AN INTEGRATED APPROACH TO EVALUATE SUB-SURFACE RAMP GEOMETRIES AND THEIR BEHAVIOUR IN NPDZ, POTWAR BASIN, PAKISTAN

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APPROVAL OF EXAMINATION

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DEDICATIONS

With profound appreciation, I dedicated my research work to my parents and family who have always supported and encouraged me. Your encouragement has been the wind beneath my wings, propelling me towards academic success.

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Thanks to the most merciful and Almighty Allah Who bestowed me with the ability to complete the research in the possible manner.

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ABSTRACT

North Potwar Deformed Zone (NPDZ) makes up the northern region of the Potwar Plateau in Pakistan. The area is bounded to the north by the Main Boundary Thrust (MBT), and to the south by Soan Syncline. Geological map of the study area illustrates the spatial distribution of rock units and geological structures throughout the area. Several seismic sections were interpreted to understand the subsurface geometry of the Khairi Murat Fault as the surface exposure of the rocks is not adequate to understand the subsurface structures.. The Khairi Murat Thrust is the forward breaking expression of the Main Boundary Thrust, marking the southern leading-edge of the NPDZ. Therefore, the MBT and KMF are interconnected in the subsurface, and are not two separate thrust sheets branching upwards from a Precambrian evaporite basal decollement at 10 km depth. The integrated geological and seismic data confirms the ramp-flat geometry of the Khairi Murat Thrust in the subsurface.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The Salt Range-Potwar Plateau is the portion of Indus Basin and is situated at the northern edge of Indian plate in the foothills of western Himalayas in Pakistan (Iqbal and Ali, 2001 and Porth and Raza, 1990).

There are two sections towards the vast Salt Range-Potwar Plateau. Salt Range is situated at the leading rim of an emerging thrust sheet to the south (Yeats et al., 1984; Lillie et al., 1987; Baker et al., 1988). The Potwar deformation was controlled by a widespread Precambrian basal evaporite detachment horizon (Jouanne et al., 2014; Jaumé & Lillie, 1988; Seeber & Armbruster, 1979), lying above faulted basement (Borderie et al., 2017). Overall, the Potwar region becomes less complex and deformed southwards towards the Soan syncline and Salt Range This is because of the tectonic stresses not being as intense further away from the Himalayas (Moghal et al., 2007). In the middle of Salt Range, the 90 kilometers wide thrust sheet has not changed. The thrust sheet is imbricated to the north. The western and eastern portions of this imbricated portion, known as the North Potwar deformed zone, have an emergent and a buried thrust front, respectively (Jaswal, 1990).

Salt Range and Potwar Plateau (SR/PP)'s northern region is known by the name of Northern Potwar Deformed Zone (NPDZ). The Main Boundary Thrust (MBT) in the north and the Soan Syncline in the south serve as markers for it. Jhelum Fault, a strike-slip fault, is the region's eastern extremity, while the western extremity is marked by the change in lithology and sedimentary facies.

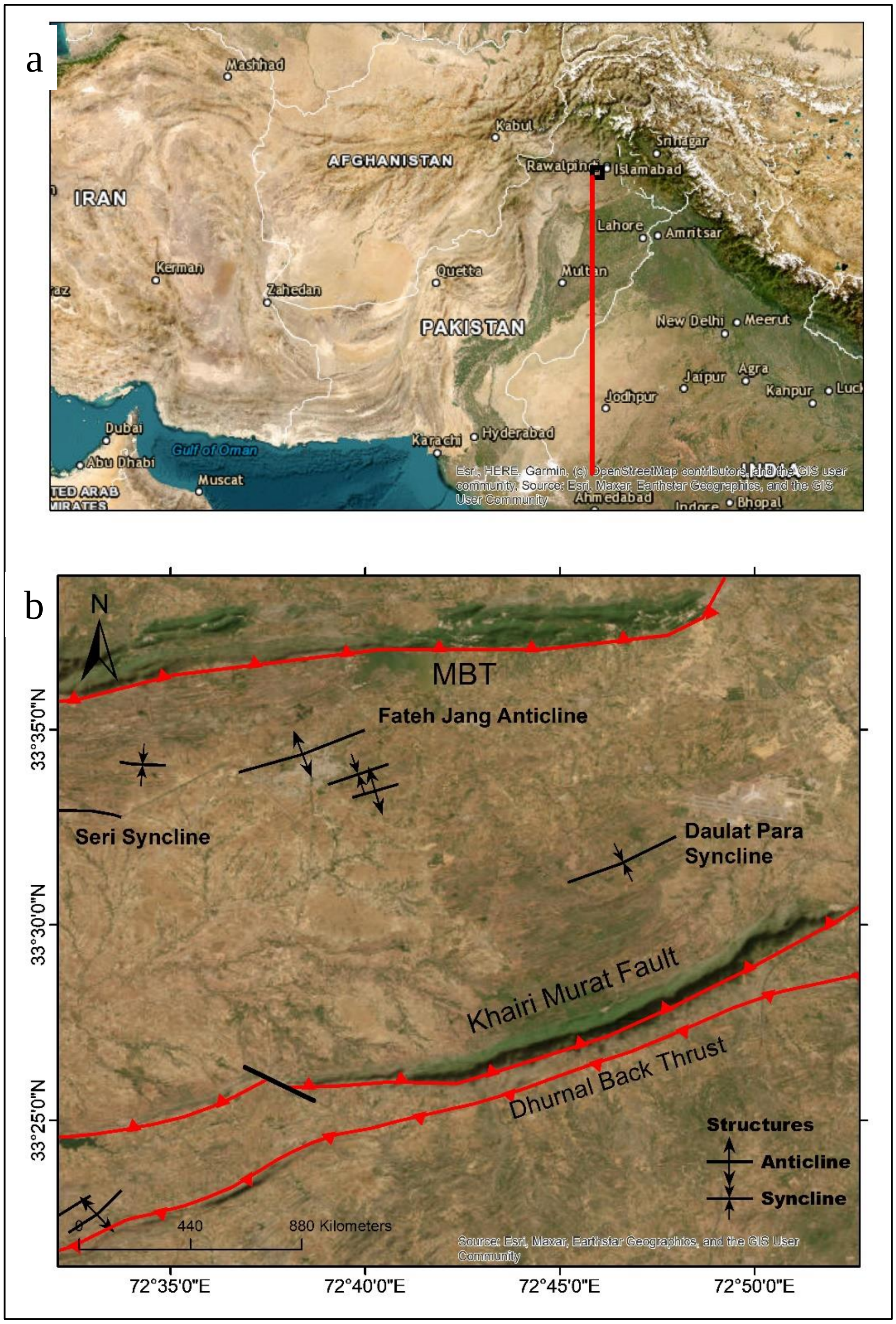

Figure 1.1: (a) Reference map showing the location of study area map below (b) Location map of the study area illustrating some prominent geological features. (Red line indicates the location of map b).

The North Potwar Deformed Zone (NPDZ) is region of Neogene distortion that extends from the MBT in north to the Soan syncline in south. Within the project area (Figure 1.1), which is located in the extensively dissected NPDZ, there are resistant rock formations that emerge above the surrounding terrain, forming ridges such as Khairi Murat and Kamlial. The Khairi Murat uplift reveals Eocene rocks, while the prevailing rock exposure in the area is primarily composed of the molasse sequence. The outcrops of formations and faults generally align in an ENE-WSW direction, which is almost perpendicular to the direction of tectonic transport.

A local syncline that has formed as a result of the surface manifestation of Khaur Anticline in the south west and Sakhwal Fault (SF) to the west of Dhurnal. Sakhwal fault (SF), which exhibits some right-lateral motion, is a back thrust that emerges within the roof structure of Dhurnal back thrust. The development of the Khaur anticline, which was formed south-west of Dhurnal, coincides with this back thrust formation. Slickensides are observed in the fault zone to the north of Sakhwal village. The Sakhawal Fault (SF) joins with the Ahmadal Fault (AF) to the southward and trends NNE-SSW before gradually dissipating within the Chinji Formation to the north. The Khaur Anticline, which surrounded by the Kamlial Formation, creates a smaller ridge (Elahi and Martin, 1961). The Kenet syncline has established at rear of Ahmadal Fault (AF) and is bordered towards east and north by the SF and Kenet Fault (KF), respectively.

At first glance, the back thrust north of Dhurnal might seem to continue the Kanet Fault (KF) to the east. These two faults, however, are distinct from one another and have different motion trajectories and genesis, according to recent surface mapping and seismic data. Dhurnal Fault (DF) is a north verging back thrust that originates from a tip line in the upper beds of Miocene Murree Formation, whereas the KF is a south verging thrust that has a major tectonic transport direction towards the south. The northern limb of the Soan Syncline was created as a result of the tilting upward of the resistant sandstone beds of the Kamlial Formation along the Dhurnal Back Thrust.

On the northern limb of Kenet Syncline, Dhurnal Fault (DF) vanishes as a deformation front manifests emerging thrusts west of Dhurnal. There are steep to vertical dips and occasionally overturning in the region between the south dipping Dhurnal Fault (DF) and the north dipping Mianwala Fault (MF). Rocks from the Murree Formation that are highly deformed and exhibit erratic trends are found in this zone. The MF, which is distinguished by secondary calcite, fault breccia, and shear zones, is a high angle intra-formational thrust that could be seen on the surface of some locations with good exposures of rocks.

The rocks that are unveiled in the area between the Mianwala Fault (MF) and Khairi Murat Fault (KMF) are the northernmost exposure of Siwalik rocks. These rocks dip dramatically. As the Eocene beds are forced up against the Siwalik rocks, the surface exposure of the KMF is clearly visible. On substantial limestone blocks close to Dhok Maiki, west of Gali Jagir, slickensides can be seen. Along the KMF, the Eocene-era Chorgali Limestone is exposed, and thick Chorgali Limestone beds with sharp dips can be found to the east of Gali Jagir.

In region to the north of KMF, which is mainly enclosed by alluvium, only a few sections of the middle to lower Murree beds can be seen. This region's exposed Murree beds are severely faulted and have moderate to high dips. A fault zone with numerous high angle thrusts that expose Eocene and older strata on the surface represents the MBT further north.

The NPDZ is distributed into two portions. The western portion of NPDZ is an emerging foreland fold and thrust front, while the eastern portion of NPDZ is buried one (Morrisley, 1986).

The development of the North Potwar deformed zone is the subject of some theories presented in a few studies (Baig, 1995; Jamshed, 1995; Treloar et al., 1992; McDougall et al., 1993). Structural complexity of deformed zone was assessed by Jaswal (1990), Jaswal et al. (1997), and Jadoon et al. (1997) using seismic reflection profiles; however, structure and kinematics of the area have not yet been established.

1.2 Literature review

Nearly 3000 km of older industrial seismic reflection profiles along with the surface geology, gravity data and drilling data, were manipulated to create the balanced cross sections of the eastern, central and western Salt Range-Potwar Plateau (Leathers, 1987; Baker, 1987; Pennock, 1988). Duroy (1986) examined lithospheric flexure in the Pakistani Himalayas using the same set of data, and Jaume (1986) looked into the thrusting mechanics of the Salt Range-Potwar Plateau. Detailed geological reports based on the incorporation of the available surface and subsurface data have shed light on many long-standing structural and tectonic issues in the area (Khan et al., 1986; Lillie et al., 1987; Jaume and Lillie, 1988; Baker et al., 1988; Duroy et al., 1989; Pennock et al., 1989).

Older seismic lines were interpreted by Baker (1987), who found that the NPDZ's overall structure abruptly shifts from south to north. Velocity analysis of new 2D and 3D seismic data and its comparison with the older seismic data interpretations was carried out by Fatima Afsar and the data combined with the well data and surface geology of Dhurnal Oil Field generated better time and depth surfaces of the sub surface structures (Afsar 2013).

Blind thrusts have been stacked in the eastern part of NPDZ as a result of sticking of tip line that has led to the formation of passive roof thrust and growth of foreland syncline (Banks and Warburton, 1986; Morley, 1986). Contrarily, the western portion of the NPDZ has an emerging thrust front with extensive synclines separating compressed, faulted folds. Overstep faults are known to exist in the Salt Range-Potwar Plateau and other foreland thrust belts (Johnson et al., 1986; Leathers, 1987; Burbank and Beck, 1989). They are mechanically justified as being necessary to preserve crucial taper, according to Davis et al. (1983). Ziegler (1969), Banks and Warburton (1986), Jones (1982), and others discuss how a passive roof thrust that occurred earlier evolved into an overstep, foreland-dipping thrust within a roof sequence. The pressure created by the imbricate thrusts found within the NPDZ is one of the prominent mechanisms causing the Precambrian salt to flow southward (Gee, 1983, 1989).

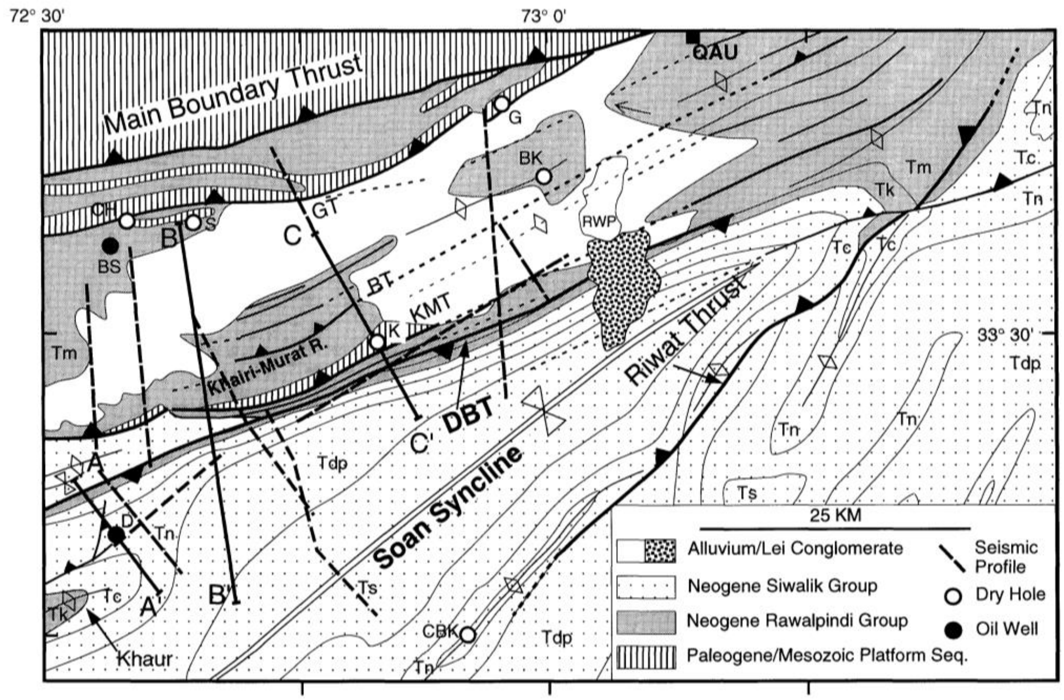

Figure 1.2: Geologic map of the eastern part of North Potwar deformed zone (based on Pennock et al., 1989; Jadoon et al., 1997).

The northern limb of Soan Syncline rotated 10° anticlockwise during the southward thrusting, according to Opdyke et al. (1982). Tauxe and Opdyke (1982) estimate that the Khaur region rotates by about 8° anticlockwise. The youngest layers of Siwalik in the Khaur region are deduced to be 6.5 Ma old. The north-eastern Potwar Plateau underwent its most recent deformation between 2.1 Ma and 1.9 Ma (Raynolds, 1980; Johnson et al., 1986). According to Lillie et al. (1987), the deformation front quickly spread to Salt Range with the decollement in Precambrian evaporite deposits, as the deformation in the NPDZ came to an end around 2 Ma. Burbank and Beck (1989) age-dated a region directly north of the Salt Range, and their findings indicated that the Salt Range may have been partially uplifted as early as 4.5 Ma. Accordingly, the Salt Range-Potwar Plateau may have undergone extensive "out of sequence thrusting" during the last 5 Ma of deformation (Burbank and Beck, 1989).

Basal décollement, which occurs when strata slide along a fault and translate into folds (prospects), is a common component of a thin-skinned deformation phenomenon (Chapple 1978). The imbricate and duplex style of deformation has developed from the straightforward ramp- flat geometry of a fold (Dahlstrom, 1970). To comprehend the relationship between surface folds and subsurface features like kink bands with panels of different dips and faults, geometric rules have been developed (Boyer and Elliot 1982; Suppe 1983; Mitra 1986). Raynolds, 1980; Burbank et al., 1986; Johnson et al., 1986; Burbank and Beck, 1989; and others have all provided in-depth documentation of the chronological order of significant deformational occurrences in the area of the NPDZ. By using this knowledge, the variety of potential structural events can be reduced.

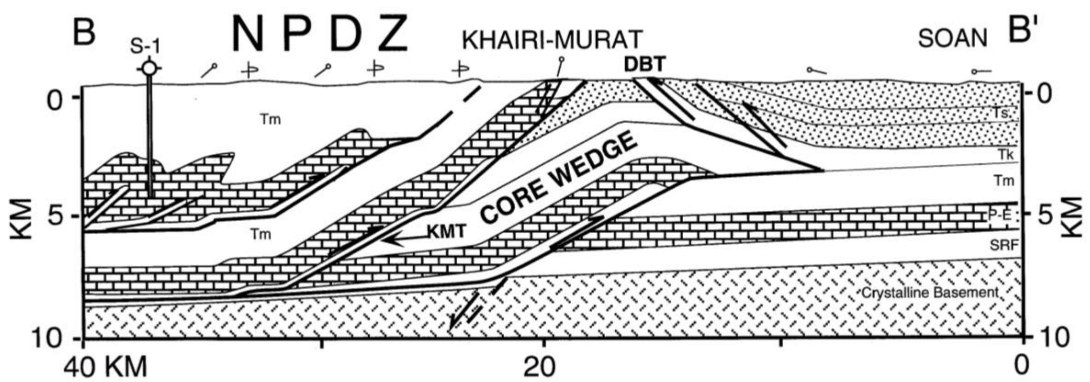

Figure 1.3: Section BB′, based on the seismic reflection profiles AW-15-N and AW-15-AF. Notice un-deformed footwall block of the core wedge.

Prior to 2 Ma, the northern Potwar was a severely deformed fold and thrust belt; since then, it has displaced the salt basin's northern edge, and erosion has eliminated its former topographic slope (Jaume and Lillie, 1988). Seismic sections were used to construct the balanced cross sections of the study area (Lillie et al., 1987; Leathers, 1987; Baker et al., 1988; Pennock et al., 1989; Jaswal et al., 1997). The geometry of triangle zone under Dhurnal oil field was identified based on the interpretation of seismic reflection profiles from the industry, (Jaswal, 1990; Jaswal et al., 1997).

In the 1980s and 1990s, a number of studies (Lillie et al. 1987; Jaume and Lillie 1988; Pennock et al. 1989; Treloar et al. 1992; Grelund et al. 2002) used integrated borehole and seismic data to examine the general structural style and mechanics of deformation. It was determined that the deformation was thin-skinned, widespread, and involved a weak detachment. It also occurred over a zone with gentle topography and symmetrical structures. The northern portion of the plateau, known as the North-Potwar-Deformed Zone (NPDZ) showed complex deformation, including duplex structures and imbricate (Jaswal et al. 1997; Jadoon et al. 1997). To understand the development of these complex structures, seismic data, borehole data, paleo magnetic data, and surface geology constraints were combined (Jadoon and Frisch 1997; Jaswal et al. 1997; Jadoon et al. 1997, 1999), leading to the calculation of approximately 55 km of shortening across the NPDZ between 8-5 million years ago (Jadoon et al. 1997). Additionally, almost 21 km of shortening was estimated across the SR-PP south of Soan Syncline (Lillie et al. 1987; Pennock et al. 1989).

More recently, using re-examined seismic and borehole data along with three regional cross sections across the SR-PP, a detailed structural interpretation was carried out (Moghal et al. 2007). The complex structures in north of Soan Syncline were either not super scribed or were divulged in an inadequate manner, whereas the cross sections generated on the basis of seismic data give a common recapitulation of the structures south of the Soan Syncline.

Thrust faults, with symmetrical structures verging towards both the foreland and the hinterland, are frequently observed in the region. This is explained by the existence of a substantial evaporites layer along the décollement, mostly to the south of the Soan Syncline. Within the Salt Range-Potwar Plateau region (SRPP), a structural analysis of 12 oil fields reveals typical compression-induced deformation styles, such as fault-propagation folds, detachment folds, triangle zones, and pop-ups. Triangle-zone structures have been discovered between the Khairi Murat Thrust and Soan Syncline in the North Potwar Deformed Zone (NPDZ), (Jadoon et al. 2014).

1.3 Objectives

The main objectives of the current research are as follows:

i. To construct a detailed lithostructural map in order to understand the spatial distribution of various structural elements.
ii. To construct an integrated depth cross section in order to understand the sub surface geometries.

1.7 Methodology

Field work

A detailed geological field work was carried out to collect the necessary data in order to understand and interpret the geology and tectonics of the area. Formations were identified in the field and their contacts were marked. Dip and strike of the formations along with their coordinates were recorded using Brenton Compass, Clino Move, and GPS. Different structural features were observed and measured in detail including the folds, faults, fractures, and other structures. Kinematic indicators including slickensides, lineation, grooves etc. were observed and measured. Different field observations and sketches were recorded and photographs were taken during the field.

Lab work

Field data was brought into the laboratory in order to generate the detailed geological map of the area. The filed data was compiled into an Excel sheet and all the relevant details were inserted into it. Dip and strike data along with the coordinates was plotted on the Google Earth. Formation contacts were drawn according to the field observations, aerial photographs and remote sensing data. Then, the whole set of data was exported into shape files and brought into the Arc Map 10.8. A detailed geological map was generated using the data collected in the field and form the remote sensing data.

Two seismic lines were interpreted by marking the horizons and faults. Dhurnal-07 well data was used to mark the deeper horizons on the seismic sections.

Dhurnal-07 well is located on the western seismic line. The well data provided as las file and the formation tops data aided in the accurate interpretation of 2D seismic lines.

The geological map was used to draw geological cross sections of the area. These cross sections were supported by the interpreted seismic sections as the depth of the section increases. The map data combined with the seismic data provide a reliable source for the generation of cross sections.

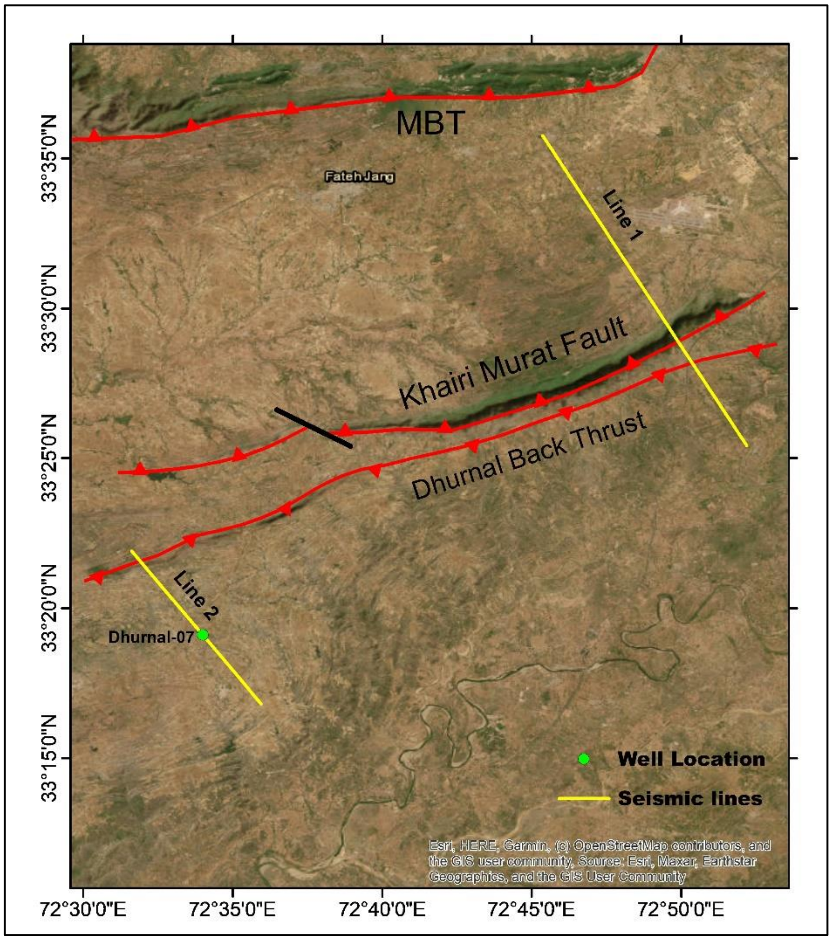

Figure 1.4: Base map of the study area showing the location of well and seismic lines.

CHAPTER 2

REGIONAL GEOLOGY AND TECTONICS

2.1 Geology and Tectonics

All the landmasses of the Earth were once joined together in the form of super continent called Pangea. Pangea remained intact until the Early Permian time. The super continent Pangea was surrounded by the Panthalassa Ocean. The break apart of the Pangea started during Early Jurassic time, some 200 million years ago. The super continent was divided into two parts; Gondwana and Laurentia. Gondwana continent that comprised of the South American plate, Indian plate, African plate, Australian plate, and Antarctic plate, drifted southward. Laurentia comprised of North American plate and Eurasian plate, drifted northward.

Indian plate has the northwestern boundary located in Pakistan. The Eurasian and Indian plates have characteristic features of continent-continent collision present in the northern areas of the country, where direct convergence of full-thickness of continental crust is preserved.

The Indian plate was a portion of southern Gondwana from the Permian to the Middle Jurassic periods. Its location in the Southern Hemisphere was close to the African, Australian, and Antarctic plates. The Lower Permian Tobra Formation tillites in the Kohat-Potwar region and other Permian-era glacial deposits on the Indian plate show evidence of a cooler paleoclimate (Shah and colleagues, 1977). Carbonates, shale, and sandstone were deposited in the region that now makes up the Indus Basin and Kohat-Potwar province. In numerous rock formations, such as the Permian

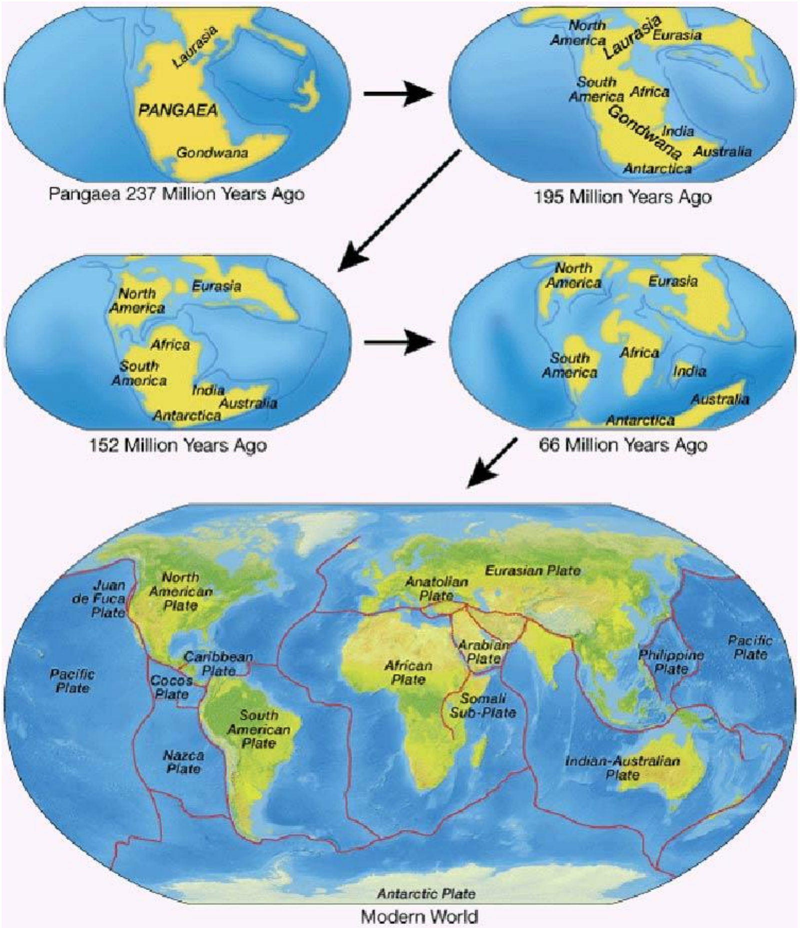

Figure 2.1: The break apart of Pangea into the modern day continents (DinoAnimals.com).

Nilawahan, Permian and Triassic Zaluch, Triassic Musa Khel, and Jurassic and Cretaceous Surghar Groups, the Kohat-Potwar geologic province preserves shelf and shallow-marine stages. The separation of Madagascar, India, Australia, Antarctica, and the Seychelles from Africa during the Late Jurassic period resulted in significant tectonic activity and the formation of the Somali Rift Basin. Australia and Antarctica were also separated from India during this time.

The Indian plate entered warmer latitudes as it drifted northward into the Early Cretaceous. Along the eastern part of the Indian plate, volcanic activity manifested as the Rajmahal Trap volcanics. Marine limestones and shales from the Cretaceous Sembar and Goru Formations were deposited on top of a regionally eroded surface on the Sulaiman Group along the northwest margin of the plate. This erosional surface is located at the top of the Samana Suk Formation in the Kohat-Potwar region, and it is covered by the lithological units of shales and sandstones of Cretaceous Chichali Formation. The Bolpur and Ghatal Formations were deposited on the eastern shelf of the Indian plate. Although carbonates are mostly found on the western and eastern shelves today, they were probably also deposited on a large portion of the northern shelf. During Late Cretaceous, when regressive sandstones like the Lumshiwal and Pab Formations in the west and the Tura Formation in the east were deposited. The formation of the Bengal Basin's sea floor and the buildup of flysch on all of the Indian plate's margins occurred as the movement of Indian plate to the north in Late Cretaceous period, towards the Eurasian plate continued. Along the Ninety-East Ridge, transform fault was also activated as a result of this movement to the north. The Mascarene Basin was first created due to the separation of Madagascar from the Seychelles, which are a part of the Indian plate. As the western part of the Indian plate sheared to the south in relation with the main plate, extensional faulting also took place (Kemal and others, 1992). The Indian plate underwent counterclockwise rotation, initiating the separation of the Seychelles portion from the Indian plate (Waples and Hegarty, 1999). The Deccan Trap basalts were driven out of western India during the Late Cretaceous due to intense volcanism (Biswas and Deshpande, 1983). Parallel rifting events occurred in the Cambay and Kutch regions, which may have been caused by extensional faulting and the emergence of shear zones in the Indus Basin.

At the northern, eastern and western shelves of the Indian plate, trap deposits and basal sands continued to assemble from the Late Cretaceous to the middle Paleocene. The formation of regional curvatures like the Jacobabad and Sargodha Highs in the Indus Basin was caused by the oblique convergence of the Indian plate and the microplates along the southern edge of the Eurasian plate (Kemal and others, 1992). The Indian plate continued to move speedily in the north direction, and as it passed over the Kerguelen hotspot, a chain of islands started to form around longitude 90°E (Scotese and others, 1988). The Tethyan Sea was gradually enclosed by the Indian plate's anticlockwise rotation and continued northward movement along the northern and northwestern plate boundaries. This oblique collision and rotation gave rise to the Sulaiman-Kirthar fold belt.

On the shelves surrounding the Indian plate, sporadic carbonate platform buildup took place from the Eocene to the middle Miocene. As the Indian plate started the subduction underneath the Eurasian Plate, so a trench is formed along the subduction zone, and the Eurasian plate contributed a significant amount of sediments to the trench. The formation of carbonate reefs along the shelf areas was suppressed as a result of the overabundance of terrestrial sediments from mountain ranges rising in elevation, such as the Himalayas and others (Roychoudhury and Deshpande, 1982).

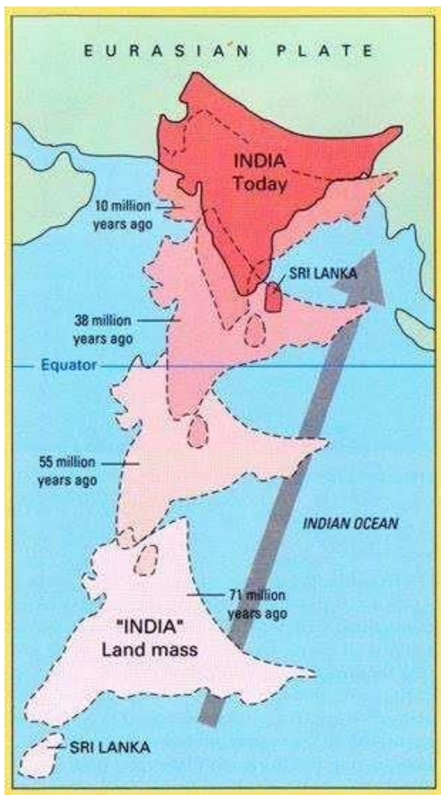

Figure 2.2: Continental drift of Indian plate through time towards its present location (Singh, 2019).

In the Kohat-Potwar geological province, shallow anticlines and overturned folds developed on the top of numerous detachment surfaces. The convergence resulted in significant crustal shortening, with as much as 55 km of shortening occurring (Jaswal and others 1997; Kemal and others, 1992. As the Himalayas and other ranges continued to contribute sediment, rivers like the Indus, Ganges, Brahmaputra, Meghna, Chindwin, and Irrawaddy developed substantial deltas. The Indian plate is currently being subducted beneath the Himalayas, and the Indus, Ganges-Brahmaputra (Meghna), and Irrawaddy deltas are all expanding rapidly. Crustal shortening also continues in the Kohat-Potwar area.

During the Late Cretaceous Madagascar and Africa split apart from India. As the Tethys Ocean closed, India began to drift northward towards Eurasia at a rate of 150 mm/year (Klootwijk and Peirce, 1979; Powell, 1979). According to calculations, the Indian plate was moving at a rate of about 130 millimeters per year relative to Eurasia, between 83 and 48 Ma using the Reunion hotspot as a reference point (Duncan, 1990). According to Powell (1979) and Duncan and Hargraves (1990), India underwent an anticlockwise rotation with respect to Eurasia around 50 Ma, which decreased its northward speed to 40-60 millimeters per year. From 36 Ma to the present, the northward convergence rate subsequently stabilized at less than 50 mm/yr (Patriat and Achache, 1984).

The collision of Indian and Eurasian continental crusts is thought to be responsible for the Indian Plate's erratic behavior around 44 Ma and plate reorganization in the Indian Ocean (Patriat and Achache, 1984). According to Powell and Conaghan (1973), Molnar and Tapponnier (1975), Quittmeyer et al. (1979), and Valdiya (1984), the Himalayas were formed as a result of crustal shortening that had been ongoing since the Late Cretaceous and that had caused thick sediment layers to thrust over the Indian craton in the south. At about 15 Ma, the deformation front gradually moved from the Main Central Thrust (MCT) to the Main Boundary Thrust (MBT) (Lefort, 1975; Klootwijk et al., 1985). MBT in Pakistan is believed to have increased from a basement offset, pushing the Neogene molasse of the NPDZ into the Cretaceous to Tertiary period (Yeats and Hussain, 1987).

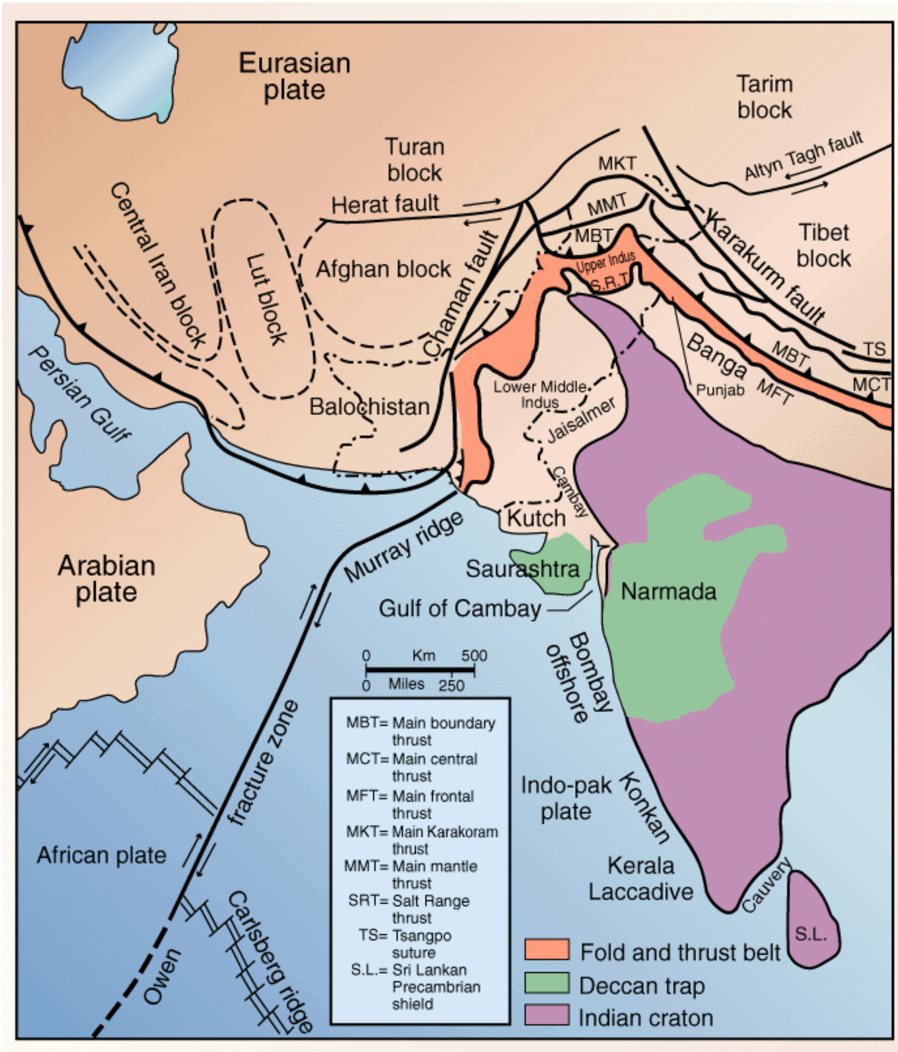

Figure 2.3: Generalized tectonic map of northern Pakistan, showing subdivisions of the Himalayan Mountains (modified after Gansser 1981; Kazmi and Rana 1982).

With ongoing uplift, erosion, and sediment deposition in nearby foreland basins, the Himalayan collision shows an ongoing collision orogeny between the Eurasian and Indian continents (Le Fort, 1975; Powell, 1979; Raynolds and Johnson, 1985; Klootwijk et al., 1985; Treloar et al., 1991; Beck et al., 1995). The foreland sedimentary strata have been detached and translated over the Jhelum plain along the Salt Range thrust in Pakistan (Yeats et al., 1984; Yeats and Lawrence, 1984; Coward and Butler, 1985; Treloar et al., 1992). A sizable area of Himalayan foreland thrusting is represented by the Salt Range-Potwar Plateau in north Pakistan. The geometry of the region, including the location and depth of the main decollement within the

Precambrian evaporites, has been examined using seismic reflection profiles (Lillie et al., 1987; Leathers, 1987; Baker et al., 1988; Pennock et al., 1989; Jaswal et al., 1997).

Because of its gentle topography, wide width, lack of internal deformation, and symmetrical structures, the Salt Range-Potwar Plateau's foreland thrusting pattern suggests the development of thrust wedges over a weak decollement (Davis and Engelder, 1985; Jaume and Lillie, 1988; Davis and Lillie, 1994). The plateau is divided into two sections: the Salt Range in the south, which has an emergent thrust sheet at its leading edge (Yeats et al., 1984; Lillie et al., 1987; Baker et al., 1988), and the North Potwar deformed zone in the north, which has an imbricated thrust sheet with a thrust front that is emerging and buried, respectively in the western and eastern regions (Jaswal, 1990). Although some studies have given insights on the complexity of North Potwar deformed zone but its evolution, structure, and kinematics are still remaining unclear (Jaswal 1990; Treloar et al., 1992; McDougall et al., 1993; Jamshed, 1995; Baig, 1995; Jadoon et al. 1997; Jaswal et al. 1997).

The Himalayas, known as the youngest and highest mountain range in the world, are currently undergoing active continent-continent collision. In India, there is a narrow zone (approximately 30 km) of foreland thrusting. On the other hand, in Pakistan, foreland deformation is characterized by a broader zone (around 130 km) of thrusting called the Salt Range-Potwar Plateau. The rapid southward movement along a weak decollement formed by tear faults and bounded thrust sheets is thought to be the cause of this zone wide width and gentle topography (Lillie et al. 1987; Jaume and Lillie 1988; McDougall and Khan 1990; Davis and Lillie 1994).

Similarly, foreland translations can be seen in the Jura Mountains in Europe (Laubscher 1981), the central Appalachian Pine Mountain thrust block (Rich 1934; Harris and Milici 1977), and the Himalayas in India and Pakistan (Raiverman et al. 1983; Jadoon et al. 1992, 1994a). In North Pakistan, the younger Himalayan deformation typically occurs nearer to the foreland. In the early Tertiary period, along the Indus suture zone, the Indian and Eurasian plates began to collide (Molnar and Tapponier 1975; Baig 1990; Beck et al. 1995). According to Tahirkheli et al. (1979), this zone is divided into the Main Karakoram Thrust (MKT) and the Main Mantle

Thrust (MMT) in North Pakistan. In the late Cretaceous to early Eocene, the Kohistan Island Arc, which lies between the MKT and the MMT, merged with Eurasia (Pudsey 1986; Treloar et al. 1989).

Rapid uplift that took place north of the fault between 30 and 15 Ma is thought to have locked the MMT around the time after 15 Ma (Zeitler et al. 1980). The Main Boundary Thrust (MBT), where unmetamorphosed Mesozoic and Lower Tertiary strata were thrust over Neogene molasse strata was the result of deformation that later spread southward. The deformation in the Salt Range-Potwar Plateau area indicates several out-of-sequence events, as indicated by magneto stratigraphy (G.D. Johnson et al. 1986; Burbank and Raynolds 1988). These constraints help in understanding the sequential evolution of the active Himalayan foreland in North Pakistan.

The cross section across the Salt Range-Potwar Plateau reveals the presence of 5-km-thick Neogene molasse Rawalpindi and Siwalik group strata below the Soan syncline, which is consistent with surface geological mapping (Gee 1980, 1989). However, the middle Miocene to Quaternary Siwalik strata abruptly disappear north of the Soan syncline, raising important questions. Was the Siwalik group originally deposited north of the Soan syncline and subsequently eroded during deformation and uplift of the NPDZ? Why do only the Rawalpindi group strata with moderate to steep and overturned dips (Akhtar et al. 1985; Treloar et al. 1992; Jamshed 1995) appear in a wide zone of over 20 km north of the Soan syncline? Is this outcrop pattern influenced by structural geometry, sedimentation, or a combination of both?

Since the collision started in the Eocene epoch, continued under thrusting of the Indian plate underneath Eurasia has caused crustal shortening, which has led to the formation of active tectonic features on the northern edges of the Indian craton. Thin-skinned tectonic structures are emerging in Salt Range and Potwar Plateau (SR/PP), which are located in the Himalayan foreland Pakistan. This happens as a wedge of sediments within Eocambrian evaporite beds contracts and thrusts southward along a décollement.

Northern Pakistan is the site to an almost 100-kilometer-long active fold and thrust belt that is part of Himalayan collision zone in its southern region. It consists of platform sedimentary rocks and molasses that have been thrusted southward along a ductile Precambrian evaporite layer (Seeber et al. 1979; Davis and Engelder 1985). The Soan syncline is formed by the Potwar Plateau's over thrust sheet and is bordered by the Salt Range to the south. The Punjab Plains have not been deformed as a result of the Salt Range Thrust (SRT), which culminates the Salt Range. The NPDZ is experiencing imbricate thrust faulting and horizontal shortening to the north of the Soan syncline. The Hill Ranges have been uplifted farther north along a different set of thrusts. The right-lateral Kalabagh Fault borders the Salt Range-Potwar Plateau thrust sheet to the west (McDougall, 1988), while thrusting declines more gradually in the east (Pennock, 1989). Basement rocks are exposed along the Sargodha High, which trends parallel to the Himalayas, about 70 kilometers south of the Salt Range, and could indicate the active flexural bulge (Yeats and Lawrence, 1984; Duroy et al., 1989).

A change in the Salt Range (SR) and Potwar plateau (PP), style of deformation can be seen in the Soan River, which runs parallel to a local NE-SW trending syncline. Folds and the emergent Salt Range Thrust (SRT) are the dominant features in the area south of the Soan Syncline. In contrast, the NPDZ is characterized by complex folding and faulting in the area north of the Soan Syncline (Jaswal et al., 1997; Jadoon et al., 1997, 1999). Along the Salt Range thrust, the Salt Range Formation is exposed and serves as a décollement. The thrust sheet is about 90 kilometers in length and has the conventional ramp-flat geometry. A north-dipping basement normal fault is located over the thrust sheet's ramp section. This period of time is thought to have started approximately 5 million years ago (Burbank and Beck, 1991).

Between 5 and 2 million years ago, several structures began to emerge in the eastern Salt Range-Potwar Plateau (Johnson et al., 1982; Jadoon et al., 1997). Between the Main Boundary Thrust (MBT) and the Soan Syncline, the NPDZ underwent complex deformation. The entire Himalayan region is covered by the MBT, which juxtaposes platform strata (Eocene) with molasses strata. Until about 8 million years ago, it was thought to be active (Jadoon et al. 1997). Between 11 and 8 million years ago, the NPDZ worked as a subsiding trough rapid sedimentation rates, with a majority of the deformation taking place between 8 and 5 million years ago (Burbank and Beck

1989; Jadoon et al., 1997). The motion was then transferred to the Salt Range thrust, which started to move around five million years ago, as the décollement propagated southward. As a result of this activity, sediments from the thrust's tip were transported northward and subjected to erosion (Burbank and Beck, 1991). Based on the deposition of the Lei Conglomerate, the northern limb of the Soan Syncline in the eastern portion of NPDZ is assumed to have tilted between 2.1 and 1.9 million years ago (Raynolds 1980; Burbank and Raynolds 1984). A record of the SRPP's late-stage subduction and significant mountain uplift can be found in the fluvial clastic molasse sediments of the foreland basin.

With age constraints primarily based on magneto stratigraphy, these sediments have been thoroughly studied to understand patterns of sedimentation and deformation (Johnson et al., 1982; Burbank and Raynolds, 1984; Burbank and Raynolds, 1988). The extensively exposed Miocene fluvial molasse strata of this region show that the Salt Range has been deformed since about 5 million years ago. The northern portion of the deformed foreland basin exposes the older sandstone strata (22- 13 million years old), which are primarily found in the Rawalpindi Group of Murree and Kamlial Formations. The younger Siwalik Group from 13 million years ago to the present, was drilled in the foredeep and is mostly exposed to the south of Soan Syncline (Lillie et al., 1987).

The most recent deformation of the NPDZ occurred between 2.1 and 1.9 million years ago, as reported by Johnson et al. in 1986. In the eastern Salt Range, Yeats et al. (1984) mapped some of the deformational features that are younger than 0.4 million years. According to Lillie et al. (1987), the décollement spread quickly towards the Salt Range front when deformation in the NPDZ stopped occurring around 2 million years ago. Since then, the SRT has undergone about 20 kilometers of horizontal shortening, which results in a calculated over thrust rate for the Salt Range-Potwar Plateau during the Quaternary period of about 10 mm/year (Baker et al., 1988). According to Chantelain et al. (1980), this rate is equivalent to about one-fourth of the overall convergence rate between India and Eurasia (37- 45 mm/year).

Depending on the type of deformation, the NPDZ can be divided into two sections. The eastern NPDZ displays a buried thrust front with the development of a triangle zone along the northern limb of the Soan syncline and the western NPDZ shows an emergent thrust front. The gently dipping basement of NPDZ, the existence of northward extending Precambrian evaporite layers, the distribution of facies and changes in the stratigraphic sequence are just a few of the factors that have an impact on the overall geometry of the thrust system. A better understanding of the deformation style and the application of new concepts in structural geology can lead to further discoveries of diverse structural configurations. Despite being a relatively young feature, this foreland fold and thrust belt can provide insight into features that may be missing or eroded in the older foreland fold and thrust belts, drawing analogies from the NPDZ.

Detachment of strata along a décollement causes thin-skinned deformation, which causes deformation above the décollement. Consequently, a thrust system can contain a variety of compressional structures. The relationship between folds and faults has been extensively studied, which has helped to clarify certain structural geometries (Jones, 1982; Boyer and Elliot, 1982; Suppe, 1985; Mitra, 1986). Understanding the relationship between folds and faults improves our understanding of foreland structures.

CHAPTER 3

STRATIGRAPHY

3.1 Introduction

The stratigraphy of the Salt Range-Potwar Plateau has been firmly recognized based on analyses of the outcrops of Salt Range (Gee, 1980, 1989), and oil wells that have been drilled in the Potwar Plateau (Khan et al., 1986). The geology of the NPDZ lacks precise constraints due to insufficient deep drilling data, but the exposed rock units along MBT and seismic sections proposed that it is similar to the strata in other areas of the Salt Range-Potwar Plateau.

3.1.1 Soan Formation

The type locality for the Soan Formation is situated north of the Soan River in the Attock District, near Mujahad Village, along the Gali Jagir- Sihal road. The predominant rock type in this formation is compact, massive conglomerate with clay, siltstone, and sandstone interbeds. Over short distances, the ratios of these various rock types changes. The conglomerate is composed of a wide variety of boulders and pebbles in different sizes. The massive conglomerate in Kohat-Potwar Province is mainly composed of grey limestone, porphyritic rocks, quartzite, schist, sandstone, diabase, gneiss, and other pebbles and boulders of the "Margala Hill" type. The size of the boulders and pebbles typically ranges from 5 to 30 centimeters, with interspersed sandstone and claystone. According to Cheema et al. (1977), the sandstone is grey, greenish grey, coarse-grained, and soft, whereas the claystone is brown, orange, pinkish, or red and has a soft texture.

An apparent disconformity between the Dhok Pathan Formation and the Soan Formation can be seen in the coarsening of the clastic and the appearance of densely packed, massive conglomerate. An angular unconformity indicates the upper contact of the Soan Formation with the Lei Conglomerate. The Soan Formation is generally lacking in fossils. Its age is assigned to the Late Pliocene to Early Pleistocene period.

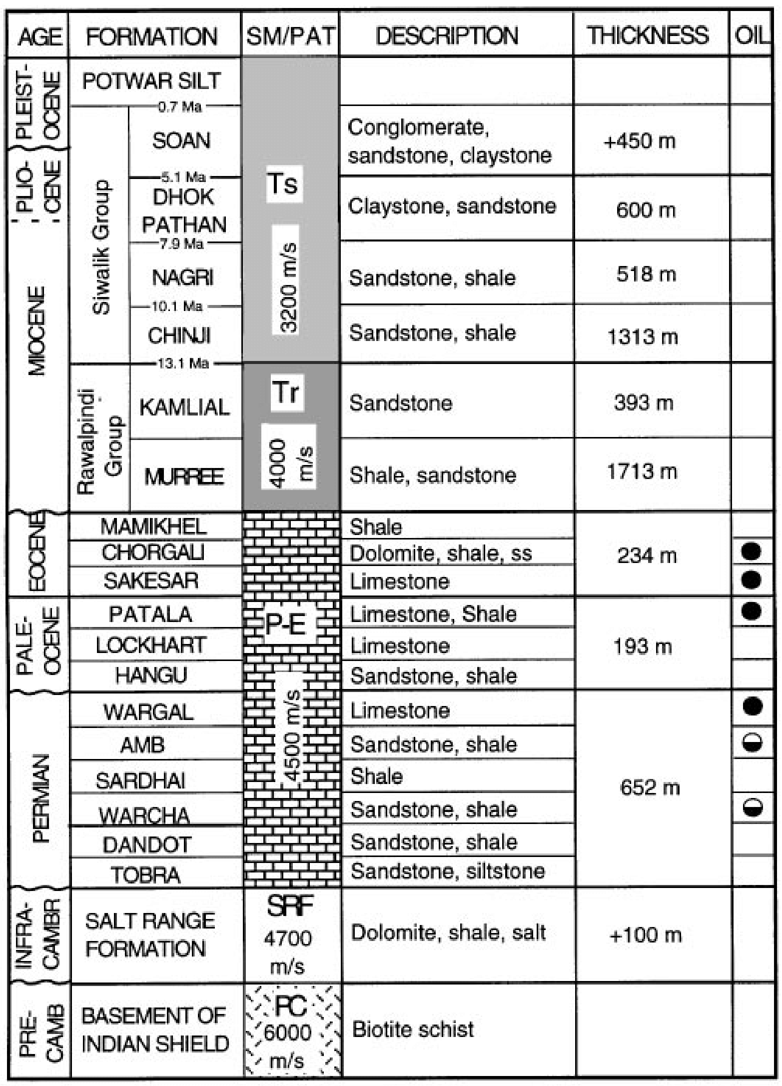

Figure 3.1: Simplified stratigraphic column of North Potwar deformed zone based on Dhurnal-3 well (after Kamran and Ranke, 1987; Jaswal, 1990; Ahmed et al., 1993).

3.1.2 Dhok Pathan Formation

Dhok Pathan village in the Attock District serves as the type locality for the Dhok Pathan Formation. Sandstone and clay bed cycles repeat continuously in this formation. The sandstone of the formation typically displays colors of grey, white, reddish brown, and on rare occasions, greenish grey, brownish grey, brown, or buff. It is soft, cross-bedded, calcareous, thickly bedded, and moderately cemented. With occasional patches of rusty orange, greenish yellow, yellowish grey, and chocolate hues, the clay is typically orange, dull red, brown, or reddish brown.

With intercalations of siltstone in a yellowish brown color, it is also calcareous and sandy. Conglomerate in the form of lenses and layers can be found in the upper portion of the formation. The contact between the Dhok Pathan Formation and the underlying Nagri Formation is visible as a transitional contact. The contact between the Dhok Pathan Formation and the overlying Soan Formation is considered to be a disconformable contact in Kohat-Potwar Province.

An abundant and diverse vertebrate fauna is present in the formation of Kohat Potwar Province. The fauna of the formation represent the Early to Middle Pliocene age based on the identified fossils. However, it is only claimed to be Middle Pliocene in age within the Kohat-Potwar Province.

3.1.3 Nagri Formation

The type locality for Nagri Formation is located at the village of Nagri in Attock District. The primary suggested reference section is Gaj River in Dadu District. Sandstone dominates this formation with clay and conglomerate. The medium to coarse grained sandstone has a greenish grey colour, is cross-bedded, and has a massive structure. The sandstone can display dull red or bluish grey hues with a distinctive "salt and pepper" pattern in some places. Additionally, it may be composed of calcium and exhibit moderate to poor cementation. The clay within the formation ranges from sandy to silty, with colors varying between chocolate brown, reddish grey, and pale orange. The proportion of clay content varies across different sections. The conglomerate beds found within the formation have diverse thickness and composition depending on the location. In Kohat-Potwar Province, they contain pebbles composed of igneous rocks and Eocene limestone.

In some locations of Sulaiman Range and the Kohat-Potwar Province, Chinji Formation is conformably overlain by Nagri Formation. There is always a transitional nature visible at upper contact with the Dhok Pathan Formation.

An abundant collection of vertebrate remains has been found in the Nagri Formation. Based on the fossils discovered, the fauna indicates an age range from late Middle Miocene to Late Miocene.

3.1.4 Chinji Formation

The designated type section of the formation is situated in Attock District, near Chinji Village. It is mainly consisting of red colored clay with layers of light grey or brownish grey sandstone. The sandstone typically has fine to medium-sized grains, but it can also occasionally have cross-bedding, a gritty texture, and a soft composition. Quartzite pebbles and thin layers of intraformational conglomerate are dispersed throughout the formation at different horizons. The interbeds ratio of clay to sandstone varies from the place to place.

The Chinji Formation is vastly distributed in Kohat-Potwar regions. It is absent from the remaining part of the Lower Indus Basin and is restricted to the southern half of eastern Sulaiman Range. The Kamlial Formation underlies Chinji Formation in Kohat-Potwar Province, with a clear and conformable contact between them. The Nagri Formation conformably overlies it.

There are many fossilized vertebrate remains that have been identified in Chinji Formation. Chinji Formation is thought to be Late Miocene in age, based on the fossils presence.

3.1.5 Kamlial Formation

The designated type section of the formation is located southwest of Kamlial in the Attock District. It primarily consists of sandstone in shades of brick red and purple grey. The sandstone is composed of grains having size range from medium to coarse grained and interbedded with purple shale and yellow to purple-colored intra-formational conglomerate. It has a typically spheroidal weathering pattern, and tourmaline predominates over epidote as the dominant heavy mineral, distinguishing it from the Murree Formation beneath.

Kamlial Formation is widely distributed in Kohat and Potwar regions. Murree Formation is conformably overlain by it, typically with a broad transitional contact. But in certain regions, it unevenly covers the Sakesar Limestone, which reveal the Eocene age. The Chinji Formation, which is a part of the Siwalik Group, conformably overlies the formation itself. Several fossilized mammal remains have been discovered in the formation. These fossils suggest that Kamlial Formation is of Middle to Late Miocene age.

3.1.6 Murree Formation

The type section of Murree Formation is located north of Dhok Maiki village in Attock District. It consists of a consistent sequence of clay in dark red, and purple colors, along with sandstone in shades of purple grey and greenish grey. There are also occasional layers of conglomerate within the formation. The lower portion of the formation is made up of calcareous sandstone and conglomerate that is greenish grey in color and rich in larger forams that belong to the Eocene period. This particular horizon is represented as Fatehjang Member.

The formation is extensively present in Kohat-Potwar Province. Throughout its distribution, it unconformably overlies various formations dating back to the Eocene period. The Kamlial Formation is broadly separated from the upper contact of the formation. Only a few plant remains, fish remains, silicified wood, mammalian bones, and frog fossils have been found in the formation. Murree Formation represent the Early Miocene age based on the fauna found there.

3.1.7 Chorgali Formation

The type section of the formation is present in the Chorgali Pass of Khairi Murat Range. Shale and limestone represent a large portion of the formation. It can be divided into two separate units in the Khairi Murat Range. Shale and dolomitic limestone compose the lower unit. The medium-bedded dolomitic limestone has colors ranging from white to light grey and yellowish grey. In contrast, the shale is calcareous, greenish grey in color, and is found as interbeds in upper part of the unit. The predominant lithology of the formation changes from limestone to shale as it rises, with a bed of nodular argillaceous limestone and a thick bed of dark grey limestone present close to the top.

The shale in this upper portion displays colors such as greenish grey, red, occasional variegation, and it also exhibits calcareous characteristics. Intercalated within the formation, there are some grit beds.

The formation is conformably underlain by the underlying Sakesar Limestone in Salt Range, and the Margala Hill Limestone at various other places. The upper contact between the underlying Chorgali Formation of Eocene age and the overlying Murree Formation of Miocene age, is unconformable in Salt Range, whereas a conformable contact with Kuldana Formation can be observed in other areas.

Several researchers have reported a diverse fossil assemblage, including foraminifers, mollusks and ostracods. The Early Eocene age is suggested by the fauna found inside the formation.

3.1.8 Sakesar Formation

The Sakesar Peak in the Salt Range is the designated as the type locality of the formation. Limestone makes up the majority of the formation with minor marl occurrences. The limestone, which dominates the formation, exhibits a cream-colored to light grey appearance. It is nodular in nature and typically appears as massive rock units. In the upper part of the limestone, there is a significant development of chert. On the other hand, the marl is a persistent layer that ranges in color from cream to light grey and is found near the top of the formation.

The Salt Range and Surghar Range both contain a significant portion of Sakesar Formation. Sakesar limestone has a lower conformable contact with Nammal Formation, which suggests continuous deposition.

It has an upper conformable contact with Chorgali Formation in eastern side of Salt Range. However, Sakesar Formation is unconformably overlain by the rocks of Rawalpindi or Siwalik Group in Salt Range as well as in Surghar Range, indicating a break in deposition.

A variety and abundance of foraminifera, mollusks, and echinoids have been found in the formation. These fossils represent the formation age, which is determined by the fossil evidence to be Early Eocene.

3.1.9 Patala Formation

The type locality of the Patala Formation is present in Patala Nala in the Salt Range. Shale and marl constitute the majority of the formation in the Salt Range region, while minor amounts of limestone and sandstone also present. Typically, dark greenish grey color shale is present with selenite crystals. It has carbonaceous and calcareous characteristics in some places and has marcasite nodules. The limestone of the formation is nodular and has a color spectrum from white to light grey. It can be found as interbeds in the shale. In the upper part of Patala Formation, there are also interbeds of yellowish brown and calcareous sandstone. Locally, Dandot region contains economically significant coal seams.

The Patala Formation, which is found in the Kohat region, is distinguished by dark grey shale that may be carbonaceous and contains light grey argillaceous limestone beds. In Hazara, the shale has interbeds of nodular limestone and a coloration ranging from green to brown to buff. The formation in Kala Chitta Range is made up of thin interbeds of limestone and light brown and grey marl.

The Patala Formation has been observed in the subsurface of Potwar region. The Patala Formation conforms to the underlying Lockhart Limestone throughout its distribution, while the upper contact with Margalla Hill Limestone is conformable within the study area. The formation contains a wide variety of fossils that include forms, mollusks, and ostracods. These fossil varieties are abundantly present. Based on the appearance of fossils, Patala Formation has been given Late Paleocene age.

3.1.10 Lockhart Limestone

The type locality for the unit is a section exposed near Fort Lockhart in the Samana Range. The Lockhart Limestone, found in the Kohat area, displays a range of characteristics. It is typically medium to dark grey, medium to thick-bedded, and at some places can be massive, rubbly, and brecciated. The basal portion of limestone has a flaggy texture and is dark grey to bluish grey in color. The limestone in the Salt Range has a medium-bedded structure and appears grey to light grey. In the lower part, it has dark bluish grey, calcareous shale, nodules, and trace amounts of grey marl. The limestone takes on a dark grey and black coloration and has intercalations of marl and shale in Hazara and Kala Chitta regions. When freshly exposed, limestone typically has a bituminous nature and odors foul. The Kohat-Potwar Province has a good development of the Lockhart Limestone.

Regarding its stratigraphic position, the Lockhart Limestone conforms and transitions to the underlying Hangu Formation and overlying Patala Formation, respectively. Vast varieties of foraminifera, corals, mollusks, echinoids, and algae are found within the Lockhart Limestone. These fossil assemblages indicate a Paleocene age for the formation.

3.1.11 Hangu Formation

The type section of Hangu Formation is at Fort Lockhart. The Hangu Formation in the Kohat region is primarily made up of sandstone, with interspersed patches of grey shale in its upper part. The sandstone has a range of colors, including white, light grey, and reddish brown. As it ages, it takes on a dark rusty brown color. It forms medium to thick beds, is fine to coarse-grained, and occasionally conglomeratic. The formation in Salt Range is made up of nodular, argillaceous limestone with rare color variations, carbonaceous shale, and dark grey sandstone.

There is a localized increase in carbonaceous content, resulting in coal seams in parts of the Surghar Range. A two to three meters thick ferruginous and pisolitic sandstone bed can be found at the base of the unit. The "Langrial Iron Ore" can also be found in this section. The Kohat-Potwar and Hazara regions have extensive subsurface exposure of the Hangu Formation. In the Kohat, Kala Chitta, and Hazara regions, Kawagarh Formation disconformably overlies the formation, which in turn disconformably overlies a number of Paleozoic and Mesozoic formations. The Hangu Formation is uniformly covered by the Lockhart Limestone. Cox (1930), Davies and Pinfold (1937), Haque (1956), and Iqbal (1972) all provided reports on foraminifera, in addition to corals, gastropods, and bivalves. The formation is assigned to the Early Paleocene because the aforementioned foraminifera are present.

3.1.12 Wargal Limestone

The type section of Wargal Limestone is situated near the village Wargal in central Salt Range. The limestone and dolomite that make up the formation's lithology have light to medium grey, brownish grey, and olive grey colors. According to Teichert (1966), the following is a summary of the detailed lithology in Zaluch Nala, along with each layer to corresponding thickness.

Wargal Limestone has been deposited conformably over Amb Formation showing continuous deposition. An unconformity can be observed at the boundary between Permian Wargal Limestone and overlying Paleocene Hangu Formation.

The fauna found within the formation is diverse and includes profuse amount of gastropods, bryozoans, bivalves, brachiopods, trilobites, nautiloids, crinoids, and ammonoids. Furthermore, Kummel and Teichert (1970) reported the presence of pollen and spores, conodonts, and ostracods within the formation. The age of the formation is assigned to be Permian period.

3.1.13 Amb Formation

The type section of Amb Formation is situated in the village of Amb. Amb Formation, which comprises of limestone, sandstone, and shale, has unique characteristics. Brownish-gray, medium grained, and calcareous sandstone with medium to thick bedding makes up the lower portion of the formation. This sandstone is connected to a bed of calcareous material that is rich in fusilinids. Limestone and shale are mixed together as moving in the sequence. The limestone is sand-like, brownish-gray, medium bedded, and highly fossiliferous and having massive Productus like Derbyia and Neospirifer. On the other hand, the shale is grey to dark grey and shows signs of Glossopteris and Gangamopteris flora. The lower part of Amb Formation is mainly composed of dark colored shale with thin bands of limestone that have produced a few brachiopods in Khisor Range. The Wargal Limestone has conformity with the upper contact of Amb Formation, and the lower contact is conformable with the Sardhai clays.

In the western Salt Range, Amb Formation is well-developed, but it becomes thinner in the east. It is highly fossiliferous, showcasing a rich array of fossils. The age of the formation is attributed to be Permian period.

3.1.14 Sardhai Formation

According to Gee, the type section is situated in the eastern Salt Range's Sardhai Gorge. Blue and greenish grey clay dominates the Sardhai Formation, with minor beds of sandstone and siltstone. It also has a small amount of carbonaceous shale. The clay within the formation exhibits a distinctive lavender color and contains traces of copper minerals, including chalcopyrite. Disseminated within the formation are minor occurrences of jarosite, chert, and gypsum. Calcareous beds are sporadically found in the upper portion of the formation.

In Salt Range, the facies of Sardhai Formation are primarily lavender-colored clays, while in the Khisor Range they are black shale and brownish argillaceous limestone. Sardhai Formation overlies Warchha Sandstone and exhibits a transition contact. It is overlain by Permian Amb Formation and has been deposited conformably above Sardhai Formation’s lavender clays. Although occasional fish scales and plant remains can be found in Salt Range, the formation is largely devoid of fossils. Well-developed limestone beds have produced distinguishable brachiopods and bryozoans in Khisor Range. The age of Sardhai Formation is assigned to be Early Permian period.

3.1.15 Warchha Sandstone

The Warchha Gorge in Salt Range has been designated as the type section of Warchha Sandstone. Medium to coarse grained and cross-bedded sandstone dominates this formation with occasional conglomeratic intervals and shale interbeds. The sandstone displays varying colors, including red, purple, and lighter shades of pink. It is characterized as being arkosic, meaning it contains abundant feldspar grains. The pebbles found within the formation are predominantly pink-colored granite and quartzite.

The Warchha Formation exhibits local speckling. It has carbonaceous shale and rare coal seams in the Burikhel region of the western Salt Range. Although coal mining occurs in this area, production is limited and the coal quality is poor. It is worth noting that this Permian coal represents the only known occurrence of its kind in Pakistan.

The Warchha Sandstone is widespread distributed throughout the Khisor Range and Salt Range. It conformably overlies the Dandot Formation in most areas. However, in sections such as Zaluch Nala and Saiyiduwali, it directly overlies the Tobra Formation. The Sardhai Formation lies on top of the formation, and there is a transitional contact between them. The Warchha Sandstone has reportedly contained some plant remains. It is assigned an Early Permian age.

3.1.16 Dandot Formation

The type section of the Dandot Formation is the section near Dandot Village in Salt Range. At this location, the predominant lithology is sandstone that is light grey to olive green in color. Thin pebbly beds can be occasionally found within the sandstone. Subordinate layers of shales are also present that exhibit dark grey and greenish coloration.

In eastern Salt Range, Dandot Formation is exposed and well developed and gradually reduces in thickness towards the west. In the Khisor Range and western side of Salt Range, mostly it is not developed. It contains a gradational lower contact with Tobra Formation, while a conformable contact can be observed with the overlying Warchha Sandstone.

Fossils are present within the Dandot Formation, with numerous species of Bryozoa and Ostracoda having been identified from this unit. These fossils provide valuable insights into the age and paleo environment of the formation. The age of Dandot Formations inferred from the fossils found, is Early Permian period.

3.1.17 Tobra Formation

In the eastern Salt Range, close to Tobra Village, is the designated location for the type section of the Tobra Formation. This formation exhibits a diverse range of lithologies and can be divided into three recognized facies, as described by Teichert in 1967:

i. Tillitic facies: This rock unit, which is exposed in the eastern Salt Range, transforms into marine sandstone that is the site to the Eurydesma and Conularia fauna, which are characteristic of the Dandot Formation.
ii. Freshwater facies: Found in the central Salt Range, this facies consists of alternating layers of siltstone and shale with minimal to no boulders. It contains spore flora and represents a freshwater environment.
iii. Complex facies: This unit displays a combination of diamictite, sandstone, and boulder beds. In the direction of the western Salt Range and Khisor Range, it becomes thicker.

The Tobra Formation gradually transitions into the overlying Dandot Formation. The lower contact with the rocks of Cambrian age, is marked by a disconformity, indicating an interruption in deposition.

Pollen and spores, which are found in the lower portion of the Tobra Formation, are important indicators of age. It is considered to be of Early Permian age.

3.1.18 Salt Range Formation

The reference section for Salt Range Formation is the Khewra Gorge, which is situated in the eastern region of Salt Range. Gypsum, dolomite, beds of greenish clay and low-grade oil shale, as well as reddish gypseous marl and thick salt seams, make up the lower part of this formation. The "Khewra Trap or Khewrite," is an extremely weathered igneous body that can be observed in the upper portion of the formation. The thickness of Khewrite is about six meters and is colored from purple to green. It is primarily composed of radiating needles of pyroxene mineral, which are highly decomposed.

The clay, gypsum, and dolomite which make up the red-colored marl are occasionally accompanied by quartz grains and crystals of various sizes. The thick salt beds, which may reach up to a meter in thickness are pink in a variety of shapes and have well-developed laminations and color bandings. The shale beds are associated with trace amounts of potassium and magnesium sulphates. The gypsum in the formation is massive and ranges in colour from white to light grey. It is related to earthy, friable gypseous clay and bluish-gray, clayey gypsum. Dolomite typically has a light color and has flaky and cherty features. It coexists with bituminous, low-grade oil, and dolomitic shale.

Asrarullah proposed its division into three members, as follows:

i. Sahiwal Marl Member: (a) This member is made up of bright red marl beds, gypsum and dolomite beds. It also contains the Khewra Trap, an igneous body that has undergone extensive weathering. (b) Additionally, there are dull red marl beds within this member, which contain some salt seams. At the top of this member, there is a thick gypsum bed measuring 10 meters in thickness.

ii. Bhandar Kas Gypsum Member: This member primarily comprises massive gypsum with minor occurrences of dolomite beds and clay.

iii. Billianwala Salt Member: The Billianwala Salt Member is characterized by ferruginous red marl containing thick salt seams.

The Salt Range Formation records the deposition of evaporite sediments within a restricted basin under arid conditions. Clastic material, likely sourced from Peninsular India, was transported and deposited in an oxidizing environment. The formation is found above metamorphic rocks, believed to be of Precambrian origin. It has a conformable upper contact with the Khewra Sandstone. Early Cambrian to Late Precambrian are the ages assigned to the Salt Range Formation.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The area north of Soan Syncline is extremely complex and highly deformed in the subsurface. There are very few rock units exposed and mapped. These rock units are of Eocene age and younger strata. In order to understand the complexity of the area, the surface geological data was combined with the 2D seismic data.

4.2 Geological field observations

The surface geology of the area is comparatively simple. A major portion of the area north of KMR is covered with quaternary alluvium with the predominant provenance of the Himalayan Fold and Thrust Belt. The prominent features that can be observed in this area are the east-west trending ridges of Miocene Murree Formation. These ridges are distributed all the way form the Khairi Murat ranges in the south

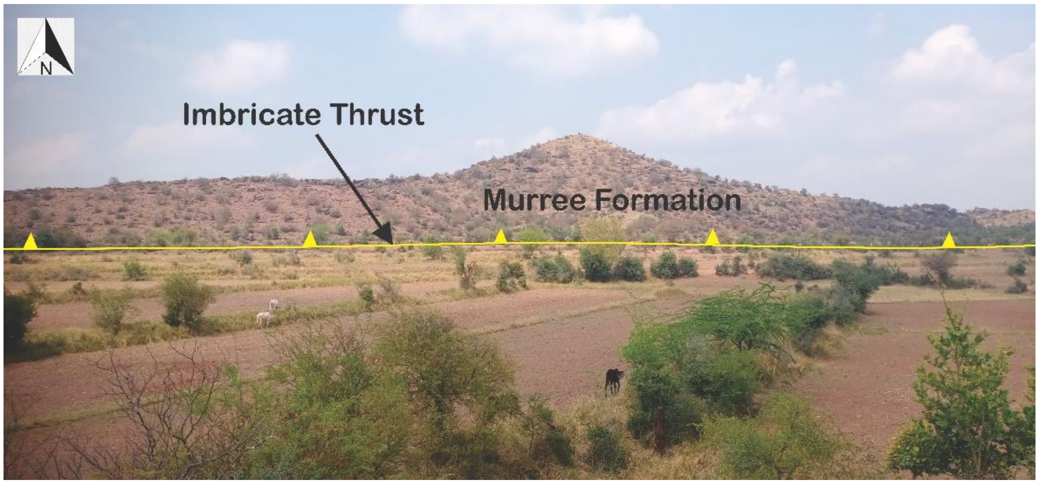

Figure 4.1: Ridges of Murree Formation formed as a result of imbrications between MBT and KMF.

to the MBT in the north. These are known to have formed as a result of imbrications in order to accommodate the high compressional stresses exerted by the collision of Indian and Eurasian plates. The inclination of the imbrications are measured to have steep dips and the tectonic transport direction is towards the south i.e. these are north dipping and south verging imbrications. The oldest strata exposed in the area are the Eocene rocks that have been thrusted over the younger Miocene strata along the Khairi Murat Fault. As a result of increasing compression, the MBT transferred the stresses to

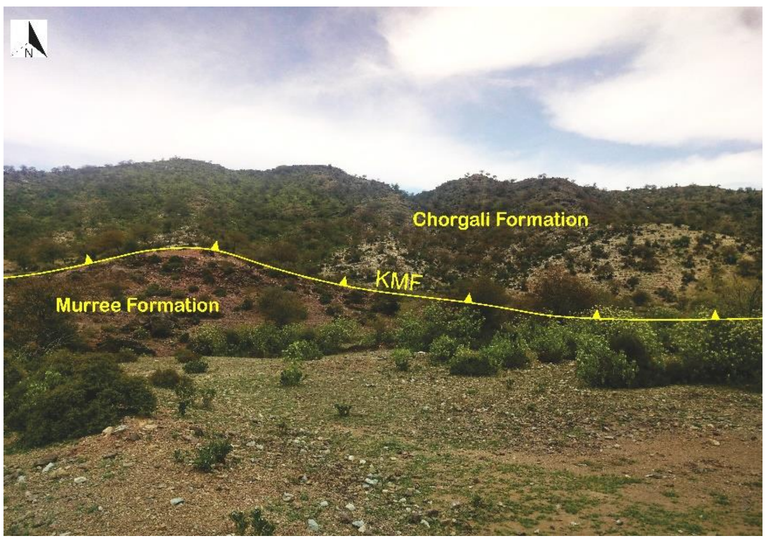

Figure 4.2: The field evidence of Khairi Murat Fault.

the Khairi Murat Fault. KMF is a splay of MBT that has accommodated the stresses of India-Eurasia collision in the north. Folding can be observed in the thrusted sheet of Eocene rocks along KMF at the Chorgali Pass section. Fault breccia and fault gouge can also be observed along the fault as the Eocene strata has been deformed during its up thrusting over the Miocene and younger strata. The boundary between the overriding Eocene carbonates and the underlying Miocene sandstone can easily be recognized in the field and is marked as the fault surface. Siwaliks are absent in the area north of KMF. The other prominent ridge comprising of Kamlial Formation south of KMF is formed by the north verging Dhurnal back thrust. The predominant lithology south of KMF are the Siwaliks. Various anticlines and synclines can be seen in the area that are mostly fault bounded and contain Siwaliks in their cores.

4.3 Surface geology

The collected data through remote sensing and fieldwork is used to create a geological map of the study area. The data was collected in the form of formation contacts, dip directions, and dip amounts, imbrication ridges, and other geological structures. The map shows several faults and folds. The various structures delineated are briefly discussed;

The Main Boundary Thrust (MBT) encircles the northernmost boundary of the study area. It is a north dipping thrust fault that has thrusted Lesser Himalayas over the Sub Himalayas. The major transport direction is southward and forms a range called Margalla Hill.

The area south of MBT is an imbricate zone within the Murree Formation. These imbrications are identified on the surface as low altitude ridges with the north dipping imbrications. This imbricate zone extends from MBT to the north of Khairi Murat Fault.

The area contains some prominent anticlines and synclines in the form of Seri Syncline, Fateh Jang Anticline, Daulat Para Syncline and various smaller one. These structures have been formed in Miocene Murree Formation. The area north of KMF is devoid of the Siwaliks.

Khairi Murat Fault is a splay of MBT and a north dipping thrust fault. Eocene rocks have been thrusted over the Miocene and younger strata. The fault surface can be identified by the presence of fault breccia and fault gouge. It is trending North-east and South-west. Mianwala Fault lies south of the KMF and is trending parallel to the KMF. It is a south verging thrust fault within the Murree Formation.

Dhurnal Back Thrust lies north of Soan Syncline and is a back thrust with major tectonic transport direction towards the north. It has thrusted Kamlial and Siwaliks and marks the boundary of the norther limb of Soan Syncline. Siwaliks are the major rock units exposed south of the KMF. Soan syncline marks the southern boundary of the North Potwar Deformed Zone. The core of the Soan Syncline contains Soan Formation.

The norther limbs exposed on the surface comprise of Kamlial, Chinji, Nagri, and Dhok Pathan Formation.

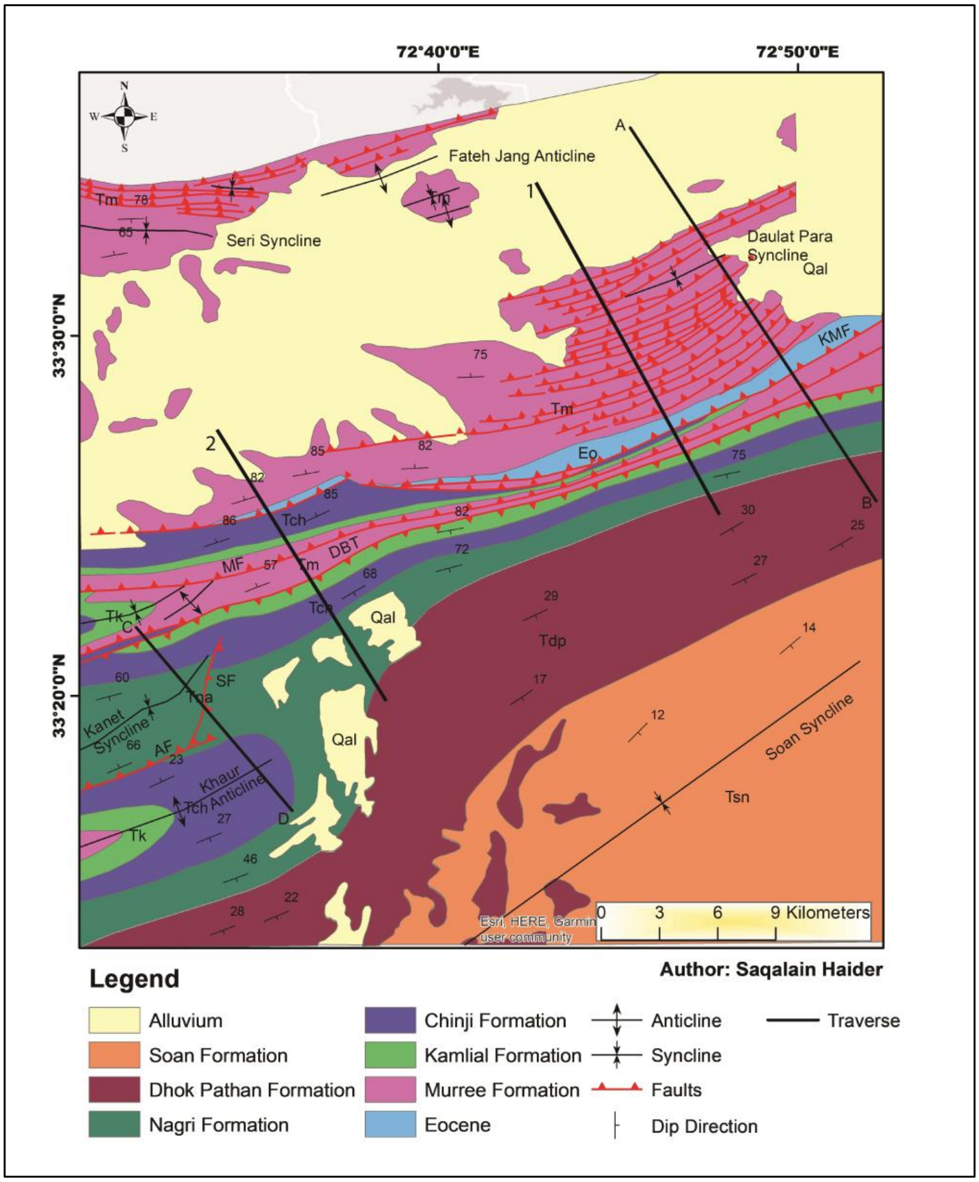

Figure 4.3: Detailed geological map of the study area illustrating spatial distribution of rocks and geological structures.

Kanet Syncline near Dhurnal has Nagri Formation deposited in the core of the syncline. It is bounded to the south by the Ahmadal Fault and to the east by Sakhwal Fault. Further south of the Kenet Syncline lies the Khaur Anticline. It is NE and SW trending and NE plunging anticline. Murree Formation lies at the core of the anticline while Kamlial, Chinji, Nagri, and Dhok Pathan Formations make the limbs of the Khaur Anticline.

4.4 Seismic Interpretation

The seismic line 'Line 1' passes through the Khairi Murat range. Fault bend folding in the sub surface above the basement level along with the staked duplex structures have been interpreted in the region below Dhurnal Back Thrust and Khairi Murat Fault. Dhurnal Back Thrust has been interpreted to have thrusted Kamlial Formation and the full sequence of Siwaliks above the Murree Formation south of Khari Murat Fault. Steeply dipping Khairi Murat Fault has thrusted Eocene strata over the Miocene Murree Formation and younger strata. KMF along with the underlying duplexes exhibit ramp geometries in the subsurface due the presence of evaporate layer. This evaporite layer in the form of salt shows ductile behavior and support only gently dipping faults in the form of flat sections of the ramp-flat geometry. The imbrication in Miocene Murree Formations form ridges north of the KMF all the way to the MBT.

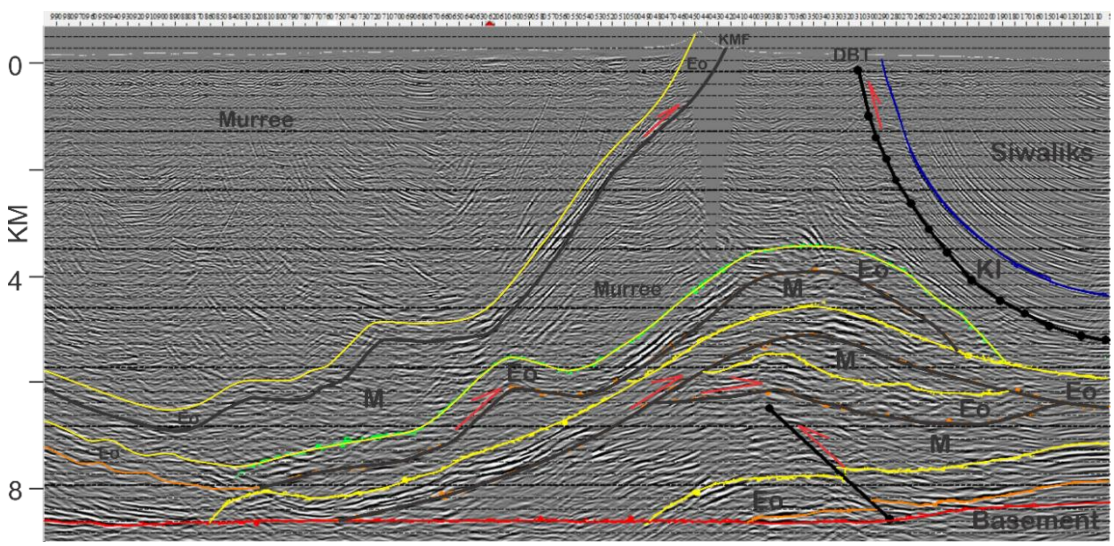

Figure 4.4: Interpreted seismic section along seismic Line 1.

The complexity of the sub surface can only be studies form the seismic data as there is very limited surface exposure of the rock units. A few lines were selected form the area of Dhurnal and Khairi Murat. The seismic line ‘Line 2’ is selected form the Dhurnal area. The section shows a triangle zone formed by the thrusting of Eocene strata along the oppositely dipping blind thrust faults. The ductile behavior of the salt make it easy to flow. The triangle zone is overlain by the thick sequence of Murree Formation above which the Kamlial Formation and the Siwaliks have been thrusted along Dhurnal Back Thrust, which is hinterland ward dipping back thrust.

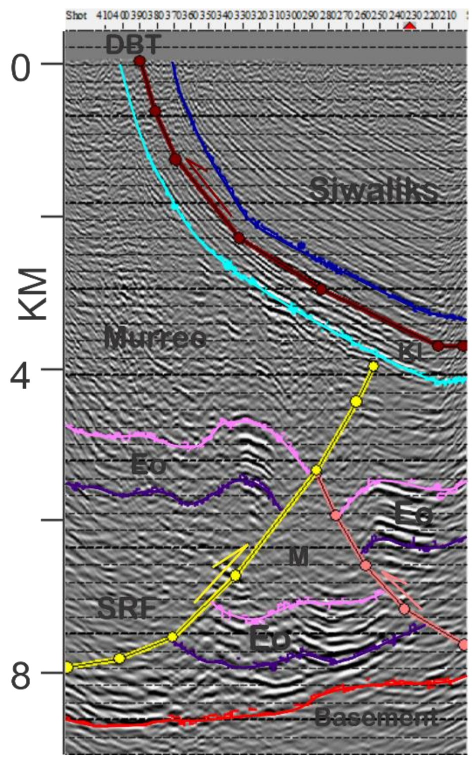

Figure 4.5: Interpreted seismic section along seismic Line 2.

4.5 Seismic sections

The seismic sections of the area were generated using the geological data form the map and field and the seismic sections. The cross section profile across the Khairi Murat range shows a steeply dipping fault surface of the Khairi Murat Fault at low depth, which become nearly horizontal at increasing depth. The stacked duplexes below Khairi Murat Fault and Dhurnal Back Thrust also shows ramp-flat geometries

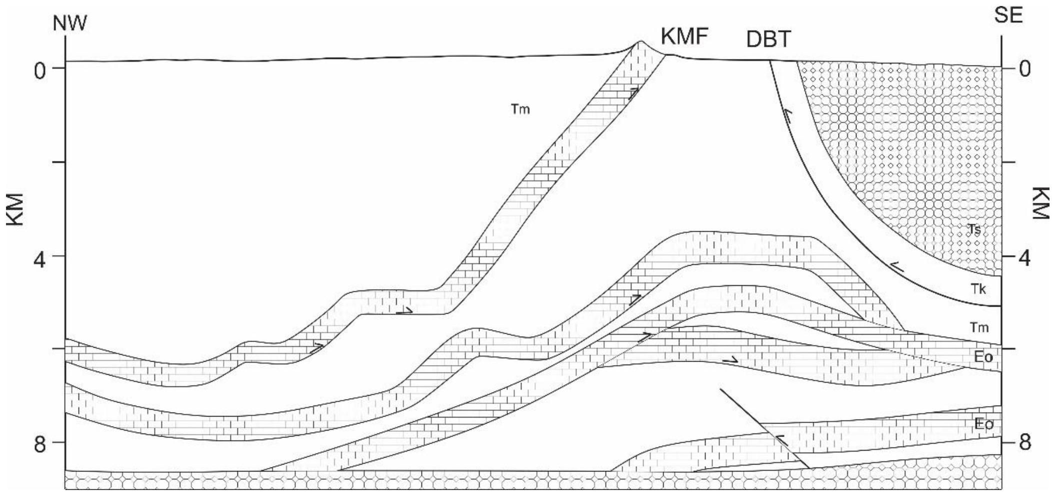

Figure 4.6: Cross section AB, depicting the ramp-flat geometry of Khairi Murat Fault.

in the form of fault bend folding. The Eocene strata has been severely deformed and faulted along the KMF and in the adjacent areas. The Eocene strata has raised to the surface only along the KMF, while majority of the area is covered with molasses. The area in the vicinity of Dhurnal contains molasses exposed on the surface, while the subsurface contains some complex structures. The surface expression of the Dhurnal Back Thrust is represented by the ridge formed by Kamlial Formation. Siwaliks have also been thrusted along the DBT. The subsurface structures indicate a triangle zone structure formed by the thrusting of Eocene strata along two oppositely dipping thrust faults. Theses faults are the blind thrusts and terminate below DBT. These structures are supported by the ductile flow of the evaporites of Precambrian Salt Range Formation.

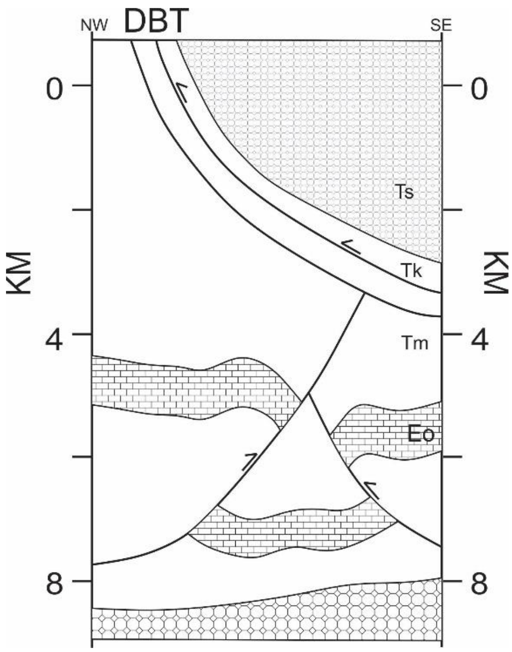

Figure 4.7: Cross section CD, illustrating the triangle zone geometry in the subsurface.

4.6 Integrated geological cross sections

The geological cross section AB has been generated using the surface geology and the seismic data. The northern portion of the section illustrates the imbricate zone within the Murree Formation, where ridges have been observed on the surface confirming the subsurface imbrication. The southern extremity of the imbricate zone is marked by the Khairi Murat Range that has been uplifted along the Khairi Murat Fault (KMF). KMF is a north dipping thrust that exhibits a ramp flat geometry. Mianwala Fault (MF) is north dipping thrust within the Murree Formation. Dhurnal Back Thrust is the southernmost thrust in the NPDZ. It is a north verging back thrust that has thrusted Kamlial Formation. The area below Dhurnal Back Thrust shows a fault propagation fold and duplex structures.

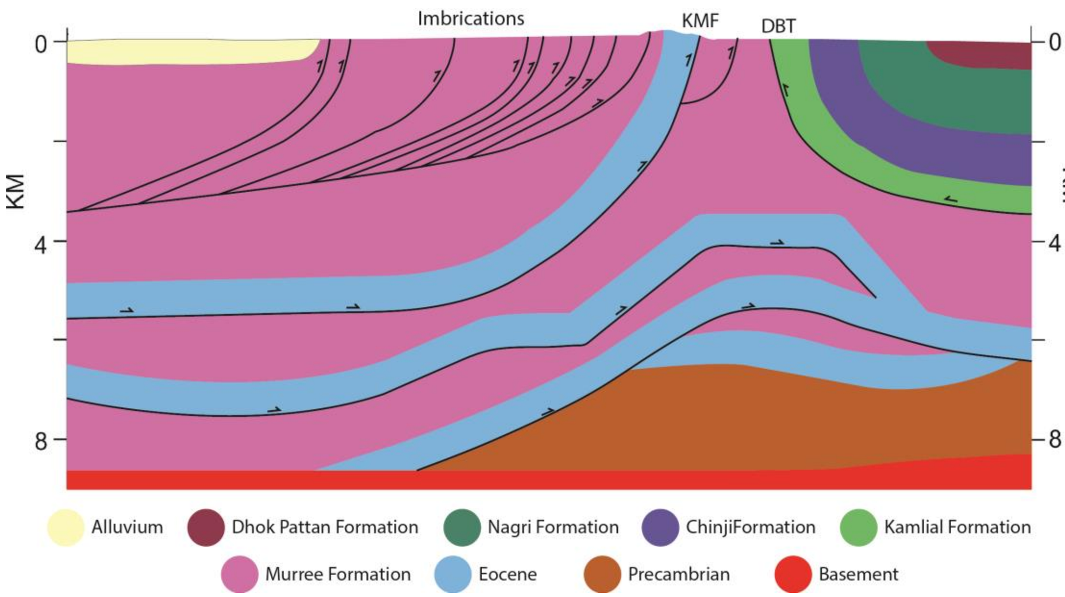

Figure 4.8: Integrated geological cross section AB illustrating the various structures.

The cross section CD has a smaller thrust in the northern portion that has been responsible for thrusting Murree Formation over Chinji Formation. Dhurnal Back Thrust can be observed south of the smaller thrust. It has thrusted Kamlial Formation over Chinji Formation. Further south of the DBT, Kanet Syncline has been developed. This syncline comprises of Nagri, Chinji, and Kamlial Formations. Nagri Formation lies in the core of Kanet Syncline. As we move further south, the syncline ends into an ancline, the Khaur Anticline. The oppositely dipping beds of Chinji Formations can be observed on the surface as they indicate the surface expression of plunging Khaur Anticline. The subsurface area below DBT shoes a triangular zone geometry. The triangular zone has been formed as a result of two oppositely dipping thrust faults that intersect at a low depth. Both the faults thrust Eocene and older strata over Miocene Murree Formation.

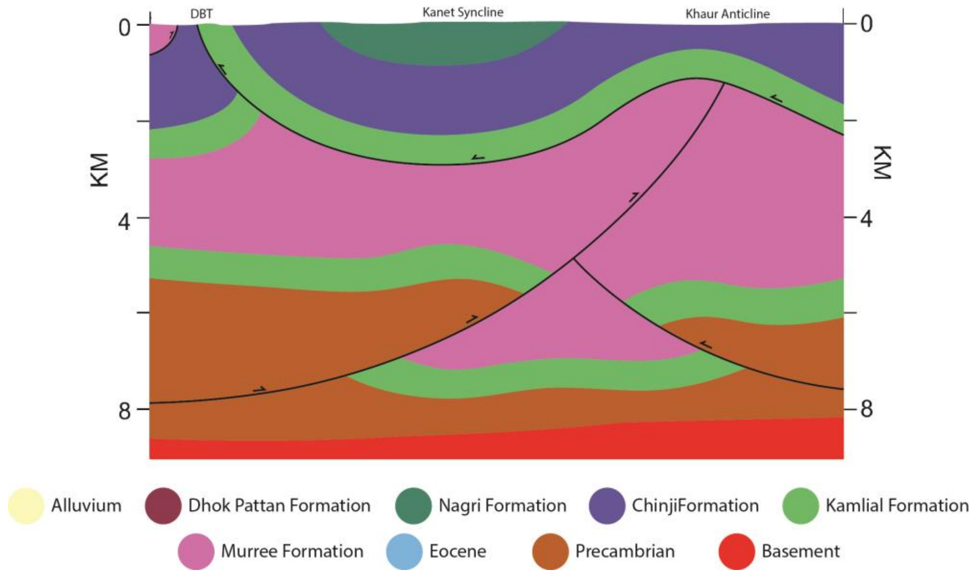

Figure 4.9: Integrated geological cross section CD showing the deformation structures.

4.7 Discussion

The Potwar Plateau is within the foothills of the Himalayas, in Pakistan, extends approximately 130 km south (Moghal et al., 2007; Qayyum, 1991; Jaswal, 1990), bounded to the north by the Main Boundary Thrust, and to the south by the Main Frontal Thrust/Salt Range Thrust. Its eastern and western extremities are bounded by strike-slip faults, the Jhelum and Kalabagh fault respectively (Moghal et al., 2007). The Potwar deformation was controlled by a widespread Precambrian basal evaporite detachment horizon (Jouanne et al., 2014; Jaumé & Lillie, 1988; Seeber & Armbruster, 1979), lying above faulted basement (Borderie et al., 2017). Overall, the Potwar region becomes less complex and deformed southwards towards the Soan syncline and Salt Range This is because of the tectonic stresses not being as intense further away from the Himalayas (Moghal et al., 2007). Deformation of the North Potwar Deformed Zone occurred during the Neogene, approximately 2.1-1.9 Ma (Johnson et al., 1986), and potentially on-going, creating the south verging structures. The deformation front propagated suddenly, creating the Salt uplifted Salt Range (Lillie et al., 1987). With the combination of the digitized geological map on ArcGIS acting as surface constrained for seismic interpretation, well information providing stratigraphic constraints in the seismic interpretation, and picking of artefacts and previous research to draw valid interpretation of the study area; it can be said that the MBT merges with the Precambrian evaporite basal decollement at approximately 10 km depth (Tiwari, Rajasekhar & Mishra, 2008; McDougall et al., 1993, Seeber & Armbruster,1979), with displacement of the MBT to be around 40 km (Jaswal, 1990). The Precambrian basement has a dip of 2° towards the north (Lillie et al., 1987). However, as the seismic is limited spatially, the full shortening of this could not be shown. South of the MBT, shortening is accommodated by blind thrusts, which is localized to the Western Syntaxis (McDougall et al., 1993). As suggested by Jaswal (1990) and McDougall et al. (1993), as well as the DEM topographic display above the seismic, the Potwar Plateau has an almost flat topography due to high rates of erosion occurring as the faults developed. The thickness of most sediments in the hanging wall of the Main Boundary Thrust is unknown or unreliable due to significant erosional processes that took place during the uplift and emergence of the MBT by the late Miocene (Meigs, Burbank & Beck, 1995). However, the footwall has preserved thickness of most of the stratigraphy in the Potwar.

MBT is a long travelled thrust sheet, and the Khairi-Murat Thrust is a splay of the Main Boundary Thrust, rather than a separate thrust sheet, which was suggested by Jadoon et al. (1997). The evidence for this comes from the little stratigraphic displacement produced along the Khairi-Murat as it climbs up-dip and thus resulting it to be a thrust sheet of low finite displacement; therefore, purely accommodating localized stresses derived from the Main Boundary Thrust as the Main Boundary Thrust was becoming inactive. In other words, the Main Boundary Thrust is segmented continuously across the basin with multiple blind thrust emerging from it and the Khairi-Murat Thrust is the forward breaking expression of the ranges propagation into the foreland.

The Main Boundary Thrust was active by the Cenozoic (Mugnier et al., 1994), during the formation of the Himalayan Mountain Range, and thus acting as a major floor thrust, and triggering the southward movement and folding of the Potwar (Mukherjee et al., 2015). The MBT marks the boundary between the Lesser Himalayas, made up of pre-orogenic Paleozoic-Mesozoic metamorphic and platform strata as well as Precambrian metamorphic and evaporitic rocks; and the Sub-Himalayas, made up of syn-orogenic Neogene molasse sediments (DiPietro & Pogue, 2004; Jouanne et al., 2013).

It can be said that this Precambrian decollement is much older than the MBT and acted as the primary gliding horizon to accommodate shortening, and due to changes in mechanical behavior of strata, the MBT emerged and ramped up-dip off from the Precambrian detachment, accommodating stresses southwards. Within the study area, the Main Boundary Thrust acts a major decollement horizon for the syn-orogenic platform sequence southward over the granitic basement, the Indian shield rocks. Thin skinned tectonics can be observed in this foreland fold and thrust belt setting of Potwar Plateau, allowing the distribution of stresses and crustal shortening, with detachment faults gliding along ductile lithologies such as evaporites and shales (Jaume & Lillie, 1988).

CONCLUSIONS

The lithostructural mapping of the study area revealed that Khairi Murat Fault is the main emergent thrust present, dipping at high angle towards NNW.

KMF divides the study area in the north (as its hanging wall) and in the south (as its foot wall) whose surface geology can be explained as follows:

i. Hanging wall of Khairi Murat Fault is strongly imbricated with a number of small reverse faults present mainly in Murree Formation forming a leading imbricate fan with major displacement along KMF.
ii. Foot wall of Khairi Murat Fault is mostly covered with Siwaliks with DBT (Dhurnal Back Thrust) and to the west, presence of Khaur Anticline and syncline sequence presenting more passive style of deformation.

To understand the subsurface geology and fault, two geo-seismic sections were made, incorporating geological cross sections and seismic lines which helped to conclude the following points.

i. The overall structural architecture of the study area is being controlled by the blind thrust SRT, gently dipping towards north and SRT acting as decollement act as sole thrust for the upper sheet along with another decollement at Miocene level acting as roof thrust.
ii. Repetition of brittle and ductile lithology provided bending in the faults to fault ramp and flat geometries and consequently forming fault bend folds, ideal sites for hydrocarbon exploration.

iii. South of KMF represents the masking effect of DBT (Dhurnal Back Thrust) over a pop up geometry at Eocene level, also a triangle zone, hosting famous oilfields in Pakistan.

iv. Khairi Murat Fault is segmented into eastern and western segments by a strike slip fault. But the geo-seismic sections helped to reveal it as a tear fault as KMF is acting as the frontal ramp for the hanging wall movement towards the south. This ramp geometrical complication resulted into a lateral ramp appears to be a strike slip fault.

v. The overall fault system is linked and can be divided into imbricate style of faulting in the north and a passive roof duplex in the south.

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