangle zone in the southern Potwar platform zone (SPPZ) are also well documented today (Aamir and Siddiqui, 2006).

The tectonic activity in the Rajian area is related to the collision of the Indian plate with the Eurasian plate. This collision began about 50 million years ago and is ongoing. The collision has resulted in the formation of the Himalayan mountain range and has caused the deformation and uplift of the rocks in the Rajian area. The tectonic activity in the Rajian area has resulted in the development of several structural features, including folds, faults, and thrusts. These structures have played an important role in the development of hydrocarbon reserves in the Eastern Potwar sub-basin. The Rajian area is known to contain significant oil and gas reserves, which are trapped in the folds and faults of the sedimentary rocks. Overall, the Rajian area is an important location for the study of geology and tectonics, as it provides valuable insights into the processes that have shaped the Earth's crust over time (Khan et al., 1986).

The Potwar Sub-Basin is among the most established and ancient oil zones where triangle zone plays are common. In the Northern side of Pakistan, location of study area is at Western side of Himalayas region. Jhelum plain, Potwar plateau as well as salt Range are also present in this region. The collision between Eurasian and Indian plate resulted in the origination of the Himalayan Orogenic belt (Dobrin and Savit, 1976). Sedimentary record from basement is separated by the reduction of Indian plate. Broad arrangement of thrusts and nappes has covered the sequential arrangement (Butler et al., 1987).

The Salt Range and Potwar Plateau are part of the active foreland fold-and-thrust belt of the Himalaya in Northern Pakistan. In this region the distance from the Main Boundary Thrust (MBT) to the front of the fold-and-thrust belt is very wide (100-150 km) because a thick evaporite sequence forms the zone of decollement. Recent studies have combined seismic reflection profiles, petroleum exploration wells, Bouguer gravity anomalies, and surface geology to construct cross sections in the eastern, central, and western Salt Range-Potwar Plateau areas (Steven et al., 1988).

Distorted sedimentary sequence from Palaeocene to Pleistocene is covered by the foreland basin of Kohat-Foreland and its Southern part is along Salt Range Thrust and Northern part is along Main Boundary Thrust. In West there is Kalabagh fault along with Indus River and on its East Jhelum fault is present. Region in between Kalabagh and Jhelum Fault is known as Potwar sub basin and the area towards the West of Kalabagh fault (Figure 2.1). Kohat Sub Basin is the area between MBT and SRT. Surghar Range is located in western side of Kalabagh fault and Khisor Range is located beneath this range. Between the River Indus and Jhelum River are the Surghar, Cis-Indus Ranges and Khisor Ranges which are collectively called Trans-Indus Ranges (Riva, 1983).

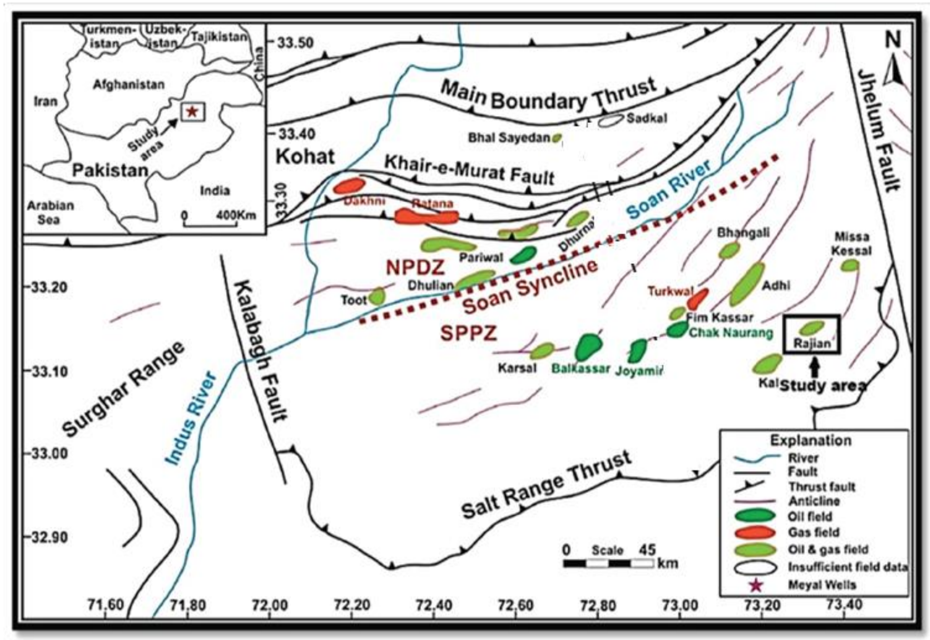


Figure 2.1 Regional Tectonic setting of the Rajian Area (Riaz et al., 2019).

2.2 Potwar Sub-Basin

Geographically, Pakistan is divided into two major basins namely Baluchistan and Indus Basin. The Indus basin is divided in three basins, the Upper, Lower and Central Indus basins respectively. Upper Indus Basin is separated from Lower Indus Basin by Sarghodha Hills. Upper Indus basin is divided in the East as Potwar Sub Basin and in the West as Kohat Sub Basin. Precambrian to Quaternary age sediments are preserved in Potwar Sub Basin. Potwar is divided into two segments, Southern Potwar deformed zone (SPDZ, area between SRT and Soan Syncline), and Northern Potwar deformed zone (NPDZ, area between Soan Syncline and MBT). The tectonic framework of the area is very complexed. Rajian is in the SPDZ region (Butler et al., 1987). SPDZ has been further divided into Southern Potwar and Eastern Potwar (Warwick, 2007).

Kohat-Potwar is the most tectonically complex region of the northern Pakistan. The Kohat area is a complex tilted plateau similar to a ‘cuesta’ region with its difficult geological attributes, viz. moderate to steep dips and asymmetrical structures which may have been formed by a large number of thrusts/normal faults. The interpretation of the geological and geophysical data has indicated that the area has several salt affected and/or basement involved thrust/reverse fault systems formed as a result of transpressional tectonics (Paracha, 2001).

The 36,000 km2 Kohat-Potwar Basin contains more than 5,000 m of marine sediments of Infra-Cambrian (Neoproterozoic to Early Cambrian) to Eocene age, with a major break in deposition between the Ordovician and the Carboniferous. The marine sedimentation in the Kohat-Potwar Basin stopped around 50-49.5 Ma and the youngest marine sediments are of Middle Eocene (Upper Lutetian) age (Ahmad et al., 2012).

NPDZ is a foreland fold and thrust belt found in the Northern Potwar region. SPDZ salt cover is thicker. Salt controls the deformation. Salt exhibits ductile behavior while the material above behaves brittle. Collisions do not disturb the basement and salt and gypsum act as lubricant, but upper hard strata are deformed which is why SRT is known as Decollement fault, and it doesn’t affect basement rock. Such tectonic behavior is referred to as thin skin tectonic or salt tectonics (Butler et al., 1987)

The Eocence to Cambrian shallow marine facies are present above the sedimentary column with majority of the unconformities appeared in the age of Paleocene as well as Permian. In this region Mesozoic period is the second most considered divergence, without any evidence of sediment deposition. After that, third important divergence is Oligocene age divergence and there is no record of sedimentary record has founded (Riaz et al., 2019).

2.3 Geological Framework

The Kohat–Potwar foreland basin encompasses a distorted sedimentary sequence from the Paleocene to the Pleistocene. Its northern boundary is with the Main Boundary Thrust (MBT); its southern boundary is with the Salt Range Thrust (SRT);

the Kalabagh fault and Indus River are to its west; and to its east is the Jhelum fault. The portion between the Jhelum fault and Kalabagh fault is known as the Potwar sub-basin, and the area west of the Kalabagh fault between the SRT and MBT portion is known as the Kohat sub-basin. To the west of the Kalabagh fault, the range causing a bend is known as the Surghar, range and below this is the Khisor range. The ranges between the two rivers (Jhelum and Indus) are known as the Cis-Indus ranges, and the Surghar and Khisor ranges are known as the Trans-Indus Ranges (Hussain et al., 2018).

The study area lies in eastern Potwar. Eastern Potwar is an area with a highly active tectonic framework composed of low-angle thrust faults with observable shortening when compared to other regions of Potwar fold. The thrust belt and faulted structures are very prominent in the area under study (Figure 2.1). Most of the folds in eastern Potwar have a direction of NE–SW, and there are very few east–west (E–W) trending folds in the focal district. Imbricate thrusts, popup structures, and triangular zones are found here. Over-thrusting in the area resulted in the formation of fault-limited hydrocarbon (HC) traps. Potwar is bounded by a salt range thrust in the south. The second important thrust is the Domeli thrust fault in eastern Potwar. This Domeli thrust is predicted to be a foreland-verging thrust that demonstrates a great deal of shortening. Potwar is limited by the Domeli thrust in the east (Riaz et al., 2021).

In eastern Potwar, the Domeli back thrust can be observed. No other obstructed back thrust in any sub-district of Potwar is greater in size than the Domeli back thrust. The structure present in the Rajian area is a fault-limited anticline. Other fundamental structural faults compensate their separation level that occurs in Precambrian salt. The Potwar Plateau involves disturbed landscapes. The sub-basin of Potwar is structurally arranged to the south of the western lower regions of the Himalayas and falls in the Potwar Plateau. The Main Boundary Thrust (MBT) limits the basin in the north and toward the east it is limited by the Jhelum left lateral strike slip fault, by the salt range thrust toward the south, and by the Kalabagh right lateral strike slip fault toward the west. Fundamentally, the Potwar sub-basin is unpredictable, and surface structures do not truly mirror the subsurface structures (Riaz et al., 2019).

In Eastern Potwar all study area is present. The Eastern Potwar region possess highly active basaltic framework. This framework consists of low angle thrust faults along with observable shortening that is not present in any region of thrust belt. In area under study faulted and folded structures are prominent. Most of the folds in eastern Potwar have direction of North Eastern to South Western and some east-western trending fold in central district. In this region thrusts, popup structures and triangle zone are present. Over thrusting in region causes emergence of fault limited HC traps and composed of Domeli Back thrust, Dill Jabba for thrust and SRT (Khan et al., 1986).

Salt Range Thrust surrounds Potwar from South. Domeli thrust fault is second important thrust in Eastern Potwar. Domeli thrust is foreland-verging thrust that elaborates big deal of shortening. In eastern part Domeli thrust limits Potwar (Khan et al., 1986). In Eastern Potwar, one of common back thrust is Domeli back thrust. Domeli back thrust is biggest back thrust in sub district of pothwar. In Rajian area currently present structure is faults limited anticline. In Precambrian salt, some basic structural faults are continuously compensating their separation level. (Khan et al., 1986).

Disrupted landscapes are present in Potwar sub-basin. Arrangement of Potwar sub-basin is on the South of lower Western areas of Himalayas, and also lies in Potwar Plateau. MBT limits the basin in North. Eastern side is surrounded by Jhelum fault known as “left strike slip fault”. In south Salt Range Thrust is present. Western side is surrounded by Kalabagh Fault known as “right lateral strike slip fault”. (Riva, 1983).

2.4 Jhelum Fault

This fault somewhere at western margin of such axial zone of both the structure, named as Jhelum fault (Kazmi, 1997), is indeed a left lateral strike - slip fault. At Balakot & Muzaffarbad, Jhelum fault is still a left lateral strike slip fault across which is something the Murree, Abbottabad & Hazara formations were extensively distorted. Jhelum fault appears to deform the MBT & terminate its eastward development of both the N-W Himalayan fold & thrust belt structures, indicating it is the syntaxial zone's youngest important tectonic feature. This series of east-west moving faults intersect with seven Jhelum fault at such an extreme angle towards the north, showing left-lateral strike slip displacement .The Jhelum Fault is a major geological feature located in the Eastern Potwar sub-basin of Pakistan. It is a major fault that extends for over 200 km in a northeast-southwest direction and has been an important geological feature of the region for millions of years. The Jhelum Fault is a strike-slip fault, which means that the two sides of the fault move horizontally past each other. It is part of a larger fault system that extends from the eastern Hindu Kush in Afghanistan to the Salt Range in Pakistan. The Jhelum Fault is a major tectonic boundary that separates the Indian Plate from the Eurasian Plate. The fault has been active for millions of years, and its movement has resulted in the formation of several structural features, including folds, faults, and thrusts. The fault has played an important role in the formation of hydrocarbon reserves in the Eastern Potwar sub-basin. The movement of the fault has resulted in the development of structural traps that have trapped oil and gas reserves in the sedimentary rocks of the region. Overall, the Jhelum Fault is an important geological feature of the Eastern Potwar sub-basin, and its movement has played a significant role in the formation of the geology and hydrocarbon reserves of the region. It is also an important area of study for seismologists and earthquake engineers due to its potential to generate large earthquakes in the future. (Kazmi and Jan, 1997).

2.5 Kalabagh Fault

Somewhere on the western salt range Potwar plains, the transgression lateral strike slip fault forms as Kalabagh fault region. It's indeed approximately 120 meters. Such faulting raised & relocated Holocene terraces strata, but also shifting that Indus River's path eastward. This Kalabagh fault zone must be classified functional & earthquake-prone due to the important displacement rates and related seismic activity. (Kazmi and Jan, 1997)

The Kalabagh Fault is a major geological feature in the eastern Potwar sub-basin of Pakistan. It is a north-south trending fault that separates the Patala Formation to the west from the Siwalik Group to the east. The fault is approximately 150 km long and is believed to have formed during the late Miocene to early Pliocene period, about 5-6 million years ago. The fault is a thrust fault, which means that the rock on one side of the fault has been pushed up and over the rock on the other side. The fault has a vertical displacement of several kilometers and is still active, with minor earthquakes occurring along it from time to time. The Kalabagh Fault is an important geological feature because it played a role in the formation of the Potwar Plateau, which is an area of relatively flat land in northern Pakistan. The uplift of the plateau is believed to have been caused by the compression and folding of the sedimentary rocks along the fault. In addition to its geological significance, the Kalabagh Fault is also important because it poses a potential seismic hazard to the surrounding region. The fault is capable of producing earthquakes of up to magnitude 7.0, which could have significant impacts on the local population and infrastructure. (Khan et al., 1990)

2.6 Salt Range Thrust

Its Himalayan Frontal thrust fault is however referred as that of the Salt Range Thrust Fault (SRT). Its foothills of such a divergent structure are marked either by Salt Range as well as the Trans-Indus Himalayan range. The Salt Range Thrust is a major geological feature in the Punjab province of Pakistan. It is a north-south trending thrust fault that separates the younger sedimentary rocks of the Punjab Platform to the east from the older, highly folded and faulted rocks of the Salt Range to the west. The fault has a total length of about 300 km and a maximum displacement of more than 10 km. (Kazmi and Jan, 1997).

The Salt Range Thrust is believed to have formed during the Eocene epoch, about 50-60 million years ago, as a result of the collision of the Indian and Eurasian tectonic plates. The collision caused the Indian plate to be thrust northwards over the

Eurasian plate, resulting in the formation of the Himalayan mountain range and associated geological features such as the Salt Range Thrust. The Salt Range itself is composed of a series of sedimentary rocks that were deposited in a shallow sea during the Cambrian to Eocene periods. The rocks in the Salt Range have been subjected to intense folding and faulting, resulting in a complex series of geological structures that are of great interest to geologists. The Salt Range Thrust is an important geological feature because it has exposed a significant portion of the Earth's crust, providing a window into the geological history of the region. It is also an important source of natural resources, including salt, gypsum, and limestone, which are mined from the rocks in the Salt Range. The Salt Range Thrust is also important from a seismic hazard perspective, as it is capable of producing earthquakes of up to magnitude 7.5. The region is considered to be at moderate to high risk of earthquakes, and ongoing research is being conducted to better understand the seismic hazard posed by the Salt Range Thrust (Ghazi et al., 2015).

2.7 Stratigraphy

Potwar sub-basin contains broader Pre-Cambrian evaporate deposits. Cambrian to Eocene deposits are present over Pre-Cambrian evaporate deposits. Cambrian to Eocene are then overlain by wide deposit layer of Miocene to Pliocene molasses. Salt is present on SRT that acts as base along thick sand sequence is preserved. Formations of Jutana, Kussaj and Baghanwala are mainly contains Shales, Siltstone, Sandstone, and Dolomites. Unconformities have interrupted Stratigraphic sequence on large scale and in Pliocene to Pleistocene time during Himalayan time it is highly deformed (Ahmad et al., 2021).

Study area have reported three major unconformities. These are Oligocene, Carboniferous to Ordovician and Mesozoic to Paleocene unconformities. Potwar Basin uplift was started during the period of Ordovician to Carboniferous, that why sedimentation is ceased in this time zone. (Riaz et al., 2019).

One of oldest formation also present here known as Salt range Formation of Pre-Cambrian. It is composed mainly of dolomite, shale and Halite with subordinate marl. Formation of salt range over the basement is lying unconformable. Sedimentary column overlying includes founded unconformities during the reign of Permian and Paleocene and Eocene to Cambrian age shallow marine. (Riaz et al., 2019).

Mesozoic age in the region with no sediment deposition is seen to be second major unconformity. During the time of Mesozoic, thick sedimentary succession of Mesozoic age is preserved at epicenter whose location is in Central Potwar Basin. Oligocene age unconformity is third major unconformity founded where no sedimentary record is present (Riaz et al., 2019).

2.8 Stratigraphy of Eastern Potwar Basin

The detailed stratigraphic sequence for the Potwar Basin is given below in table. In this table a complete sequence of the formations, lithology, and age have been mentioned for each time period for certain formations and lithology (Table 2.1).

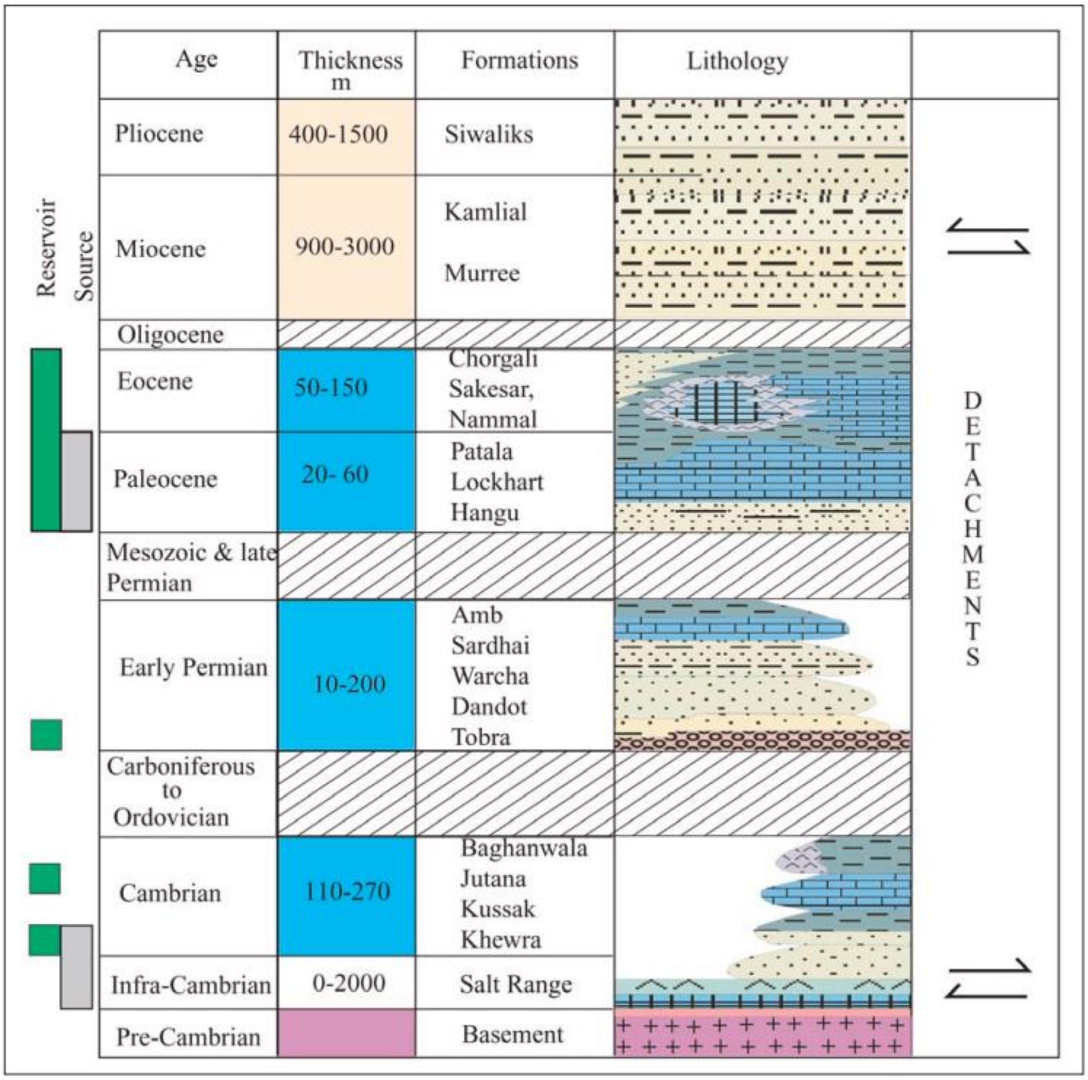


Figure2.1 Stratigraphy of Eastern Potwar (Aamir & Siddiqui, 2006).

2.9 Borehole stratigraphy

The generalized borehole stratigraphy of the area comprises of following formation.

2.9.1 Kamlial Formation

The Kamlial Formation comprises light purple and dim block medium to coarse grained sandstone and consists of intercalations of dark shale of purple color, yellow and purple intraformational conglomerates. Formations in Murree observed to be content of mineral and normal orbicular weathering where tourmaline dominates over epidote (Shah, 2009).

2.9.2 Murree Formation

The Formation is made from a repetitive succession of purple and dark red and dim green sandstones along with supporting intra formational conglomerates. The bottom layers of formation comprise of sandstones with light green siliceous and mixture of plentiful inferred bigger foraminifers of Eocene age (Shah, 2009).

2.9.3 Chorgali Formation

Formation is likewise separable into two sections in Salt range. Bottom section comprises of limestone and shale on other hand upper section contains limestone. Shale of bottom section is dim greenish and siliceous, and the limestone is argil and dark light, formations also have huge beds (Shah, 2009).

2.9.4 Nammal Formation

Formation contains marl, sediments and limestone. Sediments are greenish in color like olive color and are darker, on the other hand sediments and limestones are lighter to dimmer pale blue along with argil limestone in spots. Bounteous fossils, molluscs and primarily foraminifers have been accounted from formation. In age of Eocene Numilities and Assilina are listed fossils (Shah, 2009).

2.9.5 Patala Formation

Formation consists of sediments and clay with minute amount of limestone and sandstone in Salt range. Sediments color is darker greenish with dim look selenite-bearing, in spots marcasite nodules are founded in calcareous and carbonaceous. Nodular limestone that is light dark to whiter in color. The upper portion consists of subordinate interbedding of brownish yellow and siliceous sandstone are available in upper section (Gee, 1989).

2.9.6 Lockhart Limestone

Lockhart Formation consist of limestone which is dim to light-dim, medium had relations with, nodular, with minor measures of dim marl and dim pale blue dim siliceous sediments in bottom section, in Salt Range as well as in Trans-Indus ranges. Color of the outcrop is lighter darkish in color. Smell like pungent comes from fresh surface due to carbonic material. Formation also have Sulphur content. Fossils with micro size also founded, shape is like umberella that are called as Lockhartia, Large fossils are found in this region (Gee, 1989).

2.9.7 Hangu Formation

Hangu Formation contains darker grey, hardly bright sandstone, sediment, carbonic shale and nodular, clayey limestone in salt range and Trans Indus ranges. In parts of Surghar carbonaceous content increase locally and constitutes coal seams range (Shah, 2009).

2.9.8 Warcha Sandstone

Warcha Sandstone is primarily composed of medium in size and rough grain cross sandstone, accumulated in spots having interbedded shale. Sortation of grains is very poor and are less solidified (Shah, 2009).

2.9.9 Dandot Formation

The formation comprises sandstones with more frequently thin craggy beds and secondary very brittle shales. It is deposited in marine environment (Shah, 2009).

2.9.10 Baghanwala Formation

The Formation comprises of sediments and clay with alternative layer of flabby sandstone. Baghanwala Formation is deposited in arid climatic condition and lagoonal environment (Shah, 2009).

2.9.11 Jutana Formation

Jutana Formation is primarily composed of sandy dolomite in lower part, while composed of massive dolomite in upper part (Shah, 2009).

2.9.12 Khewra Sandstone

The Formation consist of sandstone with minor claystone. Sandstone is purple to light brown in colour, Fine to medium grained, current bedding, occasionally sorted and argillaceous. Claystone is light brown to brick red and fissile and non-calcareous. The environments of deposition are shallow marine, littoral to sublittoral. Khewra Formation is of Cambrian age (Kadri, 1995).

2.9.13 Salt Range Formation

Salt Range Formation comprises of three members, Billianwala Salt member, Bandar Khas Gypsum and Sahiwal Marl member. Billianwala Salt member mostly contains haematitic and gypsiferous dully red marly layers with broader deposits of salt. Bandar Khas Gypsum composes massive marl, gypsum, and dolomite. Sahiwal Marl member comprise of a top bright clay unit that contains dull red clay (Kadri, 1995).

Table 2.2 Borehole Stratigraphy of Rajian 01

Formation	**Age**	**Formation Top**	**Formation Bottom**	**Thickness**
Chinji	Miocene	0	570	570
Kamlial	Miocene	570	768	198
Murree	Miocene	768	3306	2538
Chorgali	Eocene	3306	3335	29
Sakesar	Eocene	3335	3414	79
Nammal	Eocene	3414	3425	11
Patala	Paleocene	3425	3439	14
Lockhart	Paleocene	3439	3450	11
Hangu	Paleocene	3450	3460	10
Sardahi	Early Permian	3460	3473	13
Warcha	Early Permian	3473	3477	4
Dandot	Early Permian	3477	3484	7
Tobra	Early Permian	3484	3490	6
Baghanwala	Middle Cambrian	3490	3505	15
Jutana	Middle Cambrian	3505	3537	32
Kussak	Middle Cambrian	3537	3623	86
Khewara Sandstone	Early Cambrian	3623	3700	77

Table 2.3 Borehole Stratigraphy of Rajian 3A

Formation	**Age**	**Formation Top**	**Formation Bottom**	**Thickness**
Chinji	Miocene	0	532	532
Kamlial	Miocene	532	770	238
Murree	Miocene	770	3302	2532
Chorgali	Eocene	3302	3328	26
Sakesar	Eocene	3328	3407	79
Nammal	Eocene	3407	3418	11
Patala	Paleocene	3418	3430	12
Lochart	Paleocene	3430	3441	11
Hangu	Paleocene	3441	3447	6
Sardahi	Early Permian	3447	3450	3
Warcha	Early Permian	3450	3460	10
Dandot	Early Permian	3460	3474	14
Tobra	Early Permian	3474	3484	10
Baghanwala	Middle Cambrian	3484	3497	13
Jutana	Middle Cambrian	3497	3541	44
Kussak	Middle Cambrian	3541	3621	80
Khewara Sandstone	Early Cambrian	3621	3655	34

Table 2.4 Borhole Stratigraphy of Daiwal 01

Formation	**Age**	**Formation Top**	**Formation Bottom**	**Thickness**
Nagri	Recent	0	395	395
Chinji	Miocene	395	1035	640
Kamlial	Miocene	1035	1197	162
Murree	Miocene	1197	2038	841
Chorgali	Eocene	2038	2074	36
Sakesar	Eocene	2074	2153	79
Nammal	Eocene	2153	2159	6
Patala	Paleocene	2159	2167	8
Lockhart	Paleocene	2167	2175	10
Hangu	Paleocene	2175	2182	7
Sardahi	Early Permian	2182	2189	7
Warcha	Early Permian	2189	2200	18
Dandot	Early Permian	2200	2210	10
Tobra	Early Permian	2210	2218	8
Jutana	Middle Cambrian	2218	2255	37
Kussak	Middle Cambrian	2255	2338	83

Khewara Sandstone	Early Cambrian	2338	2455	117
Saltrange	Pre Cambrian	2455	3224	769
Murree	Miocene	3224	4587	1363
Chorgali	Eocene	4587	4615	28
Sakesar	Eocene	4615	4690	75
Nammal	Eocene	4690	4700	10
Patala	Paleocene	4700	4705	5
Lockhart	Paleocene	4705	4721	16
Hangu	Paleocene	4721	4725	4
Sardahi	Early Permian	4725	4731	6
Warcha	Early Permian	4731	4741	10
Dandot	Early Permian	4741	4755	4
Tobra	Early Permian	4755	4763	8
Jutana	Middle Cambrian	4763	4810	47
Kussak	Middle Cambrian	4810	4890	80
Khewara Sandstone	Early Cambrian	4890	4950	60

2.10 Petroleum system

The Petroleum system generally consists of collection of all elements and processes which are required for the production of hydrocarbons (oil and gas). Few of these elements are source rock, reservoir rock, seal rock, and traps. In petroleum system few elements are in involved in creating moving and the preservation of oil and gas (Ishwimwe, 2014)

2.10.1 Seal and trap

The trap is a impervious rock which resists the movement of hydrocarbons from the reservoir. Those reservoirs which are overlain by shale, in such structures shale act as a seal. In the area inter-bedded shale and the fault truncations are present in the seal. (Ishwimwe, 2014).

2.10.2 Reservoir rock

A coarse-grained rock with just enough porosity and permeability can store & protect hydrocarbon but permitting a secondary into happen. About 90 % of the reservoirs is made up of sedimentary rocks and the remaining 10 % is occupied by the Igneous and metamorphic rocks (Ishwimwe, 2014).

Chorgali Formation (Eocene age). Fractured limestone of Sakesar Limestone (Eocene age), Lockhart Formation (Palaeocene age), arenaceous rock of Tobra Formation (Permian age) and Khewra sandstone (early Cambrian age) are the conceivable reservoir rocks in Potwar basin. Within the investigation region the reservoir zone is Top Eocene which include Chorgali and Sakesar Limestone.

2.10.3 Source Rock

A source rock is usually defined as the subsurface rock which has a high porosity but having limited permeability. It is generally considered as the crucial part of the petroleum system because it consists of the precursors to the formation of hydrocarbons mostly Kerogen (organic matter). Until it migrates a source rock acts as a host for the processes that result in the hydrocarbons (Magoon and Dow, 1994).

Patala Formation seems to be the primary source of most of the oils encountered in the basin (Raza, 1973; Quadri and Quadri, 1996), oils from the Dhurnal, Pindori, Bhangali and Adhi fields contain less than 0.2% sulphur due to the varying percentage of aromatic napthenes and different biomarkers and appear to be different from the oils that are known to be sourced from the Patala Formation, suggesting that there are more than one active oil source systems in the basin (Khan et al., 1986; Malik et al., 1988; Fazeelat et al., 2010).

2.11 Petroleum Pay

Table 2.5 Petroleum system of study area

Formation	**Age**	**Rock type**
Murree	Miocene	Seal
Chorgali	Eocene	Reservoir
Lockhart, Patala	Paleocene	Source

CHAPTER 3

SEISMIC INTERPETATION

3.1 Introduction

Seismic interpretation begins by mapping large scale subsurface structures in area i.e. marking faults and horizons. On seismic sections horizons are marked on strong reflectors followed by seismic data. Reservoirs and sequence boundaries are usually marked as they tell us about geological age and stratigraphic traps. Faults are marked if there is discontinuity, distortion or displacement in horizon (Bakker, 2002)

The method to explore the prospective oil and gas deposits is referred as seismic data interpretation through the interpretation of the processed images using the geological models and data from well measurements including the well logs and borehole images (Bakker, 2002).

Seismic interpretation is defined as, transformation seismic data into structural view by an application of various correction. Interpretation of seismic data is very complex process as all areas are different from each other. For this purpose, an interpreter has to get really aware with the area to work it well and try different methods to get the good results from the area of interest (Dobrin and Savit, 1998).

The seismic technique is the most precise, direct, and high-resolution tool for subsurface structure investigation. The seismic method, in comparison to all other geophysical methods, provides a more complete and detailed structural investigation of the subsurface. This method is the most extensively utilized geophysical approach in exploration and production purposes for mining and production of oil and gas reserves in the basement, since it is the most advanced tool for hydrocarbon exploration up till now (Serra, 1984).

3.2 Software Used

The interpretation of the seismic section can be done by using move software and Gverse software. 2D seismic interpretation can be done in move software while 3D seismic interpretation can be done in Gverse software.

GVERSE Geophysics software is a powerful, fully integrated 2D and 3D seismic interpretation system that provides a full range of fit-for-purpose interpretation capabilities, attribute analysis, and mapping tools. Whether exploring complex structural areas or looking for subtle stratigraphic traps, today's geoscientist can use GVERSE Geophysics to solve challenging geophysical problems - without having to transfer data between applications.

The Move suite consists of the Move Core Application - a powerful stand-alone environment that can be used for 2D cross-section construction, 3D model building, data integration and analysis. The Core Application also provides the base for specialist structural modules in 2D and 3D Kinematic Modelling, Geo-mechanical, Fracture and Fault Response Modelling, as well as Strain Capture, Fault Analysis and Stress Analysis. Move can be used to build geometrically valid interpretations based on geological principles. It is designed by geologists for geologists, in order to provide a best practice environment for model building and testing geological interpretations and concepts.

3.3 Seismic Interpretation Types

The interpretation of the seismic section can be done in two ways:

i. Structural Interpretation
ii. Stratigraphic Interpretation.

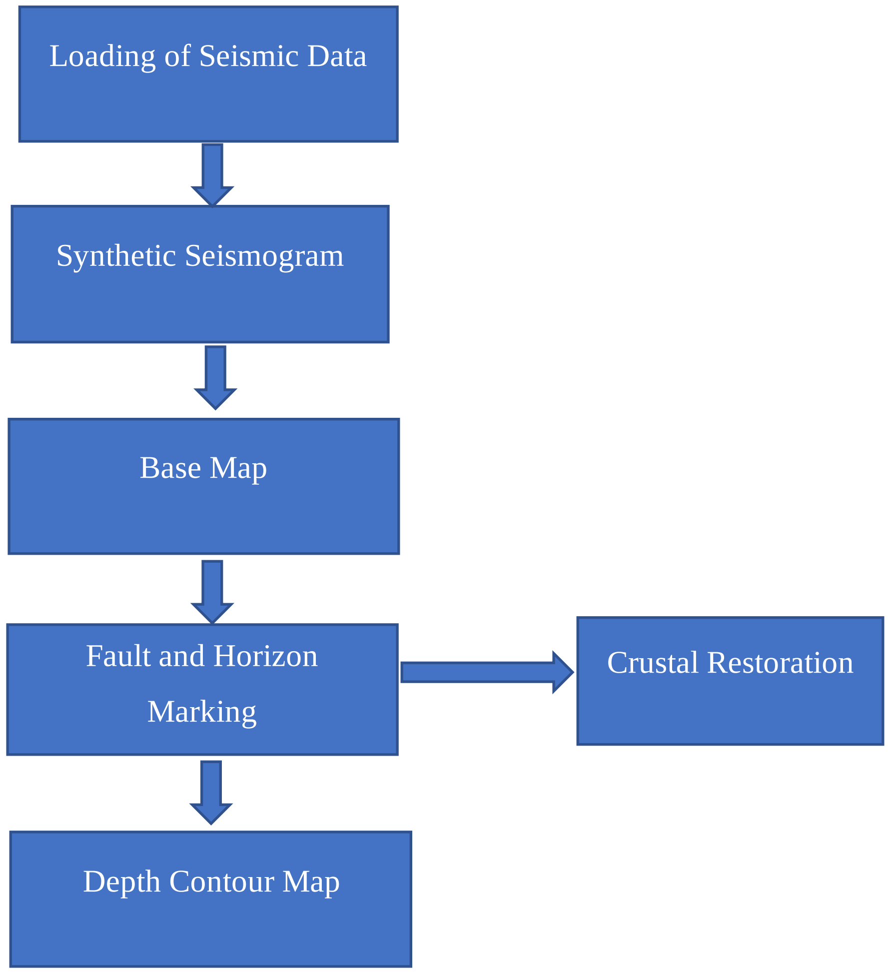
3.3.1 Structural Interpretation

The Structural interpretation of seismic reflection data is carried out to find the structures that can accumulate and trap hydrocarbons in order understand structural behavior better. Instead of depth, the two-way reflection time technique was used in the structural interpretation of seismic data (Kearey, 1988).

3.3.2 Stratigraphic Interpretation

Stratigraphic interpretation is analysis of defining the seismic sequences that display different lithological units, extracting different seismic facies features that indicate the sedimentary sequence and interpreting reflecting characteristics that are hard to examine the stratigraphic variations and depositional environments of the hydrocarbons.

3.4 Workflow of seismic interpretation.



3.4.1 Generation of Base Map

For preparing base map latitude and longitude of the area is loaded into interpretational software and then seismic lines are also loaded. 3D seismic data is provided in form of cube with inline and cross line. They are both orthogonal to each other and form net geometry. The wells lying in study area are displayed and loaded on base map. Cubic base map with 3D seismic and three wells are shown in figure below. In the figure 3.1 shows that the base map that consists of inline and crossline.

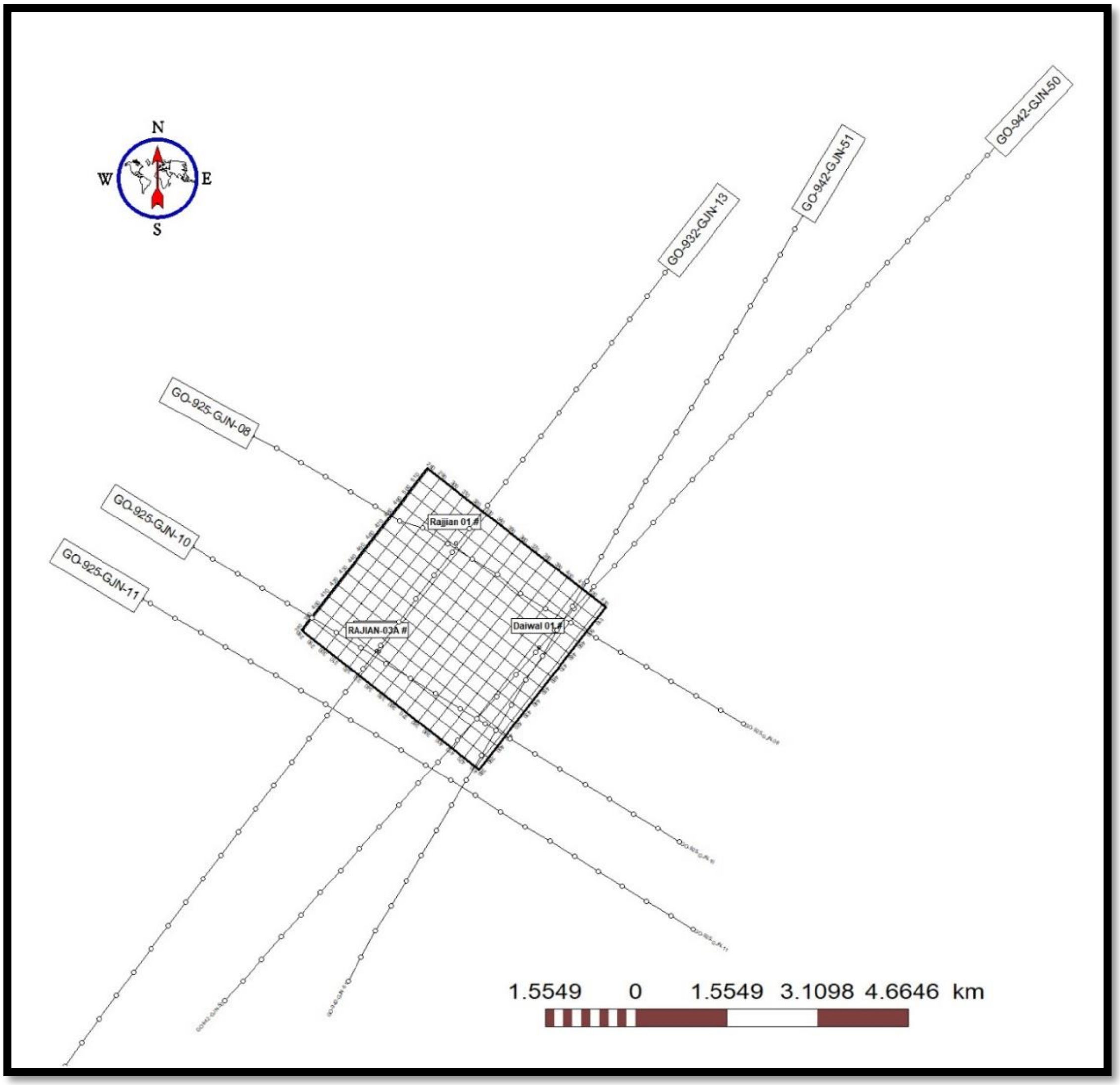


Figure 3.1 Base map of Rajian Field

3.4.2 Synthetic Seismogram Preparation

Generation of synthetic seismogram is a useful approach to correlate well and seismic data to identify the accurate position of horizons in the subsurface along with the seismic reflections. It provides the direct relation between the lithology experienced in a wellbore and those identified in the seismic section (Handwerger et al., 2004).

Sonic and density logs are essential for the generation of synthetic seismograms. Velocity and density are obtained from the sonic and density logs. The product of density and velocity gives us the acoustic impedance and then with the help of acoustic impedance we can generate the reflectivity series due to the contrast of lithologies in the subsurface. A synthetic seismogram of the specified wells is created before the horizons are marked (Chopra and Marfurt, 2005).

Synthetic seismogram of Rajian-3A is shown in figure 3.2. Chorgali and Sakesar is marked by tying synthetic seismogram with seismic reflection data in time domain. The horizon picked during interpretation are:

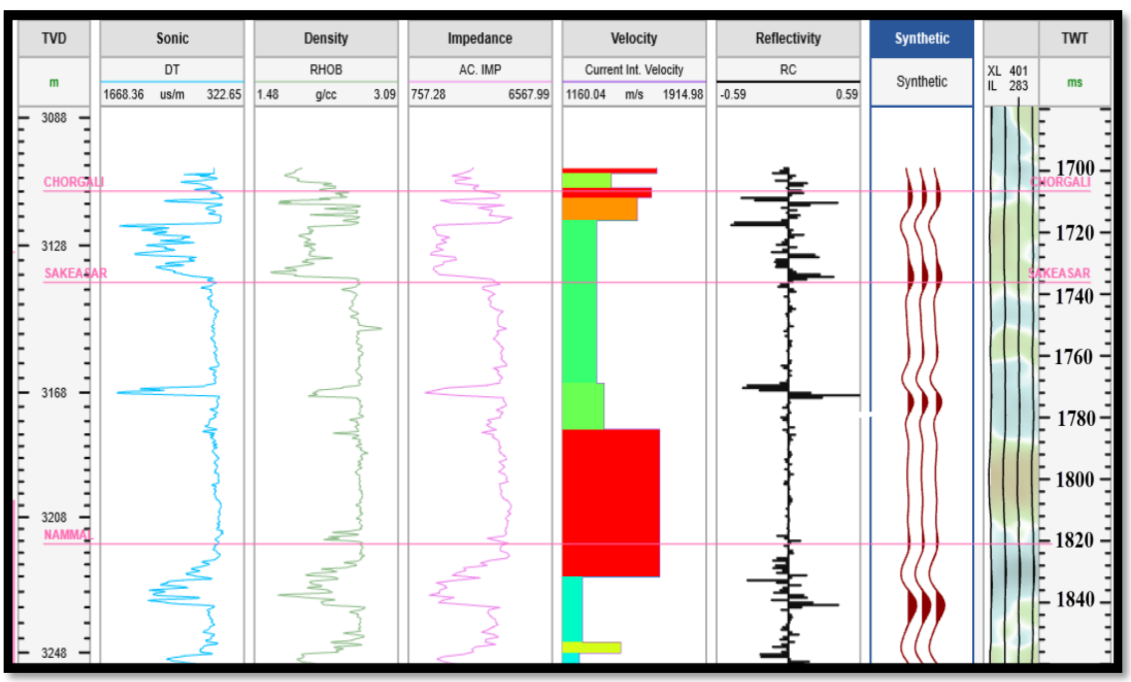


Figure 3.2 Synthetic Seismogram of Rajian-3A well

3.4.3 Horizon Marking

A seismic interpreter's major job is to indicate the horizons with a synthetic seismogram built with logs in the seismic section. To verify the horizons, this synthesis is correlated or linked to seismic data.

The selection of horizons is the next step to be marked on the seismic section. Three reflectors were marked on the seismic sections which are Murree, Chorgali, Lockhart and Salt range. As the main reservoir in Rajian area is Chorgali so, it was considered as a primary target in this course work. But, to justify the whole structure properly. A good stratigraphic, as well as structural knowledge is required for horizon interpretation (Mavko et al., 2009).

3.4.4 Fault Marking

Fault marking on the real-time domain seismic section is a fairly complex thing to do without understanding the area's tectonic background (Sroor, 2010). Faults are identified on the principle of a break in the continuity of reflection. This Discontinuity of the reflector indicates that the data is disrupted by the fault cuts.

Fault identification on the seismic signature is the most crucial task for structural interpretation. Breakage or discontinuity of reflectors observed on the seismic section indicates the presence of a fault. The background geological knowledge along with the structural history of the study area is considered to be the power tool for fault recognition. In an extensional regime, the movement of plates opposite to each other resulted in normal faulting and horst and graben structures are formed. While on the other hand, in compressional regimes, the movement of plates opposite to each other causes intense folding and reverse or thrust faulting.

3.5 Interpretation of seismic lines

3.5.1 Key Profile 01

To carry out seismic interpretation different horizons and faults were marked on the both 2D and 3D seismic data. In order to cover the overall structural trend in the study area different sections from both 2D and 3D sections seismic data were selected and termed as key profiles (Fig.3.1).

Key Profiles (GO-925-GJN-11) seismic line is a WNW-ESE trending dip line, covering approximately 1km distance. Total four reflectors were marked on the seismic line namely Top Murree Formation, Top Chorgali Formation, Top Lockhart Limestone and Top Salt Range Formation.

A number of Faults were also marked as F1, F2 and F3 which are marked as primary faults, since they contribute to the formation of main structure.

All three are fore thrust dipping towards NW. While F4 is a back thrust, dipping towards SE. There are several small faults only bounded to the packages like F7, F6 and F7 etc. The key profile can be described by episodic deformation starting down by normal faulted basement (Fig 3.3). Salt range formation is mainly responsible for providing basal decollement along which the basal thrust SRT running along, marking it into thin skin tectonic regime.

Eocene to Cambrian sequence is divided into several packages, each bounded by thrust faults. Normal fault in the basement provided ramp for the transportation of hanging wall and causing sequence /package 1 to deform as fault bend fold and positive geometry.

F2 is the second in sequence thrusting, acting as a Roof thrust for Package 1 and basal thrust for the package two which also behaving as a fault bend fold and being disturbed by nearly flat faults which seem to be created after the formation of main structure due to complexity during tectonic transportation.

F3 is serving as a roof thrust for package 2 and a sole thrust for package three also deformed into a folded geometry. The roof thrust for package three is a back thrust (Figure 3.3).

F4 is dipping towards SE and marking the structure as Passive Roof Duplex. F4 is also responsible for bringing Pre-Cambrian to Miocene sequence on the top of low thrust sequences/packages.

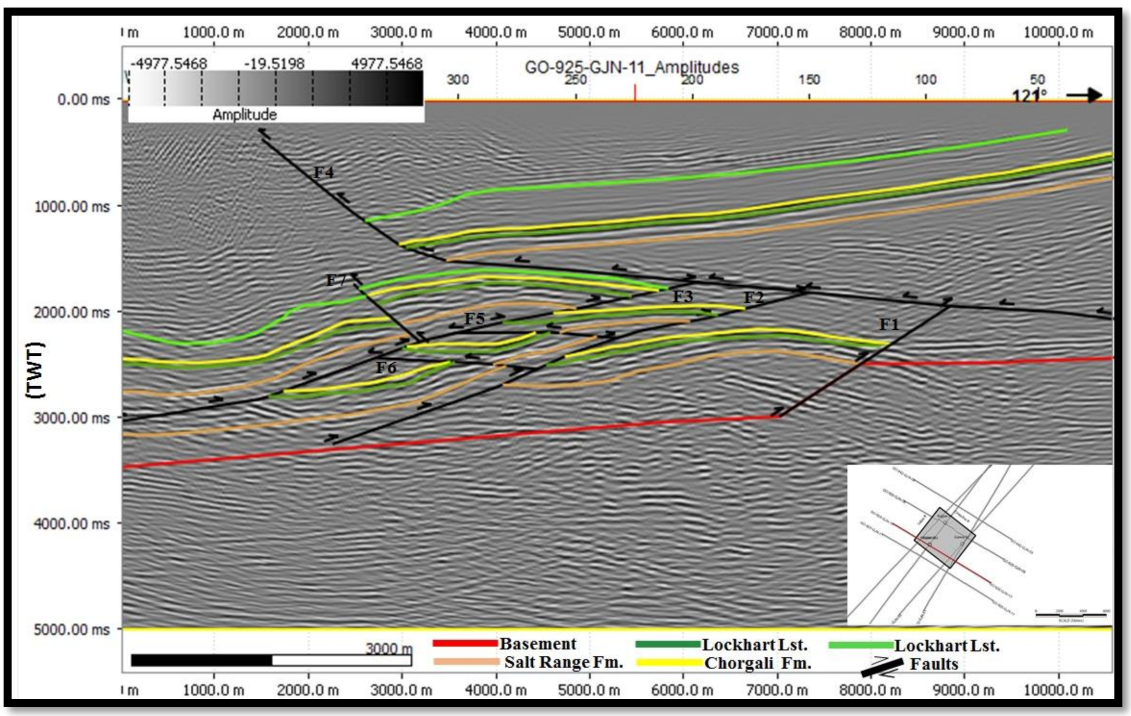


Figure 3.3 Interpreted Seismic Section GO-925-GJN-11

Inline 401, from the 3D Seismic cube was selected approximately from the same position as of key profile to compare the data quality and interpretation. It shows that line covers only the central part of the key profile 1 and the data quality decreases which increases TWT. Only upper two package are present between F4 back thrust and

F3 marking a fault bend fold geometry and with marked closure can be seen on the line (Figure 3.4).

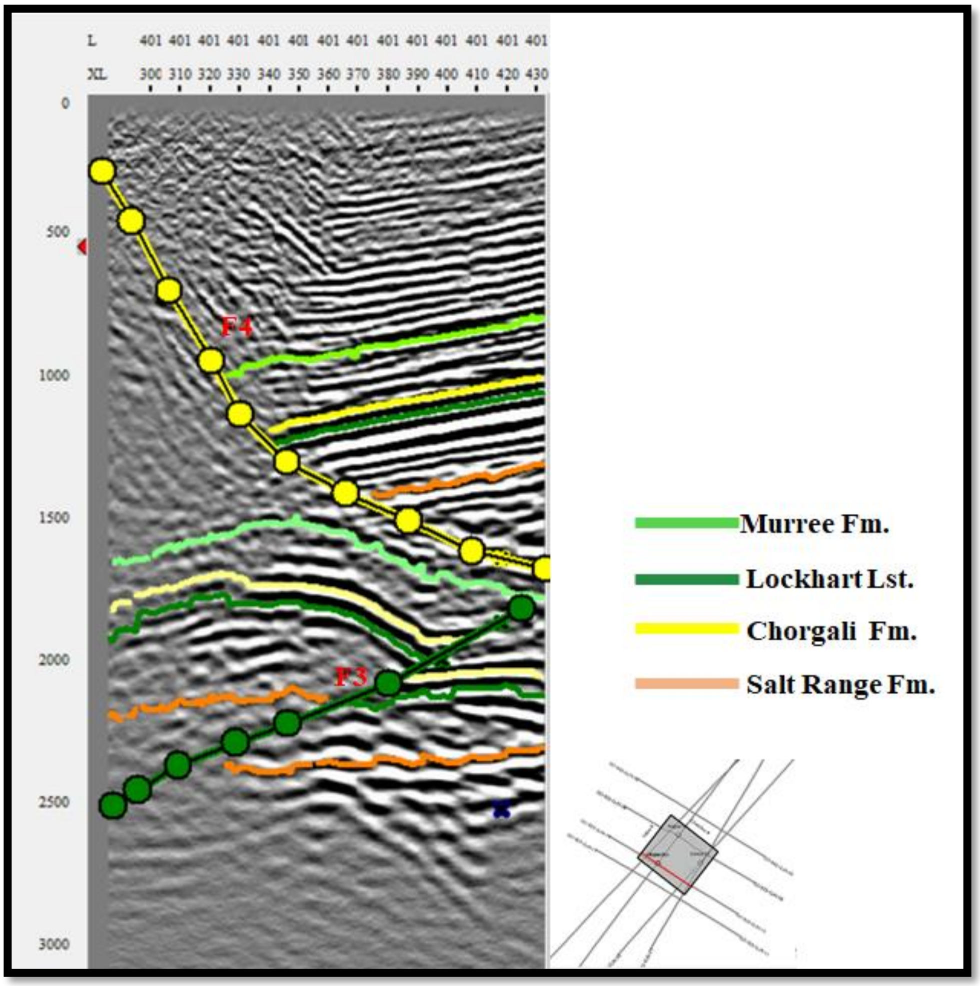


Figure 3.4 Interpreted Seismic Section Inline 401

3.5.2 Key Profile 02

The second line which was chosen as key profile 2 is dip line named GO-925-GJN-08. It is also ESE-WNW trending dip line covering the major structural units present in the study area. All four selected horizons were marked along major faults F2, F3, F4, F5 and minor faults F6, F7, F8 and F9 (Figure 3.5).

The ramp at basement level is still visible, F1 is not present at this section but package one (Eocene to Cambrian) can be marked and overlain by the roof thrust F2 and bisected by a back thrust (F4).

Package 2, which was observed on key profile 1 seems to be thinning out toward East and present with small areal extent.

Package three between F3 and F4 becomes more dominant and depicts the geometry of a pop-up structure due to the interaction of small back thrusts with basal fore thrust F3. An upper level (probably) Miocene level detachment can also be observed as (F6).

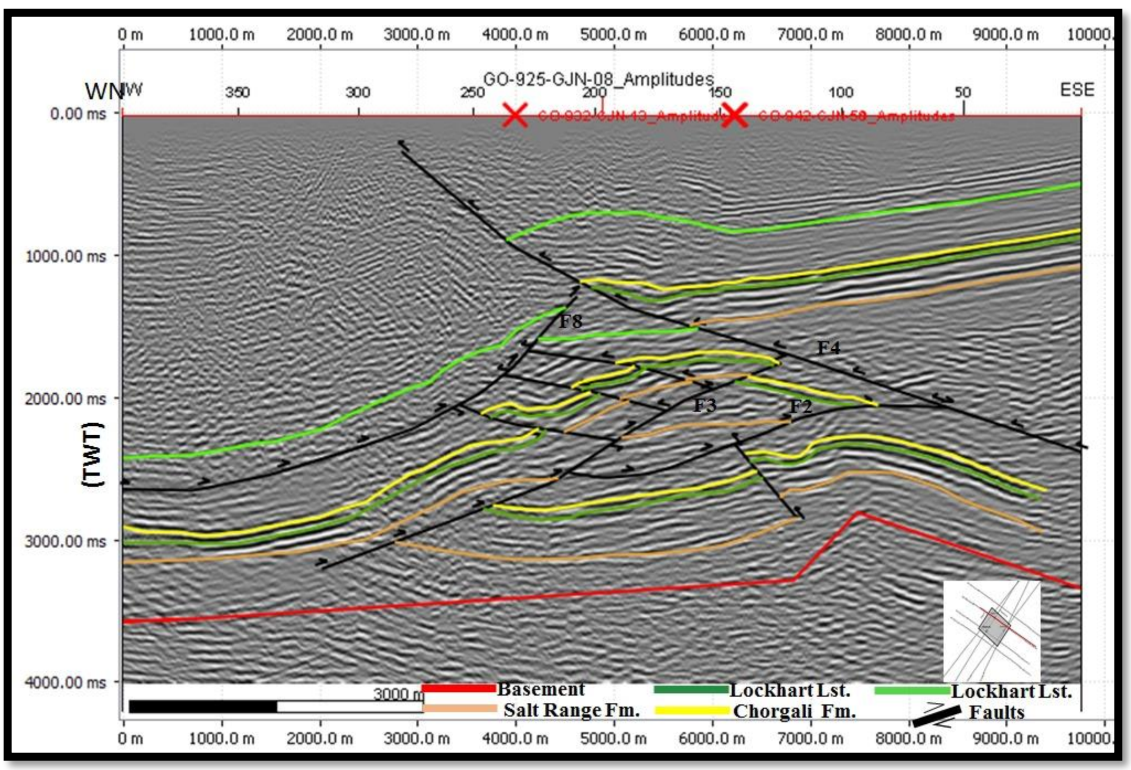


Figure 3.5 Interpreted Seismic Section GO-925-GJN-8

Inline 488 had been from 3D seismic data and has same location approximately as of key profile 2.It also shows the presence of a dominant pop up structure at package three level between F3 and F4. It only covers the central part of the area covered by key profile 2 (Figure 3.6).

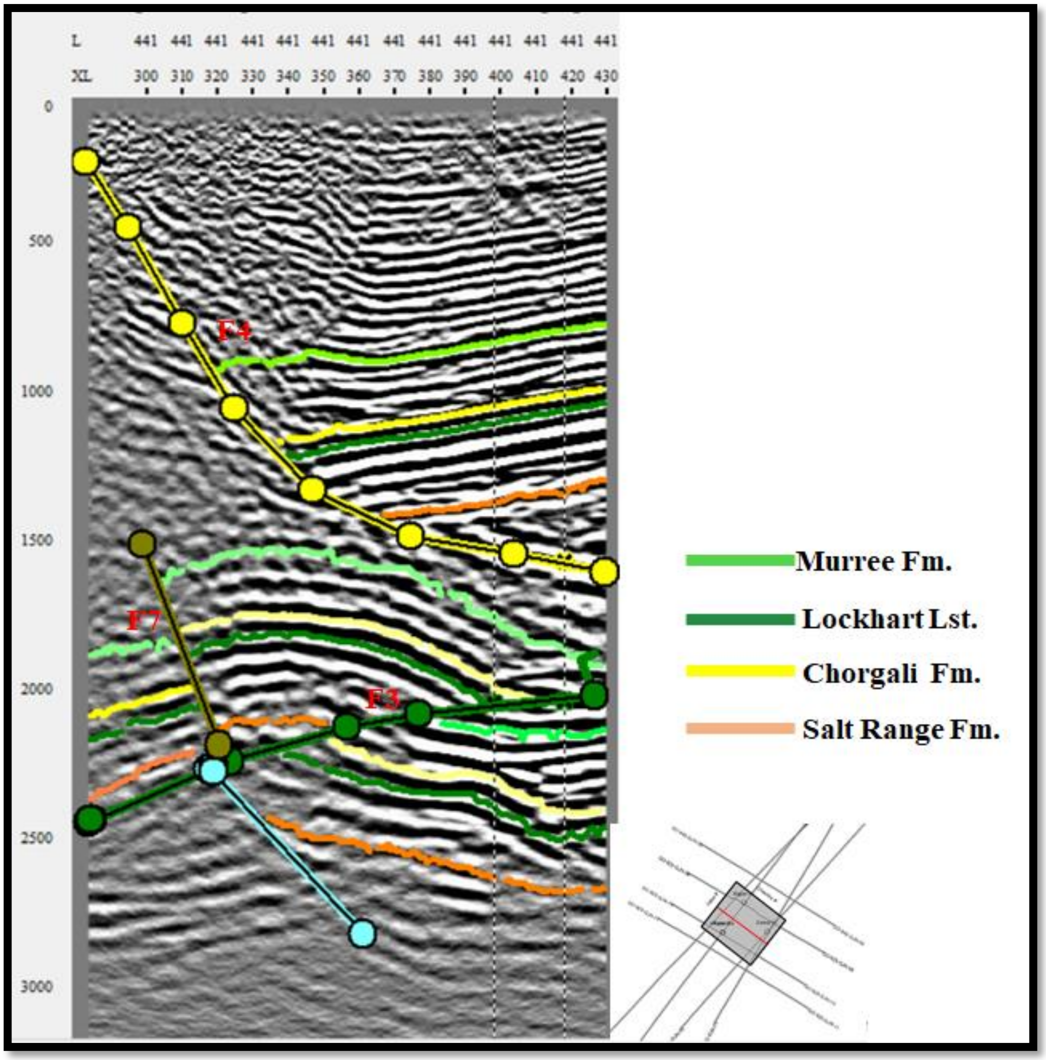


Figure 3.6 Interpreted Seismic Section Inline 441

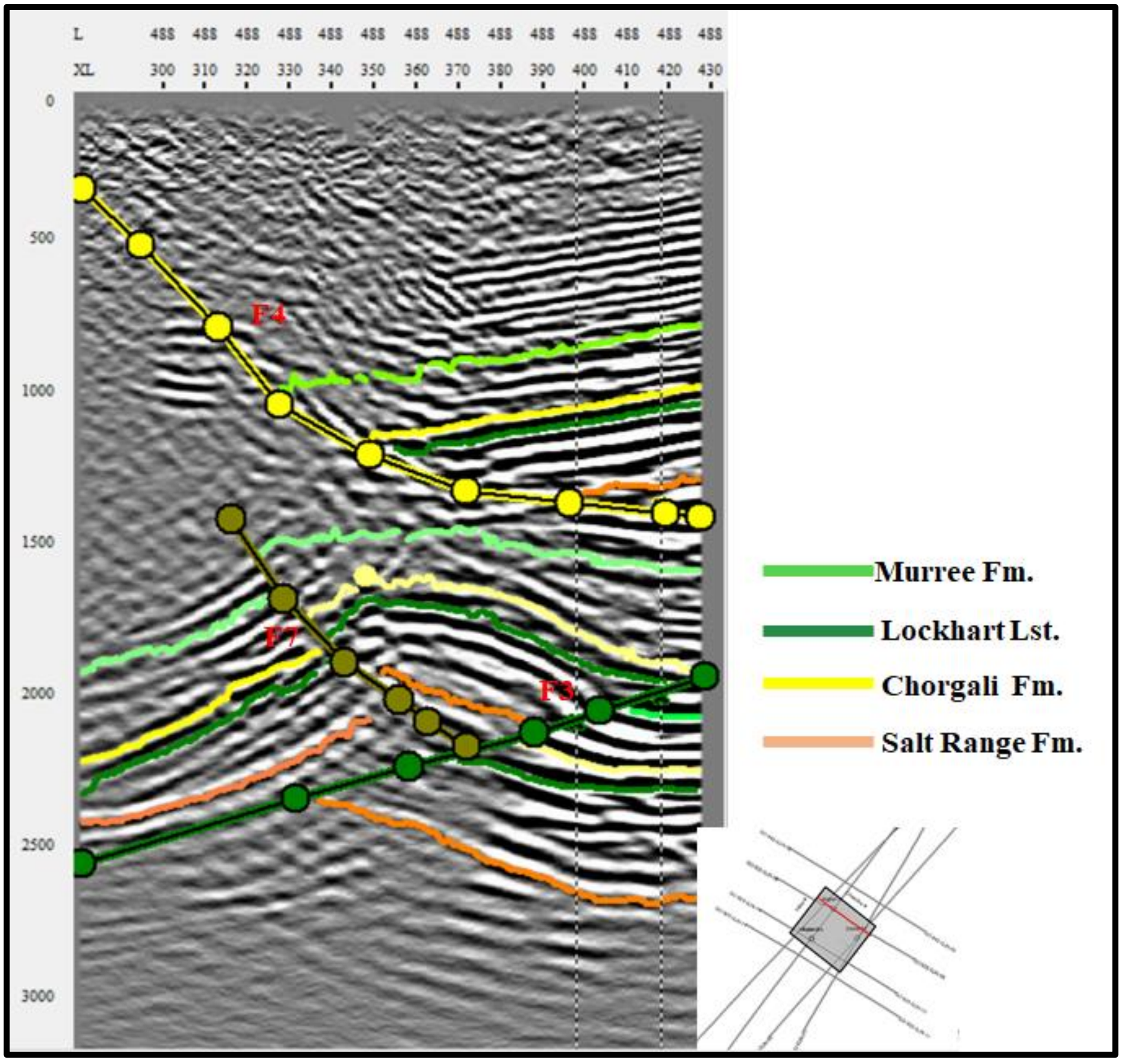


Figure 3.7 Interpreted Seismic Section Inline 488

3.5.3 Key Profile 03

The line GO-932-GJN-13 is NNE-SSW trending and serving as so called strike line was selected as key profile 3 (Figure 3.8).

The line covers the structural packages present in the northern part of study area. All four horizons were marked. Since the line is not perfectly align to the structural trend, so it gives better fault coverage and depict their geometries in good manners. All three faults present in center and north of the study area are interpreted here.

F4 which is back thrust and separates upper package from the lower one, generally have a very low dip as compared to the dip line, F3 is also interpreted separating second and third package.

The lower most unit is recognizable from its behavior and strong basement reflection and is being disturbed by quite a few faults. Reflection behavior of salt range is also useful to differentiate different packages and faults.

To the east of the seismic line, two major faults F8 and F9 can be seen dipping in the NE direction and package also dipping towards Eastern direction.

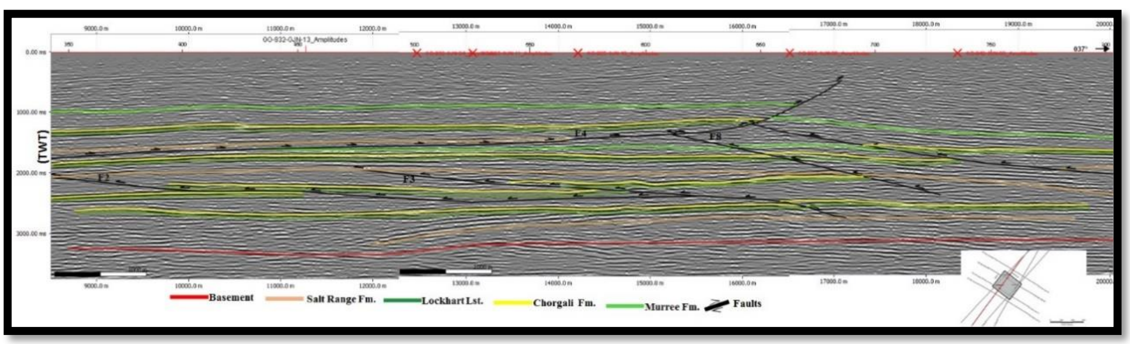


Figure 3.8 Interpreted Seismic Section of seismic line GO-932-GJN-13

3.5.4 Key Profile 4

The line GO-942- GJN-51 had been selected as Kay profile 4, this NNE-SSW striking line with approximately 1.6 km length covers the southern part of the study area. All four horizons were marked along with the major faults (Figure 3.9).

Three major Eocene-Cambrian packages can be easily recognized. The upper package is only bisected with back thrust F4 with minor displacement.

The central package had been displaced with a number of faults like F2, F3, F5, F9 and F10 marking imbrication system.

The lower most package is relatively undisturbed and smooth overlying EW dipping basement.

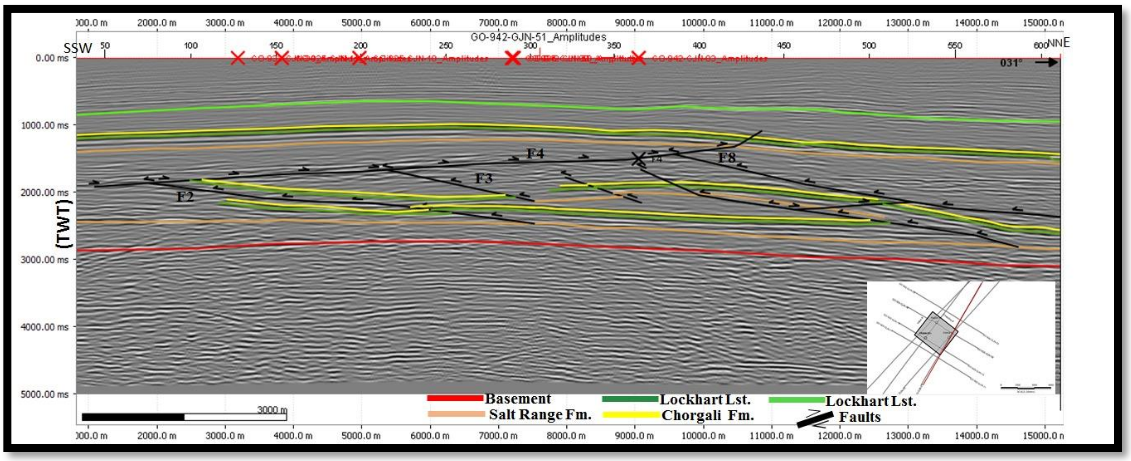


Figure 3.9 Interpreted Seismic Section GO-942-GJN-51

The presence of duplex structure can also be confirmed through these so called Strike line as if believed that SRT is running through Salt Range Formation as basal thrust and F4 is dipping oppositely roofing the intermediate imbrications F2, F3 and F5 transforming displacement from basal trust to roof thrust which is a back thrust marking the whole structure as passive roof duplex (Figure 3.9).

3.6 Two way Travel Time and Depth Contour map Interpretation

Construction of TWT and depth maps is the next step to map the sub surface geometries previously marked as individual faults and horizons on seismic lines. These maps provide us with an opportunity to understand the distribution of various structural and stratigraphic elements in context of area, trend (strike and dip), structural behavior and nature of geometries.

TWT contour maps were prepared on Geographic's using already interpreted horizon that is Salt Range Formation, Chorgali Formation, Lockhart Limestone and Murree Formation. Contour interval was 50ms. Since the major structure present in the study area is a passive roof duplex, means each hanging wall covers the formation of footwall and multiple horizons were marked so difficult to depict each hanging wall at same map. Time contour map of Murree Formation, Chorgali Formation and Lockhart Formation are shown in figure 3.10, figure 3.11 and figure 3.12.

To resolve this problem only the top sheet was mapped. Contour maps (at each interval) indicate two north east-south west trending faults which are dipping in opposite direction.

South Eastern part serves at the hanging wall of back thrust F4 and gently dipping toward NW as shown gently spacing contours. While North Western part shows the deepest area and serving as hanging wall of F7 and relatively steeply dipping as compared to F4. The middle part is shadowed by the hanging walls of both faults and show a smaller area with a positive structure.

After making the time contour map the next step is to know the exact velocity of formation. The velocity is obtained from RMS, depth contour maps being created by converting data from the time section to the depth section using the velocity function. Depth contour map of Murree Formation, Chorgali Formation and Lockhart Formation are shown in figure 3.13, figure 3.14 and figure 3.15.

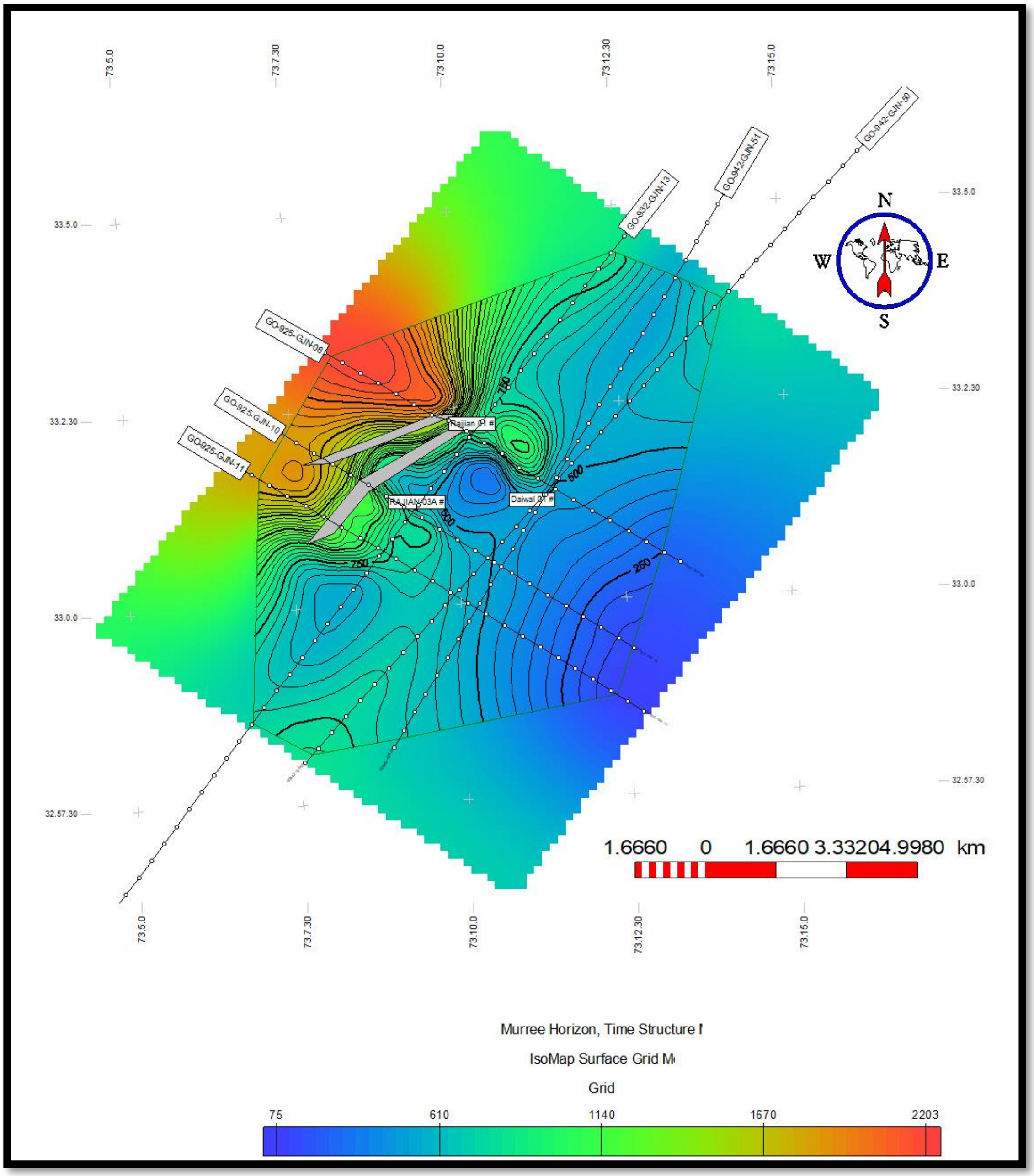


Figure 3.10 Time contour map of Murree Formation

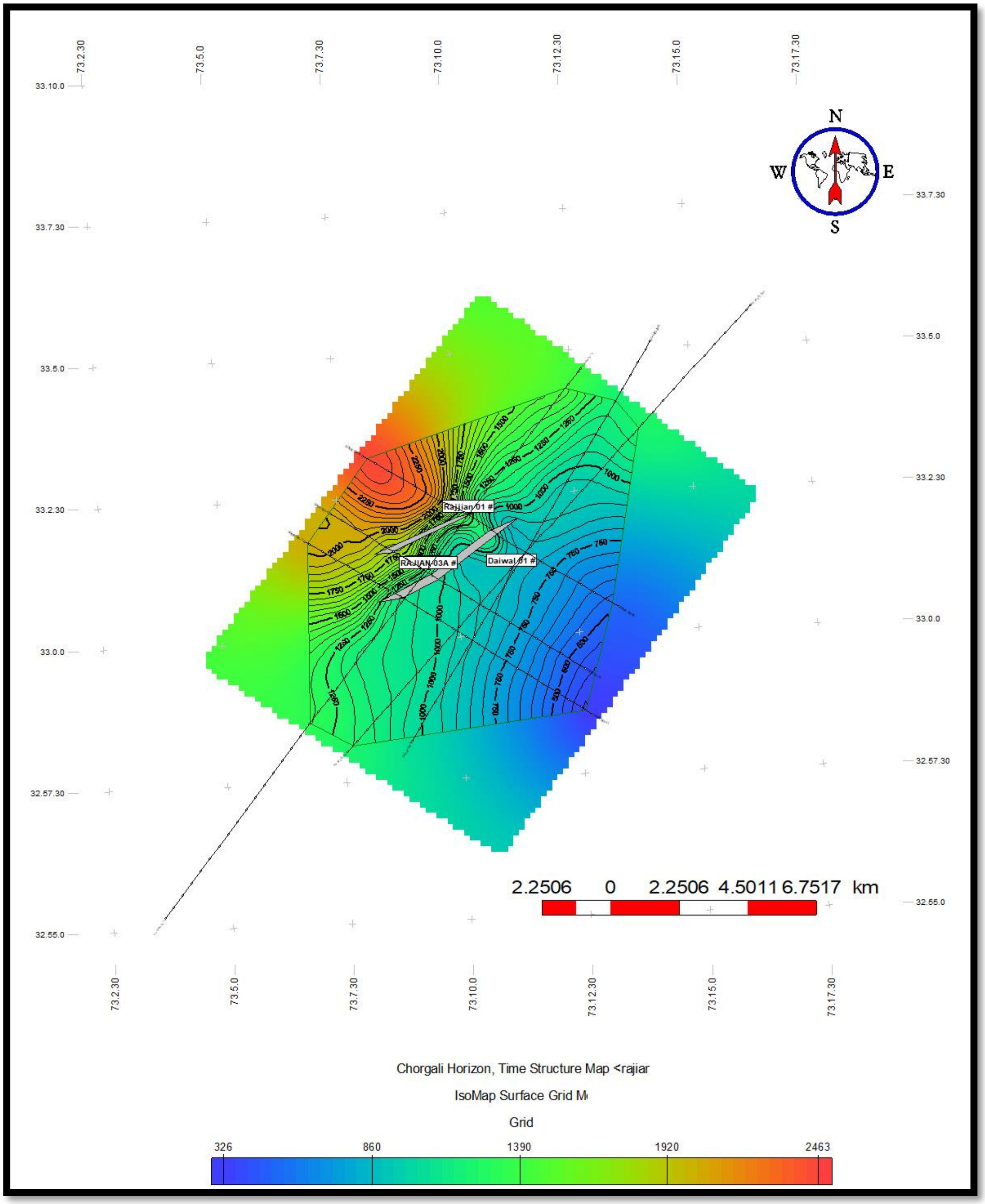


Figure 3.11 Time contour map of Chorgali Formation

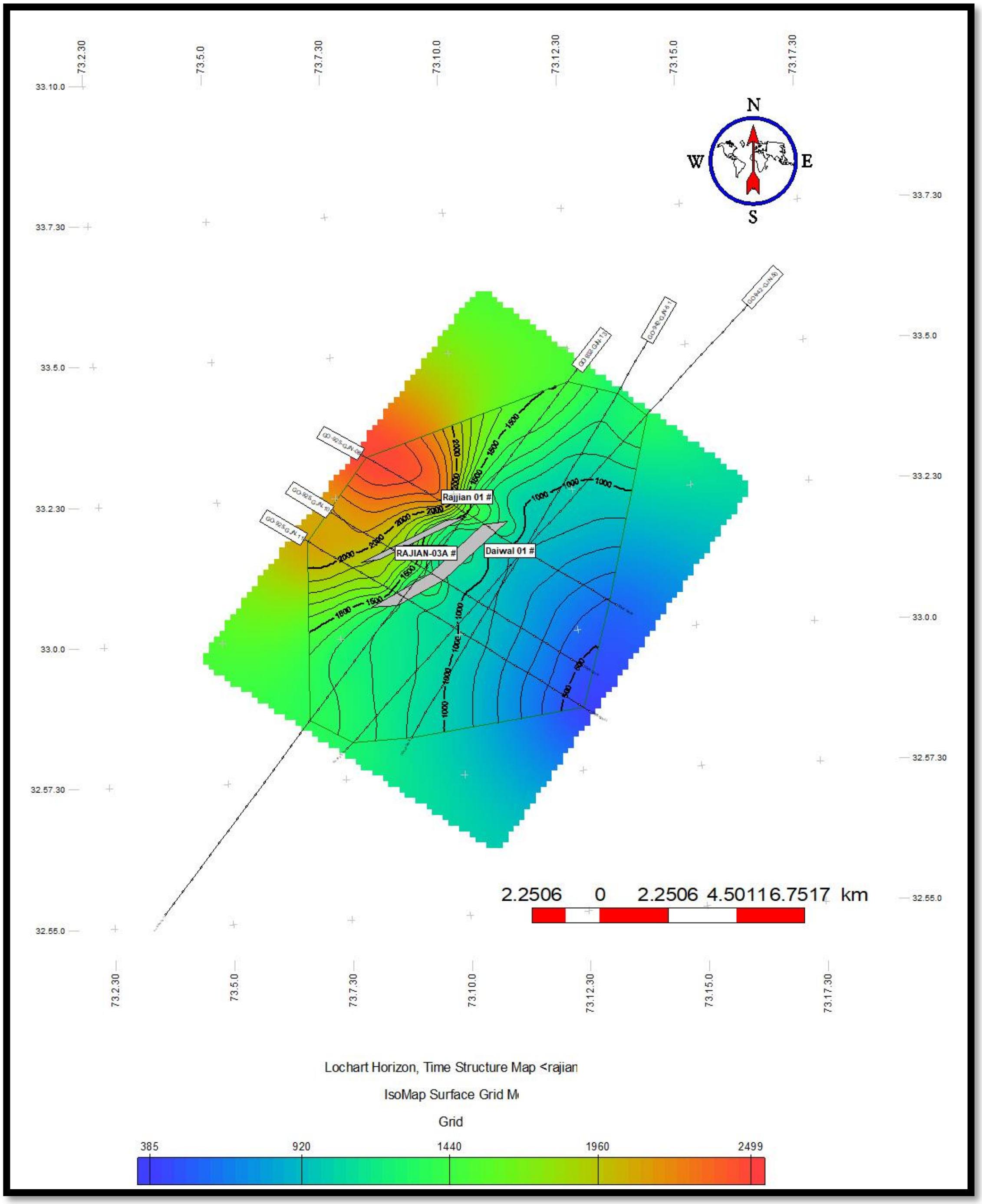


Figure 3.12 Time contour map of Lockhart Formation

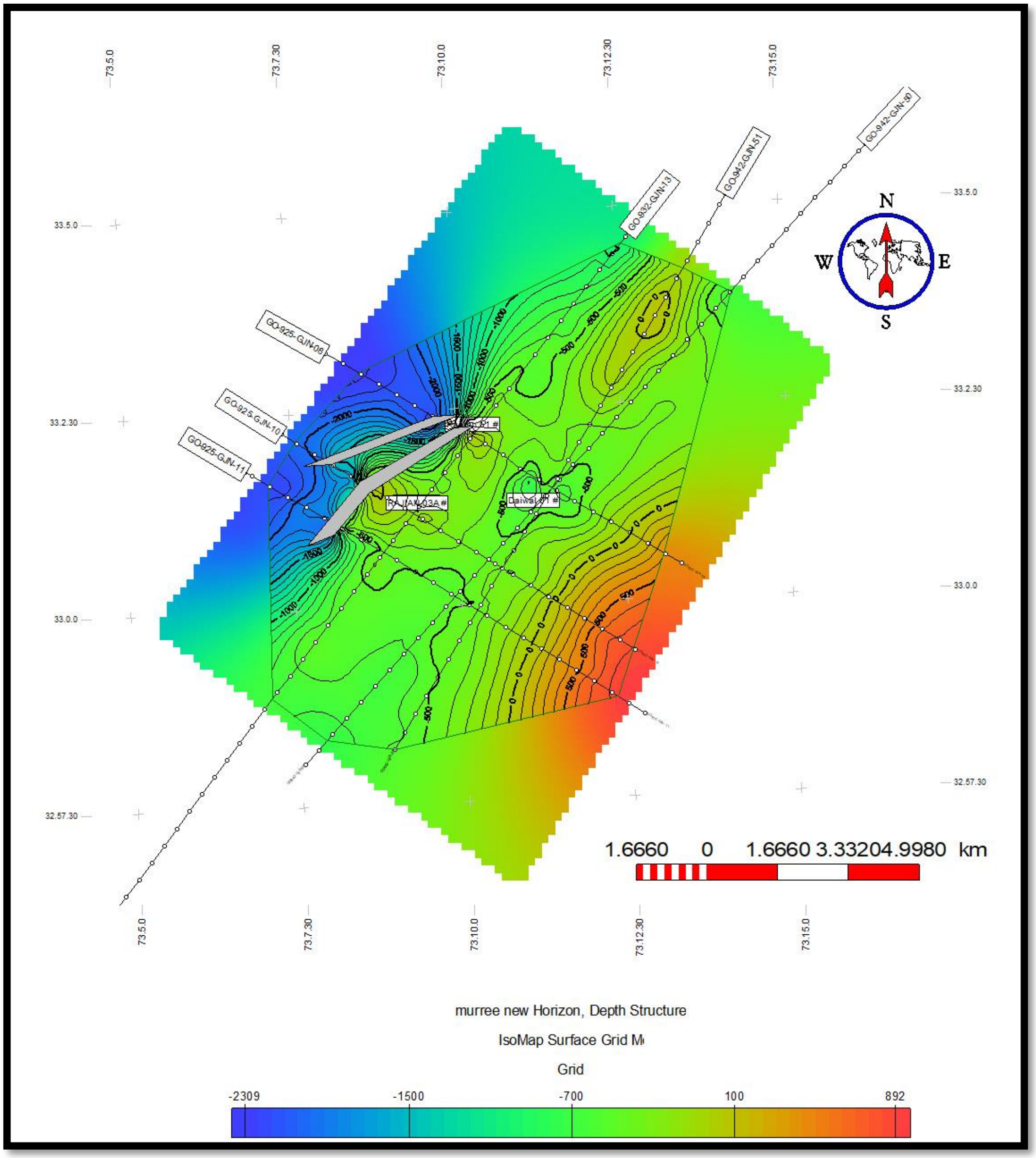


Figure 3.13 Depth map of Murree Formation

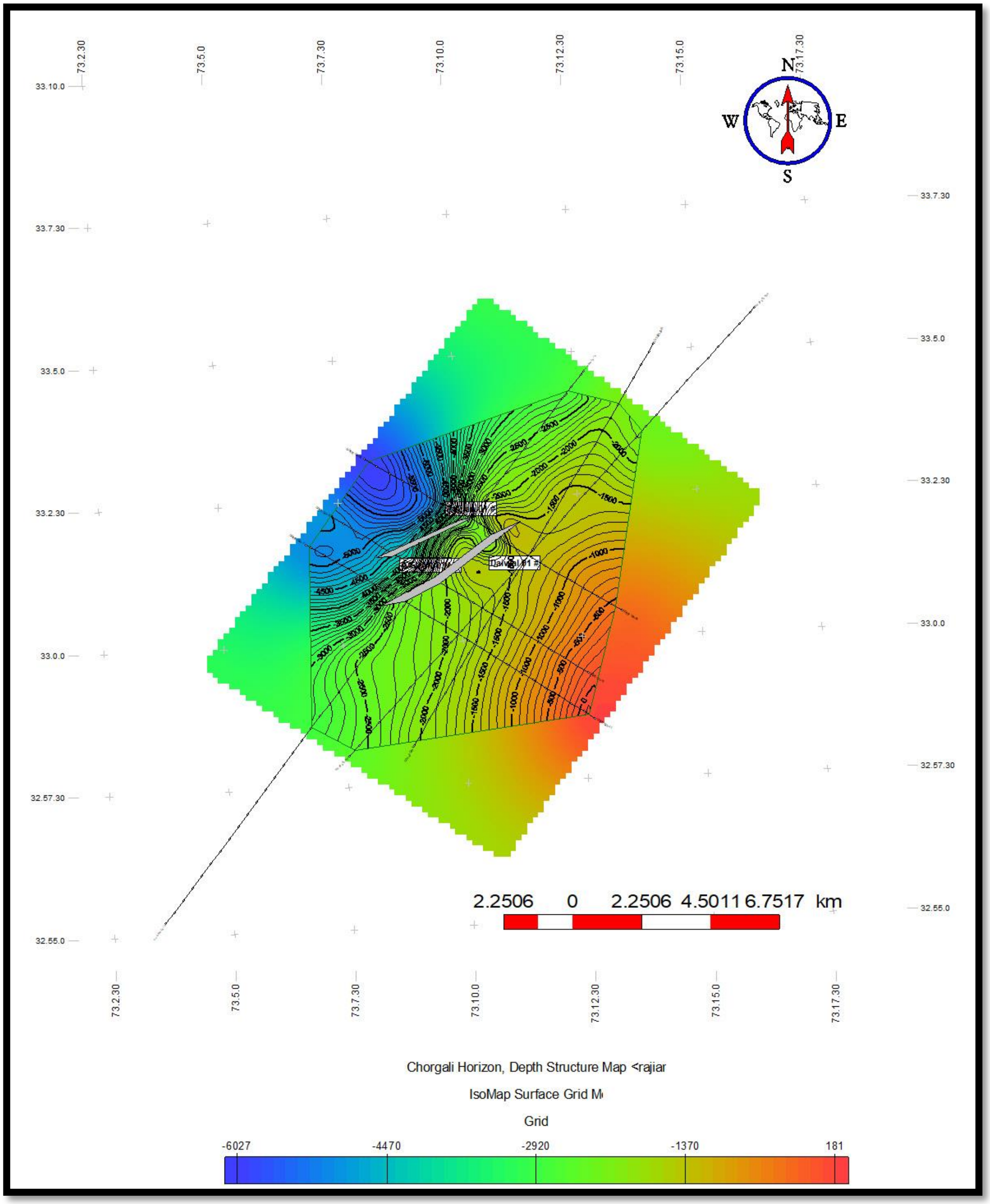


Figure 3.14 Depth map of Chorgali Formation

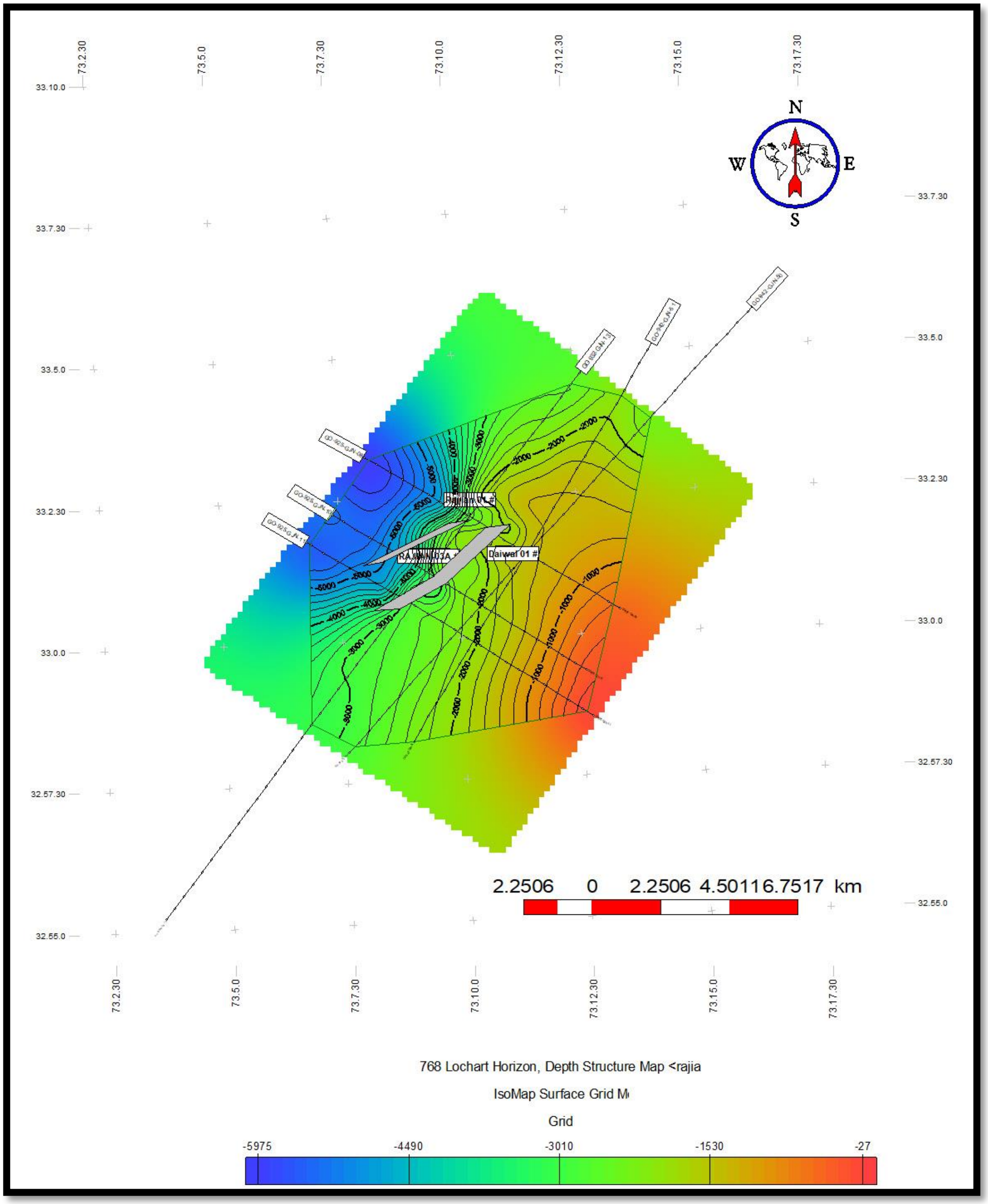


Figure 3.15 Depth map of Lockhart Formation

CHAPTER 4

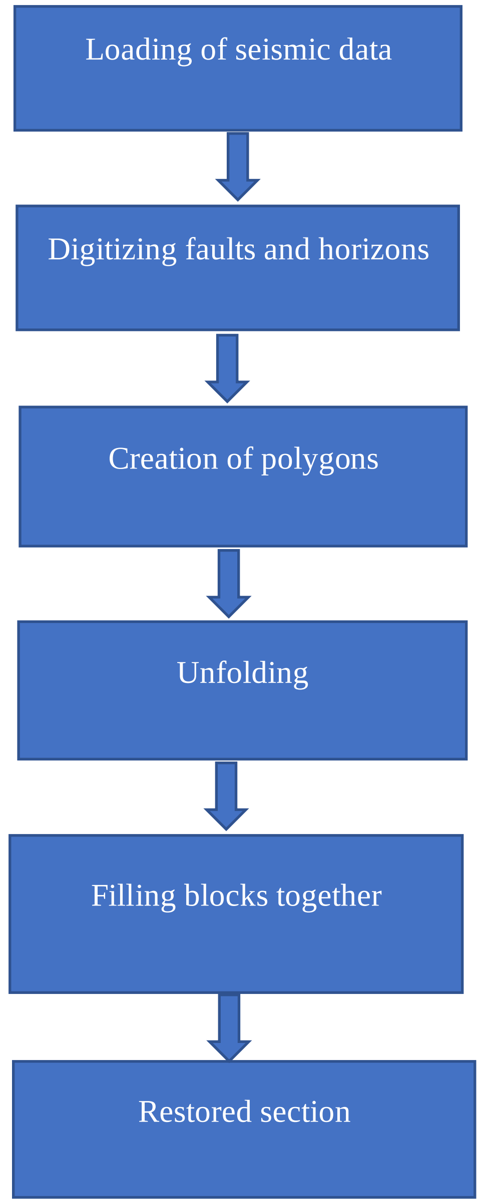
SEISMIC INTERPETATION

4.1 Introduction

Structural restoration is process of reversing rock deformation in the subsurface through time and work flow involve the removal of any post-kinematic units and de-compacting the underlying section, prior to restoring the fault relating deformation.

Structural restoration is particularly valuable when studying complex geological settings, as it helps unravel the sequence of events and the amount of deformation that has occurred over geological time. Structural restoration is process of reversing rock deformation in the subsurface through time and workflow involve the removal of any post-kinematic units and de-compacting the underlying section, prior to restoring the fault relating deformation (Nunns, 1991).

A generalize workflow adopted for this exercise is given below.



4.2 Tool Used

Structural modelling is done by using Midland Valley MOVE 2017. The MOVE suite stands out as the most comprehensive toolkit for structural modeling and analysis currently accessible. It offers a comprehensive digital environment dedicated to implementing best practices in structural modeling, thereby minimizing risk and uncertainty associated with geological models. Within the MOVE suite, users can seamlessly integrate and interpret data, construct cross-sections, build 3D models, perform kinematic restoration and validation, engage in geo-mechanical modeling, conduct fracture and fault response modeling, simulate sediment processes, and analyze fault and stress interactions. Geoscientists and engineers in over 200 companies globally rely on it to optimize the utilization of their data and mitigate risk and uncertainty in diverse resource sectors, including oil and gas, mining, CO2 storage, geothermal energy, geological surveys, and geotechnical engineering. The MOVE suite encompasses a wide spectrum of methodologies, spanning from initial model creation and rigorous structural quality control to advanced analyses like assessing reservoir compartmentalization and predicting fractures. These capabilities assist in informed decision-making and prospect planning (www.petex.com).

4.3 Methodology Adopted

In order to carry out 2D structural restoration of the study area key profile 1 was chosen, since it depoctics the subsurface geometry more accurately.

After loading the seismic line to move software, the section was converted to the depth by using 2D depth conversion tool. An interpretation of horizons and faults were made (see chapter 3).

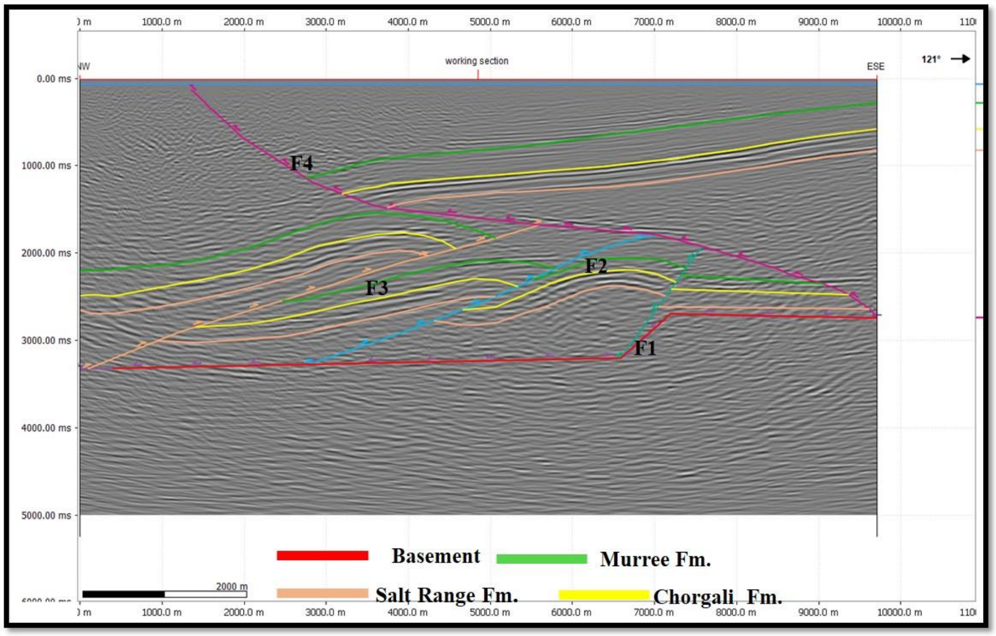


Figure 4.1 Working section

Polygons were created for each horizon. Total four horizons were marked namely Murree Formation, Top Eocene (Chorgali Formation), Top Salt Range formation and the Basement along with four major thrusts F1, F2 and F3 were fore thrusts which F4 is a back thrust (Figure 4.1). Each fault block was unfolded independently and the horizon from the fault were used to extend the template horizon.

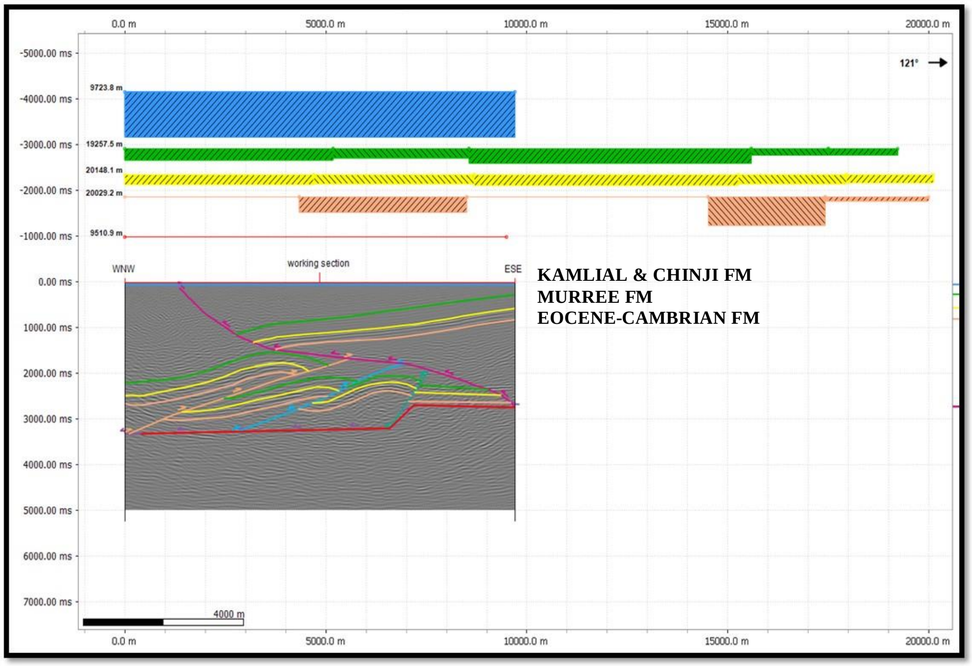


Figure 4.2 Interpreted seismic line (GO-925-GJN-11) shows section analysis

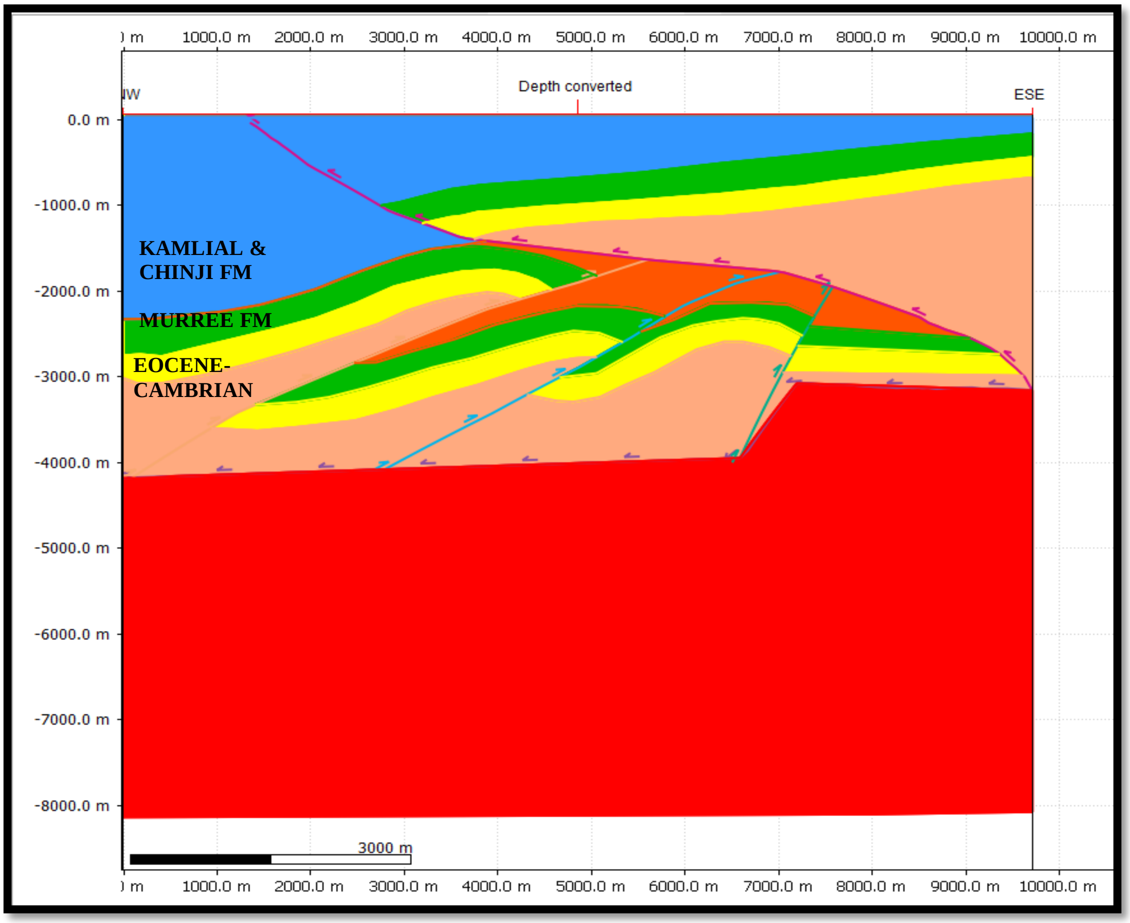


Figure 4.3 Depth converted section of interpreted line showing polygons.

During this crustal restoration, Top Eocene was selected as the base horizon considering the fact that the study area had been affected by the ongoing collision of Indian-Eurasian plate took place during Tertiary Period and older stratigraphy remained undisturbed prior to that activity. While the younger sediments affected most of the damage.

Move provide us with an opportunity to perform section analysis (Figure 4.2) illustrate that least disturbed horizon is basement, considering the fact that the area had undergone thin skin tectonic due to the presence of Infra-Cambrian salt and gypsum. A normal fault is present at basement level older than the deposition and there is no significant contribution of Basement in the deformation.

Salt Range Formation to Miocene Murree Formation package shows maximums restored length during section analysis emphasizing that deformation activity in this area had started during the deposition of either post than the deposition of Murree Formation. Since all the older package suffered a same amount of deformation. Last but not least, blue color shows the presence of Kamlial Formation and younger sequence. The shorter length can be the result of post deposition and deformational history after the onset deformation.

4.4 Final Restored Section

The final restored section display the geometry of an anti-formal stacked duplex zone. Sequential development of this model can be defined in several phases. Initially the movement took place along the basal thrust SRT, whereas the hanging wall as an intact unit started to transport towards south. Normal fault in the basement provided initial ramp and nuclei for the thrust F1 and movement of hanging wall deformation into fault bend fold. Some complication in the ramp geometry hindered the further movement of hanging wall restraining forces at back limb and development of F2 followed by development of second anticlinal structure and so on (Figure 4.4).

After the development of three duplicated anti-formal stacks, emergence of F4 (back thrust) took place which transported the southern hanging wall margin against and onto the prior developed stacked. Since the model shows multiple stacked anti-form geometries which are dipping towards north (hinterland) and bounded on the top and bottom by reverse faults forming into hinterland dipping duplex.

Since the top most thrust in this sequence is a back thrust (F4) which is dipping towards foreland so the name “Passive Roof Duplex” can be assigned to this model.

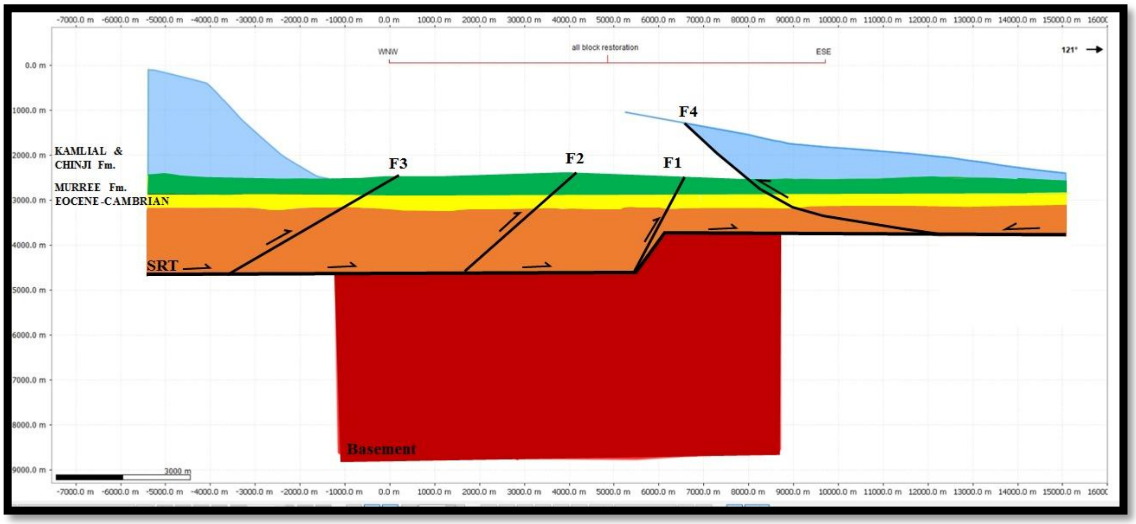


Figure 4.4 Final restored section

CONCLUSIONS

This study was carried out through 2D and 3D seismic data interpretation by measuring four horizon at various stratigraphic levels i.e. Murree Formation, Chorgali Formation, Lockhart Limestone and Salt Range Formation. Disruption of these horizon resulted in the fault interpretation like F1, F2, F3 and F4 etc. TWT and depth contour maps were generated to understand the mapping and lateral extension along with the behavior of major structural elements at different stratigraphic levels which resulted into:

i. The presence of multiple sequence i.e. Cambrian to Eocene and fault imbrications confirms presence of an anti-formal stacked system generally dipping towards hinterland.
ii. The Lower boundary of these stacked sequence is marked by SRT acting as a side thrust and upper boundary is marked by F4 which is a back thrust defining a duplex zone.
iii. The major faults F1, F2, F3 etc are connected to the sole thrust (SRT) and transferring their displacement to the Roof thrust (F4) which is a back thrust making a passive roof duplex.
iv. Structural restoration indicates maximum shortening took place at Eocene level (approximately 10.51 km) which in turn confirms tertiary was the period where main deformation started.
v. Presence of small faults cutting the limbs of folded stacks indicates influence of second episode of deformation as well.

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