Interpretation of 2-D Seismic Reflection Data of Balkasar Area, Potwar Region

SUBMITTED BY

Abdullah Afzal Khan

Usman Shah Nawaz

Iqra Mughal

BS-Geophysics

FACULTY OF EARTH AND ENVIRONMENTAL SCIENCES

BAHRIA UNIVERSITY, ISLAMABAD

TABLE OF CONTENTS

CHAPTER # 5

CHAPTER # 6

LIST OF FIGURES

LIST OF TABLES

TABLE OF ABBREVIATIONS

ABBREVIATION	STANDS FOR
AGC	Automatic Gain Control
CDP	Common Depth Point
DGPC	Directorate General of Petroleum Concessions
EL	Exploration Lease
FFID	Field File Identification Number
K/T	Cretaceous / Tertiary
LMKR	Landmark Resources
NMO	Normal Move Out
OGDCL	Oil and Gas Development Corporation
PPIS	Pakistan Petroleum Information System
SP	Shot Point
TWT	Two Way Time
VSP	Vertical Seismic Profiling
3D	Three Dimensional

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ABSTRACT

This dissertation contains the study of 2D seismic reflection data interpretation of selected seismic lines of Balkasar Area, Central Upper Indus Basin, Pakistan, for delineation of subsurface structures favourable for hydrocarbon accumulation. The seismic data for this dissertation was provided by the Land Mark Resources (LMKR) by the permission of Directorate General of Petroleum Concessions (DGPC). The data comprised ten seismic lines, base map. The lines which were used are:

PBJ-1 (dip line, SE-NW)

PBJ-2 (dip line, SE-NW)

PBJ-3 (dip line, SE-NW)

PBJ-4 (dip line, SE-NW)

PBJ-9 (strike line, NE-SW)

Three prominent reflectors (Yellow, red and Green) were marked on the basis of their reflection, which represent Eocene(Sakesar/Chorgali Formation), Lokhart Limestone, and Khewra Sandstone respectively. Two-way time (TWT) from the seismic sections and average velocities were used to create TWT and Depth Contour maps and 3D Time and Depth Surfaces.

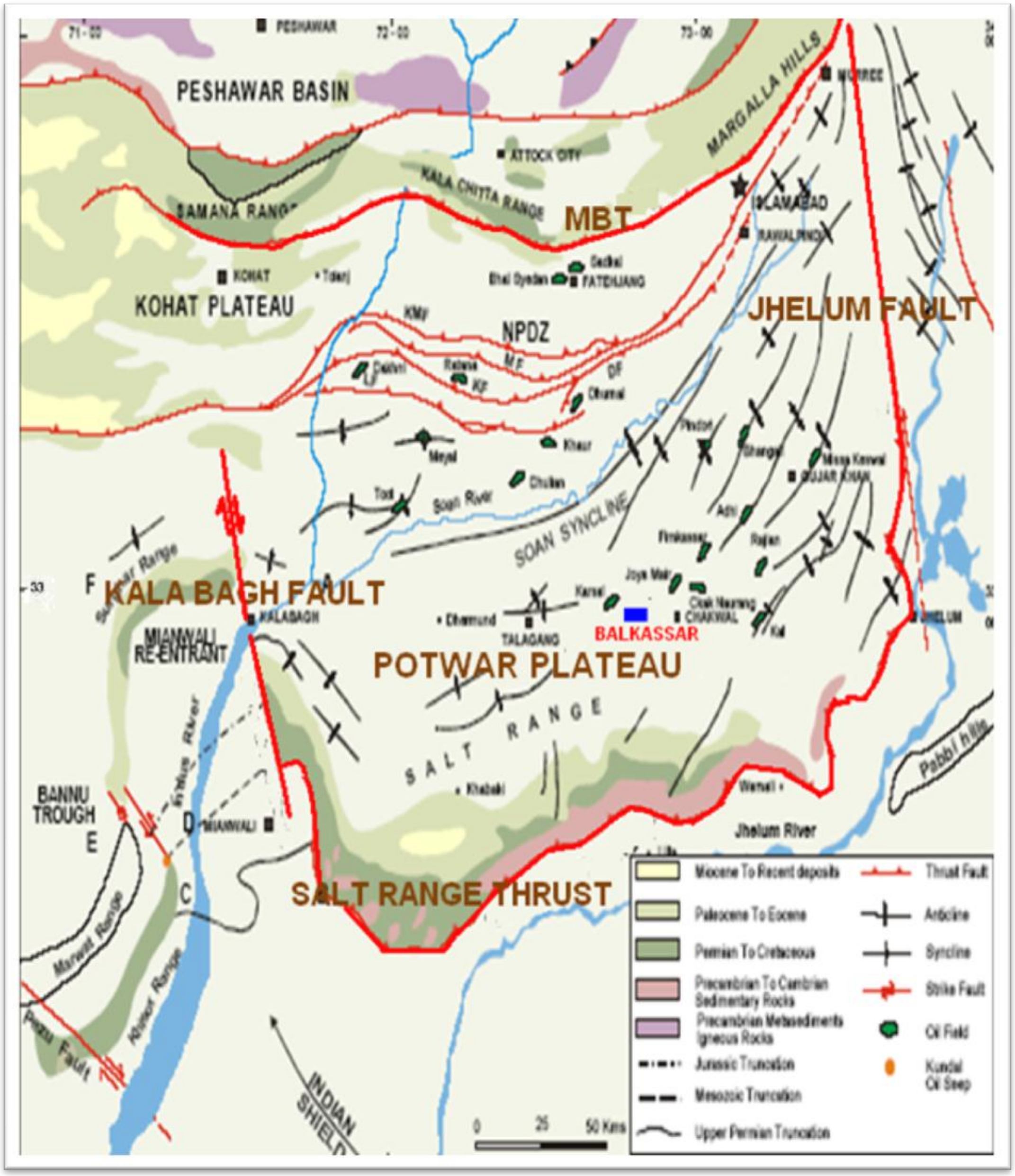
Chapter # 1

INTRODUCTION

The area north of Salt Range is called Potwar Plateau due to its relatively constant elevation and it encompasses most of the drainage area of the Soan River. Potwar is located in the western foothill of Himalayas in northern Pakistan. It includes the Potwar Plateau, the Salt Range, and the Jhelum Plain. It extends about 130 km from the Main Boundary Thrust (MBT) in the north and is bounded in the east by Jhelum strike-slip fault, in the west by Kalabagh strike-slip fault, in the north by the MBT and in the south by the Salt Range Thrust as shown in the figure1. Potwar sub-basin is filled with thick Pre-Cambrian evaporites overlain by relatively thin platform deposits of Cambrian to Eocene followed by thick Miocene–Pliocene molasse. This whole section has been severely deformed by extremely intensive Himalayan orogeny in Pliocene to middle Pleistocene times.

The Potwar sub-basin is one of the oldest oil provinces of the world, where the first commercial discovery was made during early last century in 1914 at Khaur. About 150 exploratory wells have been drilled so far in the area but many of these were pre-maturely abandoned, as these could not reach their target depths due to drilling problems related to extremely high-pressure water in mollasse deposits, which may be related to structural complexities. Sub-surface picture always provides insight into the framework and structural styles of a basin. This architecture is a function of complex interplay of compressional forces, slope of the basement, and presence of variable thickness of Pre-Cambrian salt over the basement and deposition of very thick molasse and tectonic events. Structurally, Potwar sub-basin is very complex and mostly surface features do not reflect subsurface structures due to presence of decollment at different levels. In such cases, it is necessary to integrate seismic data with geological information for precise delineation of sub-surface configuration of various structures.

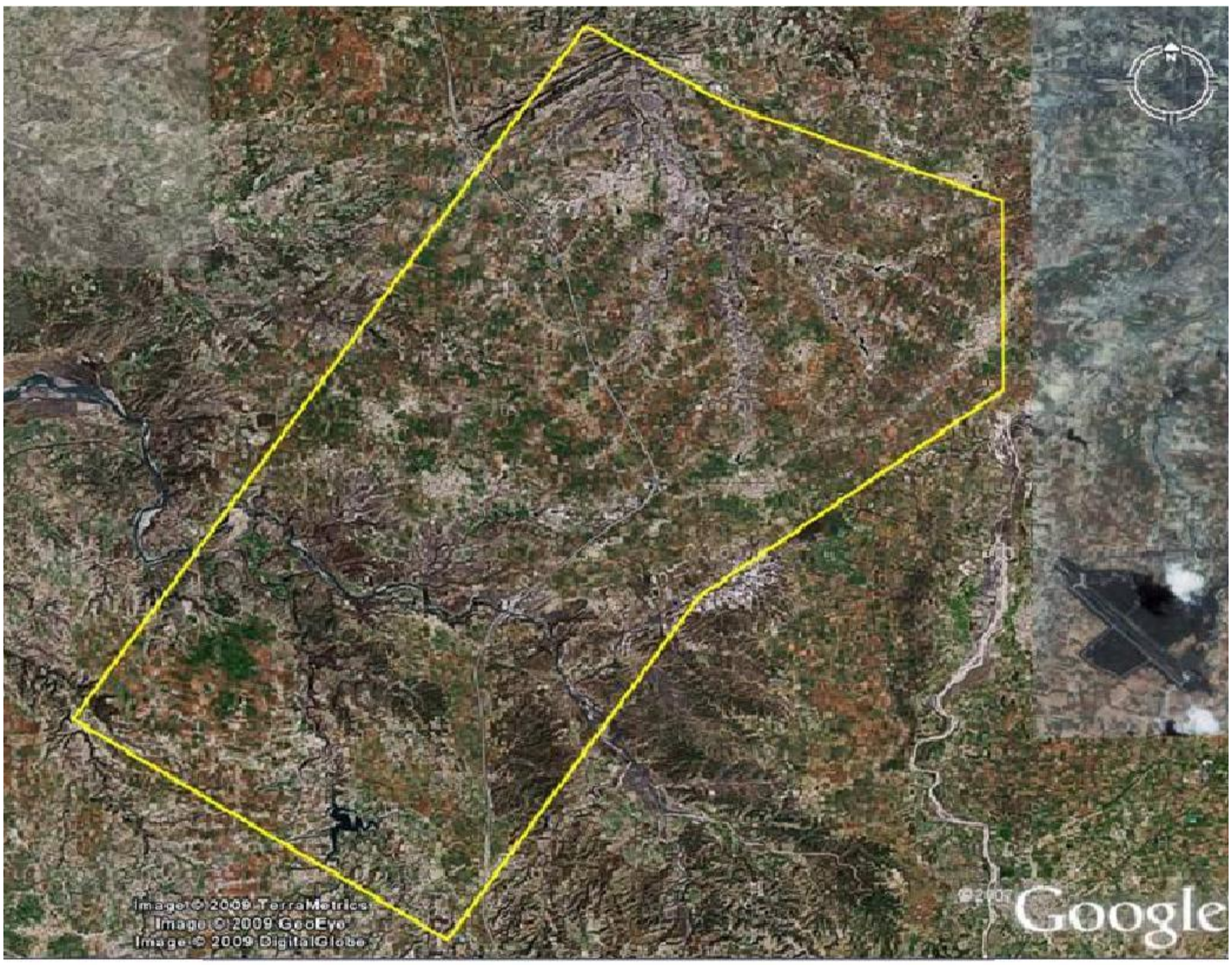
Subsurface geometry proposed for the Potwar sub-basin along seismic transects and their geological transposition exhibit distinct domains from south to north and in the eastern and western parts of the basin, which in turn may be associated with the density and occurrence of effective fracture systems in various reservoirs, particularly Eocene carbonates.



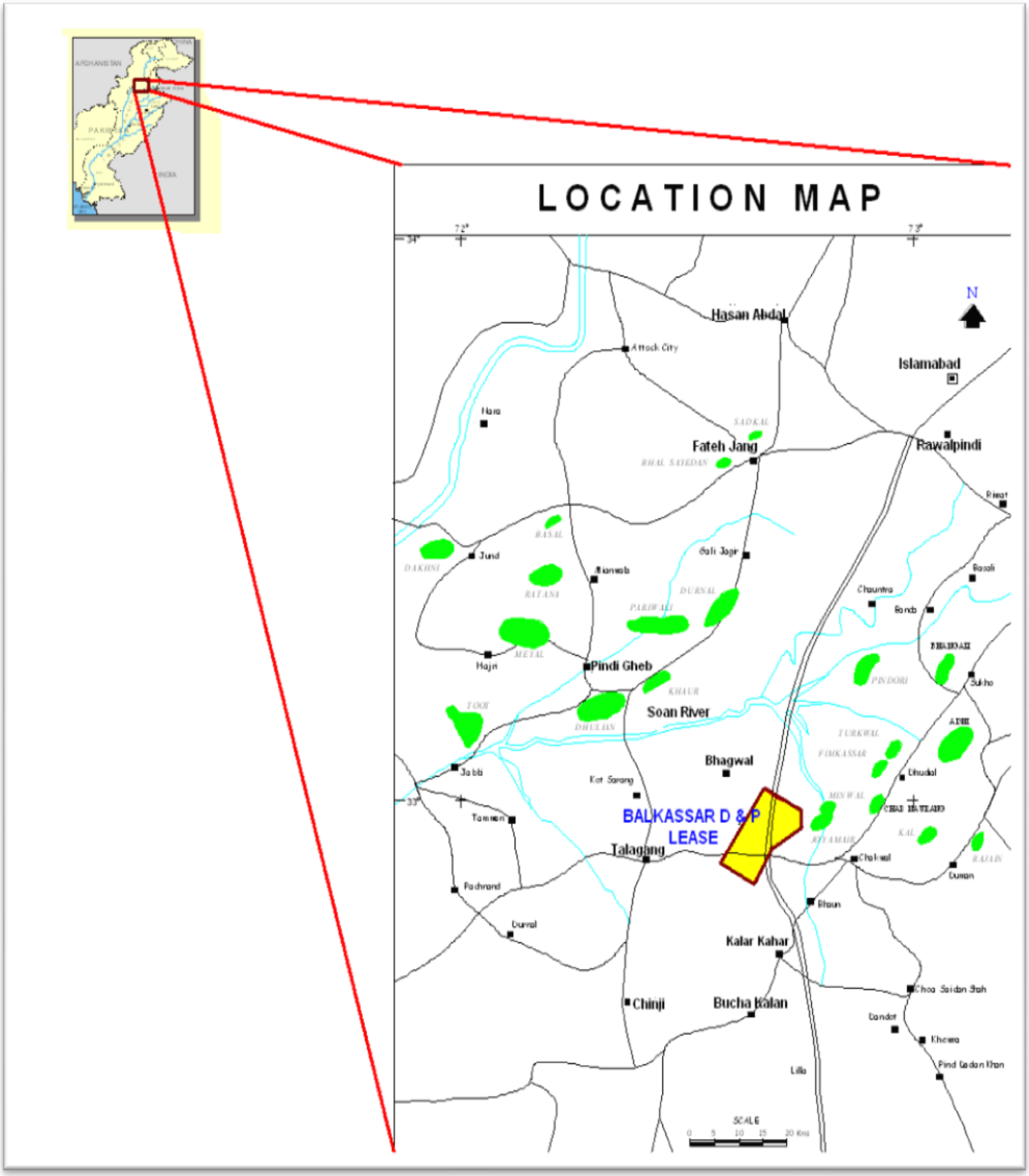
Figure#2: Structural map of the Kohat-Potwar Plateau (from Kazmi and Rana 1982, Khan et al. 1986).

1.1 INTRODUCTION TO THE STUDY AREA

Balkassar, an exclusive D & P Lease (Figure#2) of Pakistan Oilfields Limited, was discovered in 1945 by Attock Oil Company. It is situated about 105km southwest of Islamabad (figure3) in Chakwal District. Balkassar lies in Central part of Potwar sub-basin which is a part of Himalayan foreland fold-and-thrust belt. . This structure is located on the southern limb of Soan Syncline.



Figure#2: D&P lease of Balkassar Oil Field.



Figure#3: Location map of the study area (highlighted), Potwar sub-basin. (Mehmood, 2008).

The seismic reflection data was acquired by OGDCL in 1980. The data was processed by OGDCL in 1981. The Client for this survey was Oxy (Pak). At that time Balkassar Field was producing about 750 BOPD from Eocene Carbonates. Oxy acquired the lease to evaluate the deeper potentials below 1982-meter subsea. The Balkassar Oxy # 1 was the first exploratory well drilled by Oxy (Pak) in Pakistan. Primary objective of Oxy #1 was Khewra Formation (Cambrian) while the secondary objectives were Lockhart Formation (Paleocene) and Tobra Formation (Permian). The surface location of Balkassar Oxy #1(Figure#4) is:

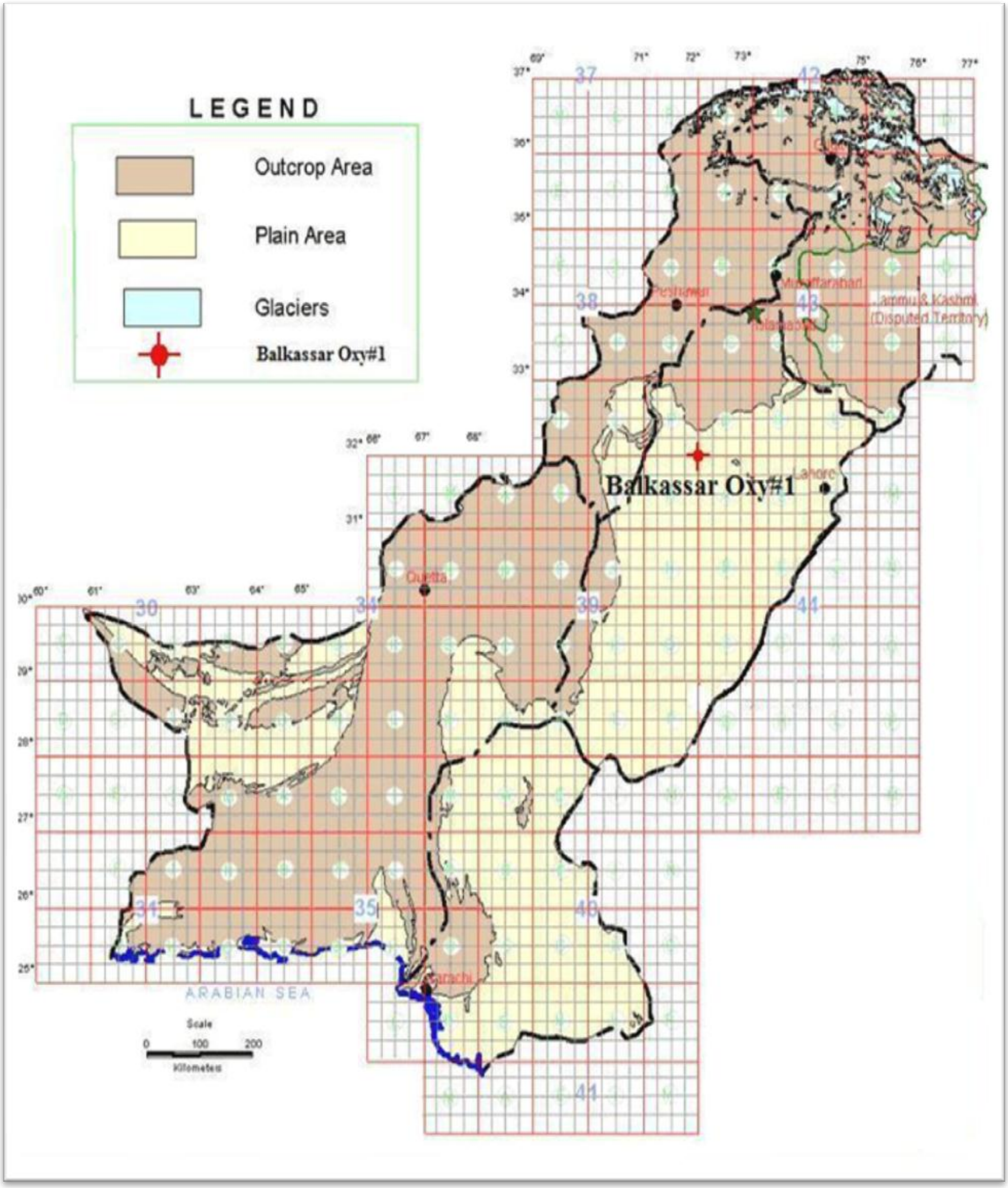
Latitude 32^0 56′ 38.8″ N

Longitude 72^0 39′ 52.5″ E

Status Plugged and Abandoned

1.2 OBJECTIVES OF RESEARCH

The purpose of this dissertation is to understand the various steps involved in seismic reflection interpretation. This study is carried out to generate reasonable model and structure of the subsurface of Balkassar exploration lease area and to understand and enhance our knowledge on different seismic interpretation techniques involved in 2-D seismic interpretation. Data gathering on tectonics, description of structure, stratigraphy, and exploration history is an integral part of this project.



Figure#4: Location of the well under study (adopted from the website of Geological Survey of Pakistan).

Chapter # 2

GEOLOGY & STRATIGRAPHY OF THE AREA

2.1 GENERAL PHYSIOGRAPHY

The area north of Salt Range is called Potwar Plateau due to its relatively constant elevation and it encompasses most of the drainage area of the Soan River 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. The Kala Chitta Range and the Margalla Hills marked its northern boundary and the Salt Ranges its southern boundary. The Soan Basin is located between the northern and southern range (Khan, A. M. & Ahmad R., 1986) Figure#1.

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. These 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 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 (Khan, A. M. & Ahmad R., 1986).

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. 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 (Khan, A. M. & Ahmad R., 1986).

Subsurface geometry proposed for the Potwar sub-basin along seismic transects and their geological transposition exhibit distinct domains from south to north and in the eastern and western parts of the basin, which in turn may be associated with the density and occurrence of effective fracture systems in various reservoirs, particularly Eocene carbonates (Khan, A. M. & Ahmad R., 1986).

2.2 REGIONAL DEPOSITIONAL HISTORY

According to Moghal M.A., et. al., 2003, the Potwar Basin is characterized by thick Infra-Cambrian evaporites deposits overlain by relatively thin stratigraphic section of the Eocene to Cambrian. Thick Miocene-Pliocene mollasse deposits are related to severe deformation in Late Pliocene to Middle Pleistocene (Himalayan orogeny). The generalized stratigraphy of the Potwar is shown in Figure 2.1. All of these formations are exposed in the Salt Range from east to west. The depositional sequence in the Potwar sub-basin may be summarized as follows: -

1) Deposition of Infra-Cambrian evaporites sequence upon the Pre-Cambrian basement took place in an intra-cratonic setting in a basin that extended from Pakistan to Turkey through Iran and Oman.

2) Cambrian rocks termed as the Jhelum Group, which comprises Khewra, Kussak, Jutana and Baghanwala formations, overlie the Infra-Cambrian evaporites sequences.

3) Deposition of the Jhelum Group was followed by a period of limited deposition from Middle Cambrian to Early Permian. Therefore, the strata belonging to these periods are missing in Potwar sub-basin.

4) The early Permian formation termed as the Nilawahan Group is restricted to the eastern part of Potwar / Salt Range and is predominantly of continental origin. This group includes Tobra formation deposited in predominantly glacial environments, olive green sandstones and claystones of Dandot, red sandstone of Warcha and lavender claystone of Sardhai formations.

5) The Zaluch Group restricted to the western and northern/central part of Potwar / Salt Range includes marine limestones and claystones of the Amb, the Wargal and the Chidru formations which were deposited during the Late Permian.

6) The Triassic formations include Mianwali, Tredian and the Kingriali formations. The former two formations were deposited in deep to shallow marine environment, whereas the later is composed of shallow water dolomite.

7) The Jurassic formations are divided into Datta Sandstone, Shinawari (limestone and shale sequence) and the Samana Suk (Limestone) formations.

8) The Cretaceous sequence is represented by the clastics of Chichali and Lumshiwal and the carbonates / clays of Kawagarh formations, later being

restricted to the northern Kohat Basin, while former present in western SR/PP and Kohat Basin.

9) Mesozoic sediments are present only in the western part of the Potwar/Salt Range, as the Base Tertiary unconformity progressively oversteps Jurassic, Triassic and Permian formations to the east. In the eastern-most Salt Range this sequence directly overlies Cambrian.

10) Shallow marine foraminiferal limestones and dark gray shale with large foraminifera were deposited during the Paleocene and Eocene time. A laterite bed marks base of this succession. The Paleocene formations include shales, siltstones and sandstones of Hangu, limestone of the Lockhart and shale and limestone of the Patala formations.

11) Deposition of calcareous claystone of the Nammal formation marking the beginning of Lower Eocene was followed by massive shelfal limestones of the Sakesar formation that is overlain by dolomitic limestones and calcareous claystones of the Chorgali formation.

12) Continental collision in the Middle Eocene resulted in uplift of the Sargodha High, which ended marine deposition in the area and started erosion to the south.

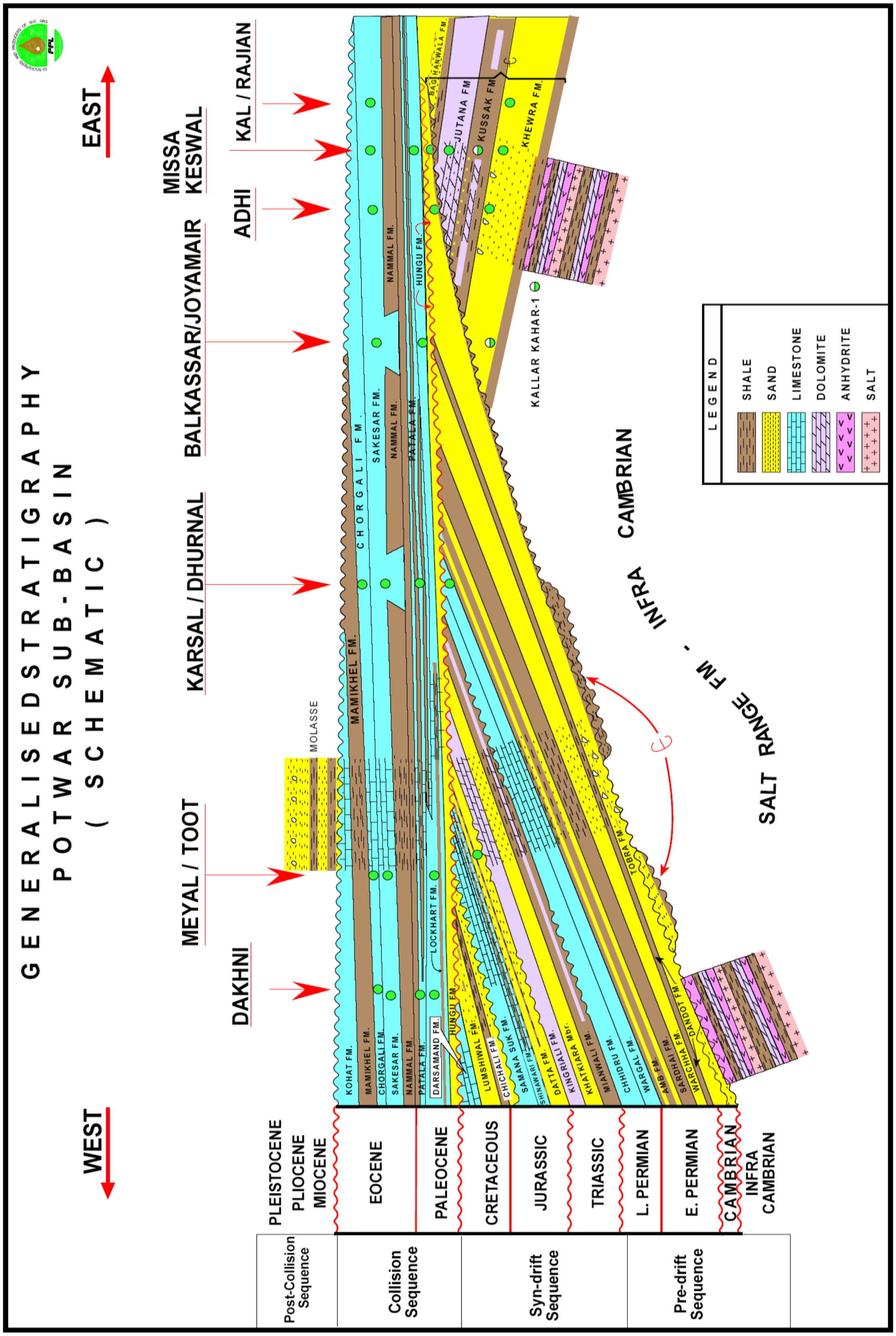
13) Oligocene age sediments are missing in the Potwar Basin, as during this time the Higher Himalayas were building for the subsequent molasse sedimentation.

14) The foreland sedimentation in the Potwar Basin commenced in Early Miocene, which is represented by fluvial and fluvio-deltaic lithology of Rawalpindi and Siwalik Groups including Murree, Kamlial, Chinji, Nagri, Dhok Pathan and Soan formations. The thickness of the Molasse sequence generally increases towards north.

2.3 STRATIGRAPHY

The general stratigraphic succession of the basin is over 6100m of rocks ranging in age from Infra-Cambrian to recent, Figure 2.1. Sedimentation in this area from Paleozoic to Mesozoic was partly controlled by recurring uplift and tilting of the Sargodha high. This movement resulted in depositional breaks and erosion, which has formed erosional wedge edges of the Pre-Paleogene sequence that are seen across the basin. Infra-Cambrian evaporites of known thickness form the oldest sediments in the basin and form the unit, which has lubricated much of the compressional movement of the basin. Periods of uplift and erosion were quite extensive, as indicated by several major unconformities (Table 1).

Early and Middle Cambrian Clastics up to 610m in thickness were deposited in littoral to shallow marine environment. Permian is about 762m thick and is composed of glacial, fluvial and estuarine clastics and shallow marine carbonates. Shallow water sediments persist up into the Late Cretaceous. Towards the end of the Cretaceous a significant uplift occurred stripping Cretaceous through Permian rocks from east to west across the basin, forming the erosional wedges. An early Paleocene marine Transgression overstepped these wedges resulting in thick deposits (+1100m) of Paleocene and Eocene



Figure#5: Subsurface Geometry of Potwar Sub-Basin (Moghal, M.A et. al., 2003. PAPG-SPE

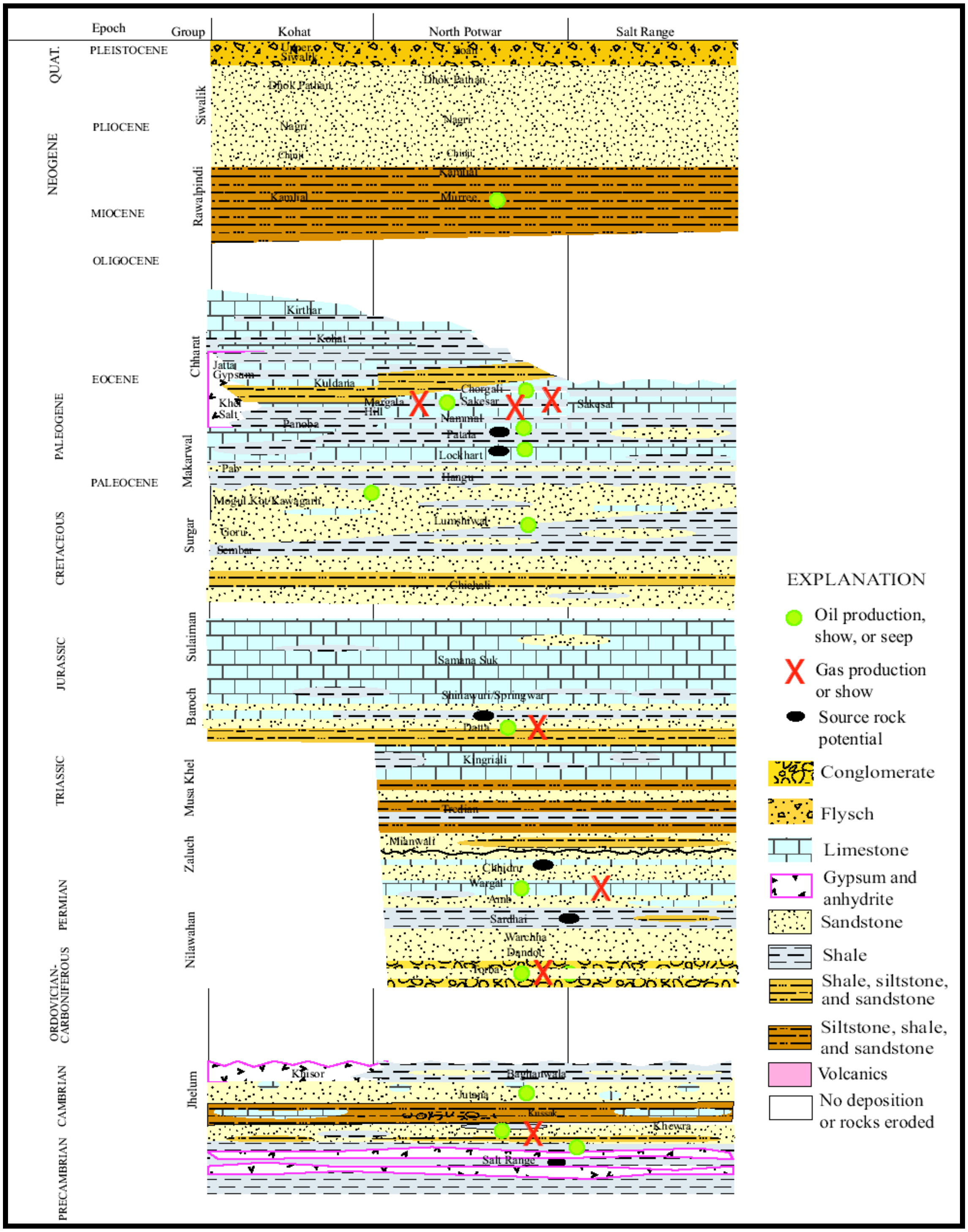


Table 1: Generalized stratigraphy of the Kohat-Potwar area (Wandrey C.J., et. al., 2004).

shallow marine carbonates over the entire area. These wide spread carbonates form the principal reservoir for the oil accumulations in the basin.

With the Himalayan orogenic movement in Late Eocene, uplift and deformation of these pre-existing rocks began. Thick molasse sediments were rapidly deposited in the orogenic foredeep covering the Potwar Basin. The molasse section itself is over pressured throughout the basin, both burying significant part of the Pre-Eocene sediments within the oil window and serving as a regional over pressured unit (Well Report of Balkassar (OXY)-01).

2.4. LITHO LOGICAL DESCRIPTION OF FORMATIONS

The stratigraphic section encountered in Balkassar (Oxy)-01 (Table 2) will be used to construct different reflectors depths interpreted in Geoseismic section.

Following are the lithological description of the section drilled at Balkassar (Oxy)-01, which was drilled down to a depth of 3131m (from KB) into Salt Range formation of Infra Cambrian age. The formation tops were initially picked at the well site, which were further refined / confirmed by the electric logs. A list of final formation tops and thickness drilled in Balkassar (Oxy)-01, are presented in the table 2. A brief, generalized description of the formations drilled in Balkassar (Oxy)-01 is given below.

2.5 PRECAMBRIAN

The oldest rocks of Pakistan are of Precambrian age, which form the basement for the lower Paleozoic sediments and in certain cases serves as the source of terrigenous elastics for the younger rocks in adjoining areas.

2.5.1 Salt Range Formation

The oldest formation of the cover sequence known to lie at top of basement is the Eocambrian Salt Rang formation. The formation is exposed along the outer periphery of the Salt Range from Kalabagh in the west to the eastern Salt Range. Both Precambrian and Cambrian ages have been assigned to the Salt Range formation on the basis of superposition as there is no definite paleontological evidence available (Shah, S.M.I., et. al., 1977). However, its age is referred to as Eocambrian by recent authors.

The formation exhibits varied lithology, dominantly composed of reddish brown to maroon gypseous marl. Interbedded with thin layers of gypsum, dolomite, clay, salt marl and thick seems of rock salt. Thin intercalation of Kerogen shales, or oil shales, have been found in the Salt Range formation. A trashy basalt trap, called the Khewra Trap or Khewrite is present in some localities, consisting of decomposed radiating needles of a light color mineral, probably pyroxene (Shah, S.M.I., et. al., 1977). One of the most important features of Salt Range formation is its behavior as a zone of decollement between underlying rigid basement and overlying platform sequence. The entire sedimentary sequence has been carried southward by a shallow dipping thrust along this decollement.

2.6. SEDIMENTARY PALEOZOIC ROCKS

Paleozoic sedimentary rocks occur at several localities in Pakistan, but a complete Paleozoic sequence is lacking. The sequence has been reported from Salt Range, Potwar Basin and from many other localities in Pakistan.

STRATIGRAPHIC SECTION DRILLED IN BALKASSAR OXY#1

K.B.E = 535 M. G.L.E = 530 M.

Age			***Group***	***Formation***	***Depth (m)***		***Thickness (m)***
Era	***Period***	***Epoch***			***KB***	***Sub sea***	
Cenozoic	Tertiary	Pliocene	Siwaliks	Nagri	Surface	530	479
		Miocene		Chinji	479	56	929
			Rawalpindi	Kamlial	1408	-873	107

				Murree	1515	-980	907
		Oligocene	**Unconformity**				
		Eocene	Chharat	Chorgali	2422	-1887	45
				Sakesar	2467	-1932	136
		Paleocene		Patala	2603	-2068	21
				Lochart	2624	-2089	35
				Hangu	2659	-2124	28
Mesozoic	Cretaceous		**Unconformity**				
	Jurassic						
	Triassic						
Paleozoic	Permian	Late	Nilawahan	Sardhai	2687	-2152	110
				Warcha	2797	-2262	141

		Early		Dandot	2938	-2403	61
				Tobra	2999	-2464	52
	Carboniferous		**Unconformity**				
	Devonian						
	Silurian						
	Ordovician						
	Cambrian	Late	Jhelum	Khewra	3051	-2516	78
		Early					
Precambrian	Eocambrian			Salt Range	3129	-2594	2
Total Depth					**3131**	**-2596**	

Table 2: Schematic Stratigraphic Column of Balkassar Oxy #1 (Well Report).

2.6.1 Cambrian

Cambrian sediments are well exposed in the Salt Range. In the Eastern Salt Range, the Cambrian sequences consist of two formations of the Jhelum Group: Khewra formation and Kussak formation (Iqbal, M.W.A., and Shah, S.M.I., 1980).

2.6.1.1. Khewra Formation

The Khewra formation overlies the Late Proterozoic Salt Range formation without any apparent disconformity. Type locality is the Khewra Gorge in the Eastern Salt Range. The Khewra formation is widely exposed in the Salt Range. The Khewra formation consists mainly of reddish brown to purple, thick-bedded to massive sandstone with few brown shale intercalations. The sandstone is characteristically cross-bedded, has abundant ripple marks and mud cracks, and, in places, exhibits convolute bedding. Thickness of the Khewra formation is 150m at the type locality in the Eastern Salt Range. Apart from rare trace fossils, the formation is devoid of fossils. Because of its position between the late Proterozoic Salt Range formation and the fossiliferous early Cambrian Kussak formation, the Khewra formation is thought to represent the basal part of the Lower Cambrian (Iqbal, M.W.A., and Shah, S.M.I., 1980).

2.6.2 Permian

The Salt Range in northern Punjab is one of the classical areas of the world where a complete Permian sequence is developed and perfectly exposed. The Permian is sub-divided into two groups: Nilawahan Group and Zaluch Group. The Eastern Salt Range has the Nilawahan Group, fully developed and exposed. The Nilawahan Group consists of four formations: Tobra formation, Dandot formation, Warcha formation and Sardhai formation (Iqbal, M.W.A., and Shah, S.M.I., 1980).

2.6.2.1. Tobra Formation

The Tobra formation rests unconformably upon different Cambrian formations and the Salt Range formation respectively (Shah, S.M.I., et. al., 1977). Type locality is the village of Tobra, north of Khewra, in the Eastern Salt Range. The formation is exposed throughout the Salt Range. It was also encountered by the wells in the Kohat-Potwar area. In the Eastern Salt Range, the Tobra formation consists mainly of polymict conglomerates with pebbles and boulders of igneous, metamorphic and sedimentary rocks. The thickness of the formation is 20m at the type locality. Its age is early Permian.

The Tobra formation was mostly deposited in glacio-marine/ lacustrine environment, which occasionally became shallow marine at places. The heterogeneous mixture stratified and faceted surface of boulders and silty matrix suggest transportation by glacio-fluvial agents. It appears that igneous fragments were derived from Kirana hills and Rajasthan (India), while slate fragments were derived from the metamorphic zone of northern Pakistan (Teichert, C., 1967).

2.6.2.2. Dandot Formation

The Tobra formation is overlain conformably by the Dandot formation. Type locality is the village of Dandot, northeast of Khewra, in the Eastern Salt Range. The formation is well represented in the Eastern and Central Salt Range. The formation mainly consists of dark greenish-grey, splintery shale and siltstone with intercalated sandstone, whereas in the Salt Range greenish grey to black, carbonaceous shales with sand flashers alternate with cross-bedded sandstones. The formation consists of rich fauna as well as spores. On the basis of its faunal content and its gradational contact with the underlying Tobra formation, the Dandot formation has been dated as Early Permian (Iqbal, M.W.A., and Shah, S.M.I., 1980).

2.6.2.3. Warcha Formation

The Warcha formation rests conformably upon the Dandot formation. Type locality is the Warcha Nala in west-Central Salt Range. The Warcha formation is widely exposed in the Salt Range. The formation is generally thick-bedded to massive, reddish-brown, cross-bedded, medium to coarse-grained and arkosic. Intercalated purple to dark grey shale layers reach a thickness of several meters each. The Warcha formation is unfossiliferous. It is considered Early Permian because of its position between the fossiliferous Early Permian Dandot and Sardhai formations. The thickness of the Warcha formation reaches 150m to 165m in the Salt Range (Shah, S.M.I., et. al., 1977).

2.6.2.4. Sardhai Formation

The Warcha formation has a transitional contact with the overlying Sardhai formation (Shah, S.M.I., et. al., 1977). Type locality is the Sardhai Nala in the Eastern Salt Range. The formation has an aerial distribution similar to the Warcha formation. The prevailing lithology in the Eastern and Central Salt Range is bluish-grey, purple or reddish claystone. Plant remains and fish scales have occasionally been found. The fossils indicate the early Permian age. The paleo-environment is interpreted as mainly terrestrial, partly lagoonal, with marine incursions, which become more frequent towards the west. The thickness of the Sardhai formation is 40m at the type section.

2.7 CENOZOIC SEDIMENTARY ROCKS

The rocks of Cenozoic (Tertiary period) range from Paleocene to Pliocene. The Oligocene is missing over the entire Potwar basin.

2.7.1 Paleogene

The sedimentary rocks of Paleocene, Eocene and Oligocene epoch are collectively termed as Paleogene sedimentary rocks (Shah, S.M.I., et. al., 1977).

2.7.1.1. Paleocene

The lower part of the Paleogene sequence, comprising the Paleocene Makarwal Group, has been deposited over the eroded surfaces of rocks ranging in age from Cretaceous to Cambrian (Gee, E. R., 1961). It extends rather uniformly over this region and includes a basal sandstone unit of terrestrial origin (Hangu formation), a middle marine limestone unit (Lockhart Limestone), and an upper shale unit with sub-ordinate sandstone and limestone (Patala formation), which was deposited in an offshore region and in a back-barrier basin (Fatmi, A. N., 1973).

2.7.1.1. A Hangu Formation

The Hangu formation unconformably overlies various formations of Paleozoic to Mesozoic age. The type locality is south of Fort Lockhart in the Samana Range. It consists largely of grey to brown, fine to coarse-grained, silty and ferruginous sandstone which grades upward into fossiliferous shale and calcareous sandstone. At places, the formation is intercalated with grey argillaceous limestone and carbonaceous shale. In the Makarwal and Hangu areas, it contains coal beds in the lower part (Fatmi, A. N., 1973). Its thickness ranges from about 15m in Hazara to 150m at Kohat Pass. The Hangu formation is early Paleocene in age.

2.7.1.1. B Lockhart Formation

The Lockhart Limestone conformably overlies the Hangu formation. Its type section is exposed near Fort Lockhart. It consists of grey, medium to thick-bedded and massive limestone, which is rubbly and brecciate at places. Its thickness ranges from about 30m to 240m. It contains foraminifera, molluscs, echinoids and algae (Fatmi, A. N., 1973).

2.7.1.1. C Patala Formation

The Patala formation overlies the Lockhart formation conformably and its type section is in the Patala Nala in the Western Salt Range. It consists largely of shale with sub-ordinate marl, limestone and sandstone. Marcasite nodules are found in the shale.

The sandstone is in the upper part. The formation also contains coal, and its thickness ranges from 27m to over 200m (Shah, S.M.I., et. al., 1977).

2.7.1.2. Eocene

The Patala formation is overlain conformably by different sequences of Eocene age in different parts of its distribution area. In the Trans-Indus Range and the Salt Range the Eocene succession consists of the Nammal formation, the Sakesar formation and the Chorgali formation (Fatmi, A. N., 1973).

2.7.1.2. A Sakesar Formation

With increase in limestone beds, the Nammal formation transitionally passes into the overlying Sakesar formation, the type locality of which is the Sakesar Peak (Gee, E. R., 1961). It consists of grey, nodular to massive limestone, which is cherty in the upper part. Near Daudkhel, the Sakesar formation laterally grades into massive gypsum. Its thickness ranges from 70m to about 450m (Eames, F. E., 1952). Its age is early Eocene.

2.7.1.2. B Chorgali Formation

The Chorgali formation rests conformably over the Sakesar formation (type locality Chorgali Pass) (Fatmi, A. N., 1973). It consists largely, in the lower part, of thin-bedded grey, partly dolomitized and argillaceous limestone with bituminous odour, and in the upper part, of greenish, soft calcareous shale with interbeds of limestone. Its thickness ranges from 30m to 140m (Gee, E. R., 1961). It contains molluscs, ostracods and foraminifera (Fatmi, A. N., 1973). The age of the Chorgali formation is Early Eocene. It is overlain unconformably by the Neogene sequence.

2.7.2 Neogene

Sedimentary rocks of Miocene and Pliocene epoch are collectively termed as Neogene sedimentary rocks. The Neogene Sequence in the Potwar region consists entirely of fluvial sediments of the Siwalik Group and the Rawalpindi Group (Shah, S.M.I., et. al., 1977). The Rawalpindi Group rests disconformably on various Eocene formations. It includes the Murree and Kamlial formations.

2.7.2.1. Miocene

The Miocene sequence comprises the Murree and Kamlial formations of the Rawalpindi Group and the Chinji formation of the Siwalik Group.

2.7.2.1. A Murree Formation

The type section of Murree formation is in north of Dhol Maiki. Murree formation is composed of thick monotonous sequence of red and purple clay and inter-bedded greenish sandstone with sub-ordinate intra-formational conglomerate. The thickness of the formation increases from 180m to 600m in the Salt Range to 3,030m in the northern Potwar area (Gee, E. R., 1961). It is poorly fossiliferous though plant remains and some vertebrate bones have been found. This fauna indicates early Miocene age of the Murree formation.

2.7.2.1. B Kamlial Formation

The type section of Kamlial formation is in the southwest of Kamlial, the formation overlies the Murree formation conformably and transitionally, though at some localities it lies unconformably on the Eocene Sakesar formation. The formation consists mainly of grey to brick red, medium to coarse-grained sandstone interbedded with purple shale and intraformational conglomerate. A number of mammalian fossils have been found (Gee, E. R., 1961). The age of the Kamlial formation is middle to late Miocene.

2.7.2.1. C Chinji Formation

The type section of Chinji formation is in south of Chinji Village. The formation is confined to the eastern Sulaiman Range and Kohat-Potwar Region (Shah, S.M.I., et. al., 1977). The formation has yielded a rich vertebrate fauna of crocodiles, turtles, monitor lizards, aquatic birds, etc (Fatmi, A. N., 1973). The age of the Chinji formation is late Miocene.

2.7.2.2. Pliocene

The Nagri formation of the Siwalik Group is the only formation of Pliocene age that was encountered in Balkassar (Oxy)-01.

2.7.2.2. A Nagri Formation

The type locality of Nagri formation is Nagri village. It is largely composed of thick bedded to massive greenish-grey medium to coarse-grained, salt and pepper textured, calcareous sandstone, inter-bedded with sub-ordinate brown to reddish sandy clay and conglomerate (Shah, S.M.I., et. al., 1977). The thickness of the formation ranges from 200m to 3000m. The formation has yielded a rich vertebrate fauna (Fatmi, A. N., 1973). The age of the Nagri formation is early Pliocene.

2.8 POTENTIAL DECOLLEMENT LEVEL AND FAULTING

According to Moghal M.A., et. al., (2003), the Salt Range and the Potwar Plateau of Pakistan are parts of the Himalayan foreland fold-and-thrust belt and the deformation / structuration in these has occurred as a result of the ongoing collision between the Indian and Eurasian Plates. In the Potwar Sub-basin at least two main decollement levels have been recognized, i.e. one at the interfaces of Eocene molasse sequence and the other at the interface of platform-evaporite sequence (Salt Range formation). Presence of different decollement levels has resulted in offset of the subsurface structures from their surface manifestations. For example, Dhurnal structure is a surface monocline and similarly, Missa Keswal and Fimkassar discoveries were made on the previously drilled surface structures by correctly delineating the position of the crest at depth by re-interpretation of the seismic data. The main decollement level at the interface of platform deposits and evaporites sequence relates to Pre-Cambrian salt particularly in the Salt Range and Southern Potwar. In the eastern part, most of the deformation appears to have been shifted toward shallower intra-molasse decollement horizons due to progressive thinning of the salt layers. There may be some other local decollement levels within under-compacted Neogene molasse sediments near the top of Kamlial formation.

Chapter # 3

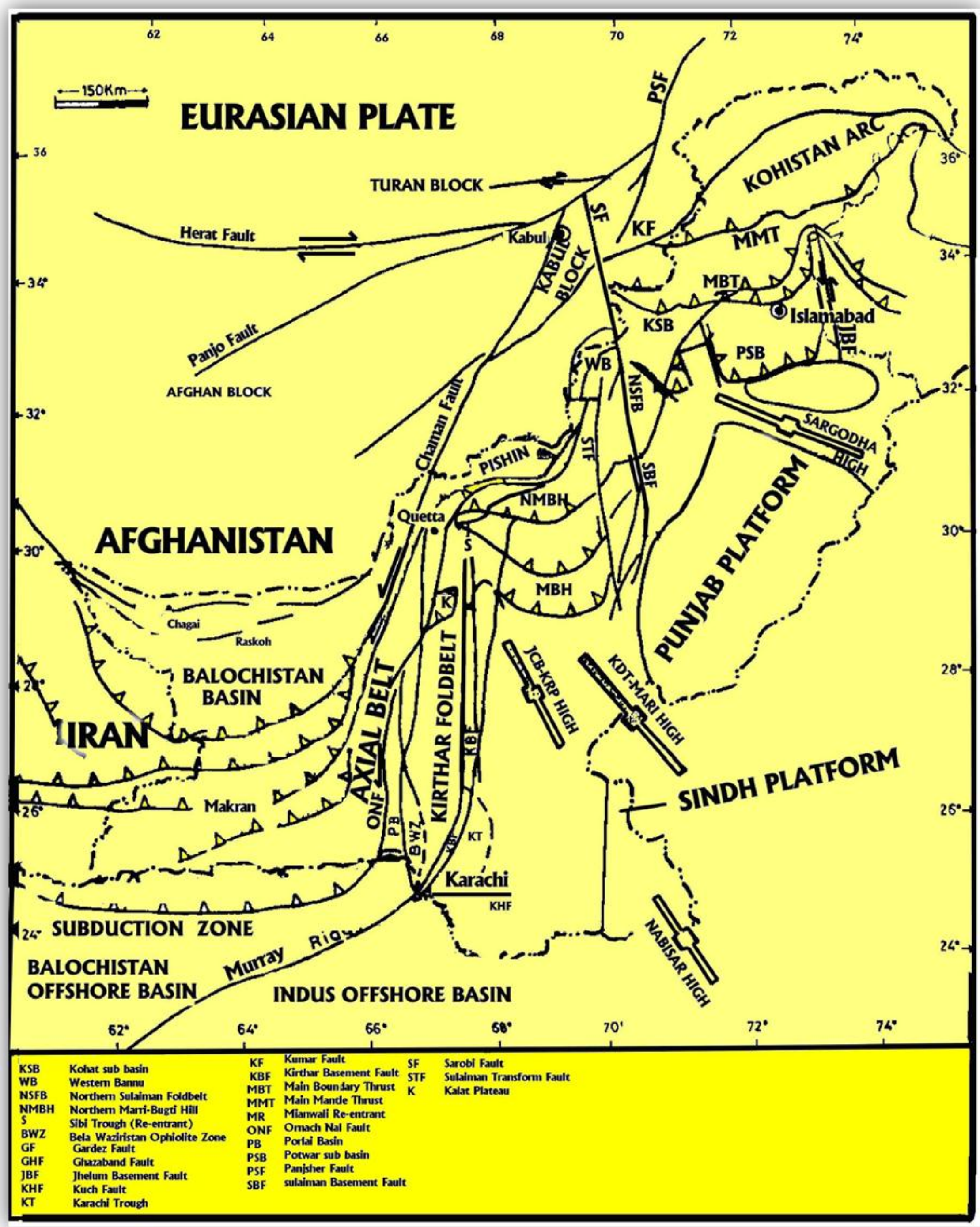
STRUCTURE AND TECTONICS

Potwar Plateau lies in the Western Sub-Himalayan tectonic zones. This east west trending fold belt comprises the low rolling hills and valleys of the uplifted Kohat-Potwar Plateau, the Salt Range and its westward extensions; it is about 85 km wide and extends for about 200 km. It is a diverted structural zone bounded in the north by the north dipping Main Boundary Thrust (MBT).

A part from the Potwar Plateau, in this region salt is only present in Kohat basin at much higher level i.e. Eocene. It forms as an allocation within the sedimentary basin gliding far in southward direction and has suffered relatively less northward movement. It is heterogeneous in style of tectonic intensity, direction and extension. An evidence for this ongoing deformation and uplifting is shown by the meandering course of the Soan River which straightens near the younger structure of Khur and Dhulian. The present tectonic framework and the position of the Potwar Plateau have resulted from the northward under-thrusting by the Indian plate under its own sedimentary cover. Tectonic of the Potwar Plateau is controlled mainly by the following factors:

1. Slope of the basement (steeper in western Potwar Plateau).
2. Thickness of the Eocambrian evaporates beneath the cover.
3. Reactivation of basement brittle tectonics (more enhanced in the eastern Potwar Plateau).

(1 & 3) are the direct result of under thrusting. The generalized tectonic map of Pakistan can be seen in Figure#6.

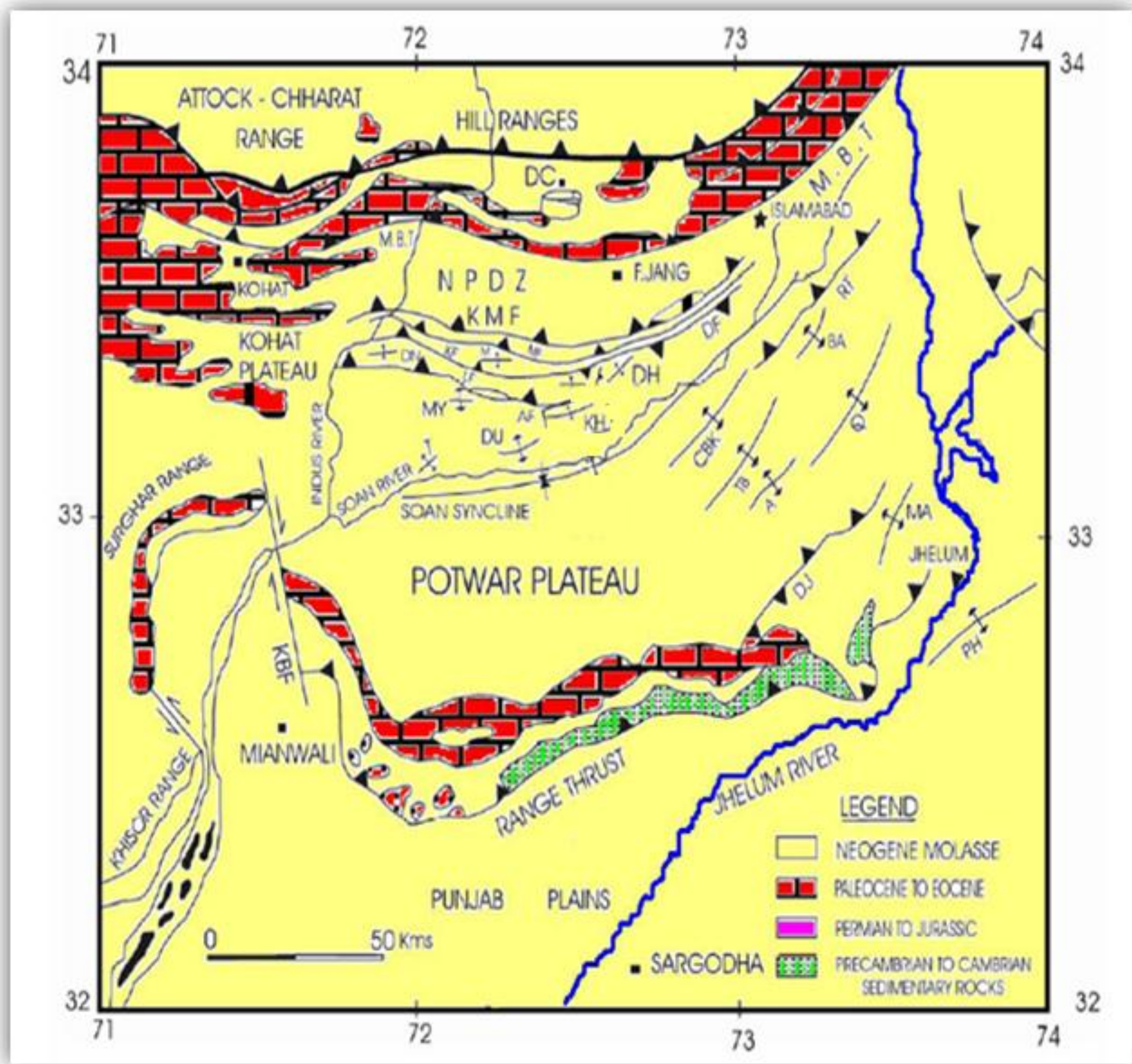


Figure#6: Generalized tectonic map of Pakistan (after: Mujtaba, 2006)

Based on the seismic interpretation, the structure in the Potwar area may be divided into the following:

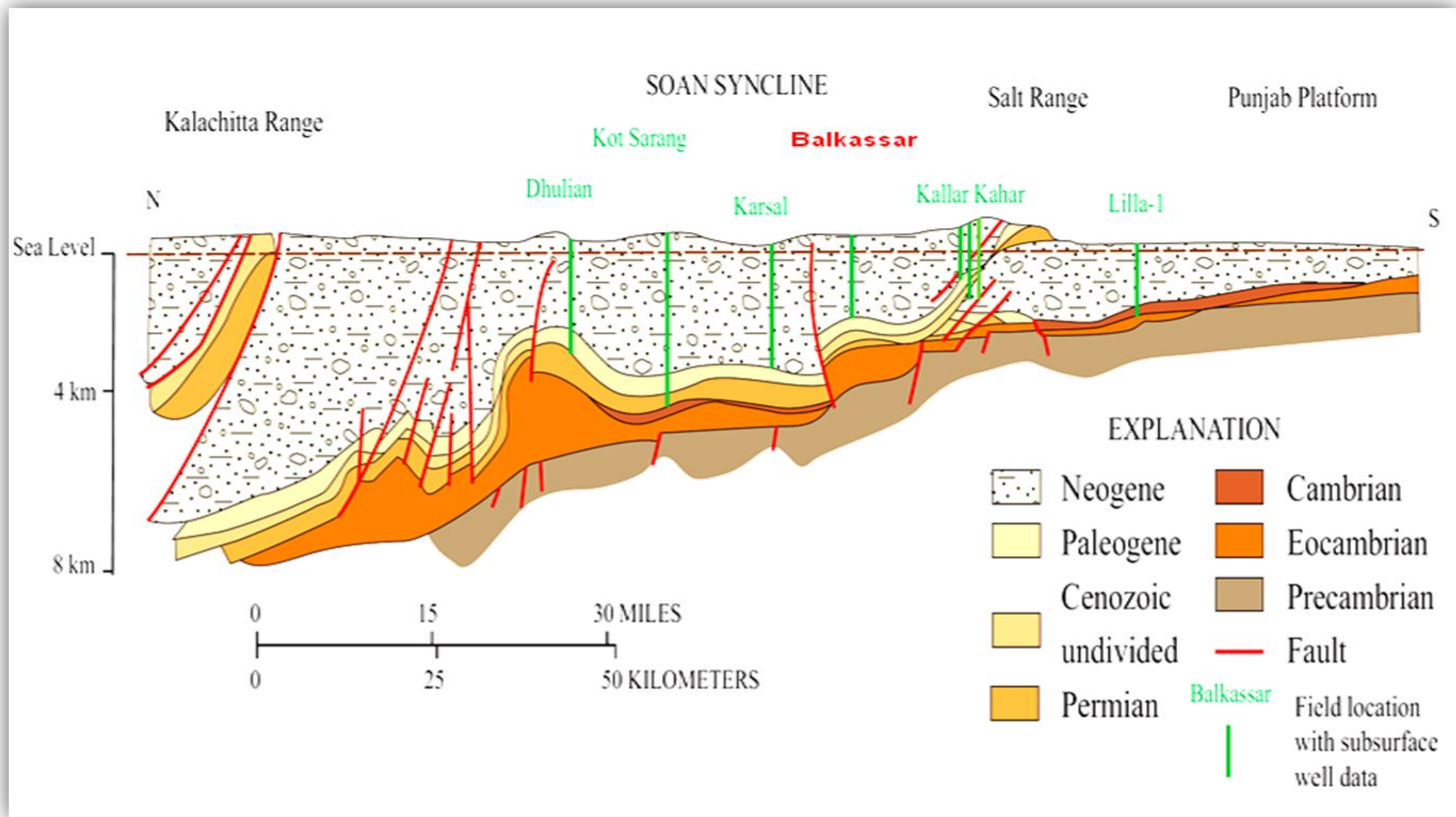
1. Pop-up anticlines
2. Snake head anticlines
3. Salt cored anticlines
4. Triangle zone

Potwar Plateau is bounded on two sided by thrusts and two sides by strike slip faults. All these boundaries are tectonically controlled. The northern boundary of Potwar Plateau, marked by Main Boundary Thrust (MBT) is characterized by thrusting of older sedimentary strata (up to Jurassic) over the Siwalik molasses. The hill ranges of Margalla and Kalachitta have been developed as a result of thrusting on the MBT. Salt Range Thrust (SRT) is folded thrust, caused by the allochthonous movement of the covered sediments on a salt lubricated decollement. It is documented to be active since 5.1 Ma. The north south trending Jhelum Fault may extend 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. Western boundary of Potwar Plateau is not very sharp. In its northern part the thrusts of Northern Potwar Deformed Zone (NPDZ) are continuing west wards into the Shakardara area in Kohat Plateau. While in the southern part of the Kalabagh Fault (KBF) marks the western boundary of Potwar Plateau. Kalabagh Fault has been documented to be a right lateral wrench fault extending from Shakardara Thrust Complex in Kohat Plateau in the north to as far a 25 kilometer south of Kalabagh Town. The generalized map of Potwar Plateau showing the geological and tectonic features (Figure#7). Figure 2.3 shows the generalized cross section showing structure through the Potwar Plateau.



Figure#7: Generalized map of the Potwar Plateau showing the geologic and tectonic features A=Adhi oil field, AF=Ahmadal Fault, BA=Buttar anticline, CBK=Chak Beli Khan anticline, DC=Dheri

Choan, DF=Dhurnal Fault, DJ=Dil Jabba Fault, DN=Dakhni anticline, DU=Dhulian anticline, KBF=Kalabagh Fault, KF=Kanet Fault, KH=Khaur anticline, KMF=Kheri Murat Fault, KRF=Kharpa Fault, LF=Langrial Fault, M=Mianwala structure, MA=Mahesian anticline, MBT=Main Boundary Thrust, MF=Mianwala Fault, MY=Meyal anticline, PH=Pabbi Hills anticline, PR=Pariwali structure, Q=Qazian anticline, RF=Riwat Fault, T=Toot oil field, TB=Tanwin-Bain anticline (modified after Jaswal, 1997)



Figure#8: Generalized cross section showing structure through the Potwar Plateau (modified from Malik et al., 1988).

The Potwar Plateau can be divided into the following zones:

1. Northern Potwar Deformed Zone (NPDZ)
2. Soan Syncline
3. Eastern Potwar Plateau
4. Central Potwar Plateau
5. Western Potwar Plateau

The Northern Potwar Deformed Zone (NPDZ) represents the severest and oldest phase of deformation within the Potwar Plateau as it is marked by imbricate stack of thrust faults, tight isoclinal to overturned folds, vertical dips and thrust bounded ridges. Pariwali, khaur, Dhulian, Balkassar, Karsal structures are the prominent tectonic features of this area. Dhulian and Khaur anticlines are oil / 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. It is in fact an allochthonous blocky of highly disturb cover which was deformed north of Potwar Plateau in an area of thin or no underlying salt and less basement slope and later thrusted over to Potwar Plateau. It is highly deformed instead of thick underlying salt and higher basement slope, due to the following reasons:

1. Unusual thickness of molasses sequence.

2. Conglomerates, in the Dhok Pathan Formation showing nearness of source. These conglomerates are present only in this zone of Potwar Plateau.

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. There is an aging of exposed formation in NPDZ from south to north which is quite compatible with the normal down cutting of an isoclinals fold stack by erosion surface.

Soan Syncline is 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 syncline indicates the following factors:

1. The deformation is still going and the river has no time to adjust its coarse accordingly.

2. During this phase, uplift in the northern side of Potwar Plateau was more then in southern side.

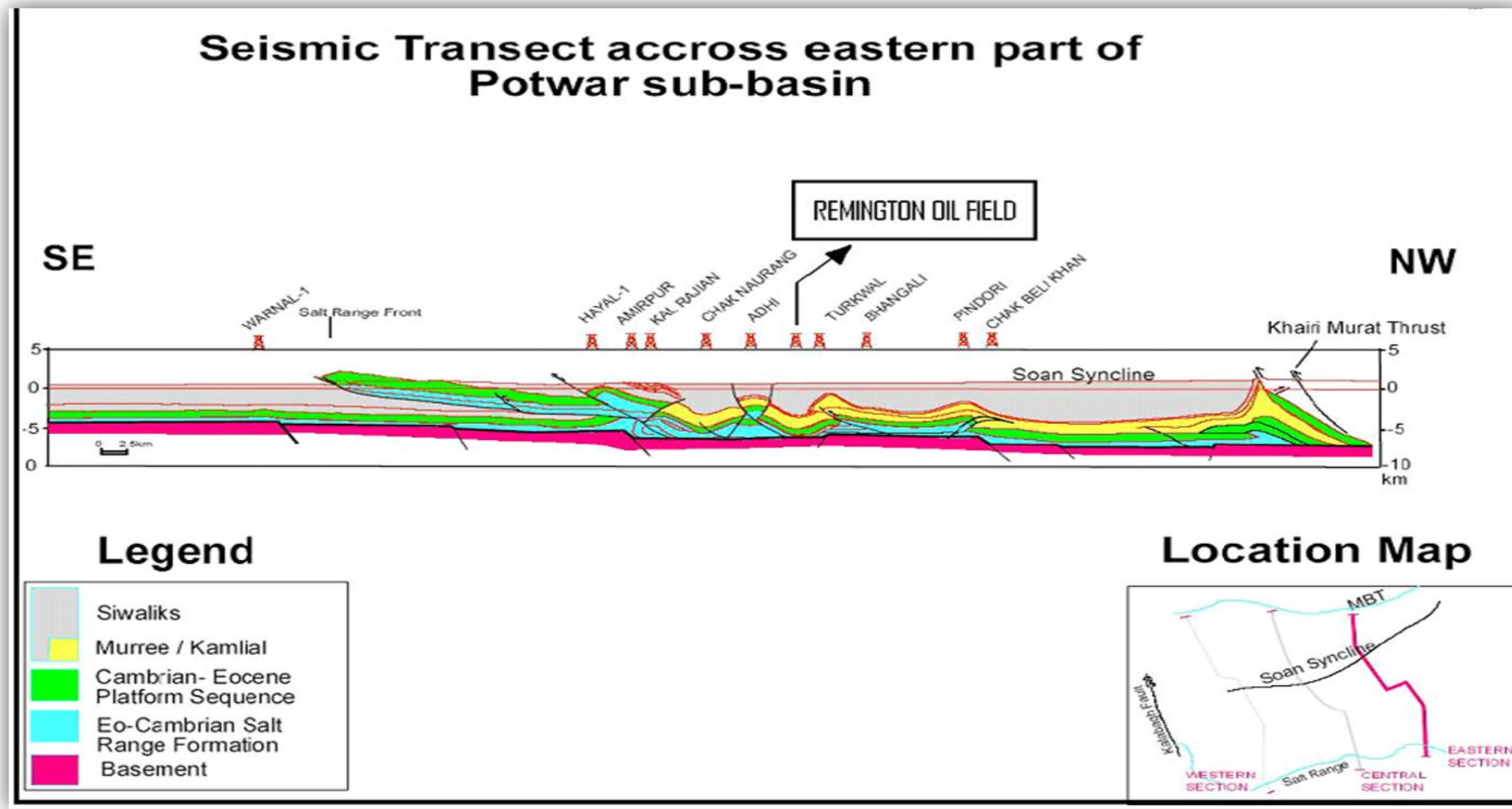
The Soan Syncline is not a true syncline. Its present configuration has resulted from deformation and rotation (more severe in eastern Potwar Plateau) of an initially broad syncline that develops in the south of NPDZ.

The Eastern Potwar Plateau is characterized by north-east and south-west trending tight, crusted, faulted, anticlines separated by broad synclines. The structural style of the central, western and eastern parts of Potwar Sub-basin shows a marked difference. This difference may be related to lesser thickness of salt in the infracambrian in the eastern area and very low dip of the basement normal faults noted to exist beneath the Chak Beli Khan, Chak Naurang, Qazian and south of Bhaun structures. (Mehmood, 2008)

Apart from the EW and NE trending normal offsets, a few north south trending basement faults with reverse offsets have also been recognized in the eastern Potwar Plateau. Folding in eastern Potwar Plateau was initiated as a result of continued horizontal stress, as well as salt build up along basement faults which after further shortening accumulate along anticlinal cores. All major salt accumulations are along basement normal faults. Initially an anticline may have started as a series of independent salt diapers along a basement normal faults which ultimately united and formed an anticlinal fold axis. The subsidiary salt build ups in the area between two basement faults have originated those folds which are not related to basement faults. These anticlines are younger and smaller in size. In eastern Potwar Plateau, major structures are parallel to sub-parallel with each other and show a wavy trend (two of the thrust i.e. Diljabba and

Rawat 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 seismic transect across the eastern part of the Potwar Sub-basin can be seen in Figure#9.The wavy nature of the structures can be explained by the interaction of various phenomena:

1. The basement is segmented and differential movement of segments with each other, and within east segment, has produced the wavy structure.
2. Development of roughly EW trending structures as a consequence of movement along basement faults and subsequent salt build up.
3. Deformation of the earlier formed EW structure by NS trending transverse faults complementary to Jhelum Fault giving rise to the present wandering configuration of the structures.



Figure#9: The seismic transect across the eastern part of the Potwar Sub-Basin (after Moghal, 2003).

All axis of anticlines in the east Potwar Plateau show faulting which is related to the northward under thrusting of the basement. These are drag thrust rooted into the basement fault. The triangular block bounded to the north by Domeli-Diljabba thrust, to the south by Salt Range Thrust (SRT) and Jhelum plains, and to the east by Jhelum Faults. 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.

In Central Potwar, structures are mainly fault bounded mostly by thrust and back thrust while at some places; asymmetric anticlines are bound by a single fault. The axial lines of various anticlines and synclines show no particular parallelism. The structural features with their structural trend transverse or oblique to the regional strike and lack of parallelism in fold axes, shape and rotation of the anticlines and synclines as well as associated faults leads to the opinion that these structural features would essentially be the result of gravitation processes (a tectonic diaprism) involving the subsurface flow of highly incompetent evaporate sequence of the Salt Range Formation due to differential loading caused by the excavation of the canyons and the erosion processes. However in the Potwar Plateau the up arching of the low density and plastic layer involves a lateral compressive stress also creating doubts in the purity of non-tectonic nature of the process. Major structures of the area include Lilla, Kalar Kahar, Joya Mir, Balkassar and Karsal.

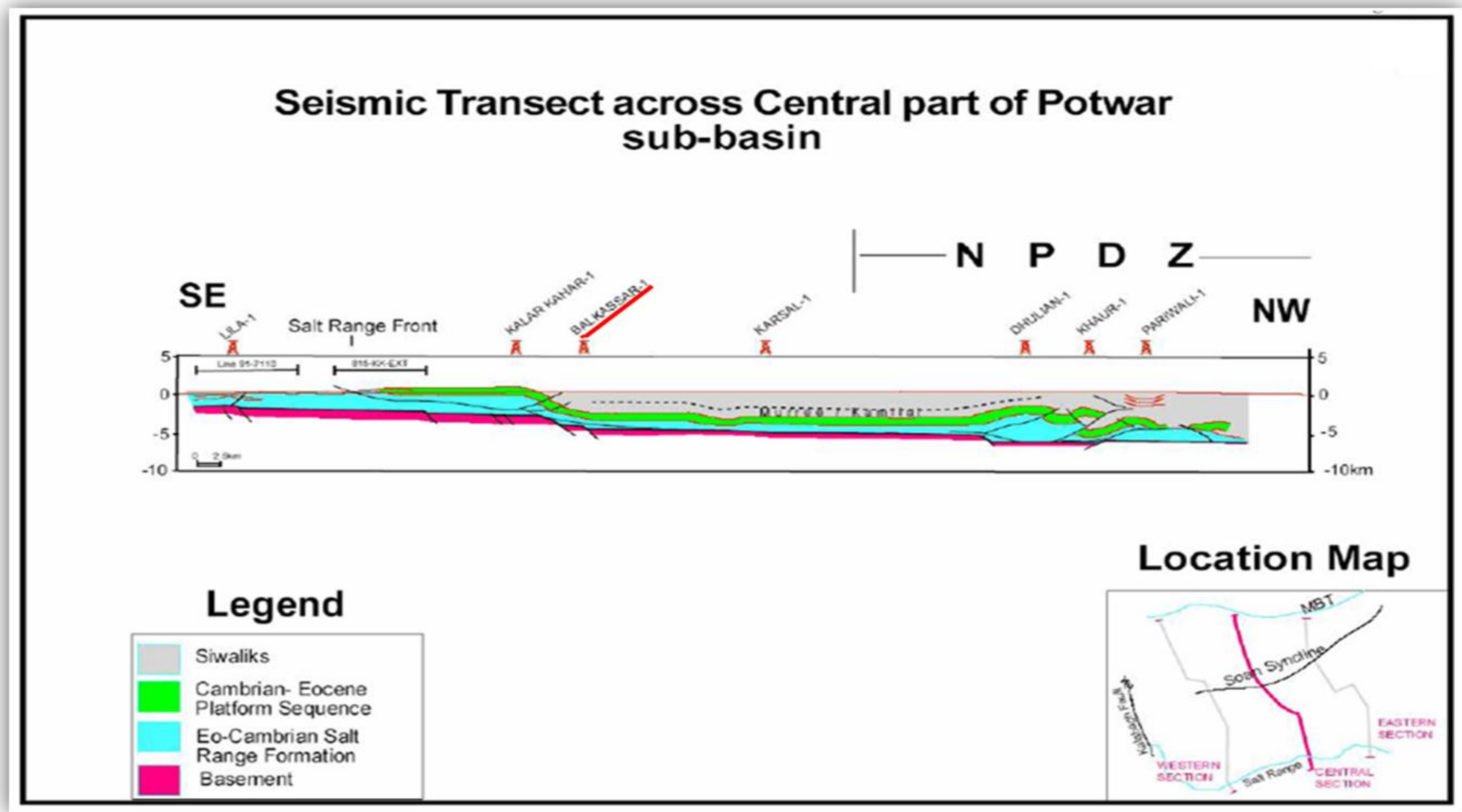
The Western Potwar Plateau is structurally much less deformed than rest of the Potwar plateau. It is characterized by a series of gentle folds, incipient in nature having a general NE to EW trend with the exception of Dhadambar Anticline which is aligned in a NW direction parallel to the Kalabagh Faults. (Mehmood, 2008)

Ramping in western Potwar Plateau occur only in north flank of Sargodha high which is farther south of basement normal fault in east Potwar Plateau that is why the Salt Range Thrust and western Potwar Plateau is on more southern side as compared to the east Potwar Plateau. Folding is southwest Potwar follows two trends, NW and NE which are the direction of the basement faulting. As the main stress is in NS direction, therefore the anticlinal structures are following the resultant NE and NW trend. Faulting in southward Potwar Plateau shows three main trends i.e. NE, NW and NNW. Most of the faults are thrust with maximum throw up to a few tens of meters. The structures in southward Potwar Plateau can be divided into two zones.

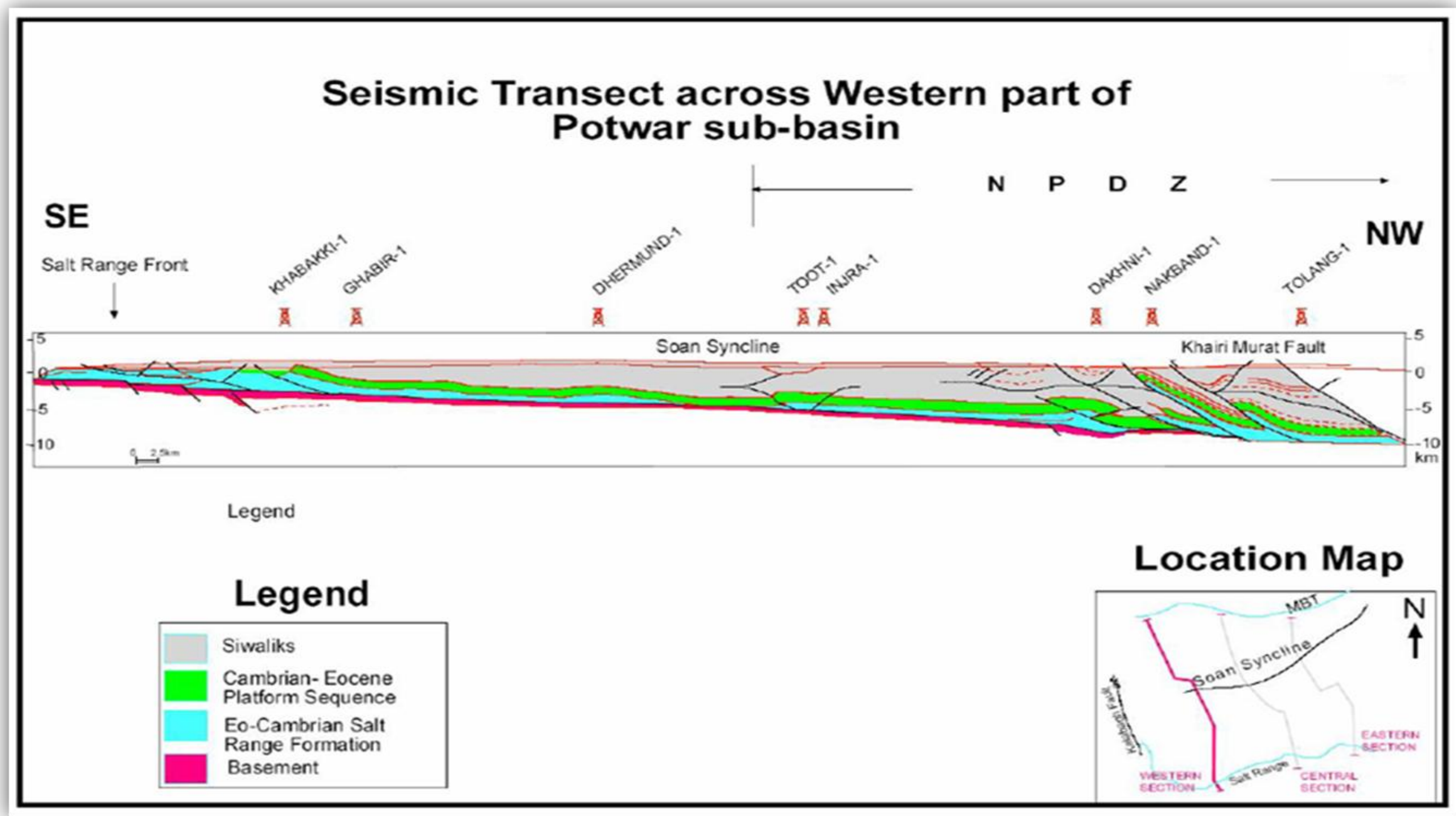
1. Northern zone close to NPDZ following a NE trend to east Potwar Plateau.

2. Southern zone which has NE and NW trends.

The seismic transects across the central and western Potwar Plateau can be seen in figure#10 and 11.



Figure#10: The seismic transects across the central Potwar Plateau (after: Moghal, 2003).



Figure#11: The seismic transects across the western Potwar Plateau (after: Moghal, 2003).

Chapter # 4

PETROLEUM GEOLOGY OF THE AREA

4.1 INTRODUCTION

This chapter deals with the petroleum geology of the Balkassar area. Tectonically the Potwar region is the part of an active foreland fold- and -thrust belt (figure 1.1).

Petroleum geology deals with the geochemistry, porosity, permeability, overburden, temperature and paleo environment. In the world as practically mostly hydrocarbon reserves occur in the sedimentary rocks. The oil traps can be structural and stratigraphic. The oil and gas are originated from organic matter buried underneath sediments. The surface is key to the subsurface theory. Therefore, the anticlinal structures are explored which are seldom visible on the surface.

4.2 HYDRO CARBON ENTRAPMENT IN POTWAR

According to Moghal M.A., et. al., (2003), oil and gas exploration in Potwar basin has a long history but it can still offer some surprises. Therefore, in addition to confirmed structural plays, there should be more focus to identify new play fairways.

The play types in the Potwar Basin are generally faulted anticlinal structures, which are mostly salt cored, occasionally highly asymmetrical to overturned. Mostly, the surface geological features are not a true manifestation of the subsurface structural style. The occurrence of hydrocarbon in various parts of Potwar sub-basin may be related to the structural styles.

- The Severe structuration in the eastern part has resulted in abundant fracturing as compared to the western part. The fracturing in the western part may be attributed to its proximity to MBT.
- The oil and gas discoveries in the eastern part of the Potwar Plateau (generally south of the Soan Syncline) are mostly from the elongated anticlines, trending NE-SW with steeply dipping flank due to salt pop-up.
- The hydrocarbons discovered near NPDZ are mostly from asymmetric Ease-West oriented anticlines (e.g. Ratana) whereas, those in the west of Soan Syncline are mainly from the symmetric north eastward to eastward trending thrust decollement Cenozoic anticlines (e.g. Dhurnal, Toot and Dakhni fields).
- Sub-thrust plays may have significant potential in the Potwar area and merit pursuance. Oil discovery in Rajian was first of its kind in the area. However, difference between single down-thrown block and sub-thrust block concept may be taken into consideration for closure identification.
- Patala shale is the dominant source rock in Potwar sub-basin. The occurrence of hydrocarbons in the older formations (Cambrian, Permian, and Jurassic) is explainable by vertical migration from the footwall across the thrust faults and also due to back thrusts.

- Besides conventional plays, there may exist various non-conventional plays including:
    - Sub-thrust (autochthonous) plays in the central and western Potwar and NPDZ.
    - Eocene carbonate diagenetic (matrix porosity) play fairway between Balkassar and Fimkassar oilfields.
    - Datta Sandstone structural / truncation play in western part, and
    - Salt diapir play in the vicinity of the Kalabagh strike-slip fault.

- In Central Potwar, Karsal field has produced about 135,000 barrels of oil. Interpretation of recent seismic by PPL (2002) over the area does not indicate any structural closure and it appears that the producing wells were located apparently on a monocline / flexure nose and the field produced from local permeability network in the vicinity of faults.

4.3 GEOTHERMAL GRADIENT AND MATURATION

The average geothermal gradient in Salt Range Potwar Foreland Basin (SRPFB) is 2°C/100 m. Balkassar Oilfield in the west of Joya Mair Oilfield has an average geothermal gradient of 2.05°C/100 m. The oil window in Balkassar Oilfield occurs at depth of 2300-4000 m in Eocene to Paleocene sediments. This suggests that the Paleocene shales of the Patala formation act as a source and have been exposed to optimum condition of geothermal maturation (Shami, B.A., & Baig, M. S., 2002). A Basin Profile (OGDCL, 1996) indicates vitrinite reflectance equivalent maturities of 0.62 to 1.0 percent for Tertiary rocks in the productive part of the Potwar Basin. Fluid-inclusion data, with vitrinite-reflectance data used for calibration, shows calculated and measured R_0 samples between 0.6 and 1.1 percent for Cretaceous, 0.5 to 0.9 percent for Jurassic, and 0.65 to 0.95 percent for Permian rocks (Wandery, C.J., et. al., 2004). North of the main boundary thrust fault, maturities are higher. In the northern and probably central basin, Cretaceous rocks are in the 1.0 to 1.6 percent R_0 range. Dry gas generation begins near 1.3 percent R_0.

4.4 SOURCE ROCKS

In Potwar Basin, Patala shales of Paleocene have proven as the main source rocks. These organic shales were partly deposited in anoxic conditions prevailing Paleocene due to buckling of the basin floor. Pre-Cambrian Salt Range formation also contains oil shale intervals, which show source rock potential.

Shales of Patala and Khewra formation are of lacustrine to marine origin and contain woody, coaly to variously amorphous (with significantly woody herbaceous) kerogen, which are capable of generating paraffinic to normal crude and gas (Kadri, I.B., 1995).

4.5 RESERVOIR ROCKS

The Paleozoic-Tertiary dominantly marine sedimentary rocks form petroleum systems in Potwar and are exposed in Salt Range along the Frontal Thrust. The fractured carbonates of Sakesar and Chorgali Formations are the major producing reservoirs in Balkassar. The limestones of the Paleocene Patala Formation also contain good reservoirs of hydrocarbons. Khewra Formation is the main potential Cambrian reservoir. Khewra Formation is generally divided into three units. The basal unit consists of thin bedded, partly shaly, fine to medium grained sandstone with thin clay beds. These represent the products of arid environment to marginal marine environment. The upper and middle units of the formation are moderately porous and display intergranular primary porosity, which ranges from 10-12 %. The uniform grain size and moderate sorting of the sandstone indicates its excellent reservoir nature ((Kadri, I.B., 1995)). The sandstone also displays fracture and jointing which may contribute to increase in effective permeability. Oil is produced in Potwar area from Khewra Formation in Adhi.

4.6 SEAL ROCKS

The seal rocks are those rocks that overly the reservoir rocks and act as a seal that prevents the upward escape of hydrocarbons from the reservoir rocks. Seals include fault truncations and interbedded shales and the thick shales and clays of the Miocene and Pliocene of Siwalik Group. The cap rocks are normally fine-grained rocks and they are essentially with very low permeability. The seal rocks are plastic as they are less likely to develop fractures when the rocks are folded or put under tension by other means. The clay, shale, salt, gypsum and anhydrite are the commonest cap rocks. The compact limestone can also act as a seal rock. The major types of seal rocks in the world include shale 65%, evaporite 33% and carbonate 2%. In Pakistan, major seal rocks are shale of Mianwali, Datta, Patala, Chorgali and Kuldana Formations (Shami, B.A., & Baig, M. S., 2002). The clays of Kuldana, Murree and Chinji Formations also act as seal rocks.

The shale of Mianwali Formation acts as a seal rock for the Triassic reservoir rocks. The top of the Datta Formation consists of variegated color shale, sandstone, and mudstone and clay stone. These beds of the Jurassic age are considered to be the top seal for the main oil sand horizon of the Datta Formation. The shale of Hangu Formation acts as a seal rock. The Patala shale is impervious and acts as a cap rock (Kadri, I.B., 1995).

The Kuldana Formation acts as lateral and vertical seal rock in the area. This Formation is present in almost all the oil fields of Potwar area. The clay layers of the Murree Formation are impervious in nature. These clay layers provide local seal for porous sandstones. The Chinji Formation is mainly composed of clays, which forms local seal in reservoirs of the area (Kadri, I.B., 1995).

4.7 TRAPS

Traps have been developed due to thin-skinned tectonics, which has produced faulted anticlines, pop-up and positive flower structures above Pre-Cambrian salt. In the Potwar area, traps are present in the form of fault-propagated folds, fault-bend folds, pop-up structures, hanging wall anticlines, triangle zones and duplex structures. Many of these folded structures are amplified, or they are only present above a detachment zone in Eocambrian salts. The latest trap-forming thrust events began at approximately 5 and 2 Ma (Jaswal, et, al., 1997).

4.8 THE FORMATION, ACCUMULATION AND MIGRATION OF OIL

According to Shami, B.A., & Baig, M. S., 2002, In the Potwar area, the oil is mainly generated in Paleocene-Eocene rocks. The generation of oil from the possible source rock needs the following four conditions to be fulfilled:

1. A sufficient amount of organic matter is present in source rocks.
2. The chemical composition of kerogen is favorable for a high yield of oil and gas upon burial in source rocks.

3. The thermal gradient is sufficient for the maturation and generation of hydrocarbons.

4. The time span is also an important factor for the generation of oil because the oil cannot generate from any source rock until it passes through a considerable time limits.

In the area, the Paleocene-Eocene rocks show an over all low energy and anoxic environment that favors the abundance and preservation of organic matter. The shale of Patala and Hangu formations are considered to be the major source rocks of this region. The TOC of Patala Formation ranges from 5-3.5% (Kadri, I.B., 1995).

The Eocene rocks also have potential to generate hydrocarbons and lot of micro calcareous animals and algal matter contributed to TOC. In Potwar, Chorgali and Sakesar carbonates contain fair to good amount of mature organic matter. The oil in these Formations shows high API gravity hydrocarbons and low sulphur contents (Kadri, I.B., 1995). The conversion of organic matter to hydrocarbons is gone through the effect of anaerobic bacteria.

The Potwar area has the average geothermal gradient of 2°c/100 M. Hence the general range of oil window is between 2750M and 5200M. The geothermal gradient of the area shows that the oil started to generate from the source rocks right at the end of Late Miocene time at which Chinji Formation was deposited and the thickness of the overlying formation reached up to 2950M (Shami, B. A. et. al., 2002). The probability of finding the gas condensate in the area is very scarce because the entire source rocks of Paleocene-Eocene time's lies within the range of oil window.

The tectonic development in the northern Potwar is older than the southern Potwar. The oil accumulated and trapped in the southern Potwar (Balkassar, Khaur and Dhulian oil fields) is heavy oil without gas condensate with high API gravity shows that the traps formed in southern part are younger and shallower structures. Whereas the oil fields in the northern Potwar (Ratna and Toot oil fields) have higher oil with gas condensate and low API gravity, which shows that the oil is accumulated in older and deeper structures (Kadri, I.B., 1995).

After the generation of oil in Paleocene-Eocene times, the oil primarily accumulated in the Paleocene-Eocene reservoirs. In the Paleocene, the limestone of Patala and Lockhart Formations are equigranular and are capable for the storage of oil and gas as reservoir rocks. The limestone of Chorgali Formation and Sakesar Limestone deposited in shallow marine supra tidal lagoonal environment posse high intragranular porosity and oil is primarily migrated in these limestones in late Miocene.

The oil accumulated during primary migration trapped by the seal shale and clays of Paleocene-Eocene. The secondary migration of hydrocarbons from the Paleocene-Eocene sequence occurred between 1.8-0.4Ma in Potwar. The source, reservoir and seal rocks are deformed to form the structural traps for the accumulation of oil and gas. The Paleogene sequence entered in oil window during the deposition of middle Chinji formation about 10 Ma and remained in oil window until 1.8 Ma. The present burial history based on well data of Balkassar indicates that the Paleogene rocks are not in oil window since 1.8 Ma. The presence of immature thick oil of 160 API with low gas content in Balkassar, Joya Mair, Chak Naurang and Amirpur area indicates that the Paleogene source rocks were in the oil window for a very short time period.

The maturity level of Cambrian strata is very high for their present depth, indicating their original deep burial and then removal of much of the overburden by up thrusting along the boundary faults of Salt and Trans Indus Ranges. There are indications that hydrocarbons were generated in Cambrian source rocks. The time of hydrocarbon generation, migration and the presence of suitable structural and stratigraphical traps, need further study in the search for oil in Cambrian reservoir.

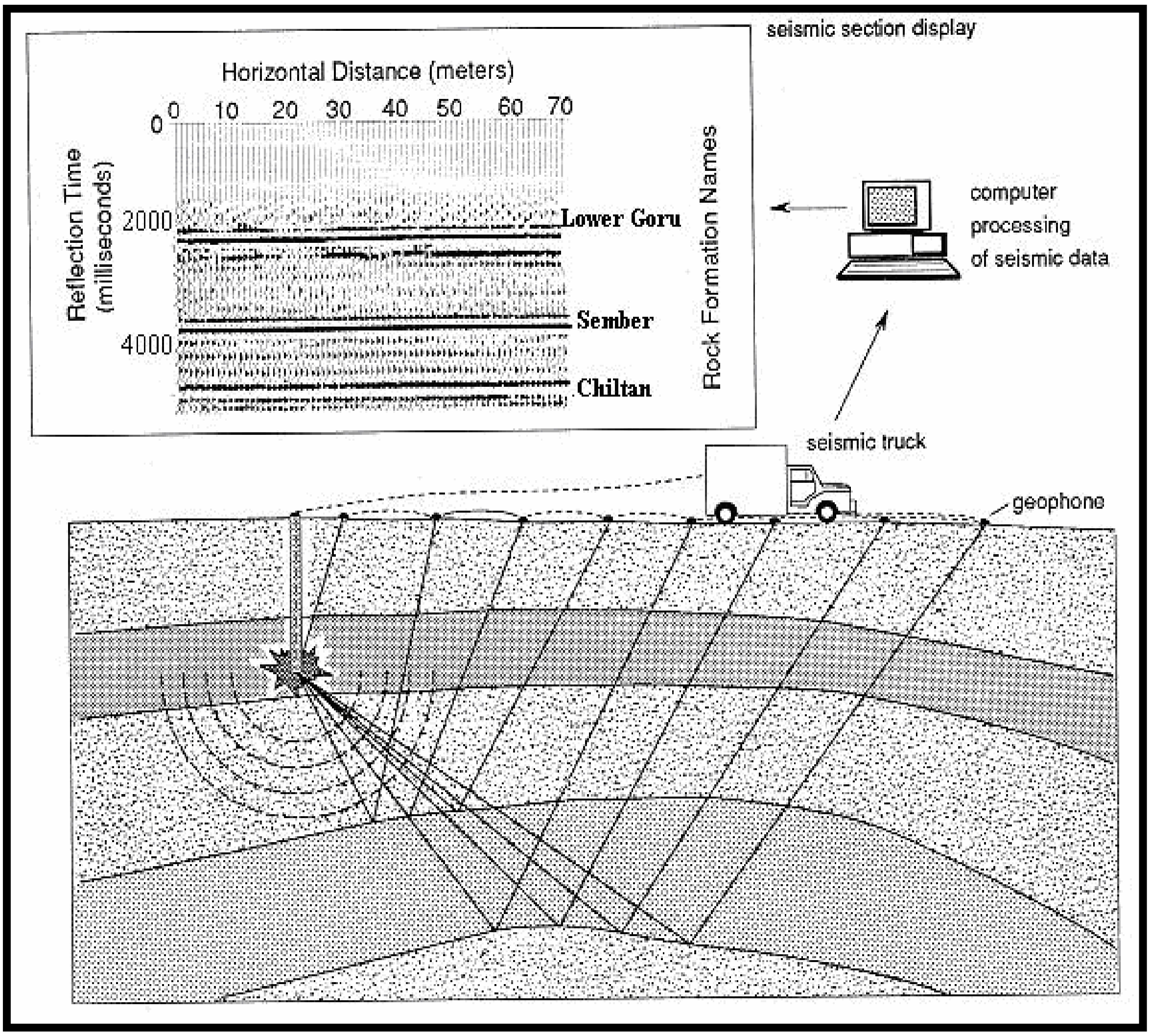
Chapter # 5

SEISMIC DATA ACQUISITION

The first step involved in seismic study of an area is the acquisition of seismic data. Acquisition of data means that the procedure through which the seismic reflection data is obtained. It is the very first step in the interpretation of seismic data. Seismic exploration is the primary method of exploring for hydrocarbon deposits, on land, under the sea and in the transition zone (the interface area between the sea and land). Although the technology of exploration activities has improved exponentially in the past 20 years, the basic principles for acquiring seismic data have remained the same.

5.1 BASIC PRINCIPLE OF SEISMIC DATA ACQUISITION

In simple terms and for all of the exploration environments, the general principle is to send sound energy waves (using an energy source like dynamite or Vibroseis) into the Earth, where the different layers within the Earth's crust reflect back this energy. These reflected energy waves are recorded over a predetermined time period (called the record length) by using hydrophones in water and geophones on land. The reflected signals are output onto a storage medium, which is usually magnetic tape. The general principle is similar to recording voice data using a microphone onto a tape recorder for a set period of time. Once the data is recorded onto tape, it can then be processed using specialist software which will result in processed seismic profiles being produced. These profiles or data sets can then be interpreted for possible hydrocarbon reserves (figure#12).



Figure#12: Seismic data acquisition, Processing, followed by Interpretation (www.kgs.ku.edu/Publications/Oil/gifs/fig21.gif)

Acquisition determines the ultimate achievable resolution and quality of data for interpretation. The selection of the survey design, equipment and the ground/sea conditions in the area of interest control:

• The frequencies in the data

• The wavelet

• Signal to noise

• Additional noise compo

5.2 COMPONENTS OF SEISMIC ACQUISITION SYSTEM

The entire seismic acquisition system is subdivided into 3 components based upon the operation that they perform. These are:

1. Input Devices
2. Field Layouts
3. Detection Of Reflected Signals
4. Recording

5.2.1. INPUT DEVICES

Also termed as energy source of seismic data, input devices are used to produce vibration in earth. Different kinds of input sources are used for land and marine survey. These input devices include explosive as well as non-explosive energy sources.

5.2.1.1. Impulsive Energy Source

Impulsive energy source make use of explosives which are detonated to produce energy. The most common energy source used from this category is Dynamite.

Dynamite is exploded inside a drilled hole at a depth raging from few meters to several tens of meters. The amount of charge per shot point depends on whether it is a single hole or a pattern shooting. As a rough estimate the charge weight is 10-50 Kg of dynamite.

Geoflux is another impulsive source which consists of an explosive cord, which is buried in the ground at a shallow depth. It is laid down by a hydraulically operated plough, which is especially designed for the purpose.

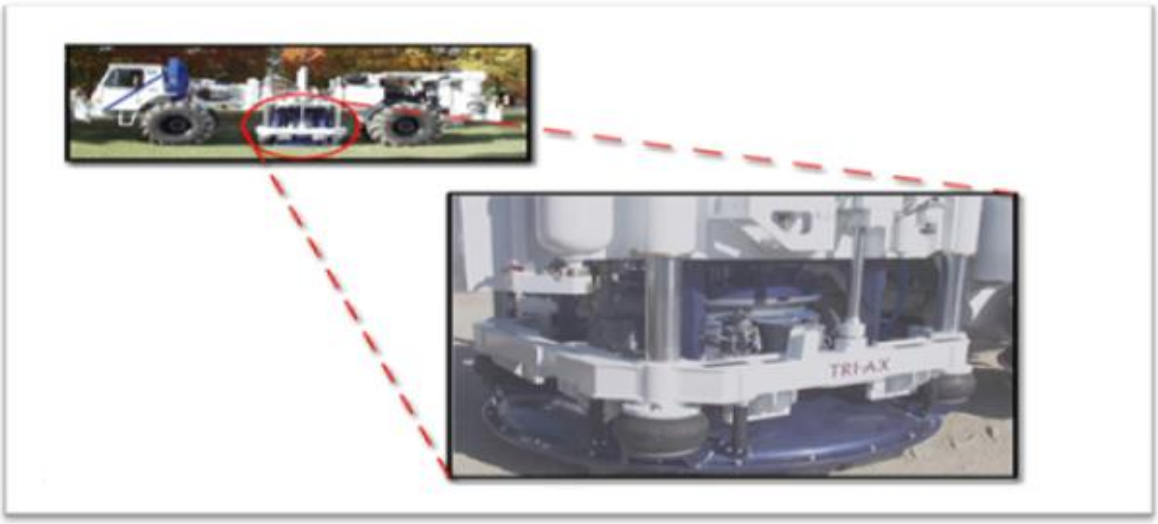
5.2.1.2. Non-Impulsive Source

These are the sources which do not use explosive detonation mechanism for generation of energy. They produce seismic energy by vibratory or other mechanisms. They are either used in marine survey or in Urban or populated areas where it is not safe to detonate explosives.

Vibroseis , which is the most commonly used vibratory input device, is based on the use of a mechanical vibrator. This is hydraulically driven to exert a force of an oscillating magnitude. It provides best productivity in shots per hour. The frequency range and strength can be controlled to meet survey requirements.

Hammer can also be used to produce seismic energy by impacting it on the ground. But this energy source is only good for shallow seismic. Geograph method, also known as Thumper, involves dropping a weight of about 3 tons from a height of about 3m on to the ground.

In marine survey, Air gun or water gun is used. Air gun discharges highly compressed air into the water. It comprises a chamber, which is charged with compressed air released by electrical triggering. In case of water gun, Compressed air is used to drive a piston that ejects water jet into the surrounding water. (Robinson and Coruh, 1988; Kearey, Brooks and Hill, 1984).



Figure#13: Vibroseis truck having its pad rested on the surface (www.gii.co.il/images/Dsc01247.jpg)

5.2.2. FIELD LAYOUTS

For a 2D seismic survey, all source and receiver points must lie in a straight line; this is called straight line shooting. Another type of shooting is called crooked line shooting in which the receivers do not lie in a straight line and it is only done when straight line shooting is impossible due to some construction etc. Numerous receiver-source configurations are used in seismic data acquisition. These include:

1. Split spread
2. End –on spread
3. Cross – spread
4. In – line offset spread
5. Split –dip spread with shot gap
6. Broad side T spread (Robinson and Coruh, 1988)

In seismic lines under study, 90 channels Symmetric Split spread have been used. Symmetric Split spread means that the geophone groups are kept on for seismic signals, on both the sides of a source point, and are equal in number.

LINE NAME	PBJ-1	PBJ-2	PBJ-3	PBJ-4	PBJ-9
LINE	Dip	Dip	Dip	Dip	Strike
LINE DIRECTION	South East	South East	South East	South East	North East
V.P	90-210	110-210	115-210	100-235	105-290

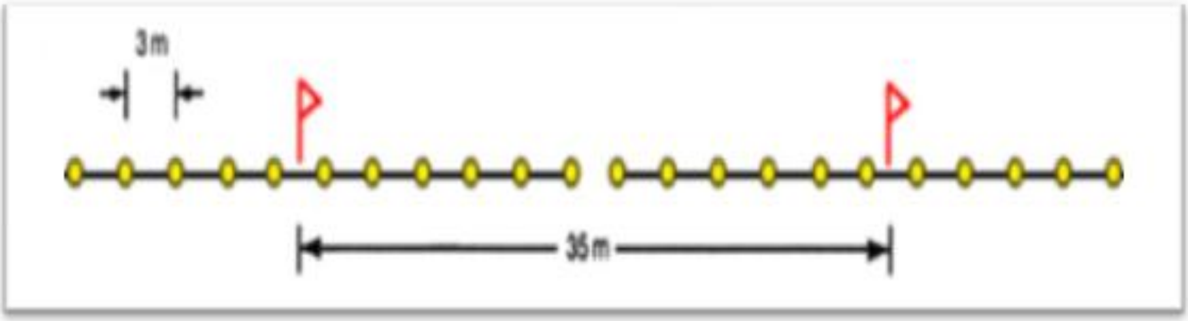
DATE RECORDED	1981	1981	1981	1981	1981
FOLD	24	24	24	24	24
DATUM	350m A.M.S.L	350m A.M.S.L	350m A.M.S.L	350m A.M.S.L	350m A.M.S.L

Table 3: General information about seismic lines under study (adopted from seismic section).

There is a number of spread configurations used in multi-channel reflection profiling these are:

5.2.2.1. Split-Spread

Geophones are arranged on either sides of central shot point.



Figure#14: Diagram illustrating the Split Spread (Sadi, 1980).

5.2.2.2. End-On spread

The shot point is located on one side of the spread in which geophones are arranged in straight line.

5.2.2.3. Cross Spread

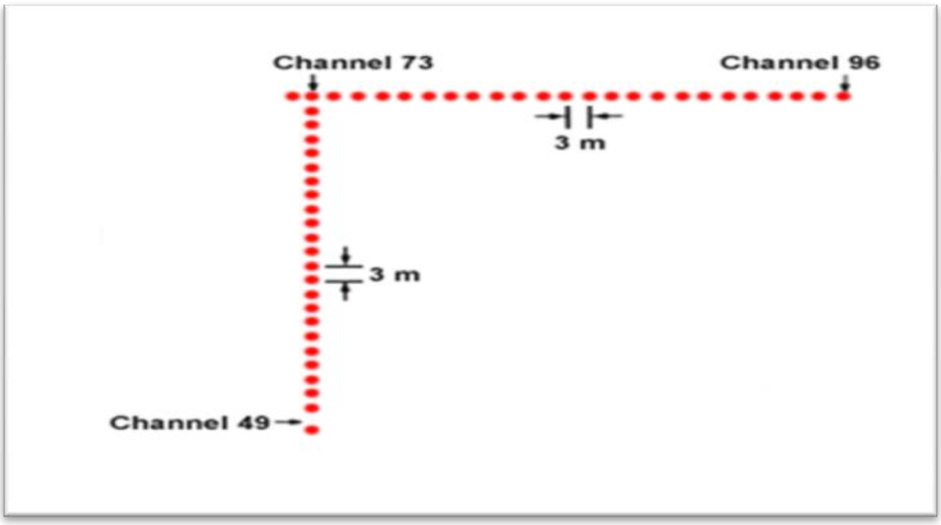
The geophones are arranged in cross shape around the central shot point.

5.2.2.4. In-Line Offset Spread

It is modified form of end spread in which shot point is located on one side, some distance away from the first geophone.

5.2.2.5. L-shaped Spread

Geophones are distributed around the shot point as L-shape. These configurations are used to collect single fold data.



Figure#15: Diagram illustrating the L-shaped spread.

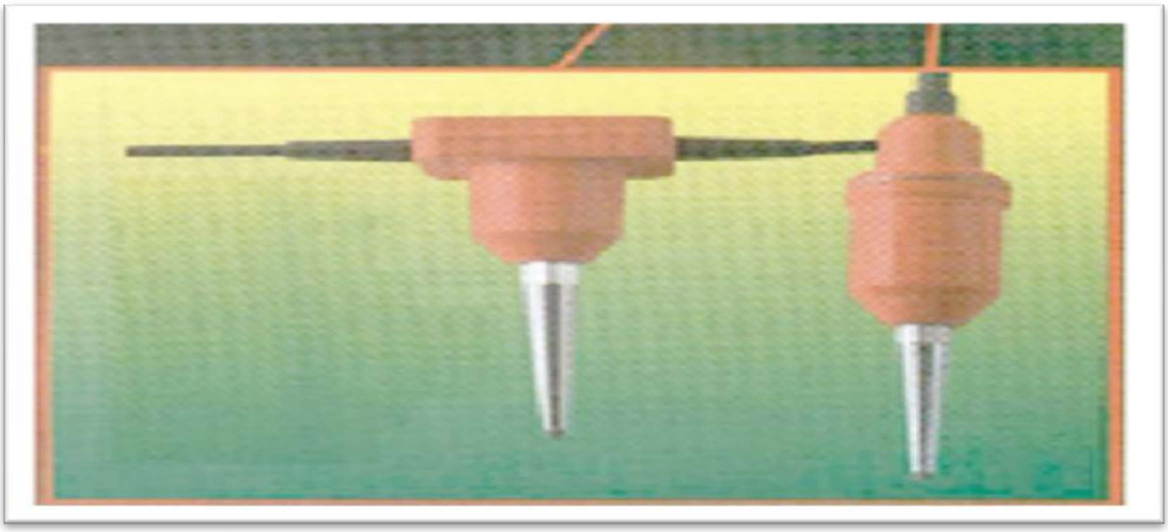
5.2.3. DECTECTION OF REFLECTED SIGNAL

After laying out the proper receiver-shot point configuration (as per need) and using energy source, there comes the stage of detection of seismic waves. Seismic equipment of adequate sensitivity, large dynamic range, and suitable frequency response is the aim of all development programs taking place in the field of seismic detection. Geophone is the most important detecting instrument used (Al-Sadi, 1980).

5.2.3.1. Geophone

The receiver used for the detection of ground vibration is called a geophone or a seismometer. It is used for seismic surveying on land, and it can also be operated on the ocean floor if mounted in a suitable container. Mechanism is that the motion of a coil around a magnet induces electric current to flow in the coil. The strength of that current depends on the speed of the motion. Table 4.1 shows the receiver parameters used in the recording of the seismic lines under study.

The response of geophones to vibration of different frequency can be tested with a device called a shake table. The frequency of vibration that stimulates the strongest geophone response is recognized as the natural frequency of the geophone. Geophones commonly have natural periods in the range of 5 to 40 Hz. (Robinson and Coruh, 1988)



Figure#16: Spike geophones (www2.informatik.hu-berlin.de/~hochmuth/bvp/geofon.htm).

5.2.3.2. Hydrophones

A hydrophone is a microphone designed to be used underwater for recording or listening to underwater sound. Most hydrophones are based on a piezoelectric transducer that generates electricity when subjected to a pressure change. Such piezoelectric materials or transducers can convert a sound signal into an electrical signal since sound is a pressure wave in fluids.

ENERGY SOURCE	Vibroseies
SWEEP FREQUENCY	7-42 Hz
SWEEP DURATION	20000 ms
NO. OF SWEEPS	42
V.P INTERVAL	100 meters
GROUP INTERVAL	100 meters

Table 4: Receiver parameters for under study seismic lines (adopted from seismic section).

5.2.3.3. Geophone Interval

The distance between adjacent geophones within a group. Some time used for group interval, the separation between the enters of adjacent geophone groups

5.2.3.4. 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.

5.2.3.5. Group Interval

The horizontal distance between the centers of adjacent geophones groups.

GEOPHONE TYPE	MARKS
GROUP LENGTH	159 m
ELEMENT SPACING	9 m

Table 5: Receiver parameters for under study seismic lines (adopted from seismic section).

5.2.4. RECORDING STAGE

All registration of signal from geophone is then recorded. There are two systems, which record the geophone signal:

1. The Analogue Recording System
2. The Digital Recording System

5.2.4.1. Analogue Recording System

This is the earliest system used to record seismic data on magnetic tapes. The analogue recording system is made up of an assembly of electronic units normally housed in a specially adapted truck called the recording station. It involves two steps. First the signal coming from Geophone is amplified and is then recorded. Table 4.2 shows the recording parameters used in the recording of the seismic lines under study.

5.2.4.2. Digital Recording System

A digital station is equipped with the facility to convert a continuous signal into a digital form. The sample value is expressed in terms of binary digits. This type of recording system amplifies the signal coming by geophone which is followed by Analogue to Digital conversion (A/D conversion) and is then recorded.

INSTRUMENTS	**R-10,COBA-2**
TAPE FORMAT	**SEG-C**
RECORD LENGTH	**25000 ms**
NOTCH FILTER	**Out**
SAMPLE INTERVAL	**4 ms**
NUMBER OF CHANNELS	**62**
NATURAL FREQUENCY	**10Hz**

Table 6: Recording parameters (adopted from seismic section).

In seismic lines under study, trace split spread has been used. Split spread means that the geophone groups are kept on for seismic signals, on both the sides of a source point. The near offset (distance from source to nearest group) is 350 meters and the far offset (distance from source to farthest group) is 2650 m.

5.3. THE CDP METHOD

CDP method was introduced by Mayne in 1963. The CDP offers some cancellation of noise, i.e., multiples and random noise. In this method the signals associated with a given reflection point (Common depth point) but recorded at different shot and geophone positions are defined. The seismic data acquisition is done such that CDP method yields greater number of shot points per unit distance along the line causing repetition of reflection point at an interface. It means, if a reflecting point is repeated twice during shooting, there would be two seismic traces corresponding to that point, so it admits 2-fold acquisition or it can be designated as 200% data. The data fold can be evaluated from the following relation:

$$F = \frac{N\Delta y}{2\Delta x}$$

Where

N = Number of recording channels

Δy= Group Interval

Δx = Shot point interval

Our current data is 24 fold meaning 2400%.

Chapter # 6

SEISMIC DATA PROCESSING

Once seismic data has been acquired on field, the second step is the processing data. Data Processing involves sequence of operations, which are carried out according to a pre-defined program to extract useful information from a set of raw data (Al-Sadi, 1980). The main purpose of processing is to convert seismic data recorded in the field into a coherent cross section, indicating significant geological horizons into the earth subsurface, related to hydrocarbon detection and seismic Stratigraphy (Hatton et al., 1986, Dobrin and Savit 1988).

Seismic data processing consist of applying a sequence of computer programs, each designed to achieve one step along the path from field tape to record section. From ten to twenty programs are usually used in a processing sequence, and these are selected from a library of several hundred programs. Each company's library is unique, although many programs are will be almost identical with those of another company. In each company's library there may be several programs designed to produce the same effect by different approaches. For example one program may operate in time domain while another works in frequency domain, yet they may yield similar results (Zia-ur-rehman, 1989).

Successful exploration and exploitation programs require the best possible "picture" of the subsurface. Seismic migration is one of the four basic steps that give us the best "picture". These four primary data processing steps are; in their usual order of application

1. Demultiplexing
2. Deconvolution
3. Stacking
4. Migration

Demultiplexing is the reorganization of recorded data to common depth point gathers. Deconvolution is a filtering process whereby the undesirable complexities in the source wavelet and reverberbration multiples are reduced or, better yet, eliminated. And stacking with its associated velocity analysis enhances real data while minimizing noise.

The fourth, and usually final, major process – seismic migration – corrects for geometric displacement of data from a dipping reflector and/or lateral velocity changes and places them in their true spatial position rather than at an assumed point in depth between the source and the receiver. The goal of seismic process id to make subsurface reflection data appear like a vertical slice or geological cross – section of the earth along the plane of seismic array. The goals of migration process are two – fold – first, to ensure that those reflections are in their correct subsurface locations, and second to eliminate the signal interference caused by point diffractors (Siraki, 1985).

6.1. DEMULTIPLEXING

The outcome of a geophone group during field recording is a continuously varying electrical voltage. Since seismic data are processed in digital computers, the continuous geophone output voltage must be converted to digital format by sampling.

Sampling occurs in the field or in the processing centre in an analog to digital converter (A/D). Consider four geophone arrays, whose outputs are brought to four terminals arranged in a circular pattern, and an arm, pivoted at the circle's center rotating counterclockwise and making with momentary contact with the four terminals in succession. The instantaneous voltage at each terminal is recorded each time the rotating arm sweeps over it, yielding an array of samples. If each sample is identified by its geophone group sources (A,B,C,D) and by its chronological sequence in that group (1,2,3,….) then the output of the A/D converter is :

A1,B1,C1,D1,A2,B2,C2,D2,CA3,B3,C3,D3,…….

This scrambled sequence is referred to as a "multiplexed" array. However, it is more convenient to process seismic data in trace sequential array:

A1,A2,A3,…, B1,B2,B3,…, C1,C2,C3,..., D1,D2,D3,…

Unscrambling a multiplexed array into a trace sequential array is called “demultiplexing”. It is accomplished by a simple computer sorting program and it is the first step in any data processing sequence (Zia-ur-rehman, 1989).

6.2. PREPROCESSOR

6.2.1. GOMETRY DEFINITION

In geometry definition the geometry of the traces is made. It consists of the information which is associated by the trace. It has information such as the File number on which the terrace is present, the Field File Identification Number (FFID), the first live channel, the last live channel, the Picket interval, total number of traces per shot, source and receiver information, fist receiver point, last receiver point, the number of misfires, deep holes, pattern shots, pop shots, etc (personnel communication).

6.2.2. EDITING

Raw seismic data inevitably contains some unwanted noise and perhaps some dead traces. If obviously useless information is to be removed from the processing stream, it must first be identified and then blanked or muted by assigning zero values to all samples in the affected time interval

Unwanted data are usually identified by visual examination of raw field traces, although obvious cases (dead traces, strong noise bursts, etc) can be detected and edited automatically.

The raw field traces used in this editing procedure can be obtained from field monitor records or from one of the trace gathers previously described (Zia-ur-rehman, 1989).

6.3. TRACE BALANCING-AGC

The AGC function does not employ a gain to the whole trace, but employs a gain to a certain time sample within a time gate. A disadvantage is that when the AGC gain is applied, it is not possible to reconstruct the original signal again. Therefore, the AGC is only used for display and printing purposes (Yilmaz, 2001).

6.4. CDP SORT

Each trace to be included in a common depth point stack comes from a different digital seismogram. A large number of digital seismograms can be sorted in computer memory after they had been prepared by demultiplexing. the process of selecting a set of traces to be stacked is called CDP Sort (Robinson and Coruh, 1988).

6.5. DECONVOLUTION

Deconvolution is a filtering process designed to improve resolution and suppress multiple reflections. Deconvolution can be considered either in the time domain or in the frequency domain. In the time domain the object is to convert each wavelet with its reverberations and multiples, into a single spike. If we know the shape of the wavelet, we can design an operator which, when convolved with the seismic trace, will convert each wavelet into a single spike.

FOUR KEY PARAMETERS FOR DECONVOLUTION:

- Type of deconvolution-spiking or prediction
- Portion of the trace to be the source of the autocorrelation.
- Length of filter operator.
- White noise factor.

6.5.1. TYPES OF DECONVOLUTION

6.5.1.1. Spiking Deconvolution

It assumes the input as minimum phase and all frequencies are to be leveled in the spectrum. The effect of this type of filter is to concentrate the energy of the pulse as near as possible to the front of the wavelet, i.e., to turn the wavelet into as near a spike as possible (Dobrin & Savit, 1976).

6.5.1.2. Predictive Deconvolution

Predictive deconvolution uses the autocorrelation of a trace to ascertain the periodicities within the autocorrelation and a gap, of time delay after the zero lag value. The f1lter designed from the autocorrelation, when convolved with the data trace, predicts reverberations and multiples. The predicted trace is subtracted from the observed trace to. give the prediction error, which should be the trace with the predicted reverberations and multiples.data. The objective of deconvolution is to compress the wavelet into a shorter impulse that is more like the intial explosive impulse and to improve the resolution of the reflected events .

6.6. CORRELATION

Correlation is simply the measurement of similarity or time alignment of two traces. Since correlation is a convolution without reversing the moving array, a similar frequency domain operation also applies to correlation. (Yilmaz, 2001).

6.6.1. Cross Corelation

Cross correlation measures how much two time series resemble each other. It is not commutative; output depends upon which array is fixed and which array is moved. As a measure of similarity, cross correlation is widely used at various stages of data processing. For instance traces in a CMP gather are cross correlated with a pilot trace to compute residual static's shift. It is the fundamental basis for computing velocity spectra.

6.6.2. Auto Corelation

Cross correlation of a time series with itself is known as auto correlation. It is a symmetric function. Therefore only one side of the auto correlation needs to be computed. *(YILMAZ,2001)*

6.6.3. Vibroseis Corelation

The signal i.e vibroseis wavelet (figure#17) generated by a vibroseis is not a short pulse but rather a sweep lasting some seven to ten seconds. The sweep is transmitted through earth and reflects signal. Each reflection is a near duplicate of a sweep itself, so the reflections in vibroseis record overlap and are indistinguishable. To make it useable, reflections are compressed into wavelets through cross-correlation of data with original input sweep. After correlation each reflection on record looks similar to impulsive source data. This involves cross correlation of a sweep signal (input) with the recorded vibroseis trace. The particular form of wavelet produced by a vibrosis corelation is called klauder wavelet The sweep is a frequency-modulated vibroseis source signal input to the ground (Yilmaz, 2001).

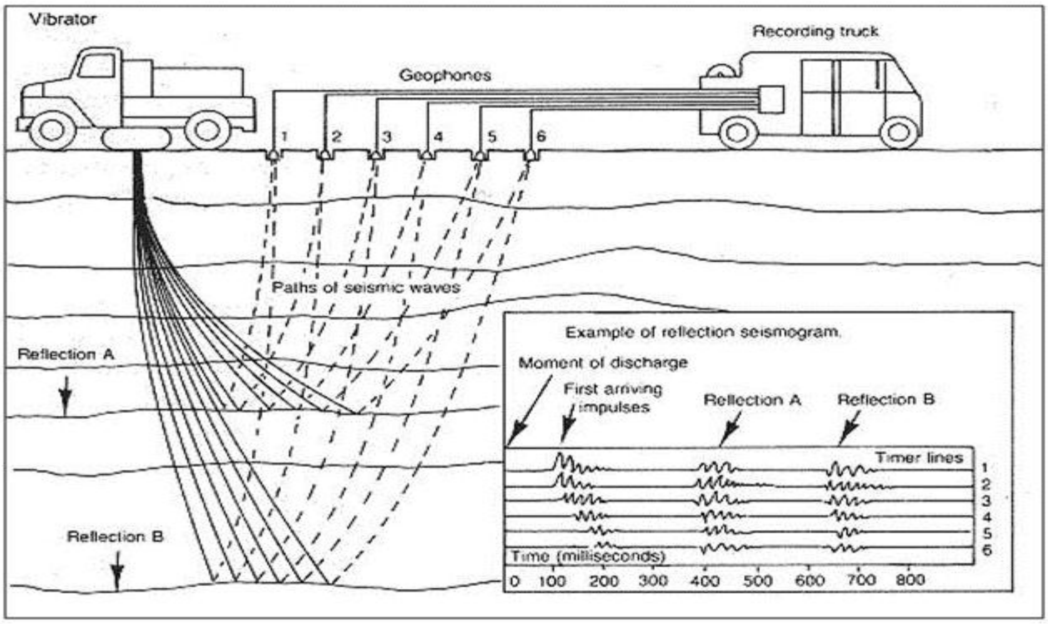
There are two types of sweep:

- Up Sweep (When frequency of the vibroseis source signal increases with time)
- Down Sweep (When frequency of the vibroseis source signal decreases with time)

Figure#17: Vibroseis wavelet. (Yilmaz, 2001)

6.6.3.1. Importance Of vibroseis Corelation

For vibroseis source (figure 26), we have a sweep (a train of waves) rather than a short pulse/source wavelet whereas most seismic impulsive sources generate a very short pulse which can be used directly to examine subsurface structure Vibroseis sweep lasts for several seconds depending upon the sweep time. So in case of vibroseis source all reflected and refracted signals on a vibroseis seismogram overlap one another extensively. Even after demultiplexing of the vibroseis seismogram it is impossible to recognize the reflections. So vibroseis correlation procedure is applied (Robinson. & Coruh,1988). Vibroseis correlation enables us to extract from each of the long overlapping sweep signals on vibroseis seismogram, a short wavelet much like those obtained with seismic impulsive source.



Figure#18: Reflection seismogram and path of reflected waves generated during vibroseis sweeps. (Yilmaz, 2001).

6.7. FILTERING

An f1lter is a system, which discriminates against some of its input. Seismic data always contain some signal information, which we want to preserve. Everything else is called noise, and we want to remove or reduce it. These systems, which are generally called filters work either by convolution in the time domain or by spectral shaping in the frequency domain.

The most common types of filters are the following:

i. Low pass frequency filters

ii. High pass frequency filters

iii. Band pass frequency filters

iv. Notch filters

v. Inverse filters

vi. Velocity filters

vii. F-K filter

Filtering can be used to separate out a particular seismic event, which is shown on the seismic section, using apparent velocity as the selection criterion. Each straight-line event, like a direct wave, refracted wave or surface wave, has a particular apparent velocity. The gradient Vapp = dx/dt of the arrivals on the seismic section gives the apparent velocity.

6.8. VELOCITY ANALYSIS

Flat horizontal interfaces in the subsurface appear on the CMP gather as discrete reflected wavelets positioned in time according to a hyperbolic tractectory. To make full use of the procedure of stacking these trajectories need to be straightened. This straightening is achieved by the dual procedures of velocity analysis and move out correction. Here, a time t0 is chosen along the zero offset trace in the gather. For each position t0, a trial velocity is inserted into equation and the time correction required to align each trace at increasing offset is estimated. This correction is applied and the traces summed and the results of this summation is plotted. A new trial velocity is selected and the process continued until a range of velocities bracketing the solution have been scanned (Figure 19). A new time t0 is selected, and the process repeated. The summed energy is contoured on a 2D map of move out velocity versus to, and the peaks are picked as the final velocity solution in TWT. Multiples also give rise to peaks in this plot, but are generally able to be identified and eliminated by their lowervelocities (Yilmaz, 2001).

$$t^2 = t_o^2 + \frac{X^2}{V^2}$$

where

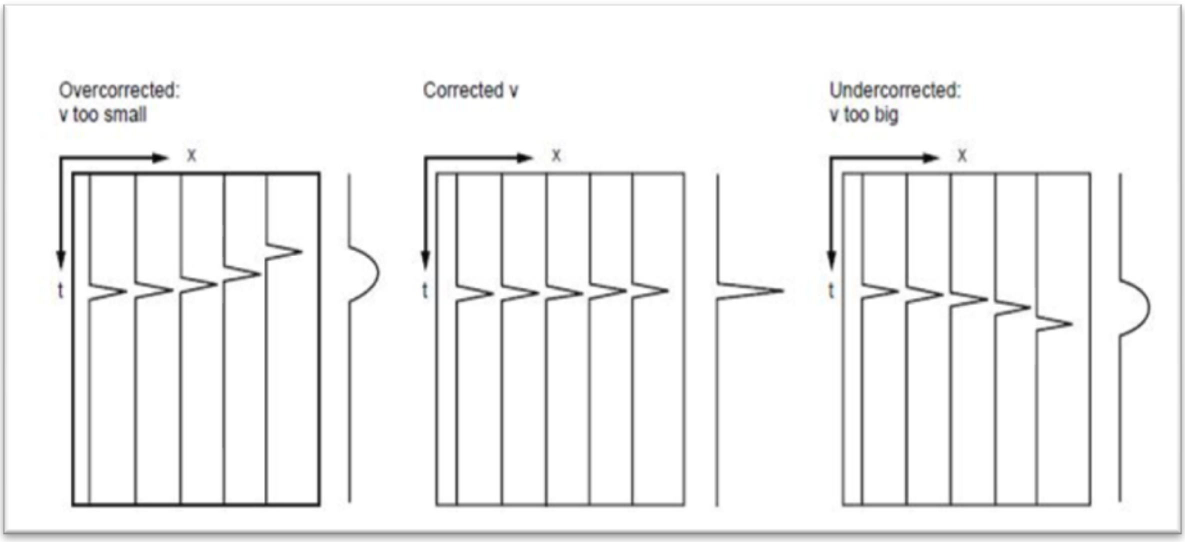
t - two-way time of reflected event

t_o - two-way vertical time

V - root mean square, or moveout velocity

X - offset

This velocity model is used to make the final correction via equation to produce the optimal alignment of the events. In practice it is too time consuming to repeat this procedure for each location across the survey and so it is applied every few CMPs only. The spacing for velocity analysis determines the ability of the survey to successfully take into account any strong lateral variations in the subsurface, and must therefore be tailored to the particular area of interest. If the velocity is chosen incorrectly this can severely compromise the final stacked image, broadening the events and reducing the overall vertical resolution (Figure#19).

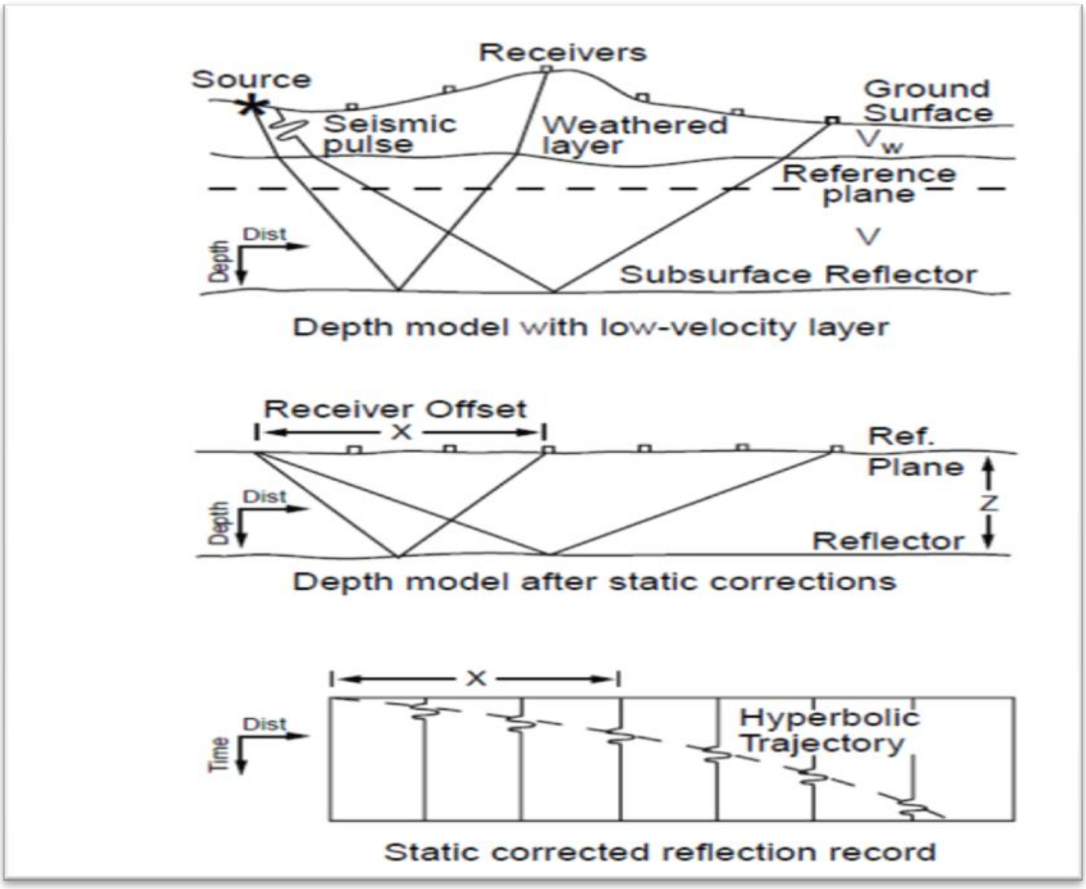


Figure#19: Effect of velocity on final stack image. (Yilmaz, 2001)

6.9. DATUM STATICS CORRECTION

This correction (figure 28) is applied to negate the effect of low velocity layer (LVL)/ weathering layer present in the sub-surface. The LVL causes a disproportionately great and variable time delay in the arrival of the desired deeper reflections. This layer also significantly absorbs the higher frequencies. The sub-weathering layer velocity mentioned on the processing sequence header of the seismic section of lines of the study area is 2500 m/sec.

Since the paths of reflected waves through the LVL are usually close to vertical regardless of offset and angle of propagation below the LVL, the correction for elevation difference can be made simply by subtracting (or adding) the time required for the wave to travel the vertical distance between a reference (datum) elevation and that of the earth's surface at the point in question. The datum elevation given in the section of study is 335m at mean sea level.



Figure#20: Static correction.

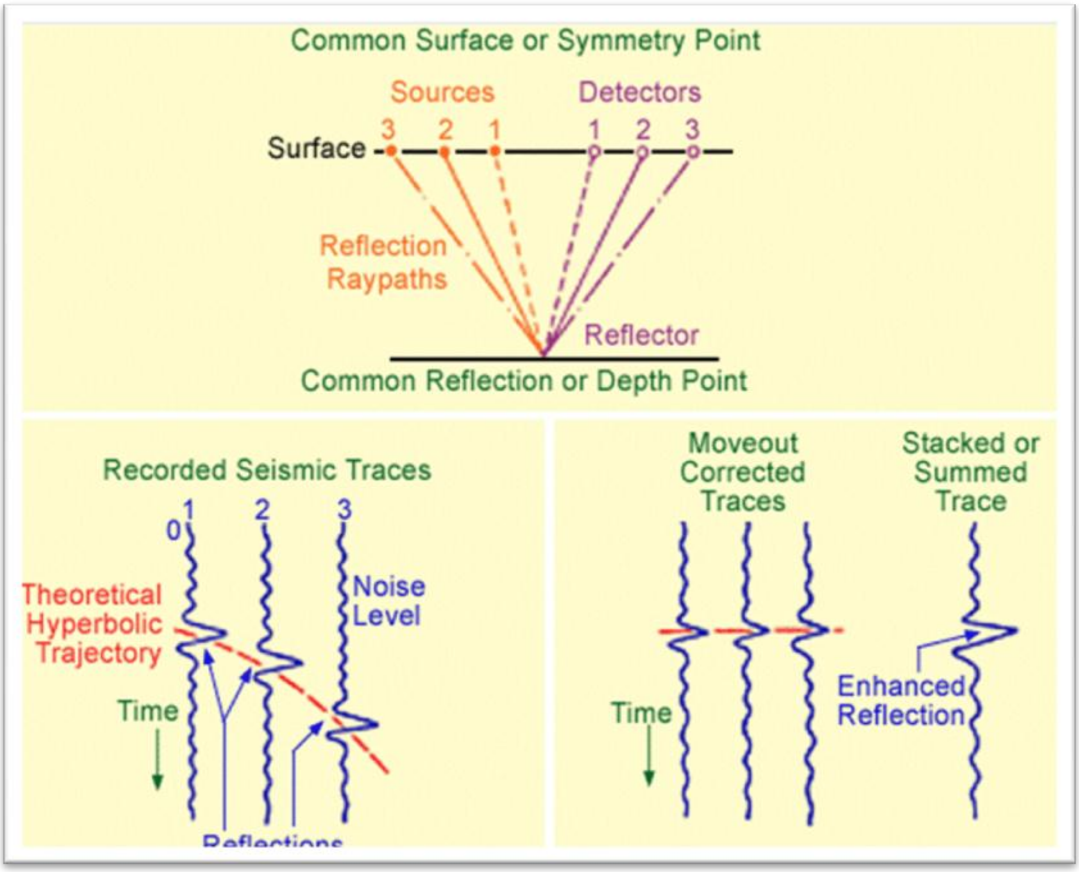
6.10. RESIDUAL STATIC CORRECTION

Due to the unpredicted variation of the velocity and thickness of the surface layer, a small but significant error may be committed in the computed static correction. These errors (or residuals) in the value of the static correction of each seismic trace, result in a deteriorating S/N ratio of the CDP-stack section.

Adjustment of the total static correction is then made, adding algebraically the residual values, which is computed for each seismic trace. The summation output (normally called the model trace) is considered to have an error-free static for each of the traces, is then found by cross correlating the model trace with each of the contributing traces in turn. By repeating the process for all the depth points of the line, the residual static for each seismic trace is estimated (Sadi. 1980).

6.11. NORMAL MOVEOUT CORRECTION

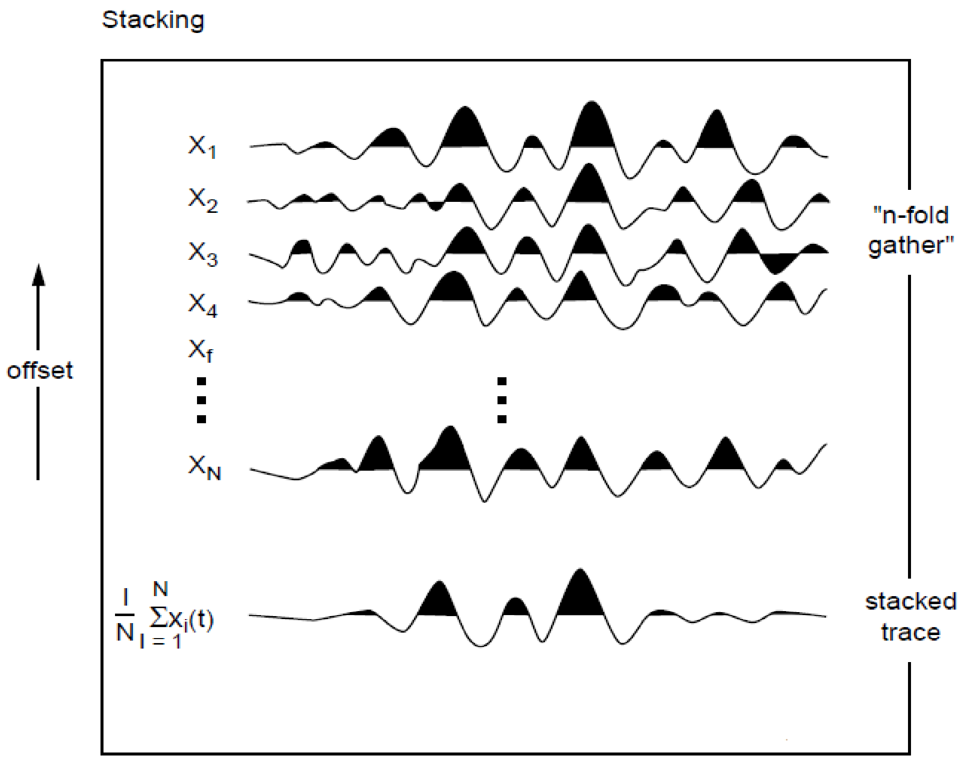
Normal Moveout (NMO) is a seismic effect as well as a seismic processing step. NMO is the moveout caused by the separation between a source and receiver in the case of flat reflector. A reflection typically arrives first at the receiver nearest to the source. The offset between the source and the other receivers induce a delay in arrival time of a reflection from a horizontal surface at depth from same point, and plot of arrival time vs. offset has a hyperbolic curvature in reflection events. After the NMO correction, the events are virtually flattened across the offset range; i.e. the offset effect is removed from travel-times.



Figure#21: Common surface and move out corrected traces (www.glossary.oilfield.slb.com/DisplayImage.cfm?ID=272)

6.12. STACKING

The stacking process is single most powerful tool for enhancing the quality of seismic reflections while at the same time reduces the level of noise. It is simply the process in which we add the traces obtained from different sources and receivers. Stacking is a powerful technique that combined N traces in the CMP gather or bin to provide a improvement in the signal to noise (Figure#22).



Figure#22: Stacking (Graul, 1999).

Digital stacking has replaced analog stacking which had a shorter dynamic range and processing flexibility. Stacking is applied only when the all necessary corrections have been applied.

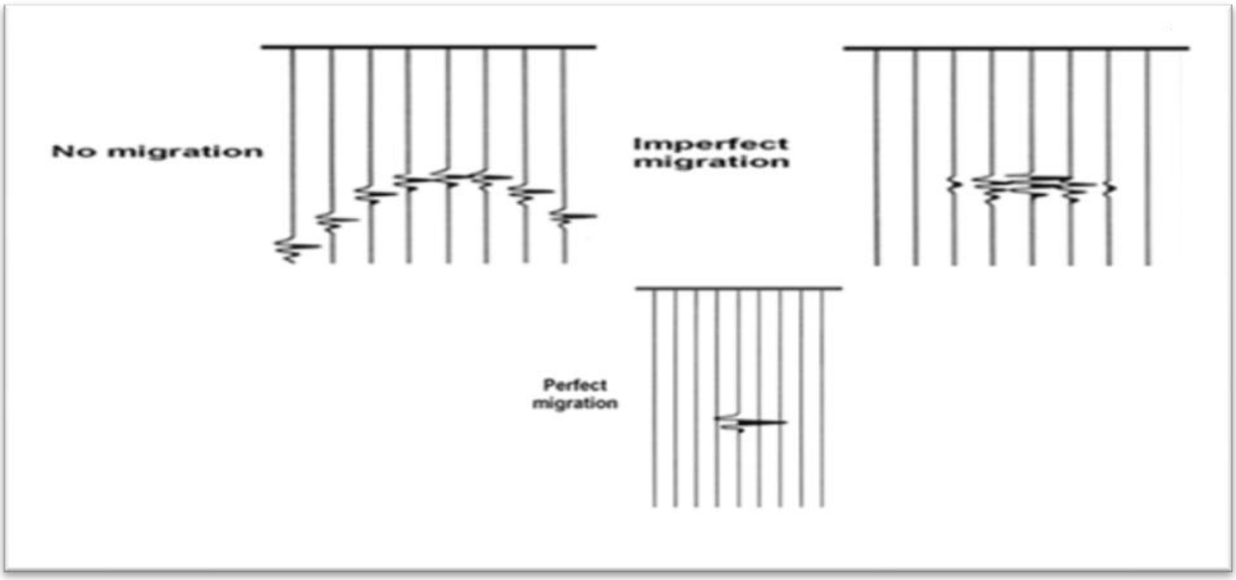
1. Select the traces and adjust them so that reflections on all the traces have the same arrival time. Joining these traces will yield hyperbola.
2. Then individually reflected wavelets are added together to produce a stronger signal.
3. Noise on the other hand tends to be different from trace to trace, so that it is reduced by destructive interference when traces are combined

6.13. AGC

Automatic gain control is required to enhance low amplitude at later times on the recorded traces. These amplitudes are low due mainly to attenuation of the wave when propagating through the earth's subsurface. To boost the amplitudes, a window is designed or a function applied which simply multiplies the trace amplitudes. Note that there is a general loss of signal amplitude due to divergence (geometrical spreading), absorption (Q factors) and reflections and scattering. This is taken care of with AGC. As a result of divergence and absorption the seismic pulse also loses its high frequency components with distance and becomes progressively a lower frequency signal. An additional step called Q-compensation is required to address the frequency loss.

6.14. MIGRATION

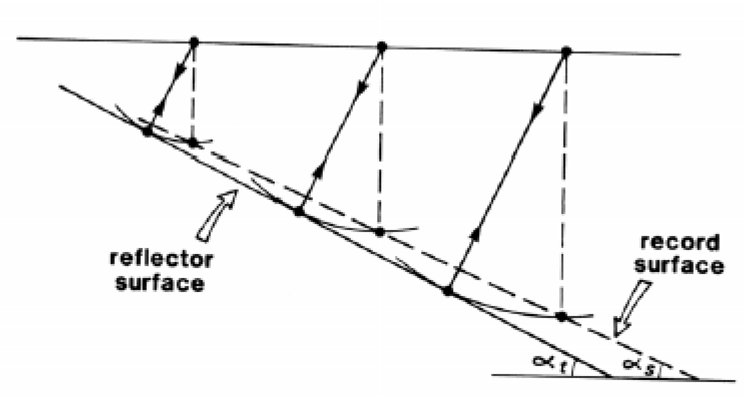
The process of shifting the reflection points to the positions that correctly image the reflector and remove diffraction images, so that we may get an accurate picture of subsurface layers.



Figure#23: Migration a process of shifting the reflection points to the positions that correctly image the reflector. (Rehman, 1989)

Migrations are highly sensitive to the velocity model used in the process. The incorrect choice or assumption about the velocity model can produce deleterious effects on the final resultant image. If the reflector is flat, the reflection point will be located directly beneath the shot/receiver station, and the record section displays the event in its true position, plotted in time rather than depth (Robinson & Coruh, 1988).

However, if the reflector is not flat, the reflection point will not lie directly beneath the shot/receiver position, and the true position of the reflector will differ from its apparent position (Yilmaz, 2001). Figure#24 shows the subsurface dipping reflector's response.



Figure#24: Seismic response form a dipping reflector, the recorded surface gives the apparent dip of the reflector surface (Rehman, 1989)

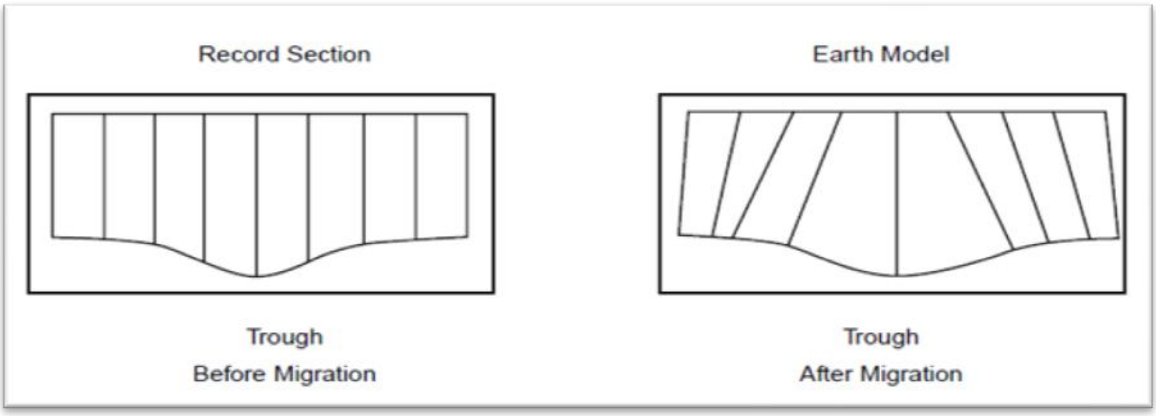
Therefore, migration is a tool used in seismic processing to get an accurate picture of the subsurface layer. It involves geometric repositioning of recorded signals to show a boundary or other structure, where it is being hit by the seismic wave rather than where it is picked up. Now, not only the position but also the dip angle ca1n be incorrectly imaged by vertically plotting (Rehman, 1989).

6.14.1. Important Features of Migration

Following are the important features of migration (Rehman, 1989):

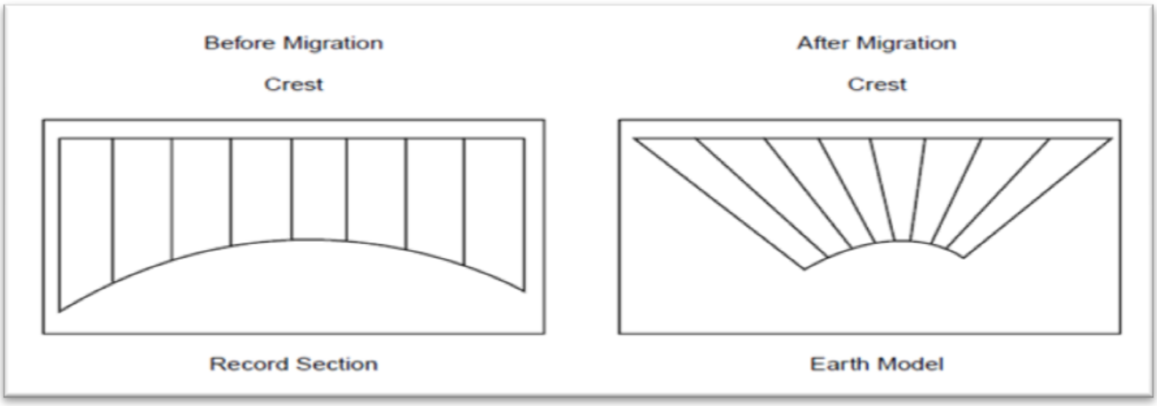
- Moves events into their correct sub-surface position - moves events up dip and ray paths normal to the reflector
- Shortens the lateral extent of events
- Adjusts to true dip - steepens the angle of dip

- **Syncline -** After migration a syncline is broader, the lowest point is flat and does not move, and closure is the same or larger(Figure#25).



Figure#25: Syncline before and after migration. ((Sadi, 1980)

- **Anticline -** Migration of anticline narrows the lateral extent and reduces dip of isolated anticlines, equal or less closure. The crest of the anticline does not move



Figure#26: Anticline before and after migration. (Sadi, 1980)

- Collapses point diffractions
- Unities bow tie feature of deep syncline
- Improves horizontal resolution by collapsing the Fresnel zone, thus giving a more accurate subsurface picture.

6.14.2. Different Flavors of Migration

There are a wide variety of choices available for migration, from the very basic dip moveout (DMO) which offers kinematic pre-stack correction to the more sophisticated pre-stack depth migrations. Each caters for various degrees of structural complexity but also carries with it an increase in compute time. It is advisable when opting to perform a migration to assess the exact type that is needed and balance cost with potential improvements in image quality.The following are in increasing order of complexity: (Kearly & Brooks, 1988).

- Pre-stack partial migration (DMO)
- 2D post-stack time migration
- 2D post-stack depth migration (secs to minutes on a pc)
- 2D pre-stack time migration
- 2D pre-stack depth migration
- 3D post-stack time migration
- 3D post-stack depth migration
- 3D pre-stack time migration
- 3D prestack depth migration (6-8 week turnaround for a block)

6.15. DISPLAY

At the end of the processing sequence, and sometimes at the intermediate stages, it is necessary to reconvert the digitized data to analog format so that they can be displayed and then examined visually. There are several methods of plotting digital data in analog form. The most common method is to pass the digital trace through a sample and hold device, which produces an output voltage proportional to each sample and which holds the voltage constant until the next sample arrives. This procedure produces a "stair step" type of analog output, which can then be smoothed into a continuous trace by passage through a low pass filter.

Chapter # 7

SEISMIC DATA INTERPRETATION

7.1. INTRODUCTION

Interpretation is the transformation of seismic data into structural and stratigraphic picture by processing issue, contouring of subsurface horizons and further depth conversion by applying some suitable velocities. Thus threading together all the available geological and geophysical information including the seismic and then integrating them all in a single picture can only give a picture closer to the reality. The influence of varying geological conditions is eliminated along the profile to transform the irregular travel times into acceptable subsurface model. This is very important for confident estimation of the depth and geometry of the bedrock or target horizon (Dobrin, M.B., & Savit, C.H., 1988).

The main purpose of seismic reflection survey is to reveal as clearly as possible, the structures and stratigraphy of the subsurface. The Geological meaning of seismic reflection is simply an indication of an acoustic boundary where we want to know that whether this boundary makes a fault or a stratigraphic contact with any other boundary. We want to distinguish the features that are not marked by the sharp boundaries. Geologists ordinarily group the sequence of sedimentary rocks into units called "Formations". These formations can be described in term of age, thickness, and lithology of the constituent layer. To distinguish different formations on the basis of seismic reflections is an important question in interpreting seismic data that may be structural, stratigraphic or lithological (Robinson, E.S., & Coruh, C., 1988).

To distinguish different formations by means of seismic reflection is an important question in interpreting seismic reflection data. For this purpose the data is correlated with the well data and geology of the area under observation, which is already known (previous literature). The well data provides links between lithology and seismic reflections. The reflector identification is the next stage by which the actual interpretation starts and it establishes a stratigraphic frame block for the main interpretation.

The seismic record contains two basic elements for the interpreter to study. The first is the time of arrival of any reflection from a geological surface. The actual depth to this surface is the function of the thickness and velocity of over lying rock layers. The second is the shape of the reflection, which includes how strong the signal is what frequency it contains, and how the frequencies are distributed over the pulse this information can often be used to support the conclusions about the lithology and fluid content of the seismic reflector being evaluated.

Extracting the geological structures from seismic data, such as fold and faults are referred as structural interpretation (Dobrin, M.B., & Savit, C.H., 1988). On the other hand, extracting non-structural information from seismic data is called, "Seismic Facies Analysis".

There are two main approaches for the interpretation of seismic section:

- Stratigraphic Analysis
- Structural Analysis

7.1.1. Stratigraphic Analysis

Stratigraphic analysis involves the subdivision of seismic sections into sequences of reflections that are interpreted as the seismic expression of genetically related sedimentary sequences. The principles behind this seismic sequence analysis are of two types.

Firstly, reflections are taken as chronostratigraphical units, since the type of rock interface that produce reflections are strata surfaces and unconformities, by contrast the boundary of diachronous lithological units tend to be transitional and not to produce reflections.

Secondly, genetically related sedimentary sequences normally comprise the set of concordant strata that exhibit discordance with underlying and overlying strata. According to Dobrin and Savit, throughout the history of the reflection method, its performance in locating hydrocarbons in stratigraphic traps has been much less favourable than in finding structurally entrapped oil and gas.

The success of seismic reflection method in finding stratigraphic traps varies with the type of trap involved. Most such entrapment features are reefs, unconformity, disconformity, facies changes, pinch-outs and other erosional truncations. Some of the parameters used in seismic stratigraphic interpretation are;

- Reflection Configuration
- Reflection Continuity
- Reflection Amplitude
- Reflection Frequency
- Interval Velocity
- External Form

7.1.2 Structural Analysis

It is the study of reflector geometry on the basis of reflection time. In structural analysis, the main objective is to search out traps containing hydrocarbons. The most common structural features associated with the oil, are anticlines and faults. In Balkassar area compressional regime resulted in the formation of thrust faults. Most structural interpretation uses two-way reflection times rather depth. And time structural maps are constructed to display the geometry of selected reflections events.

The interpretation is the last step of the seismic study of an area. In this, the final processed seismic lines are interpreted in order to construct a geological model of the area which describes areas which are favorable for hydrocarbon accumulations. This outcome is achieved through a series of processes and techniques, which will be discussed later. There are two main approaches for the interpretation, namely:

1. Structural Interpretation
2. Stratigraphic Interpretation

In structural interpretation, the reflection geometry is studied which mimics the structures present in the subsurface, and this geometry is made so that traps are formed. These traps maybe formed by faults, folds, anticlines, etc.

In the stratigraphic interpretation, areas favorable for hydrocarbon accumulation are located which are not formed by the deformation, but in this case the traps are formed by the variation in the deposition of sediments. These traps are marked by pinchouts, unconformities etc.

7.2. INTERPRETATION OF AVAILABLE SEISMIC SECTIONS

The study area falls in a compressional regime and is dominated by thrust faults. Salt layer over the Precambrian basement has acted as a decollement surface, thus resulting in the formation of faults-bounded anticlinal feature, favorable for the accumulation of hydrocarbons.

Available Data

Five migrated seismic lines (hard copies), navigation data of seismic lines, and formation tops form the well Balkassar-Oxy-01 were available for this project. Available seismic lines are as follows:

PBJ-1 (dip line, SE-NW)

PBJ-2 (dip line, SE-NW)

PBJ-3 (dip line, SE-NW)

PBJ-4 (dip line, SE-NW)

PBJ-9 (strike line, NE-SW)

Later, mapping showed that these lines were not sufficient to delineate the prospect completely. So, six more lines (migrated seismic sections) were added to the project for this purpose. Names of these lines are:

PBJ-5 (dip line, SE-NW)

PBJ-6 (dip line, SE-NW)

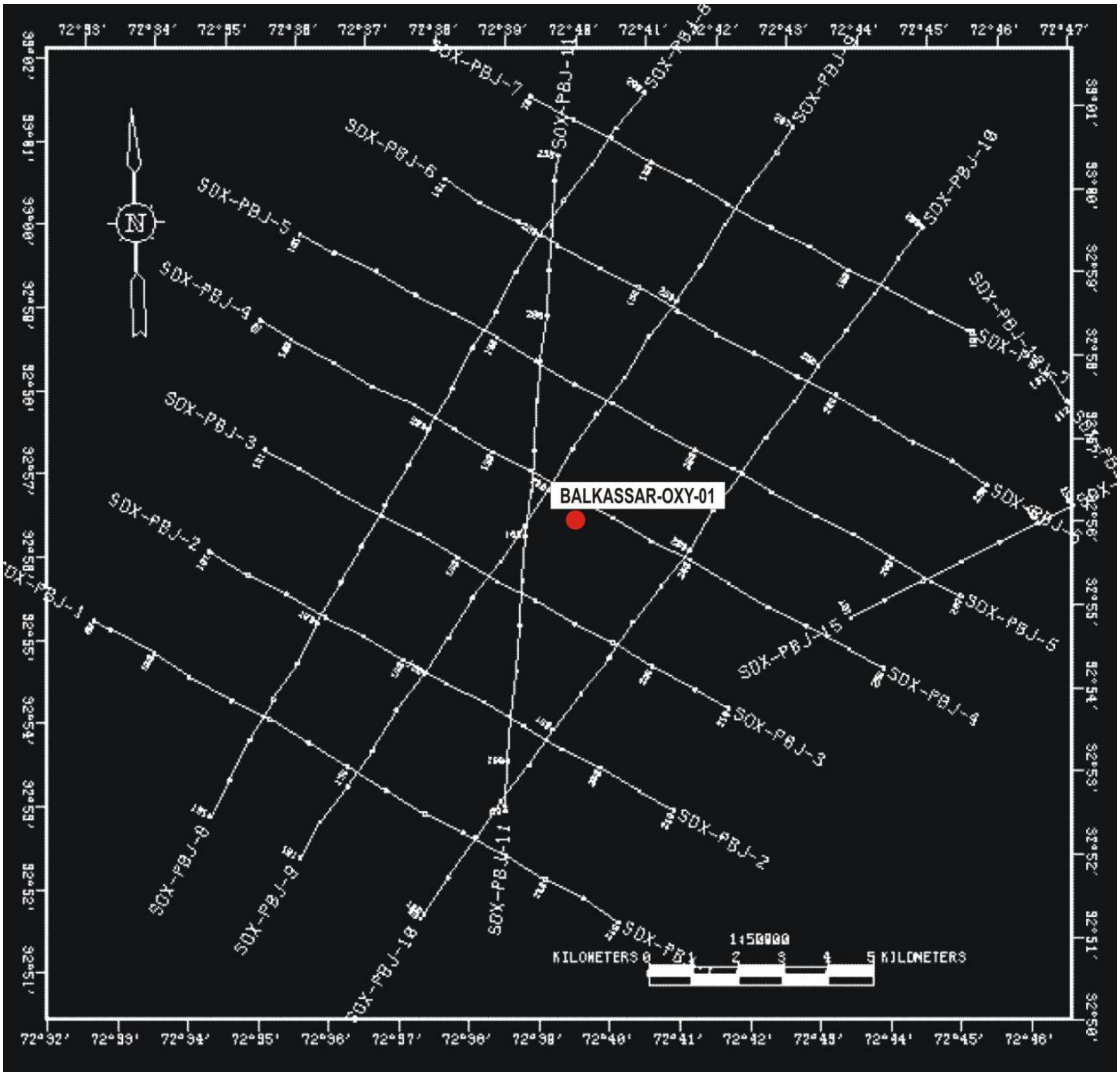
PBJ-7 (dip line, SE-NW)

PBJ-8 (strike line, NE-SW)

PBJ-10 (strike line, NE-SW)

PBJ-11 (oblique to the main dip and strike direction, N-S)

Quality of available seismic sections can be regarded as fair to good (Figure#28 to 38). However, fault-cuts were not clearly visible. A basemap showing the seismic lines and Balkassar-Oxy-01 is displayed on the next page (Figure#27)



Figure#27: Shotpoint base map of the projected area.

Interpretation of Balkassar area involved following steps:

1. Marking of prominent reflectors
2. Tracing the marked reflectors on all the available seismic lines
3. Identifying the faults, and then posting them on the base map
4. Reading the time and then making the TWT contour maps
5. Making Depth contour maps.

6. Making of 3D time and depth surfaces
7. Preparation of models of seismic lines.

7.2.1. Marking of prominent reflectors

The interpreter should choose that reflections and unconformities to be mapped which fully describe the geology and hydrocarbon potential of the area. If the area is relatively unexplored, all reflections at sequence boundaries, and those illustrating special geological features should be picked and carried throughout the grid. For specific problems, where only one level may be of interest, it is still advisable to pick additional reflectors, both above and below the target level, even though not be mapped (Badley, 1985).

In this dissertation the above mentioned approach was used. Three reflectors were marked on the seismic line PBJ-4 which is passing close to well Balkassar-Oxy-01 (Figure#311). These reflectors were marked with three different pencil colors i.e. yellow, pink and green. Basement was then marked with red color as an additional reflector. All four horizons were picked on the seismic sections on the basis of typical seismic signatures i.e. an abrupt acoustic impedance contrast.

7.2.2. Tracing the marked reflectors

Marked horizons from the line PBJ-4 were tied and then traced to the other available seismic lines. Few mistie issues were observed during this process. In order to resolve this issue, only one strike line (PBJ-9) was used for the purpose of seismic-to-seismic tie. Horizons on all dip lines were adjusted according to this line. Remaining three strike lines were ignored in the mapping process to avoid discrepancies in time and depth values of horizons. Figure#39 & 40 show seismic-to-seismic tie between strike and dip lines.

Few problems regarding continuity and thickness changes were encountered during marking and tracing of horizons from one line to another. Traces on some portions of seismic sections appeared to be mixing up thus masking the continuity of horizons. These problems normally arise due to subsurface structural changes, faults or abrupt lithological changes or presence of different types of noises during seismic acquisition that cause distortion of signals.

7.2.3. Reflector identification

The first step when starting the interpretation process is to judge the reflections and unconformities, if present, on the seismic time section. Those reflectors are selected which are real, show good character and continuity, and can be followed throughout the area (Badley, M.E., 1985).

Identification of horizons becomes easier if there are wells in or around a particular area. Balkassar is an oil field with first well being drilled by Attock Oil Company in 1946. The structure of the field is a gentle anticline, with two producing horizons, both of Eocene limestone.

Marked horizons were identified on the basis of data of Balkassar-Oxy-01 well. Moreover, study reports and geology of surrounding areas proved helpful. Horizons marked on seismic sections were identified as under:

- Yellow horizon was identified as **Top Eocene (Sakesar/ Chorgali).**
- Pink horizon was identified as top **Lokhart Limestone.**
- Green horizon was identified as top **Khewra Sandstone.**
- Red horizon was identified as **Precambrian Basement.**

The reflectors of top Eocene (Sakesar/Chorgali Limestone) and Pre-Cambrian basement were picked on the seismic sections on the basis of typical seismic signatures. As discussed earlier, well data (Balkassar Oxy-01) was also incorporated to confirm the marked horizons. Eocene horizon has a sharp contrast with the overlying Murree Clays of Miocene age, thus making it easier to correlate on different seismic lines. In the same manner, basement gives a sharp acoustic impedance contrast because of overlying salt layer. One finds an almost reflection free pattern on seismic sections below the crystalline basement.

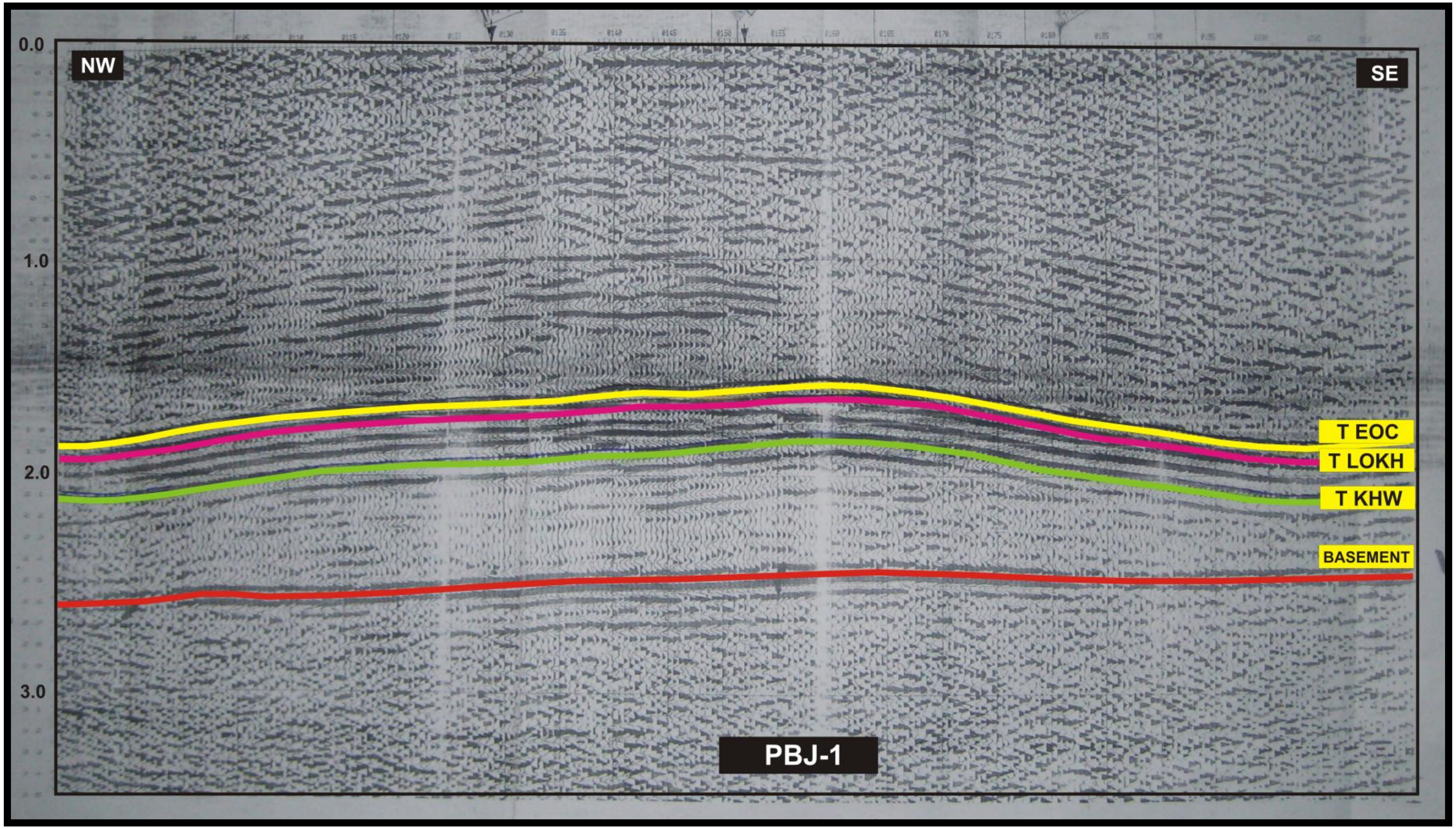
7.2.4. Fault Identification

Fault identification on seismic sections plays a vital role in understanding the major structural style in an area.

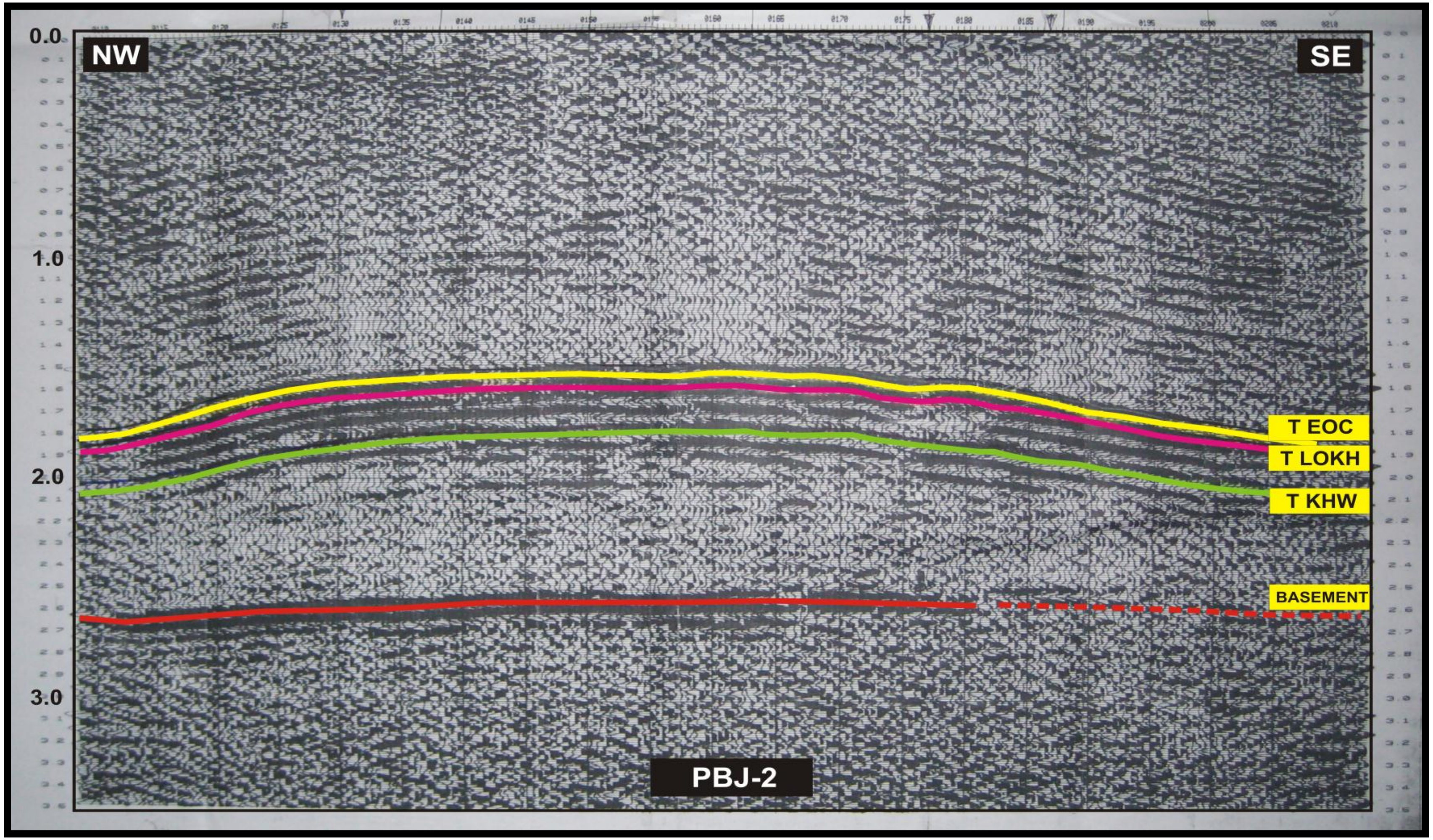
Available seismic lines portray a pop-up structure bounded by two NE-SW running thrust faults, named as fault A and fault B respectively. Fault A, dipping in SE is identified as a back thrust. It has a throw of more than 500 msec on some dip lines (figure#28 to 34). Fault B, dipping in NW direction is the main thrust in the project area however it is not completely covered by available seismic lines. For this reason, it has not been used in the mapping process. So, only the Back thrust was marked on basemap and later used in mapping of different horizons. Seismic lines show that the main thrust is ultimately merging with the basal detachment (salt decollement). Salt Range formation is behaving as a zone of decollement between underlying rigid basement and overlying platform sequence. Both thrust faults have been marked with black color on seismic lines (Figure#28 to Figure#38).

In a Back thrust displacement is in an opposite direction to that of the main thrust propagation. Back thrusts are thought to form as a result of layer-parallel shortening in a late stage of thrust sequences. Layer-parallel shortening is the homogeneous strain which is developed in a layered rock when shortening occurs parallel to the layering.

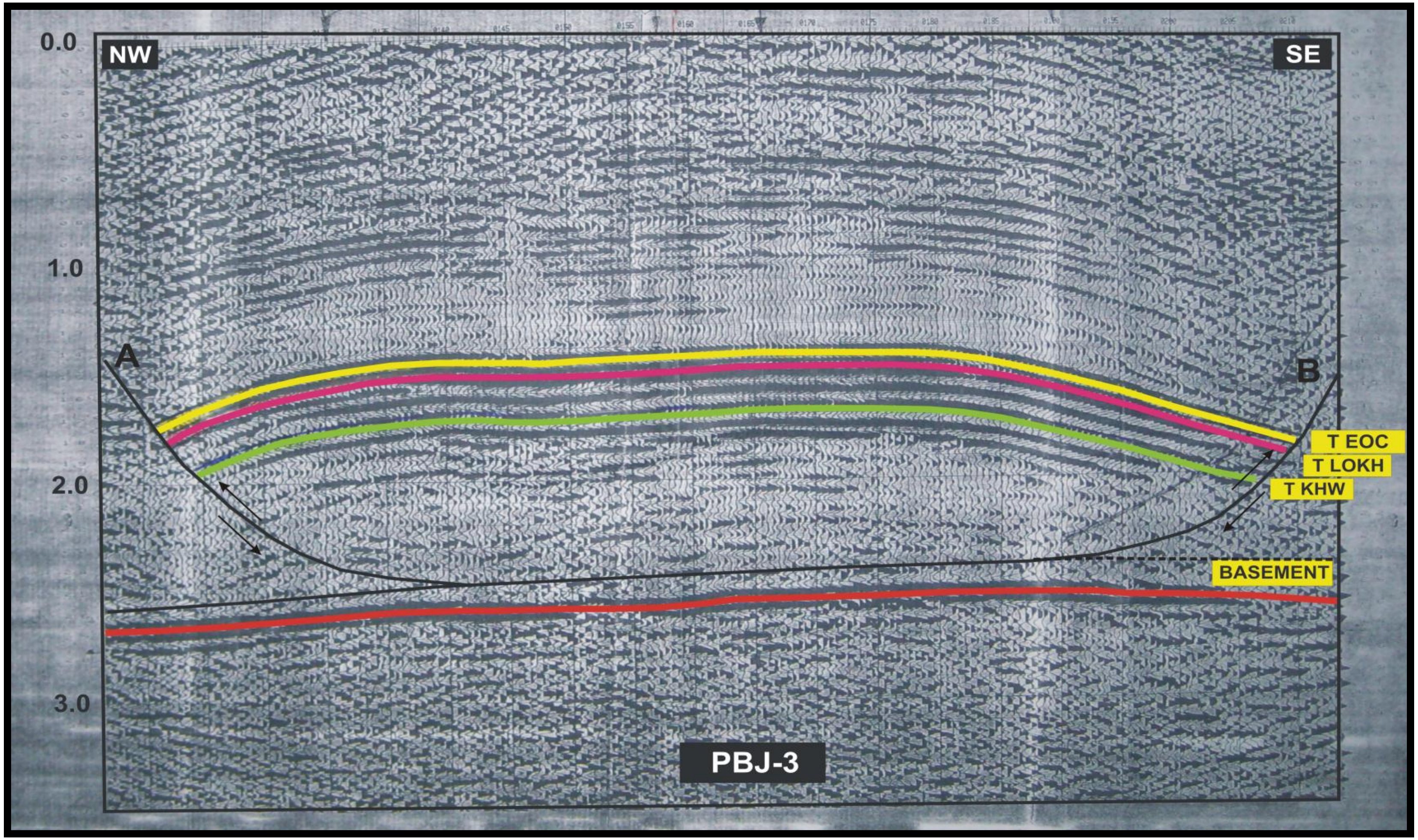
After marking the four horizons and main faults, seismic sections were scanned and edited in *Corel Draw 12*. Small faults were ignored to simplify the contouring of horizons later. These interpreted seismic sections are displayed as under:



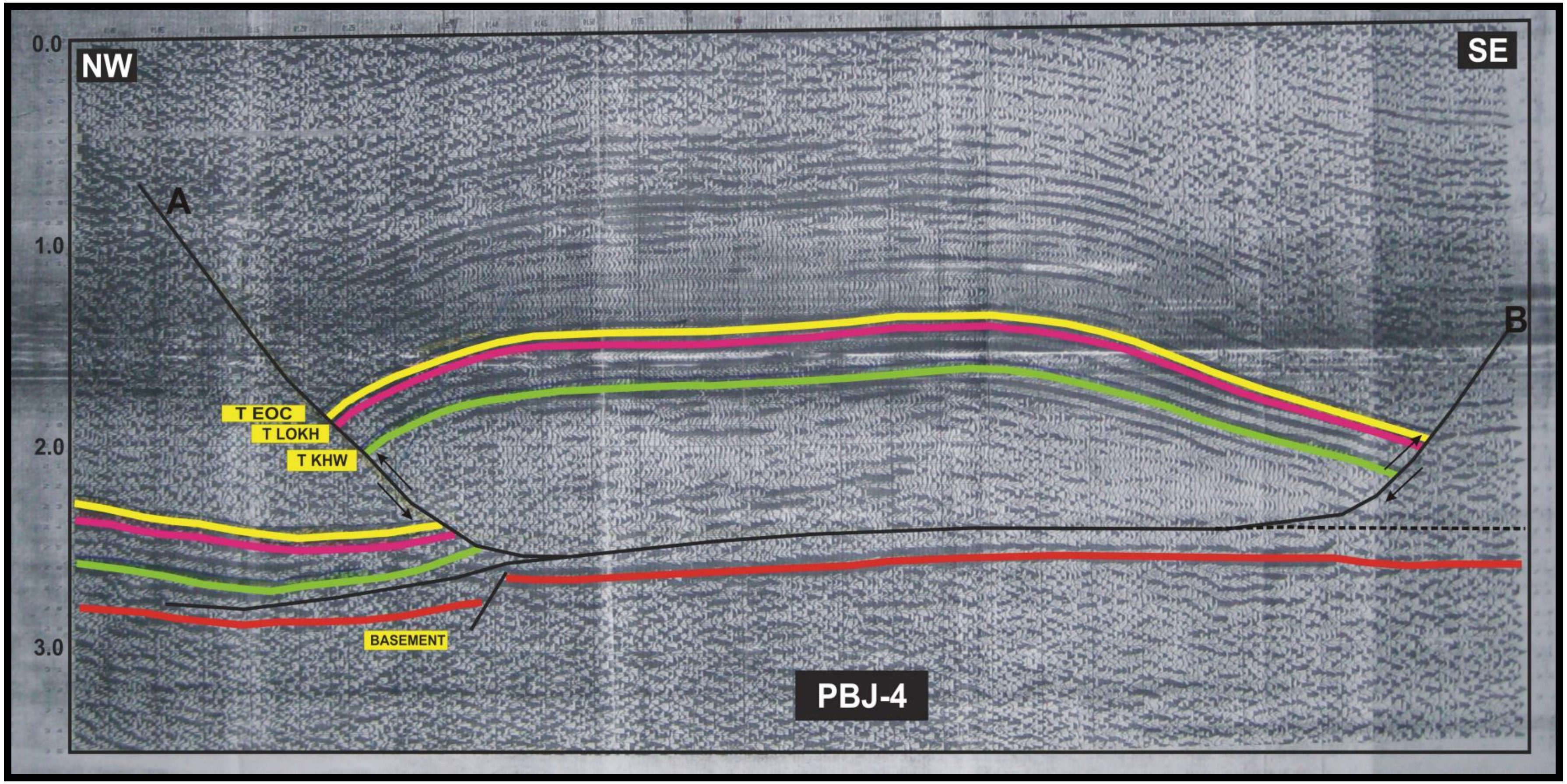
Figure#28: Interpreted seismic section, PBJ-1



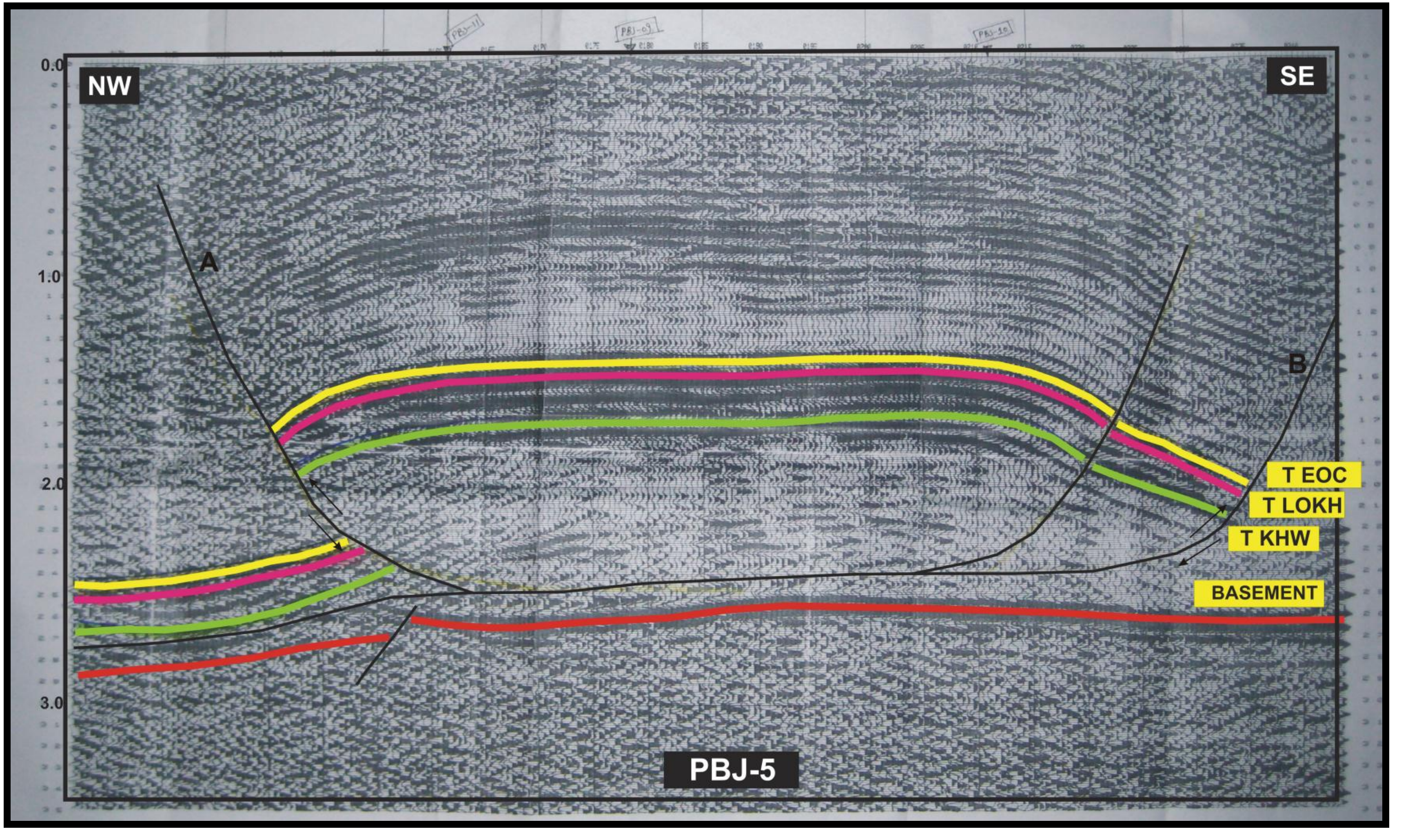
Figure#29: Interpreted seismic section, PBJ-2



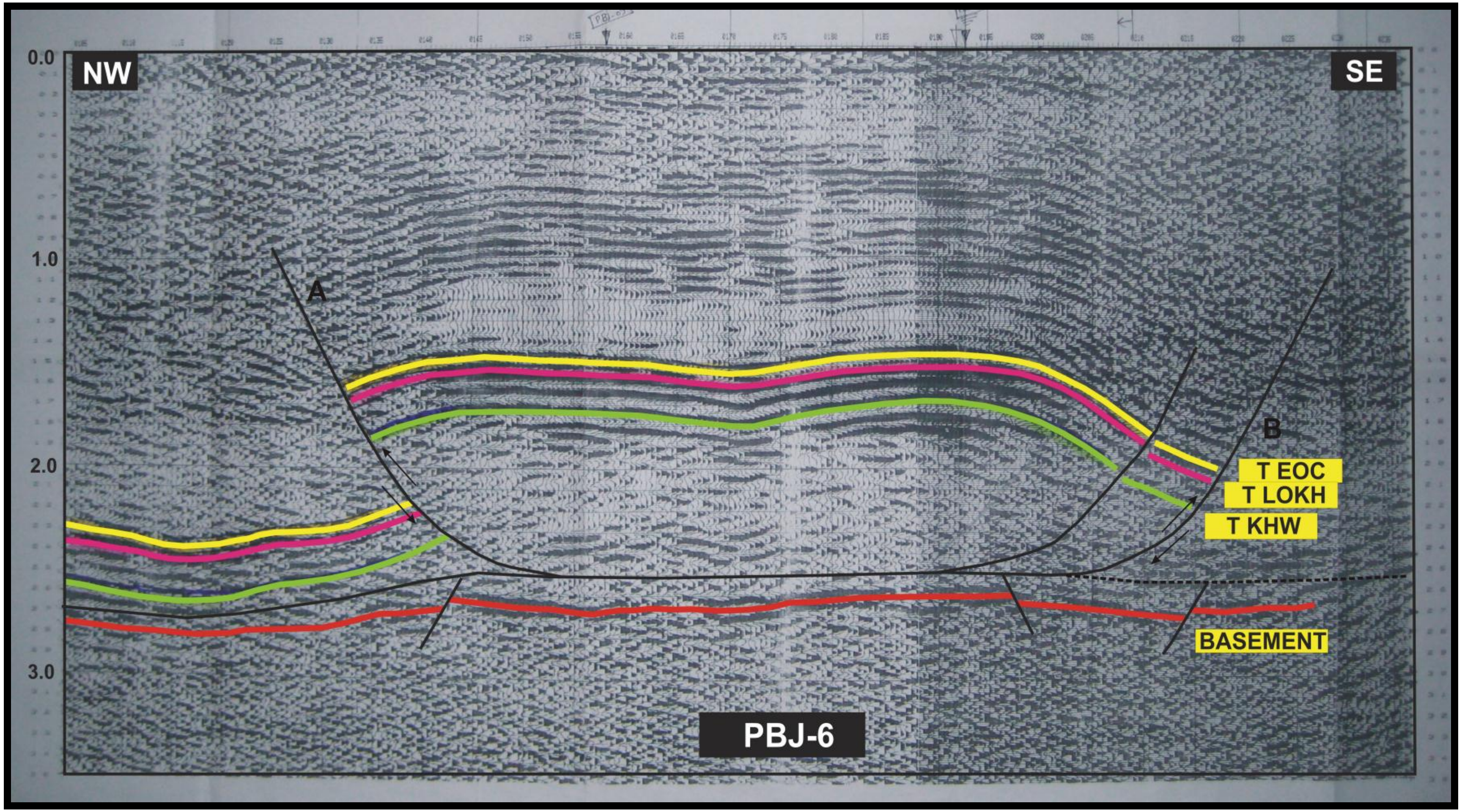
Figure#30: Interpreted seismic section, PBJ-3



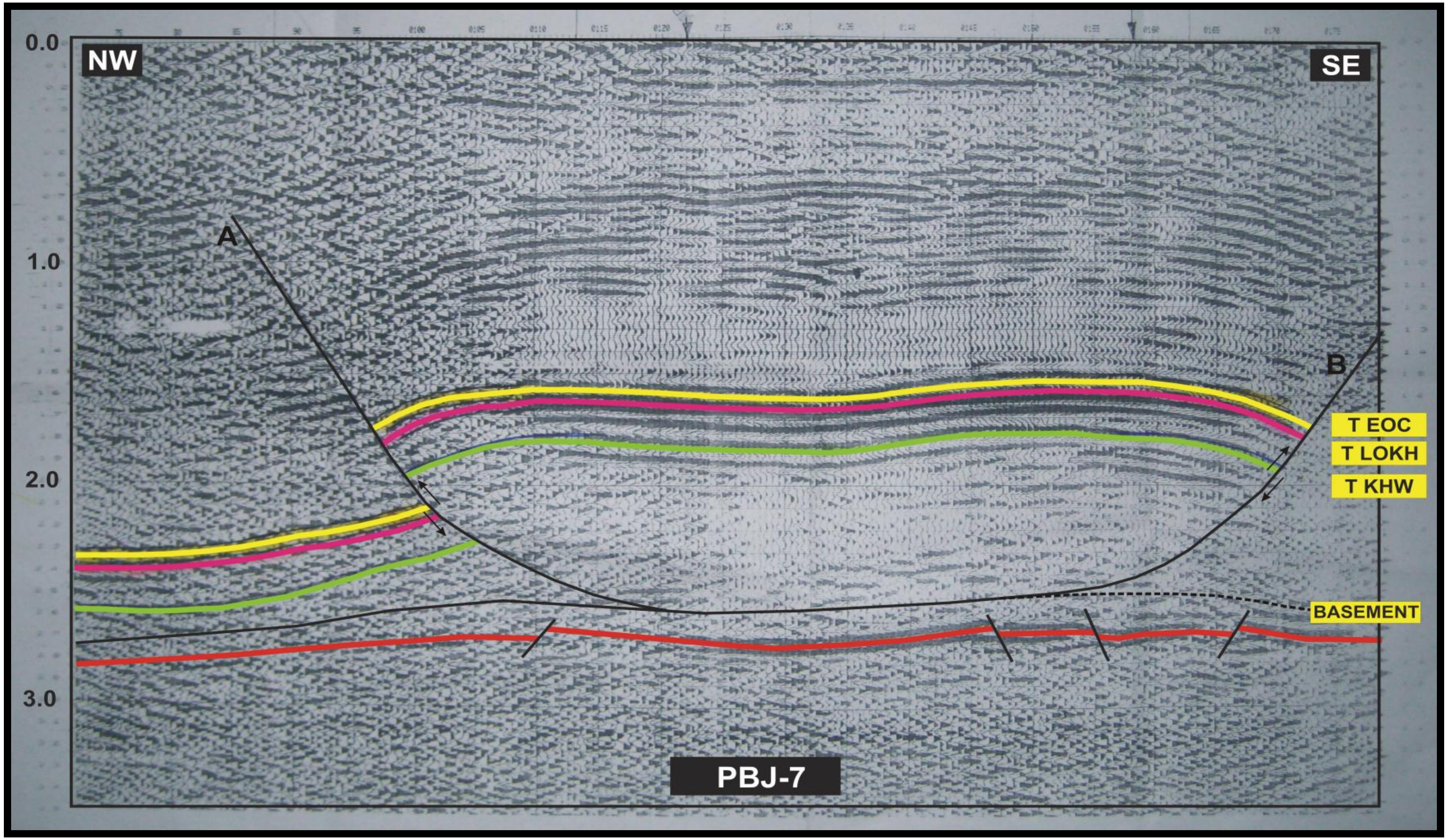
Figure#31: Interpreted seismic section, PBJ-4



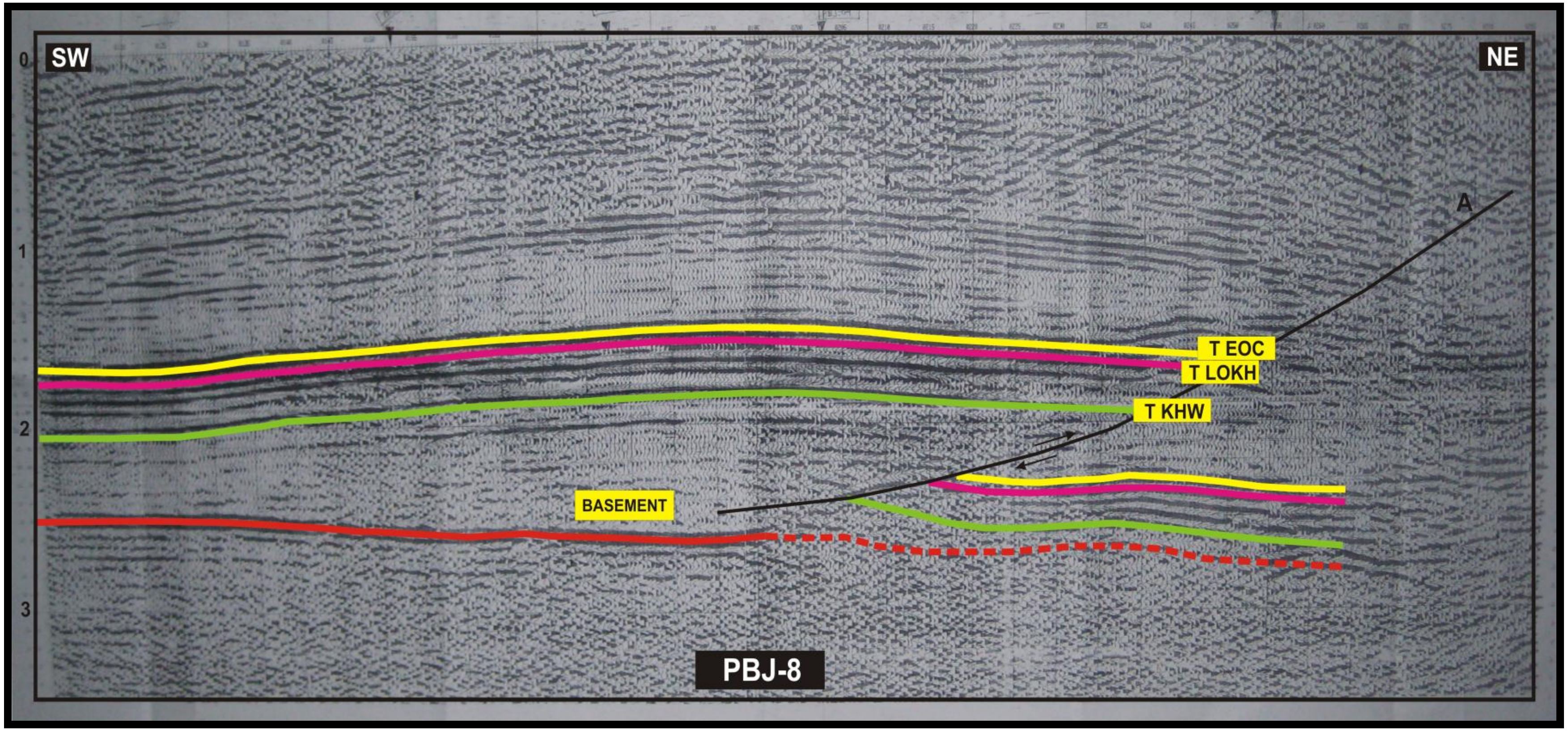
Figure#32: Interpreted seismic section, PBJ-5



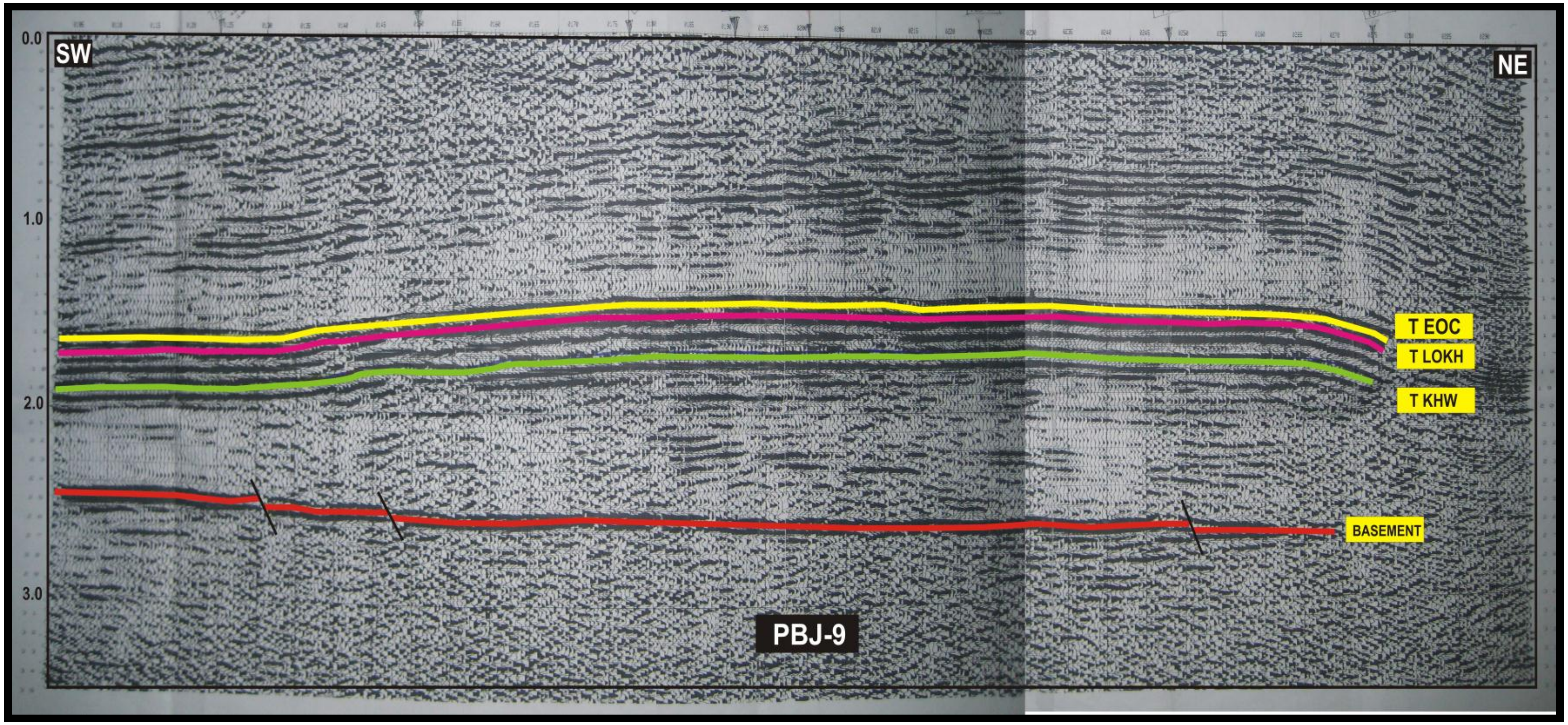
Figure#33: Interpreted seismic section, PBJ-6



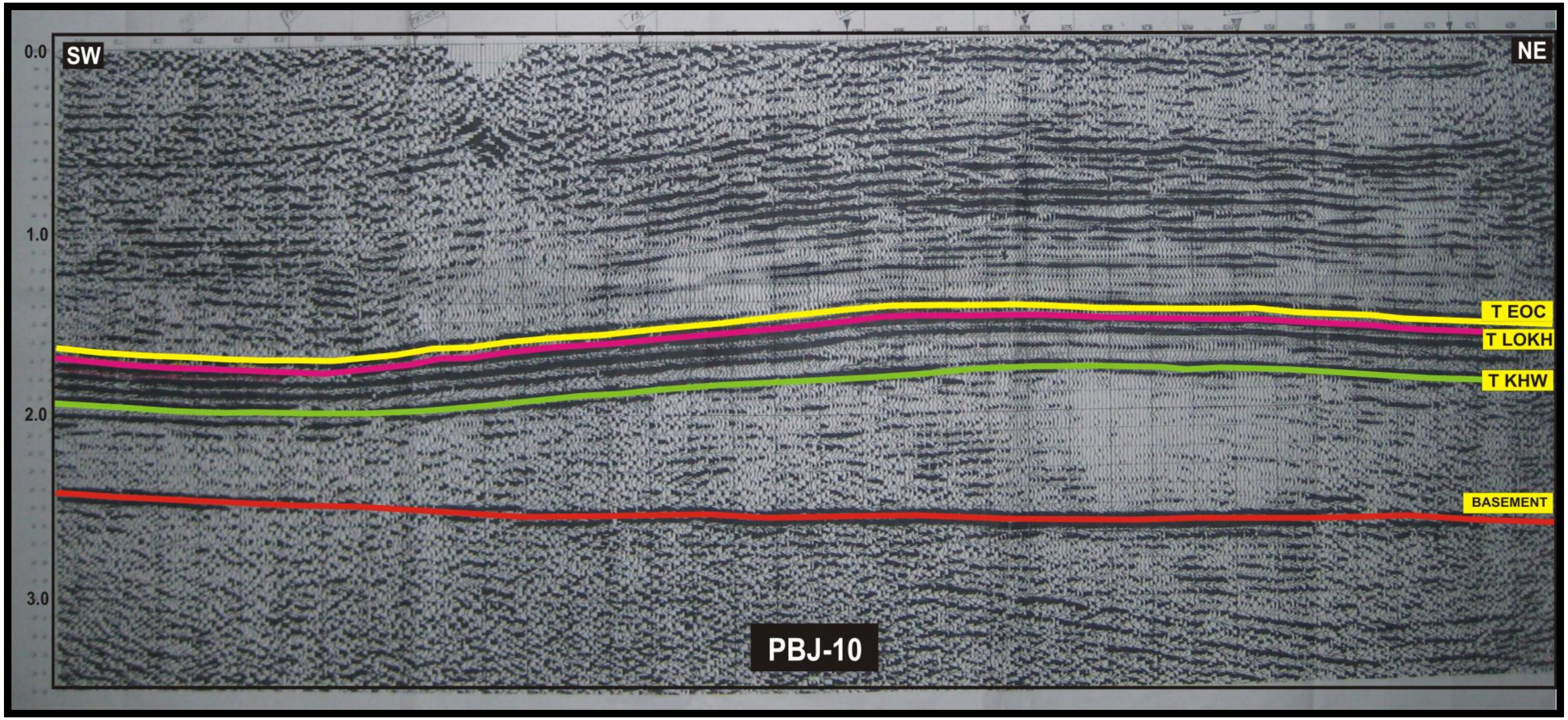
Figure#34: Interpreted seismic section, PBJ-7



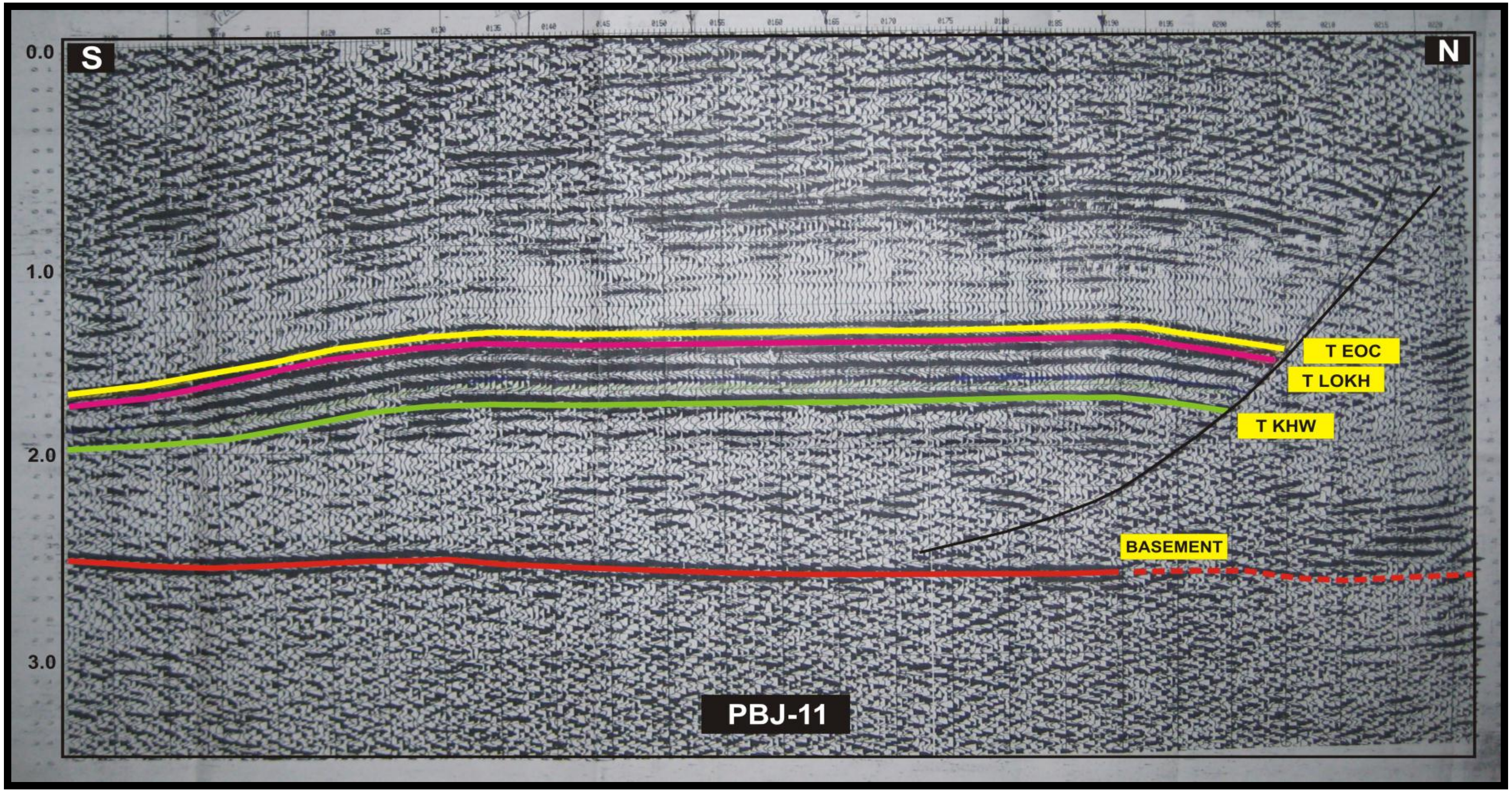
Figure#35: Interpreted seismic section, PBJ-8



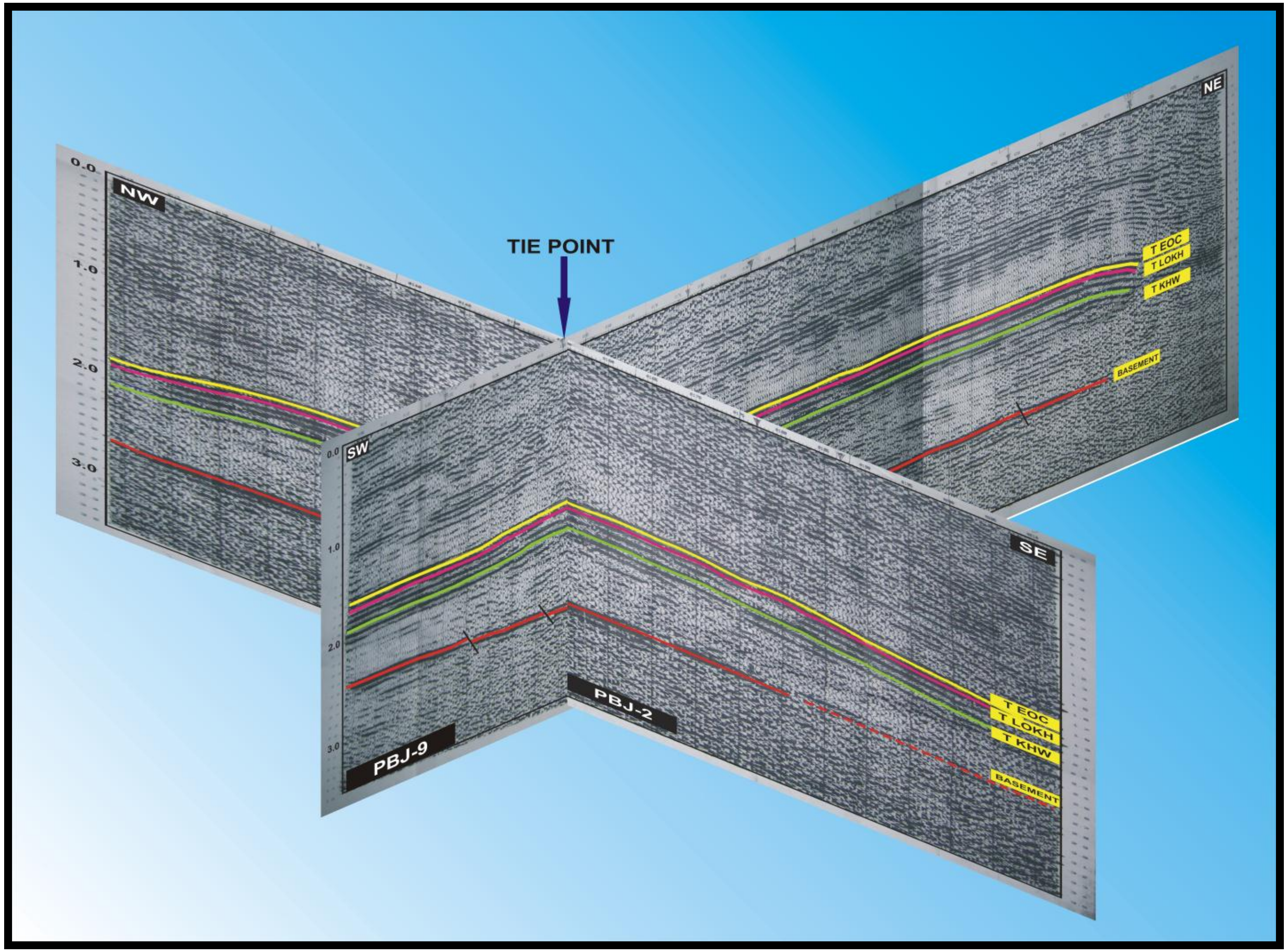
Figure#36: Interpreted seismic section, PBJ-9



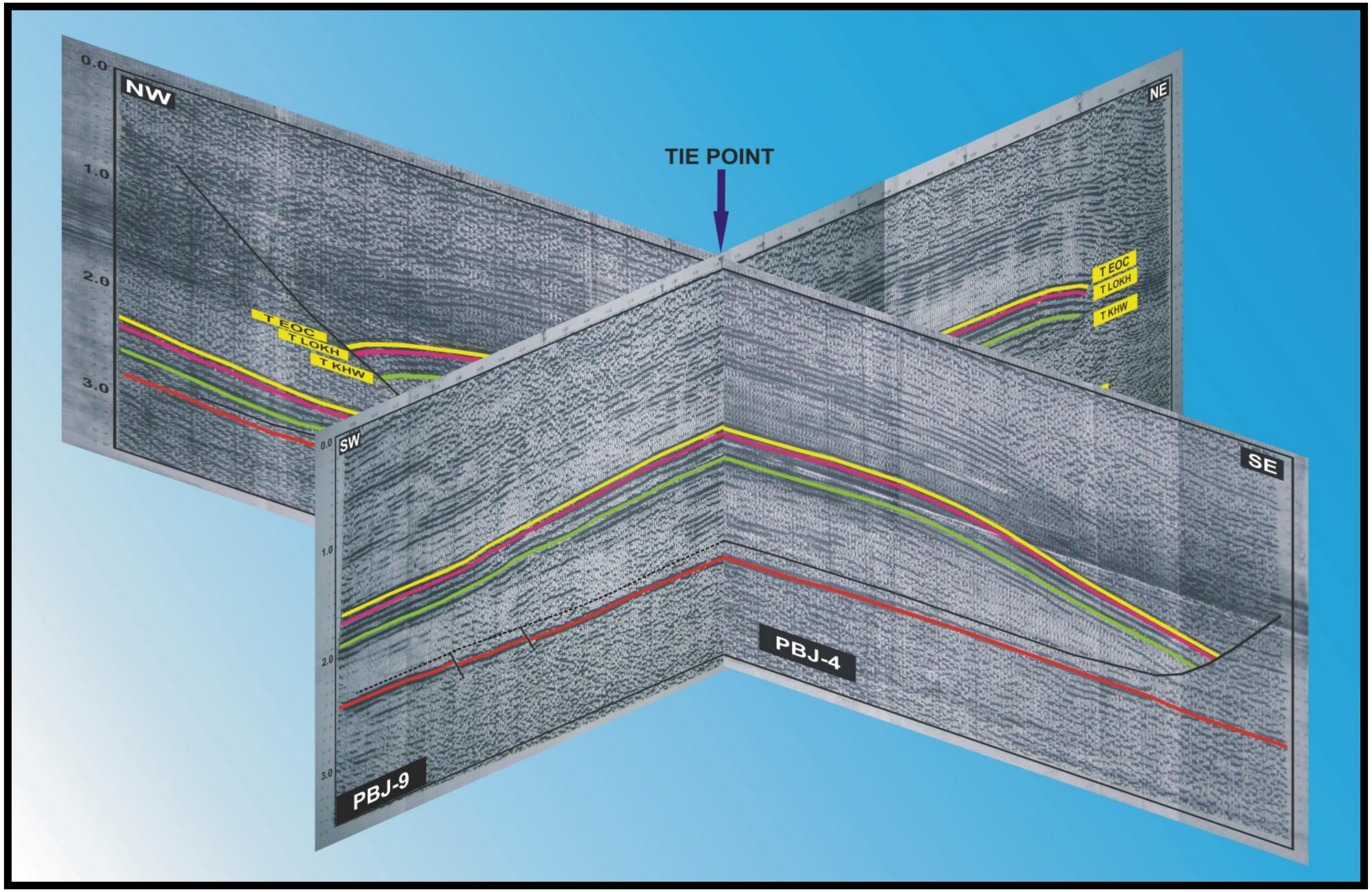
Figure#37: Interpreted seismic section, PBJ-10



Figure#38: Interpreted seismic section, PBJ-11



Figure#39: Seismic tie between lines PBJ-9 & PBJ-2, showing a four-way closure



Figure#40: Seismic tie between lines PBJ-9 & PBJ-4, showing a four-way closure

7.2.5. Two Way Time Contour Maps

Time contour maps give a reliable picture of the subsurface if drawn properly. Depth contour maps are not as common as time contour maps. Mostly, the depth estimates are made with the help of TWT contour maps in a particular area. However, depth contour maps can give an extra edge when there's a good velocity control. Contouring can be a challenging job when done over areas of extensive faulting or mapping small features in stratigraphically complex regimes. Mapping needs a good knowledge of geology of the area. When done manually, contouring interval should be appropriate so that the smaller features (channels, tilted fault blocks, horsts etc) are not missed. In case of Balkassar area contouring was not a difficult task because of the large subsurface structure that was quite evident on available seismic lines.

Except the basement (red horizon), TWT contour maps were generated on picked horizons. Firstly, contouring was done manually and then with the help of software to check for any possible errors.

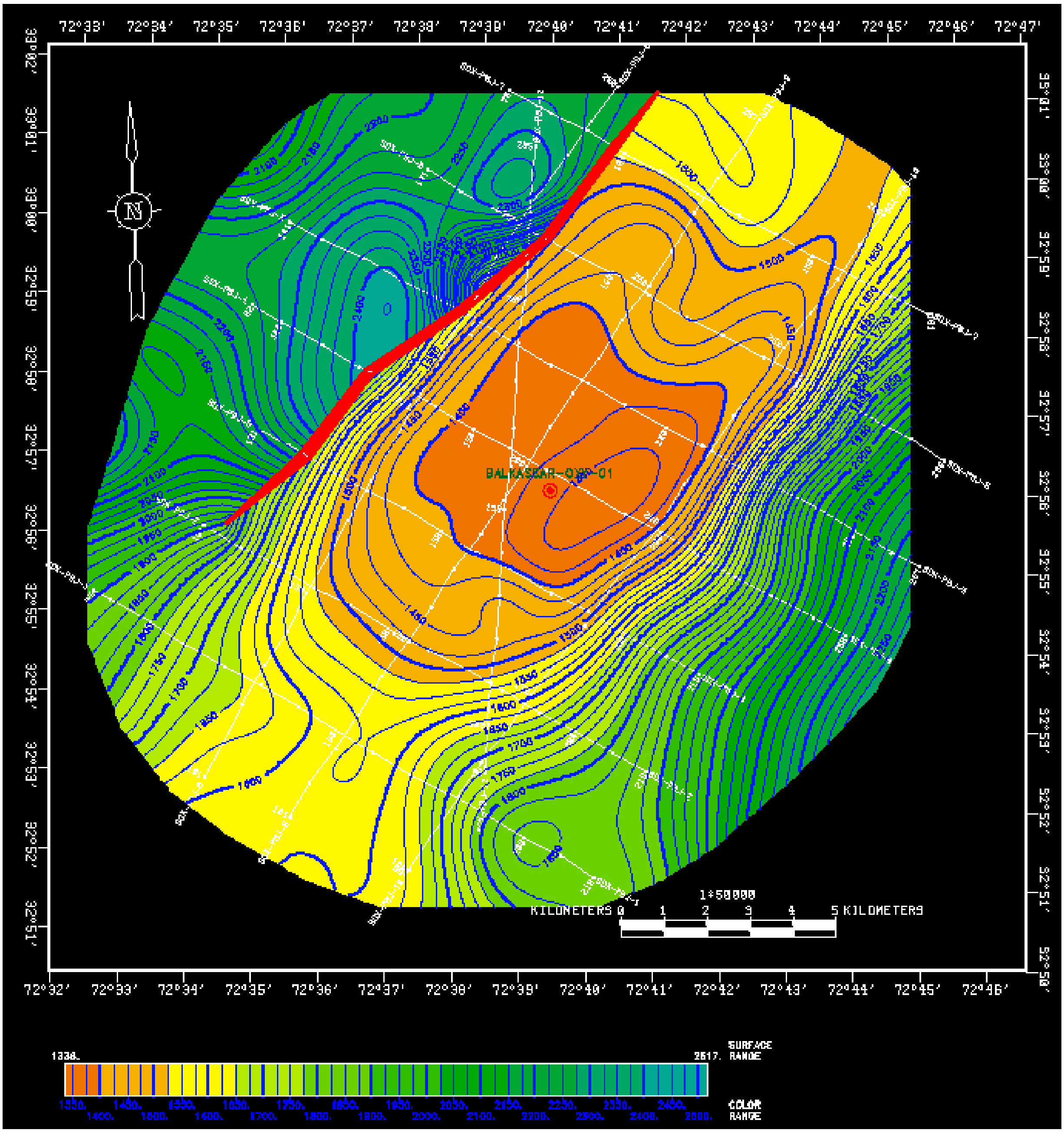
After marking the horizons and faults on seismic sections next step was to read the horizons' time. Time values were picked carefully and entered as Z-values in available navigation file.

When using software, first step is to grid the data in order to appropriately distribute the time values (depth values in case of Depth Contour Maps) throughout the project area. ***Surfer 8.0*** was used for griding purpose and ***Kriging*** was selected as the griding technique out of many choices available. Kriging was selected because it smoothly distributed the time values without creating any pseudo closures. Created Grids were then imported to ***3DFieldPro*** for contouring purpose. Zoomed images of the maps are also included in this section to have a better look at the structure

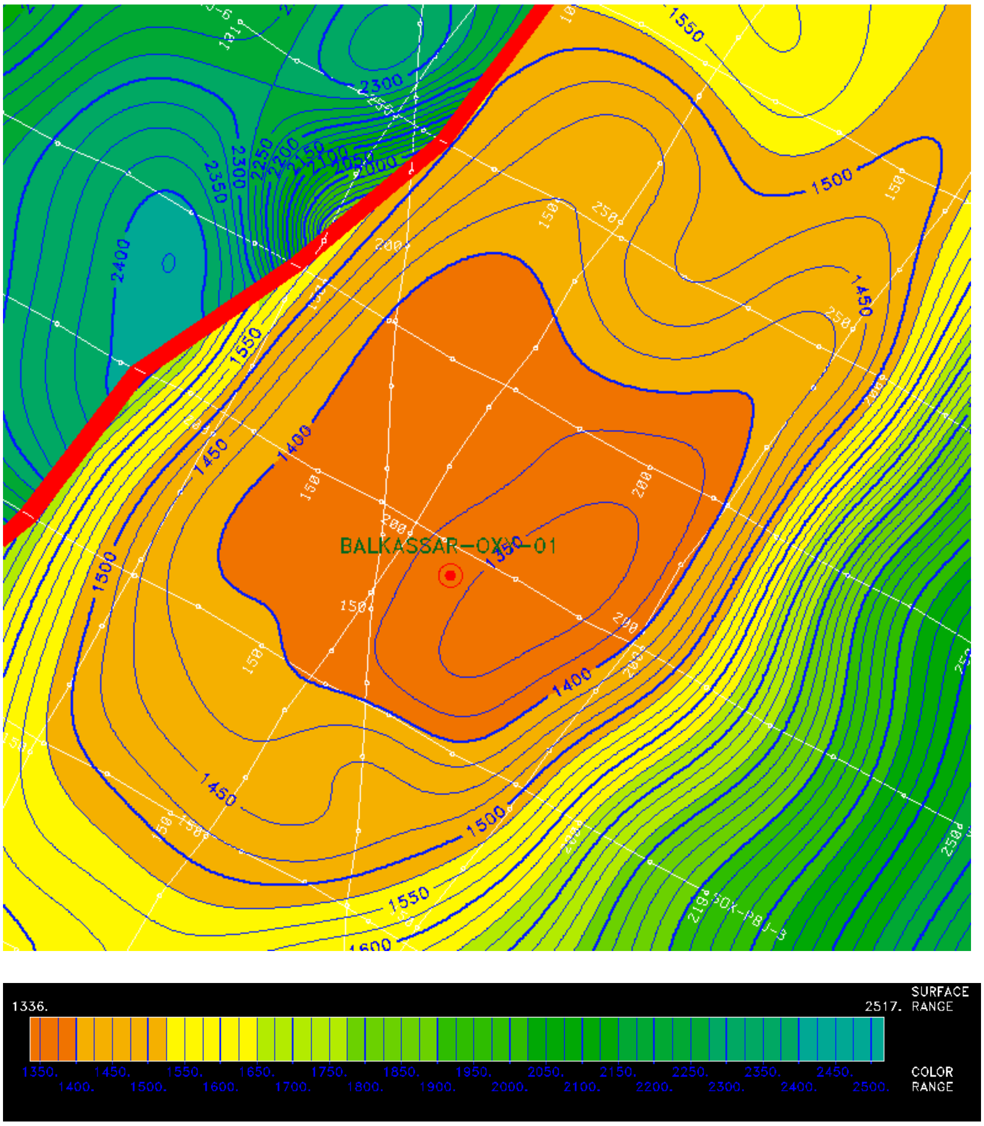
A brief description of TWT contour maps created on different levels is as under:

7.2.5.1 Top Eocene

Top Eocene, marked with yellow color on available seismic lines is the main target horizon in the project area. Contour interval was selected to be 25 msec. Figure#41 & 42 show TWT contour map of top Eocene.



Figure#41: TWT Contour Map of Top Eocene



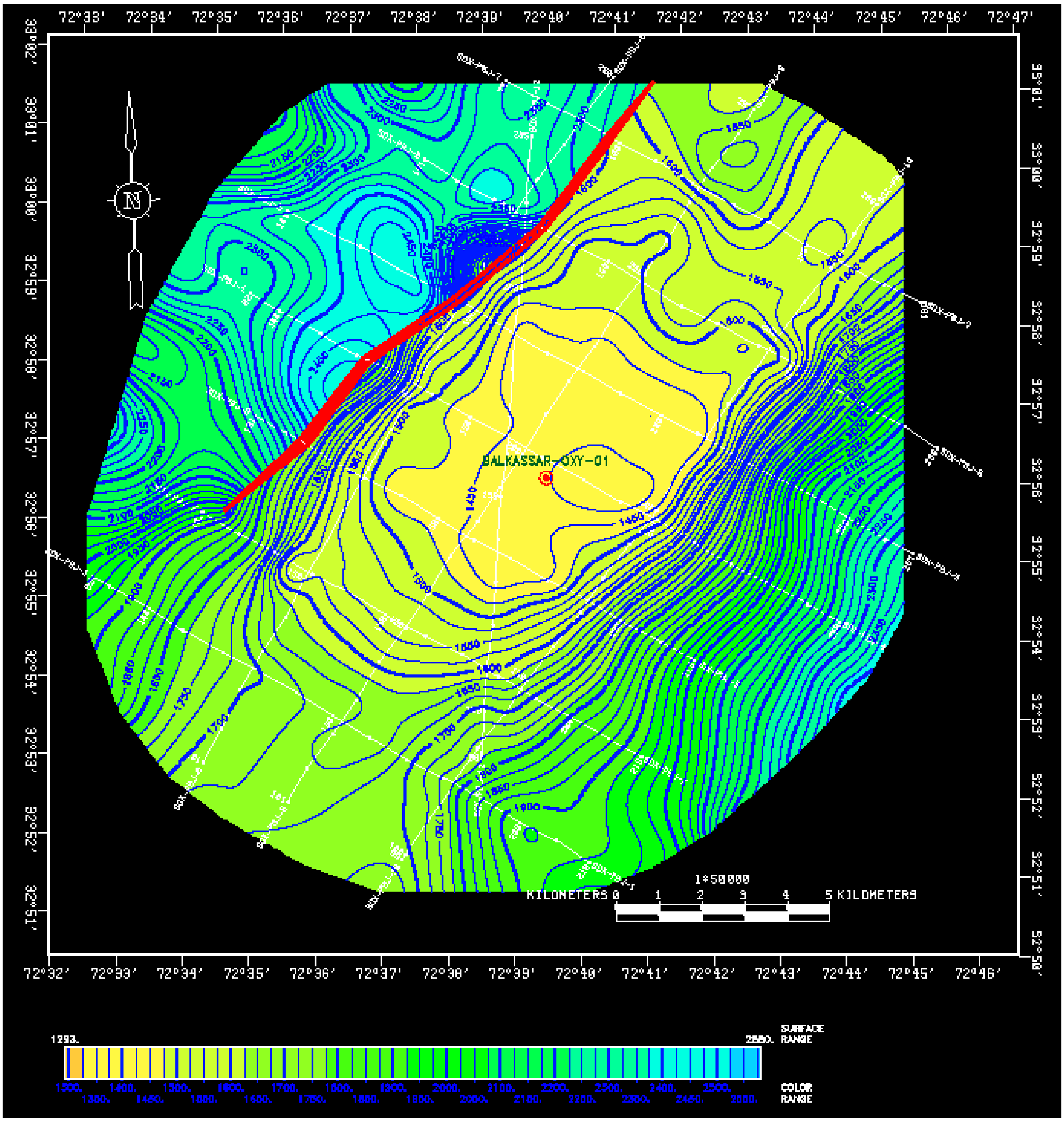
Figure#42: TWT Contour Map of Top Eocene (zoomed)

Figure#41 & 42 show a large anticline with a closure of 150 milli seconds. Area of this structure was calculated to be 70 square km approx. Red line on both figures show the Back Thrust **A** that was discussed in the earlier sections. Four way closure, which is needed for hydrocarbon entrapment is quite evident. In NE and SW structural dips are gentle as compared to the dips in NW and SE directions.

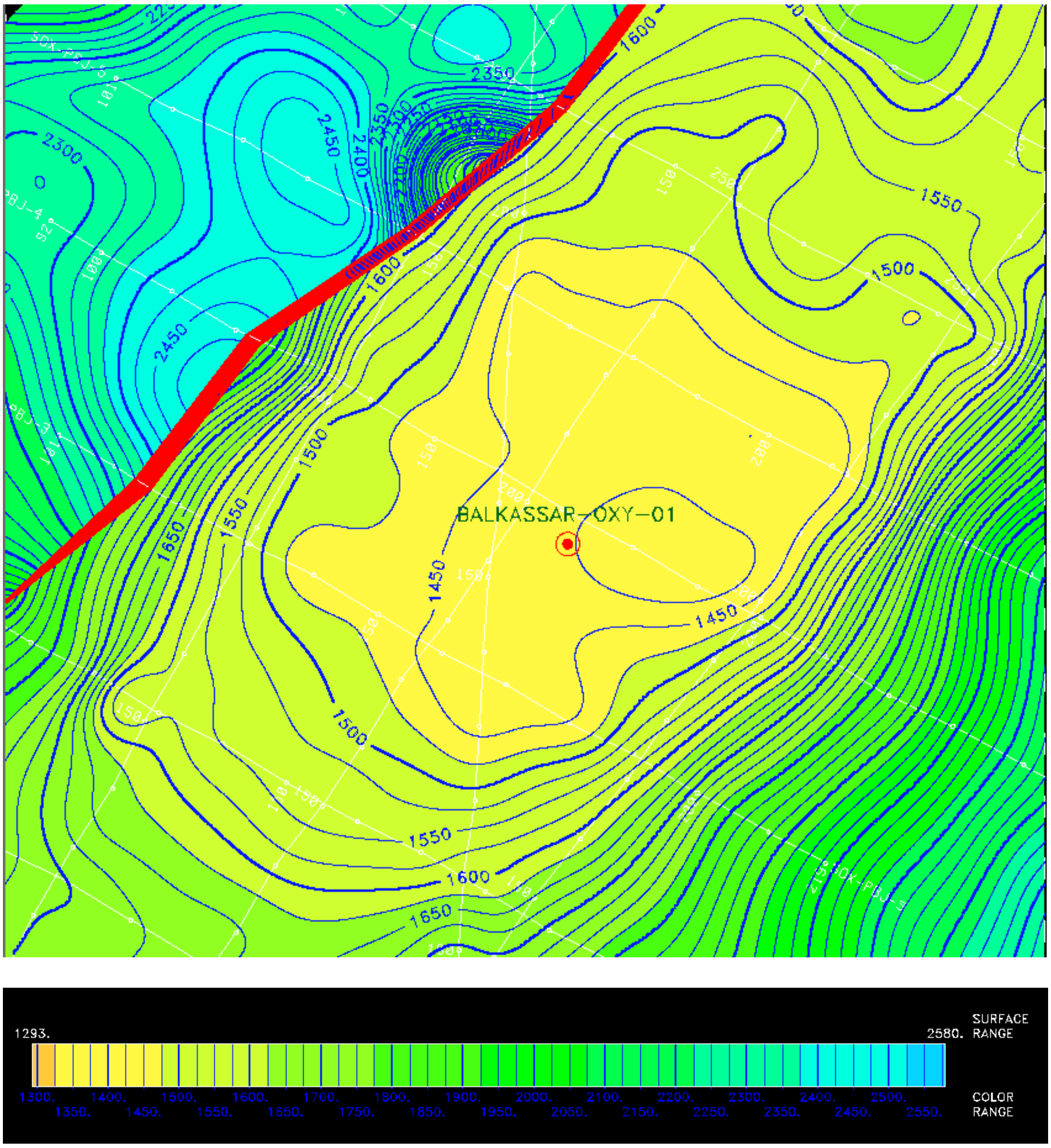
7.2.5.2. Top Lokhart

Lokhart Limestone is also a hydrocarbon producer in Balkassar area. As Lokhart horizon lies just below Eocene horizon on interpreted seismic lines, the mapped structure follows the same trend. Figure#43 & 44 show the TWT contour maps on

Top Lokhart Limestone.



Figure#43: TWT Contour Map of Top Lokhart Limestone

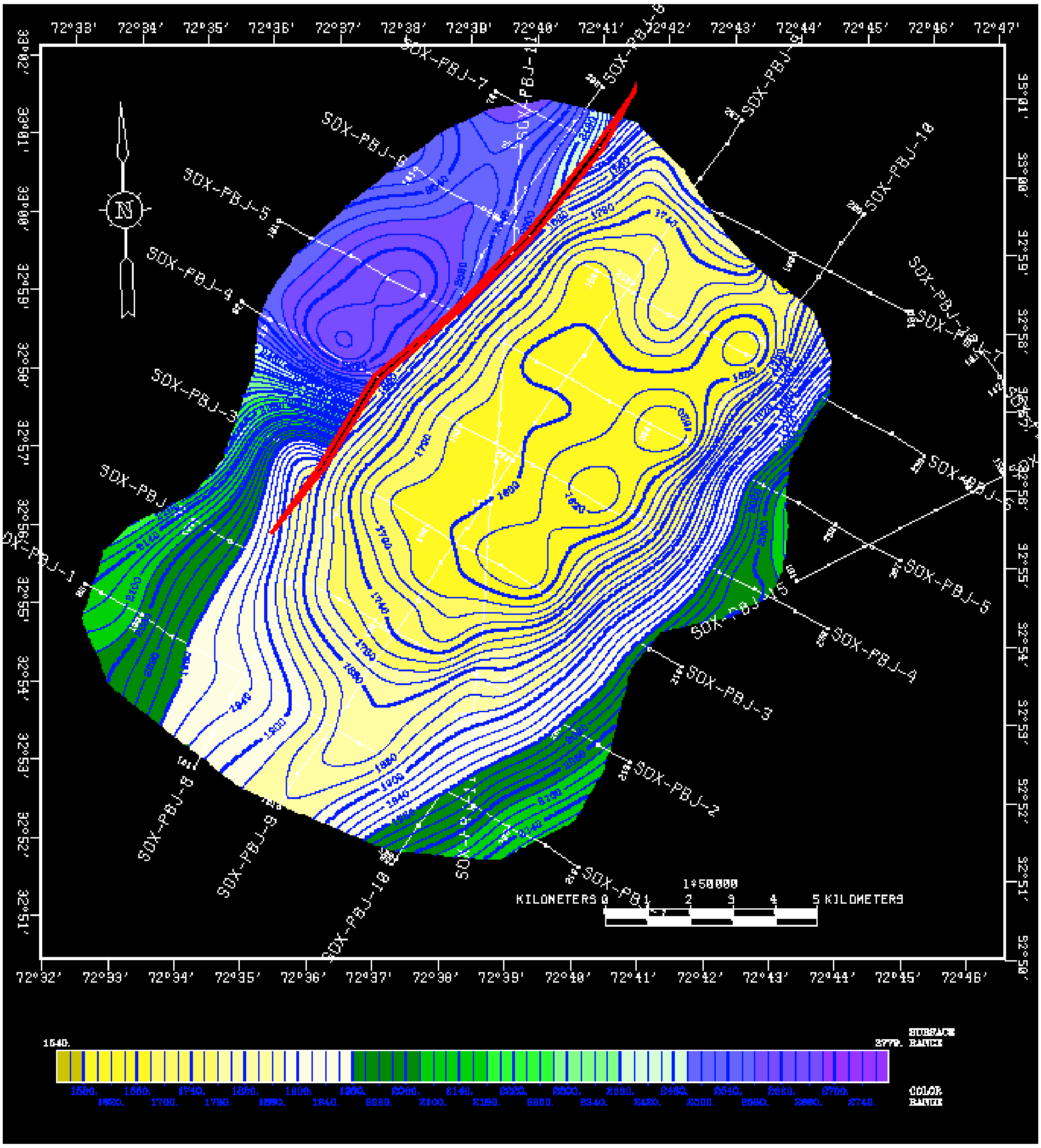


Figure#44: TWT Contour Map of Top Lokhart Limestone (zoomed)

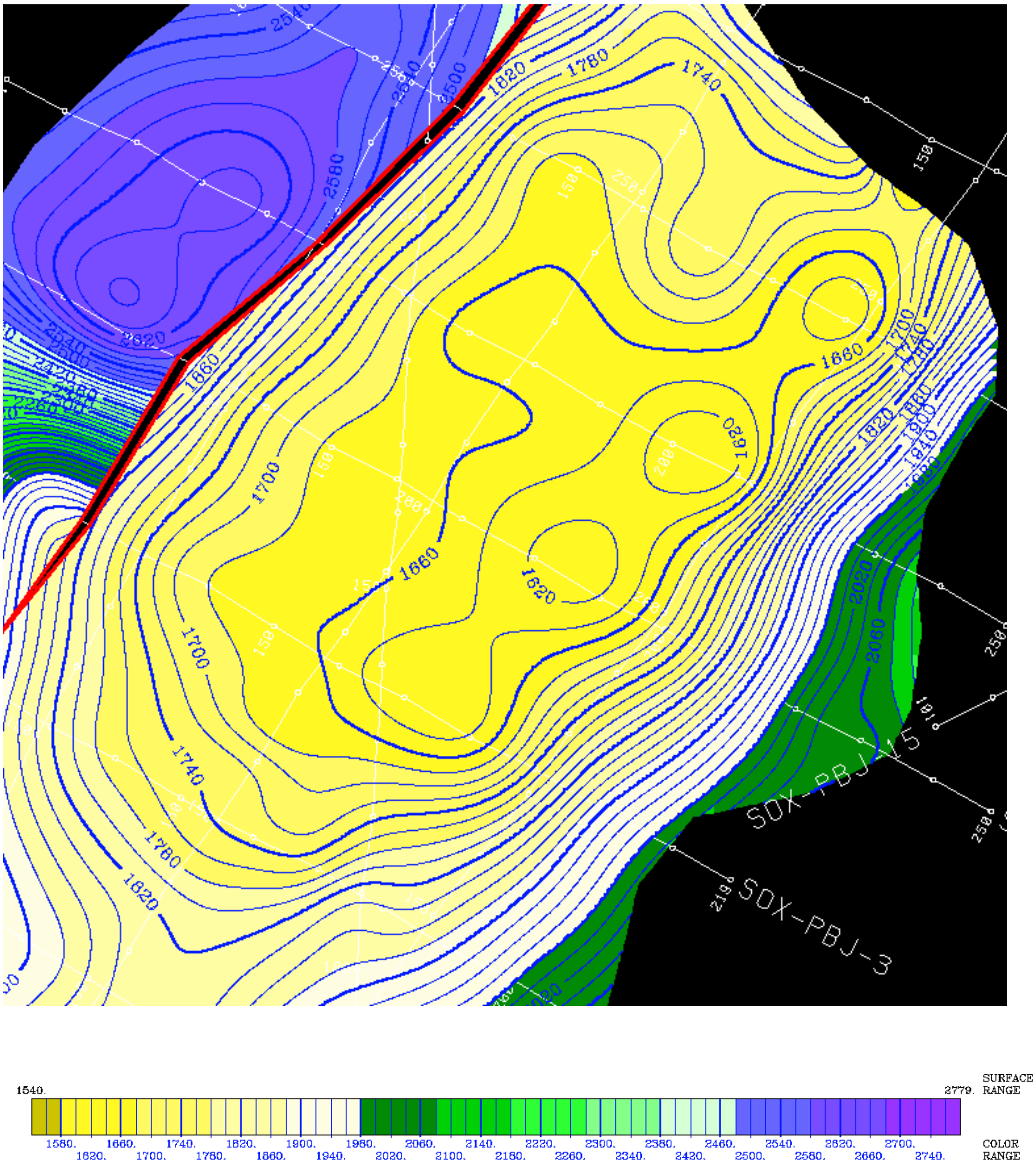
Red line is showing the Back Thrust **A.** Closed area is approximately 65 square km and vertical closure is 125 milli seconds. Dips are a bit gentle in NE and SW directions.

7.2.5.3. Top Khewra Sanstone

Khewra sandstone is not a hydrocarbon producer in Balkassar area. The reason, as available literature provides is the quality of sand in the area. Drilled wells in the area show unclean sand with low porosity values. Moreover, charging of Khewra sandstone is also doubtful. Figure#45 & 46 show TWT contour maps drawn on top Khewra Sandstone.



Figure#45: TWT Contour Map of Top Khewra Sandstone



Figure#46: TWT Contour Map of Top Khewra Sandstone (zoomed)

The displayed figures show the same anticlinal structure with the Back Thrust **A** running NE-SW. On this level, closed area was approximately 40 square km. Contour interval was taken to be 20 msec instead of 25 msec to properly map the top of anticline.

7.2.6. Depth Contour Maps

For depth conversion following simple formula was used,

S= V * (T /2)

Where S is Depth in meters,

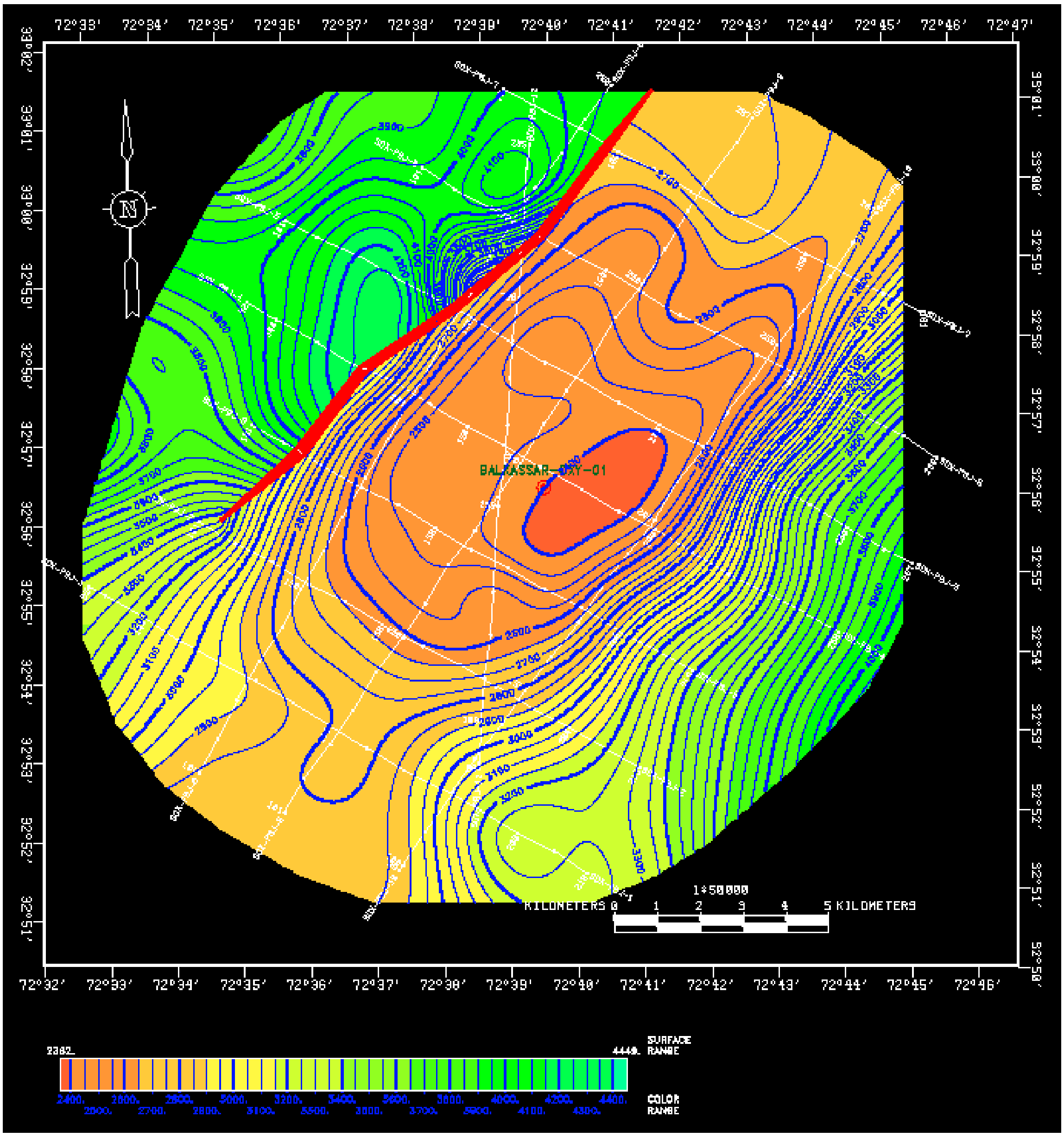
V is velocity in m/sec,

T is two way travel time in sec.

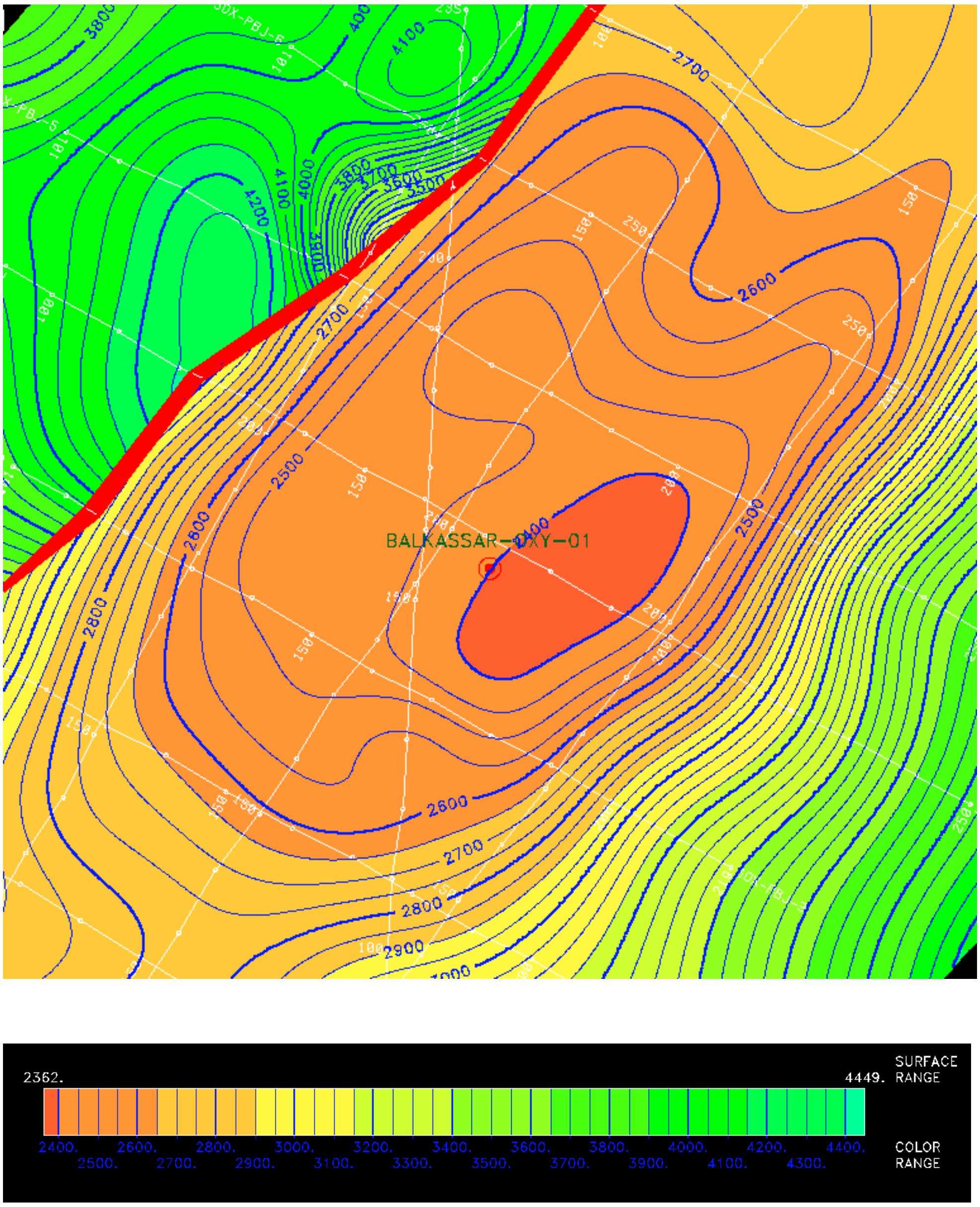
Griding and contouring were done in ***Surfer 8.0*** and ***3DFieldPro*** respectively. Available seismic sections and literature on project area were considered for velocity selection. Zoomed images of the maps are also included in this section to have a better look at the structure. A brief detail of depth contour maps created on three different levels is as under:

7.2.6.1. Top Eocene

Figure#47 & 48 show the depth contour maps on Eocene level. Depth values range from 2400m to 4320m. For depth conversion single velocity value (3535m/sec) was used. Contour interval was selected to be 50m. Smaller contour intervals created some small pseudo closures and gave figure a messy look. Vertical closure at Top Eocene level was 250 m.



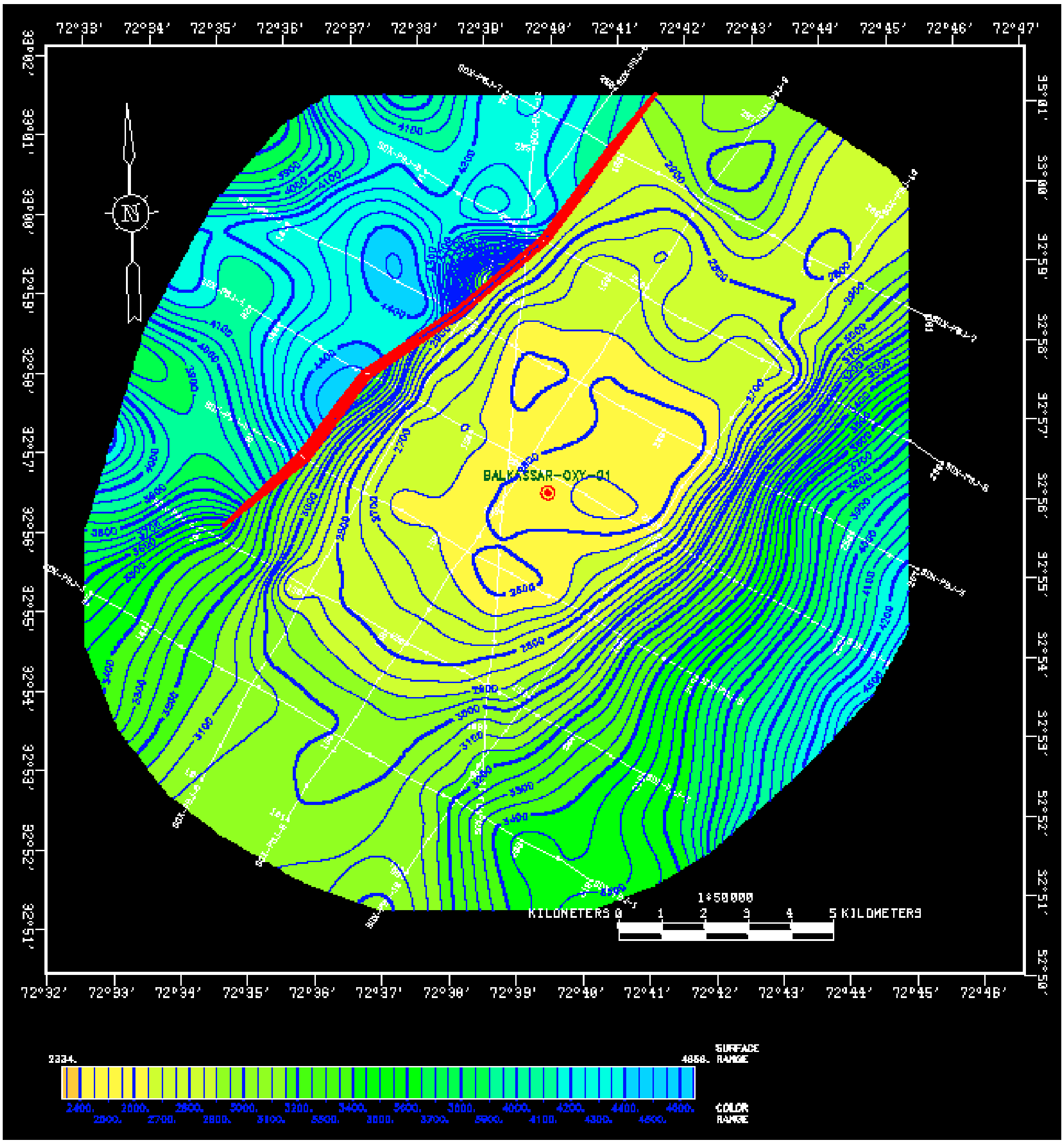
Figure#47: Depth Contour Map of Top Eocene



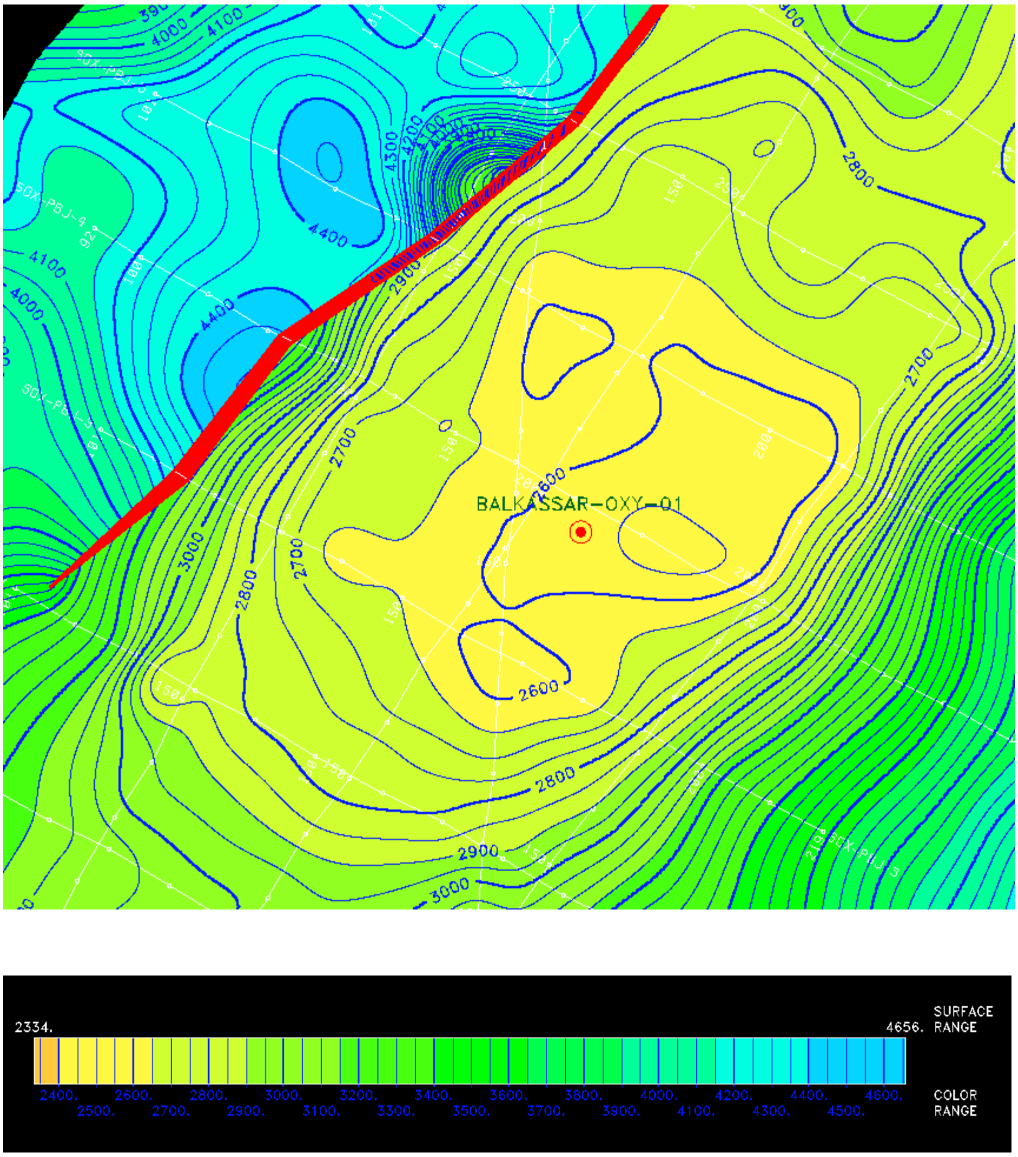
Figure#48: Depth Contour Map of Top Eocene (zoomed)

7.2.6.2. Top Lokhart

For depth conversion, single velocity value of 3610 m/sec was used for Lokhart Limestone. Contour interval of 50 m was selected for depth contouring. Depth values on contour map range from 2550m to 4570m (Figure#49 & 50).



Figure#49: Depth Contour Map of Top Lokhart

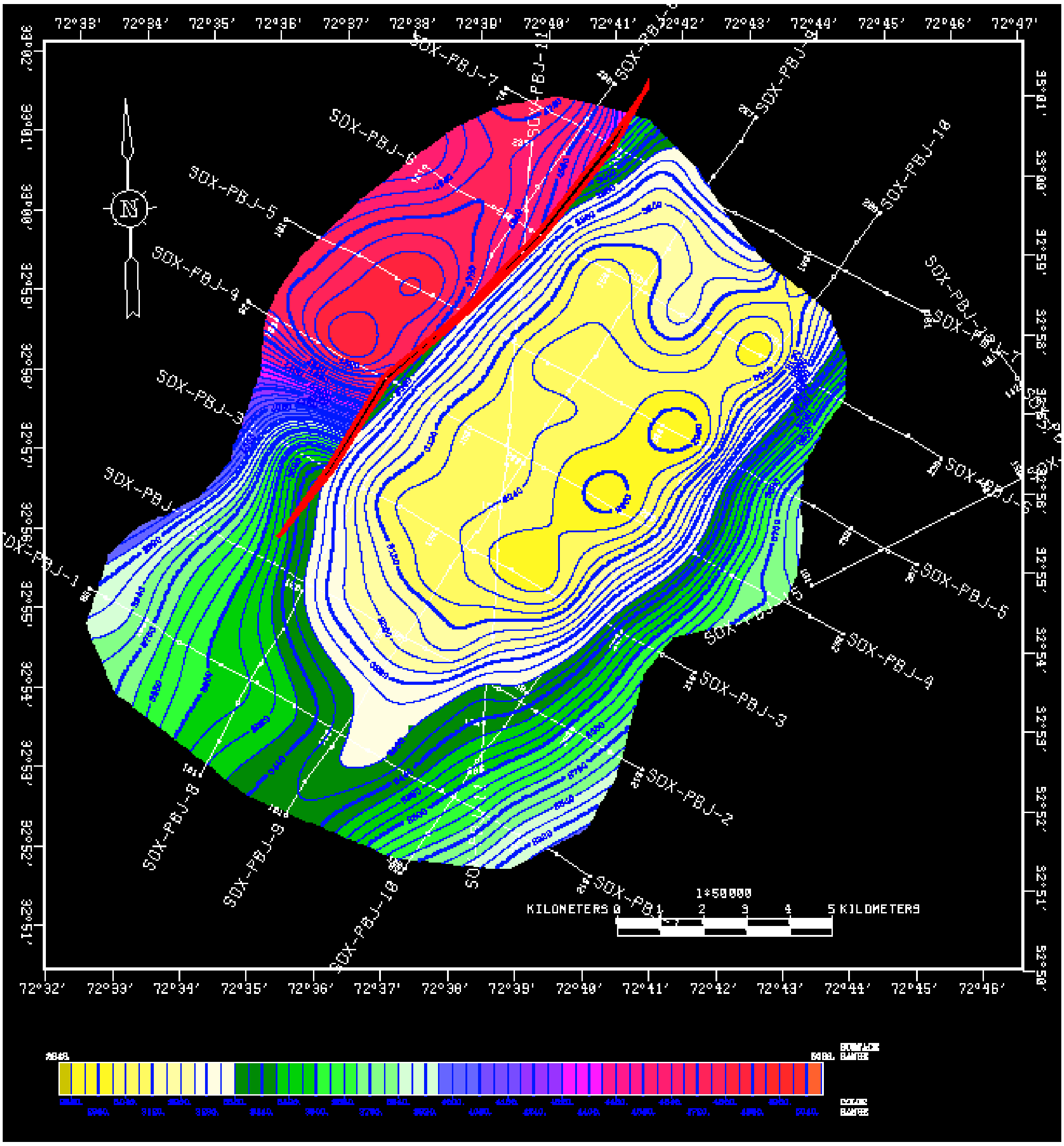


Figure#50: Depth Contour Map of Top Lokhart

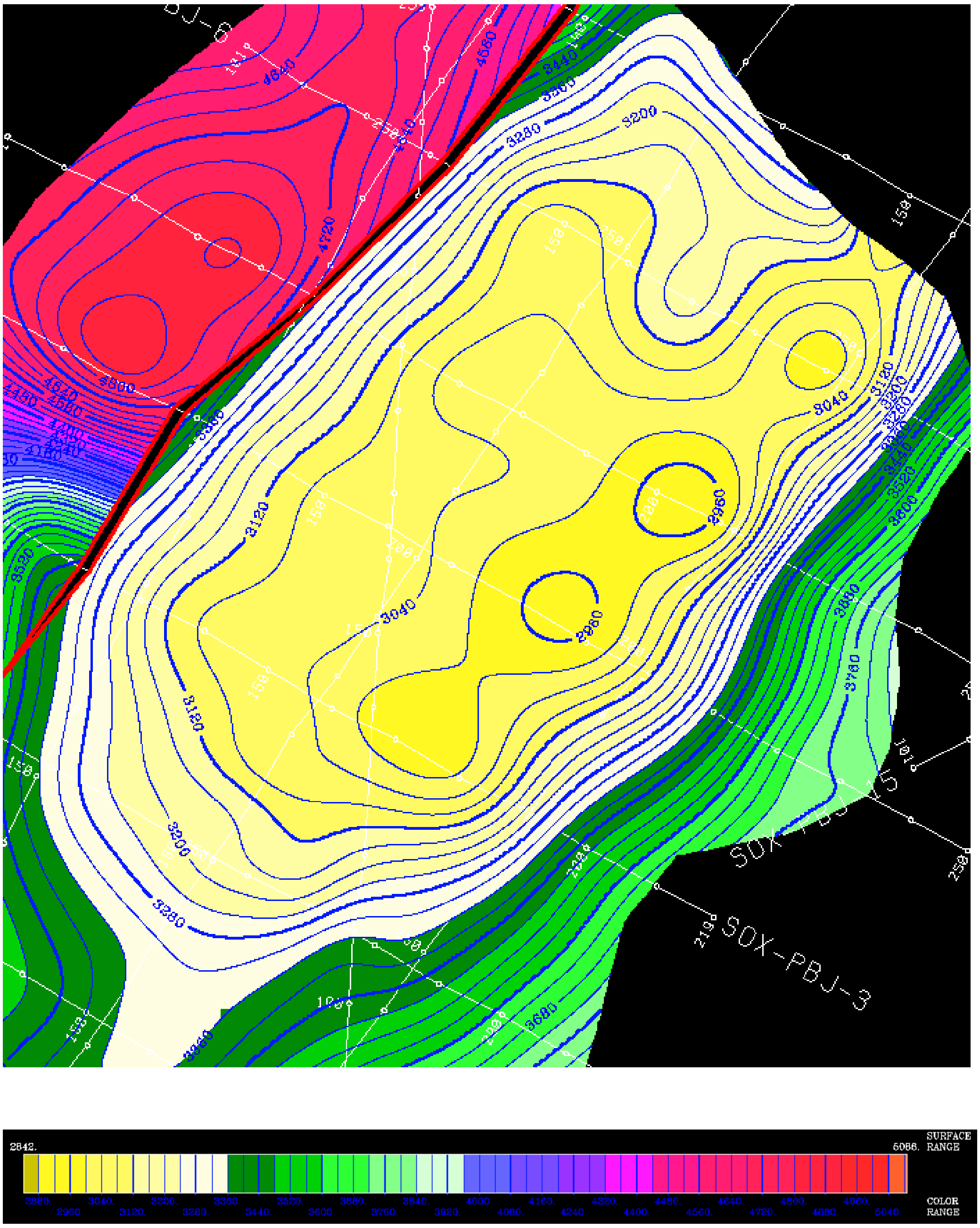
Vertical closure on Lokhart level is 250 m. Figure#48 & 49 show three small closures on crest of anticline, all with 2600m value. These three contours could have been joined to make a single closure of 2600m value.

7.2.6.3. Top Khewra Sandstone

For depth contour map on Khewra Sandstone, single velocity value of 3660 m/sec and a contouring interval of 40 m were used. Depth values on contour map range from 2960m to 4700m (Figure#51 & 52). Vertical closure on depth contour map was found to be 120m.



Figure#51: Depth Contour Map of Top Khewra Sandstone



Figure#52: Depth Contour Map of Top Khewra Sandstone (zoomed)

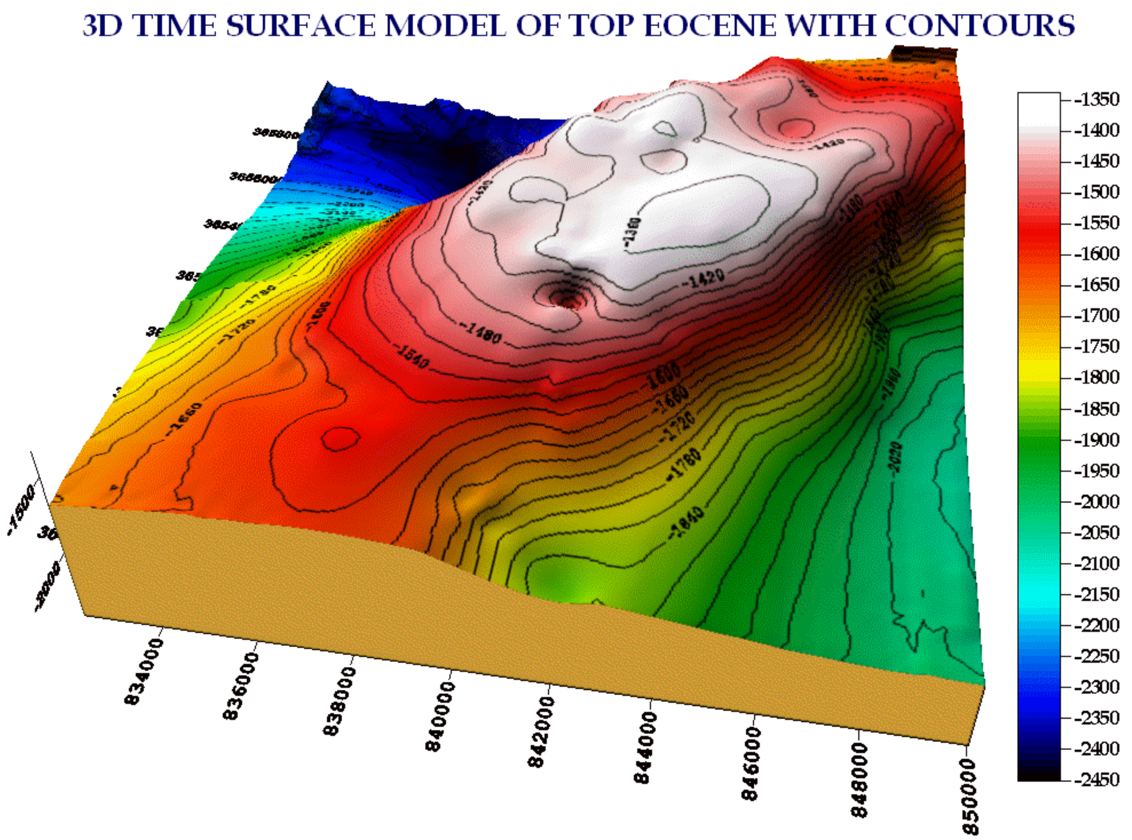
7.2.7. 3D Time and Depth Surface Models

Time and depth surface models were generated in ***Surfer 8.0*** to give a clearer image of the mapped structure .Contours were also superimposed on surfaces to give an idea about time and depth variations (Figure#52 to 56).

7.2.7.1. 3D Time Surface Models

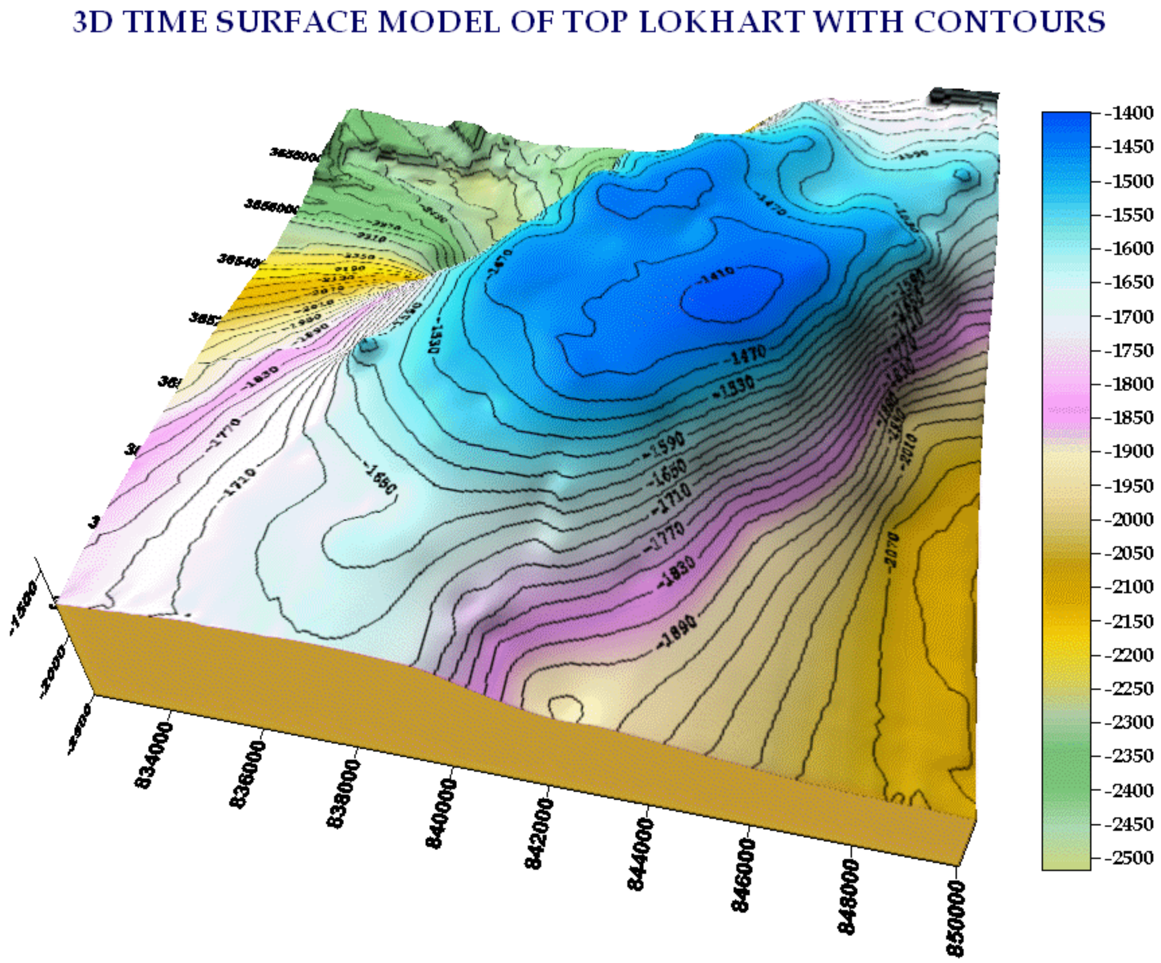
Time surface models generated on Eocene (Sakesar/Chorgali), Lokhart and Khewra Sandstone are as under:

7.2.7.1. Top Eocene



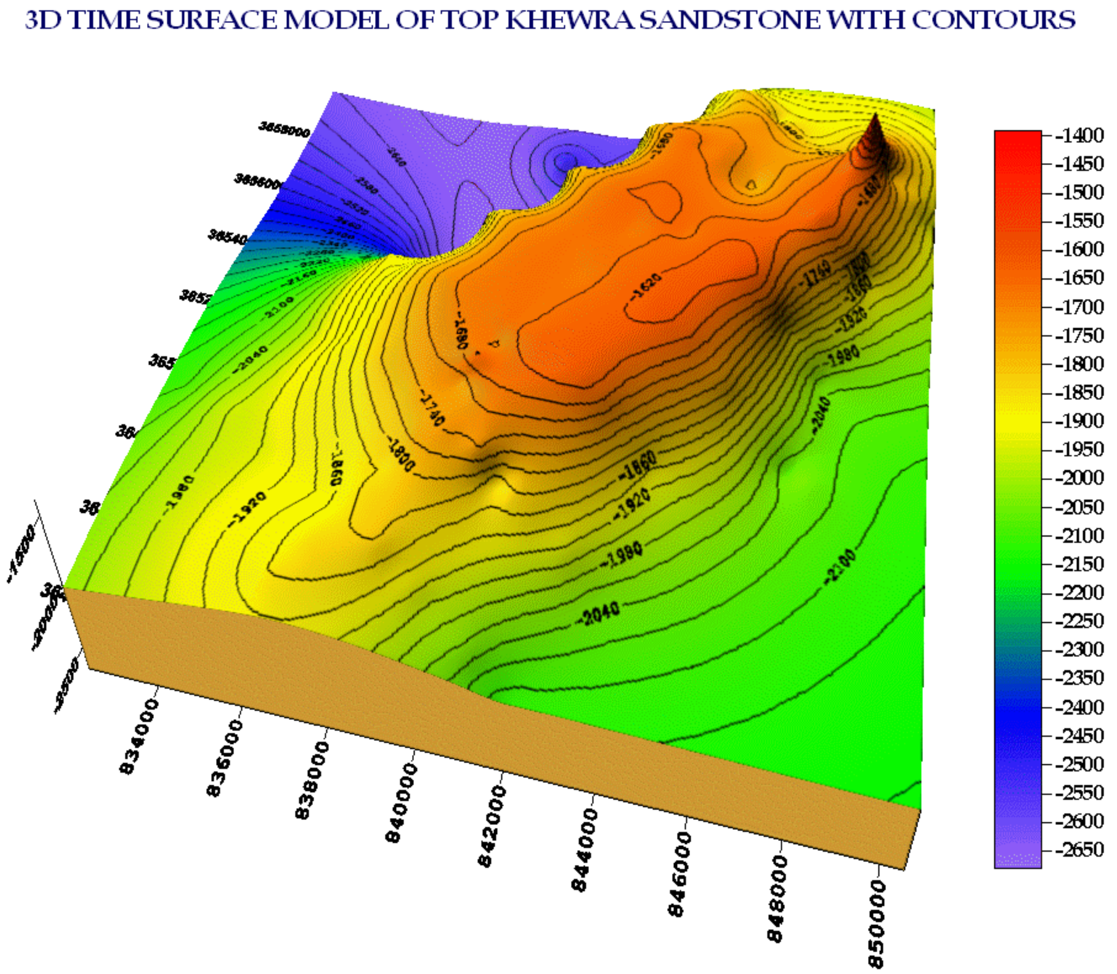
Figure#53: 3D Time Surface Model of Top Eocene

7.2.7.2. Top Lokhart



Figure#54: 3D Time Surface Model of Top Lokhart Limestone

7.2.7.3. Khewra Sandstone



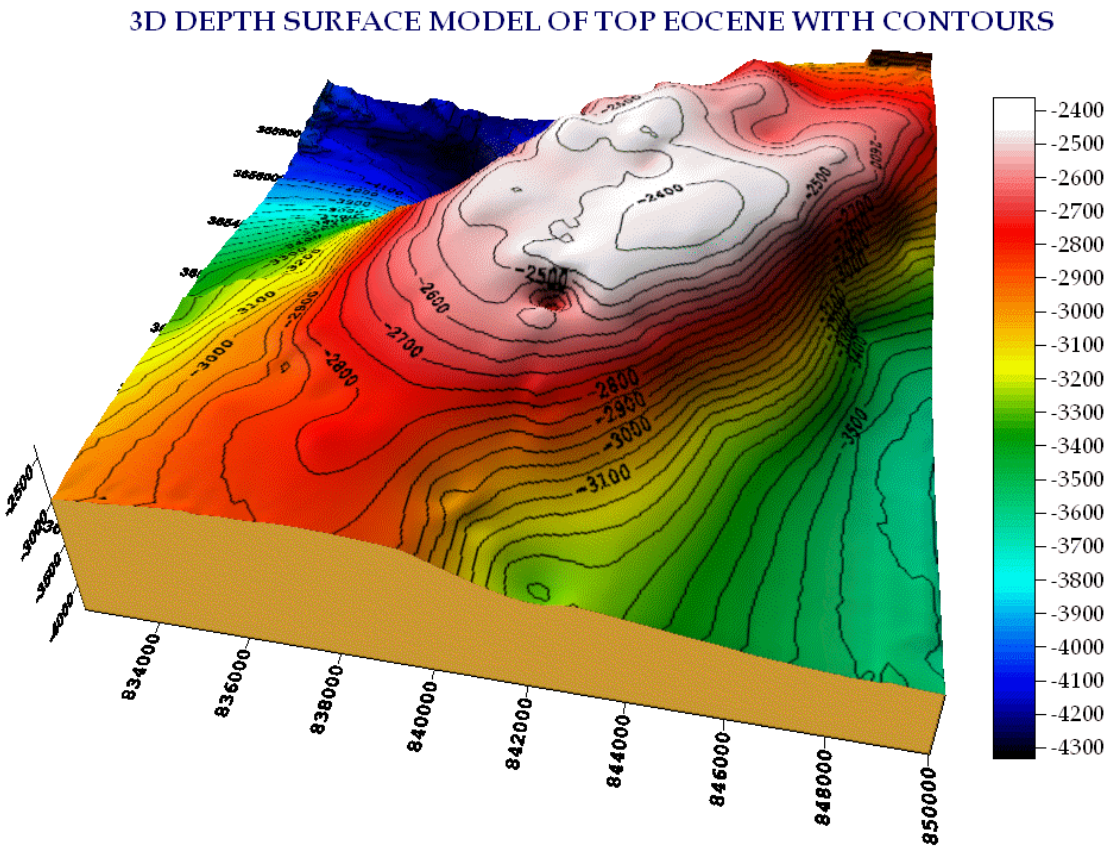
Figure#55: 3D Time Surface Model of Khewra Sandstone

A small pinnacle seen on the crest of structure is a pseudo one. It is formed because of some minor errors in depth values that were not properly gridded.

7.2.8. 3D Depth Surface Models

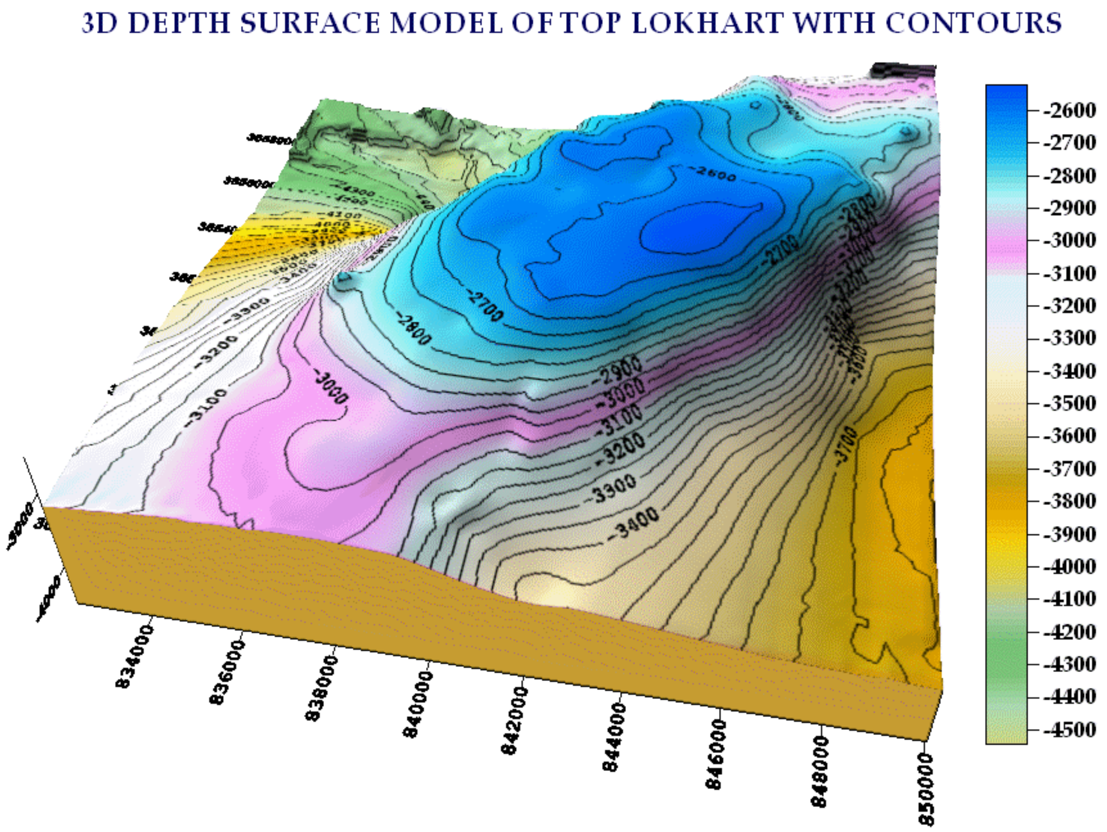
Depth surface models generated on Eocene (Sakesar/Chorgali), Lokhart and Khewra Sandstone are as under:

7.2.8.1. Eocene



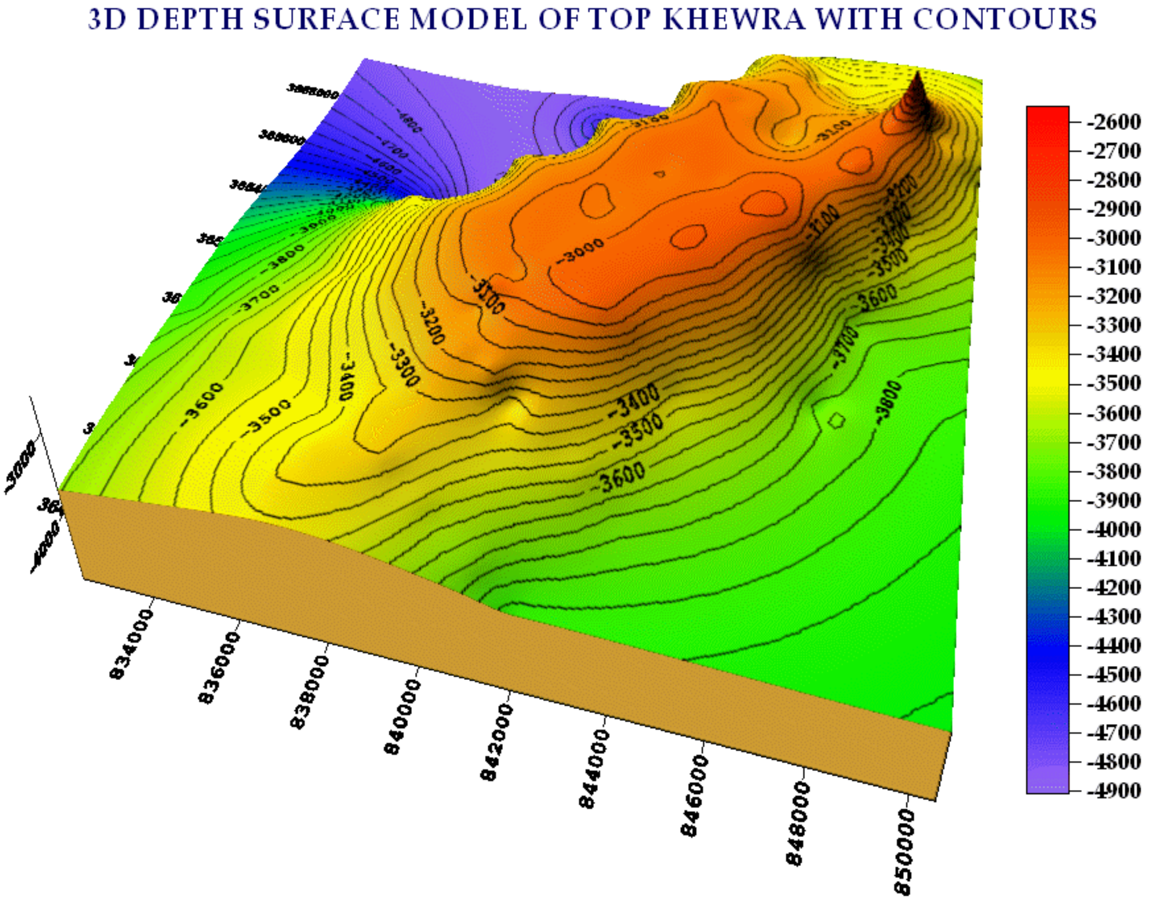
Figure#56: 3D Depth Surface Model of Top Eocene

7.2.8.2. Top Lokhart



Figure#57: 3D Depth Surface Model of Lokhart Limestone

7.2.8.3. Khewra Sandstone



Figure#58: 3D Depth Surface Model of Khewra Sandstone