3D STRUCTURAL MODEL OF EASTERN AND CENTRAL SALT RANGE, PAKISTAN. A CASE STUDY FROM KALLAR KAHAR AND SURROUNDING AREAS.

By

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Thesis submitted to Bahria University, Islamabad in partial fulfillment of the requirement for the degree of M.S in Geology

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2014

CERTIFICATE OF ORIGINALITY

This is to certify that the intellectual content of the thesis

3D Structural Model of Eastern and Central Salt Range, Pakistan. A case study from Kallar Kahar and surrounding areas.

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A thesis submitted by **Mr. Ehtisham Javed** to the Department of Earth & Environmental Sciences, Bahria University, Islamabad in partial fulfillment of the requirements for the degree of **Master of Science in Geology** (Session 2012 – 2014).

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ABSTRACT

The research work is carried out in vicinity of Salt Range, Pakistan. It marks the outer boundary of Himalayan deformation in Pakistan. In Salt Range strata ranging from Precambrian to Recent, is thrusted along Salt Range Thrust over youngest sediments of Punjab plain. Previous models proposed that the Salt Range evolution is related to simple fault bend fold geometry corresponding to thin skinned tectonics. Various 2D geological cross section are constructed from Main Boundary Thrust in north to Salt Range Thrust in south to confirm the geometry of fault bend fold however no practices were observed for 3D structural interpretation of the Salt Range Thrust. Extensive field visits are carried out to obtain field data for compilation of the revised geological map of the study area at 1:50,000 scale. The stratigraphic successions are grouped on the basis of ages into various groups that aided in understanding the structural evolution of the study area. Four north-south oriented geological cross sections are constructed with the help of field data, seismic lines and well data. The geological map and the cross sections are then incorporated to a 3D model using Midland Valley Move software. The resultant 3D structural model in this research suggests that the Salt Range Thrust emanating from the basal detachment ramps upsection across pre-existing normal fault in the basement. The Salt Range Thrust terminates in subsurface with tip line buried under the hanging wall ramp of the anticline or under the resent deposit of Punjab plain. Absence of faults zones along the previously proposed trace of the Salt Range Thrust also support this idea that Salt Range Thrust act as blind thrust along most of its trend. The presence of series of anticlines and synclines in the crestal portion of hanging wall shows that geometry of the Salt Range differs from ordinary fault bend fold geometry rather it could be best explained as multi bend fault bend fold. It is concluded that Salt Range is evolved as multi bend fault bend fold along blind thrust (Salt Range Thrust) with staircase trajectory.

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CHAPTER 1
INTRODUCTION

The southern margin of the Himalayan collision zone in Pakistan is the Salt Range and Kohat-Potwar plateau, an active foreland fold-thrust belt formed in response to the under thrusting of cratonic India beneath its own Phanerozoic sedimentary cover. At Salt Range front, Eocambrian evaporites and Paleozoic to Cenozoic strata over ride syn-orogenic fan material and alluvium (Yeats et al., 1984). The strong emergent Central Salt Range is located between a weekly emergent thrust front at the Surghar Range and a buried thrust front in the eastern Salt Range. The right lateral Kalabagh tear fault terminates the Salt Range to the west (Yeats and Lawrence, 1984) in contrast, the eastern termination of the Salt Range is divided into several fault blocks bounded by forward and rearward verging thrust (Johnson et al., 1986).

The name Salt Range was first used by Stuart Elphisntone, a British envoy to the court of Kabul. He traveled from 1808 to 1815 across this land and noted the extraction of Salt from the Salt Range Formation of the Salt Range. The Salt Range is the most important locality in Pakistan for the study of physical as well as stratigraphic geology. Since very earlier times it has attracted the attention of geologists, not only because it contains a very large portion of fossiliferous stratified record of eastern Tethys but also because of the easily accessible nature of the deposits and excellent stratigraphic exposures in its hills. So, it is because of these reasons that it gained its name as "Field Museum of Geology" (Wadia, 1975).

The study area of Salt Range is located in eastern wing of Salt Range which was previously mapped by E.R Gee under topographic sheet 43D/9, 43D/10, 43D/13 and 43D/14 of Geological Survey of Pakistan (Gee, 1980). The area lies between longitude 72°35'E to 73°00'E and latitude 32°30'N to 33°15'N. The oldest stratigraphic unit exposed in area is the Salt Range Formation. The hydrocarbon exploratory wells in both the nearby vicinity of study area provides significant data in terms of structural evolution of the Salt Range Thrust (Fig.1.1).

1.1 Location and accessibility

This research work is carried out in the southern Potwar Fold and Thrust Belt mostly along the Salt Range Thrust in region of Kallar Kahar, Chakwal, Khewra and their surroundings. Research area can be easily accessed by asphalt road from the capital territory, Islamabad. This region is noticeable for its unique geological settings as the whole stratigraphy sequence from the Precambrian to recent is well exposed. Ancient temples, lakes, peacocks and natural gardens also attracts tourist toward this region. However, the best time to carryout geological field work is winter.

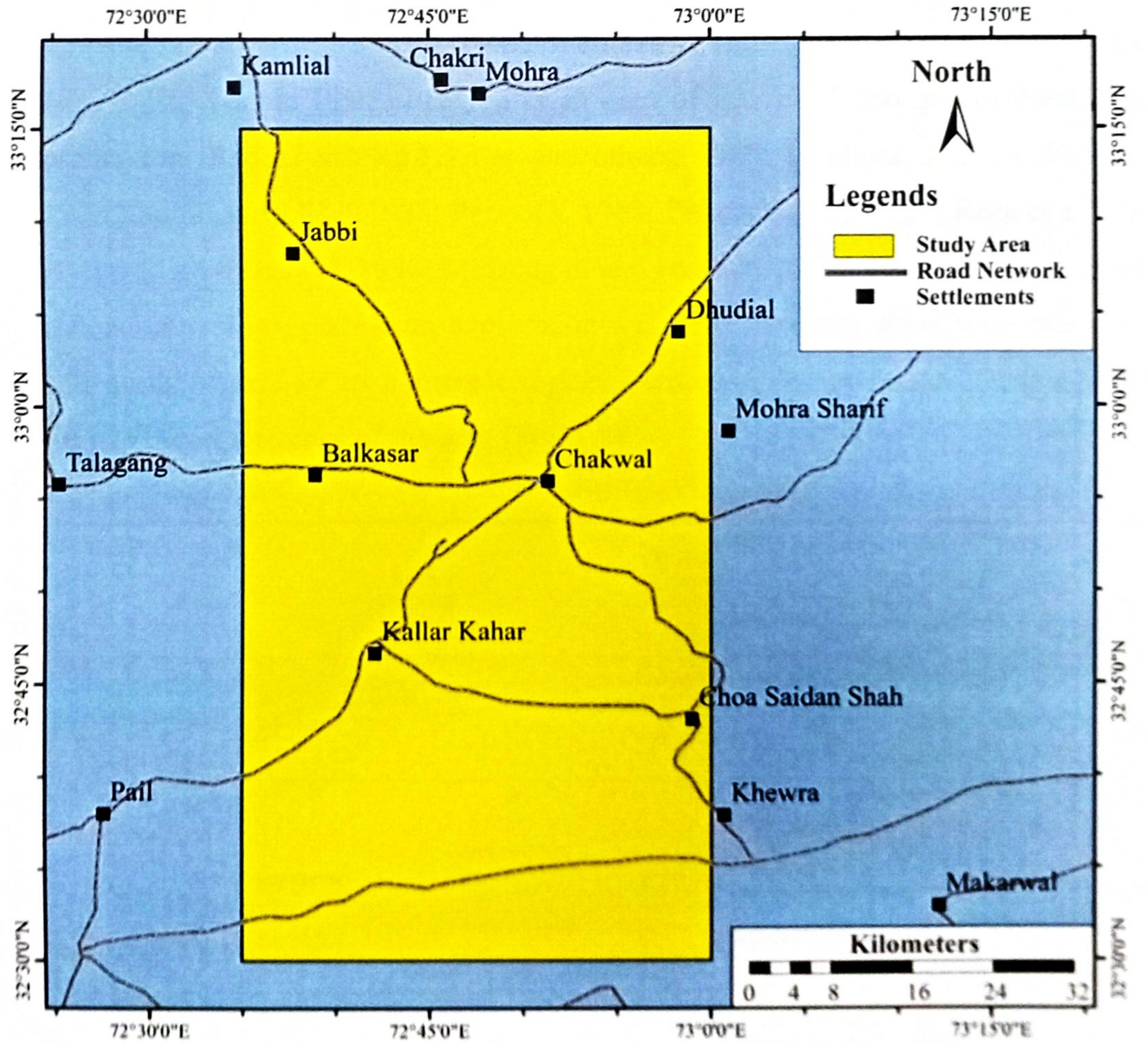


Figure 1.1. Map showing location of the research area (created using Google Imagery via Esri ArcGIS 9.3).

1.2 Previous work

The Salt Range is a part of Himalayan Foreland Fold and Thrust Belt which marks the southernmost position of the thrust front in the northwest Himalaya of Pakistan and is bordered by Potwar Plateau in the north and Punjab plain in south. The Salt Range is well studied and documented by many researchers like E.R Gee (1980), Burbank and Raynolds (1984), Yeats et al., (1984) and Danilchick (1961). In the Salt Range area, thrust faults and associated salt diapirism bring the strata to surface, containing evaporites of Precambrian age (Gee, 1980, 1989). These ductile evaporites underlie the Potwar Plateau and form a zone of décollement for regional thrusting (Butler and others, 1987; Jaumé and Lillie, 1988; Pennock and others, 1989). The Potwar Plateau region is an area of active oil and gas exploration and production. Recent studies (Butler and others, 1987; Leathers, 1987; Baker et al., 1988; Jaumé and Lillie, 1988; Pennock, 1988; Pennock et al., 1989; Raza et al., 1989; Hylland, 1990; Jaswal, 1990; McDougall and Hussain, 1991) have combined seismic-reflection profiles, petroleum exploration well logs, Bouguer gravity anomaly maps, and surface geology to construct regional structural cross sections that detail the thrust-related tectonics of the area (Fig. 1.2).

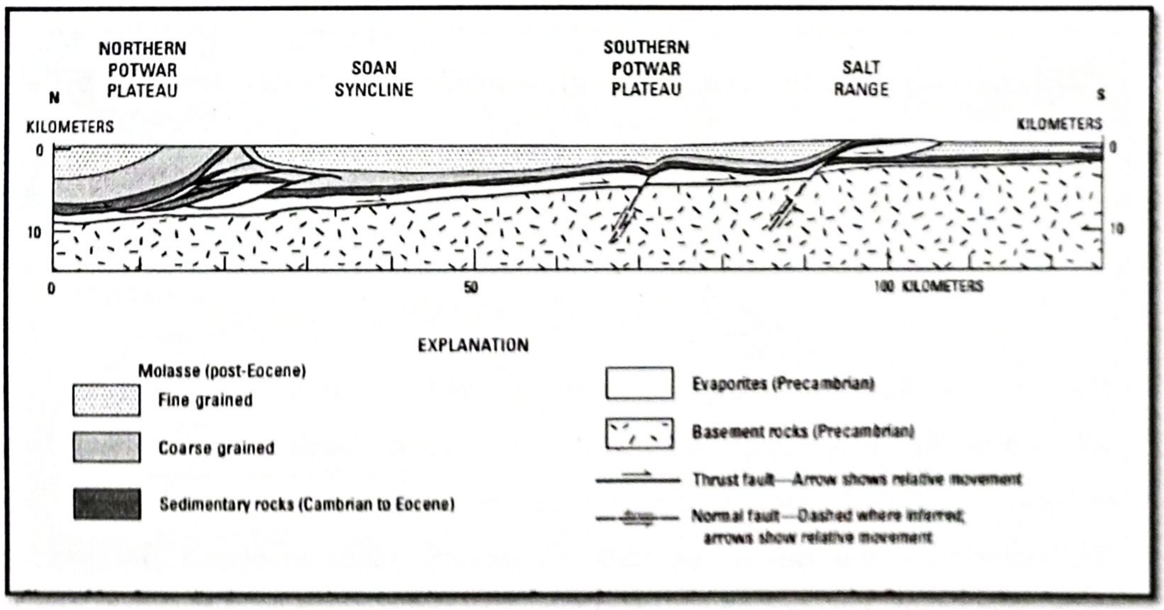


Figure 1.2. Generalized cross section across the western Potwar Plateau and the west-central Salt Range (Warwick et al., 1992).

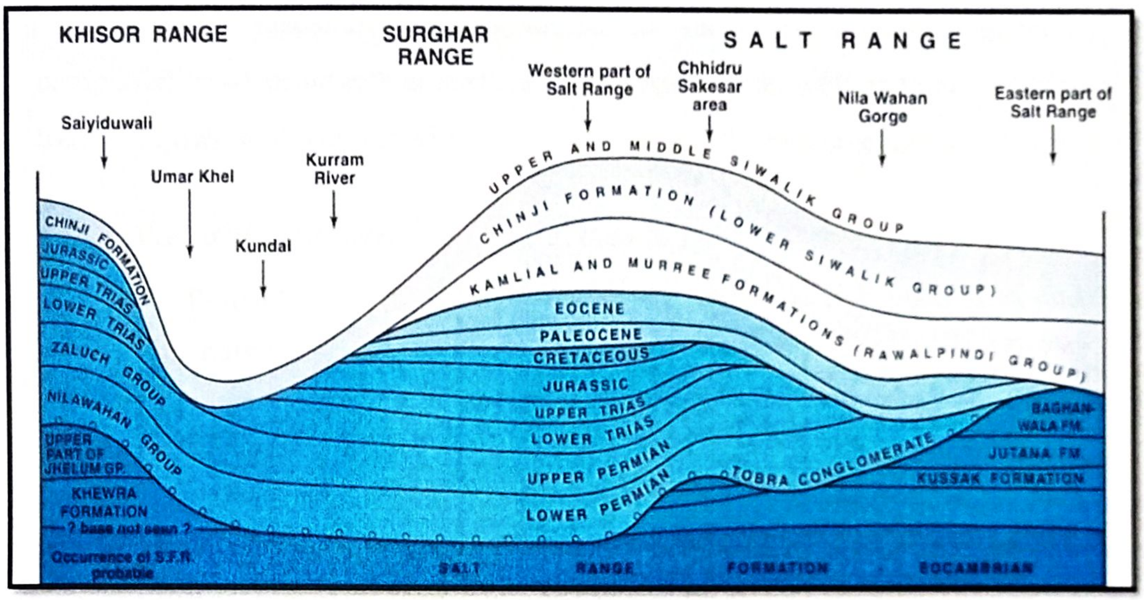


Figure 1.3. Major unconformities in the Eocambrian to tertiary sequence of Salt Range (Modified after Gee et al., 1989).

The Salt Range was mapped by Gee (1980), entitled "Pakistan Salt Range series geological maps, 1: 50,000" 6 sheets under geological survey of Pakistan. The regional dip of the detachment under the study area was assessed to be 2 degree towards north (Seeber et al., 1981). Similarly overview of the geology and structure of the Salt Range was well stated predominately by Schindewolf and Sailacher (1955), with later illustration of the major unconformities in the Precambrian to Tertiary sequence of the Salt Range was proposed by Gee (1989) (Fig. 1.3).

1.3 Objectives

The Salt Range, in terms of stratigraphy and structure geology, is extensively studied previously. The structural evolution of Salt Range Thrust is explained by the aid of widely spaced 2D cross sections extending from Main Boundary Thrust in north and Salt Range in south. Previous studies so far has not documented 3D structural architecture of the Salt Range so far. Salt Range cannot be explained just by a simple fault bend fold model unless it explains through complete geometry of structures, their structural compatibility and variations along trend. Salt Range differs from simple fault bend fold because of presence of various folds, faults and domes in its crestal portion.

Present research work is aimed to show the complete geometry and compatibility of structures at surface and subsurface as well as their variation along trend. Following objectives will be meet to achieve the research aim.

a) Preparation of revised geological map of the study area at RF 1: 50,000.

b) To prepare a 3D geological model of the area to explain fold and thrust kinematics.

1.4 Methodology

a) To observe the structural complexity of the study area, three extensive field sessions were conducted. Google Earth imagery draped with stratigraphic data from the published maps (Gee, 1980) were used as base map during field visits. Orientation data of planer and linear structures were recorded using Brunton Compass and marked on base map using GPS coordinates. In lab, data acquired from field is imported into ESRI ArcGIS v.9.3 for preparation of revised geological map.

b) Four north south oriented geological cross section were constructed using kink-balance method in Midland Valley 2D Move v.2014.2. The depth to the basement is taken from the seismic data available in the northern side where as in southern side previous research of Ghani et al, 2012 is used. Three seismic dip lines are already acquired from the Directorate General of Petroleum Concessions (DGPC) for research purpose. Orientation data, elevation data and contact relationship data of various stratigraphic units (acquired during field visits) were then used to compose the geological cross sections. The stratigraphies are the cross checked with the well data of Balkasar-01 in north and Lillah-1 in south for the precision.

c) For 3D model of the study area, revised geological map will be imported into 3D move platform. The Digital Elevation Model (DEM), downloaded from the open source website of United States Geological Survey (USGS), will be draped over the geological map to portray the real time elevation profile of the study area. The four cross sections will then be keenly placed at their respective positions. Various fault surfaces from the geological cross sections will be extended along the trend to generate 3D meshed surfaces to understand the structural evolution of the various structures.

CHAPTER 2
REGIONAL TECTONIC FRAMEWORK

2.1 Introduction

This chapter is an attempt to understand the geodynamic setting of the Indian Plate and orogeny of the Himalayas with respect to regional perspective in chronological since 130 Ma.

The world's spectacular mountain chain, the Himalayas is sandwiched between Eurasian Plate in the north and Indian Plate in the south. These mountain ranges are characterized by complex geometry having northwest-southeast trend in India, which changes to a nearly east west orientation in Pakistan and becomes more north-south along the western border of Pakistan. These are the youngest mountain belts of the world; 2500 km long, 160 to 400 km wide and towering as high as 8,854m (Mt. Everest) above sea level. The Himalayas demonstrates one of the most visible and spectacular consequences of the plate tectonics (Kazmi and Jan, 1997) (Fig.2.1).

The Himalayas are the product of geodynamic possesses of sea floor spreading, continental drift and collision tectonics. In brief, these are the result of the collision and continued under thrusting of the Indian Plate beneath the Eurasian margin and intervening micro plates that started about 50 Ma and is still active (LeFort, 1975).

2.2 Geodynamic setting of the Indian Plate

The Indo-Pakistan subcontinent separated from the Gondwanaland about 130Ma and started northward drift as a consequence the Neo-Tethys that was located between the Indian Plate in the south and Asian Plate in the north started shrinking (Johnson et al., 1976). The Indian Plate was located in the southern hemisphere with several thousand kilometers of the Neo-Tethys Ocean separating it from the nearest land to the north (Dercourt et al., 1993). It is estimated on the basis of magnetic anomalies that between 130 and 80 Ma Indian Plate moved northward at a rate of about 3 to 5cm/yr (Johnson et al., 1976). From 80 Ma India moved at an average rate of 16cm/yr relative to Australia and Antarctica (Powell, 1979; Patriat and Achache, 1984). During this period the shrinkage and continental drift was facilitated by the consumption of Neo-Tethys, opening of the Indian Ocean in the south, the transform motion along Owen Fracture zone and east Ridge located towards southwest and southeast respectively of the Indo-Pakistani subcontinent (MeKenzie and Sclater, 1976). During 60 and 65 Ma the northward drift of India was accompanied by an extensive extrusion of the Deccan Trap Basalt (Duncan and Pyle, 1988).

During the closure of the Neo-Tethys ocean intraoceanic subduction resulted in a series of arcs, namely Kohistan-Ladakh, Nuristan and Kandhar during Late Cretaceous (Searle, 1991; Treloar and Izatt, 1993) The arc magmatism occurred for a period of 40 Ma (Petterson and Windley, 1985) after which the back arc basin was finally closed and Kohistan-Ladakh Arc underthrusted the Eurasian Plate and forming an Andean type continental margin. This collision boundary is referred to as Main Karakorum Thrust (MKT) where the collisional events began in the Late Cretaceous (102~75Ma) (Coward, 1986; Powell, 1979; and Patriate and Achache, 1984)

Continued subduction of Neo-Tethys beneath Kohistan-Ladakh Arc and Eurasia resulted in the complete consumption of the leading oceanic edge of the Indian plate and its eventual collision with remnant of Kohistan-Ladakh Arc, the abrupt slowing down of the India's northward movement from 18 to 19.5cm/yr to 4.5cm/yr between 55 and 50Ma is attributed to this collision. The collision between the Indian Plate and the Kohistan- Ladakh Arc occurred during Eocene and is marked by Main Mantle Thrust (MMT) (Tahirkheli, 1979) which represents the end of marine sedimentation in suture zone (Rowley et al., 1996). These collisional zones are marked by the extensive emplacement of ophiolites along the Indus Tsangpo Suture Zone, Waziristan, Zhob valley and Lasbela area (Gansser, 1964; LeFort, 1975). The south migration of the Himalayan deformation from the site of MMT is represented by Main Boundary Thrust (MBT) along which the northern deformed fold and thrust belt is thrusted southward over the mollasse sediments of Potwar and Kohat Plateau (Ahmed, 2003).

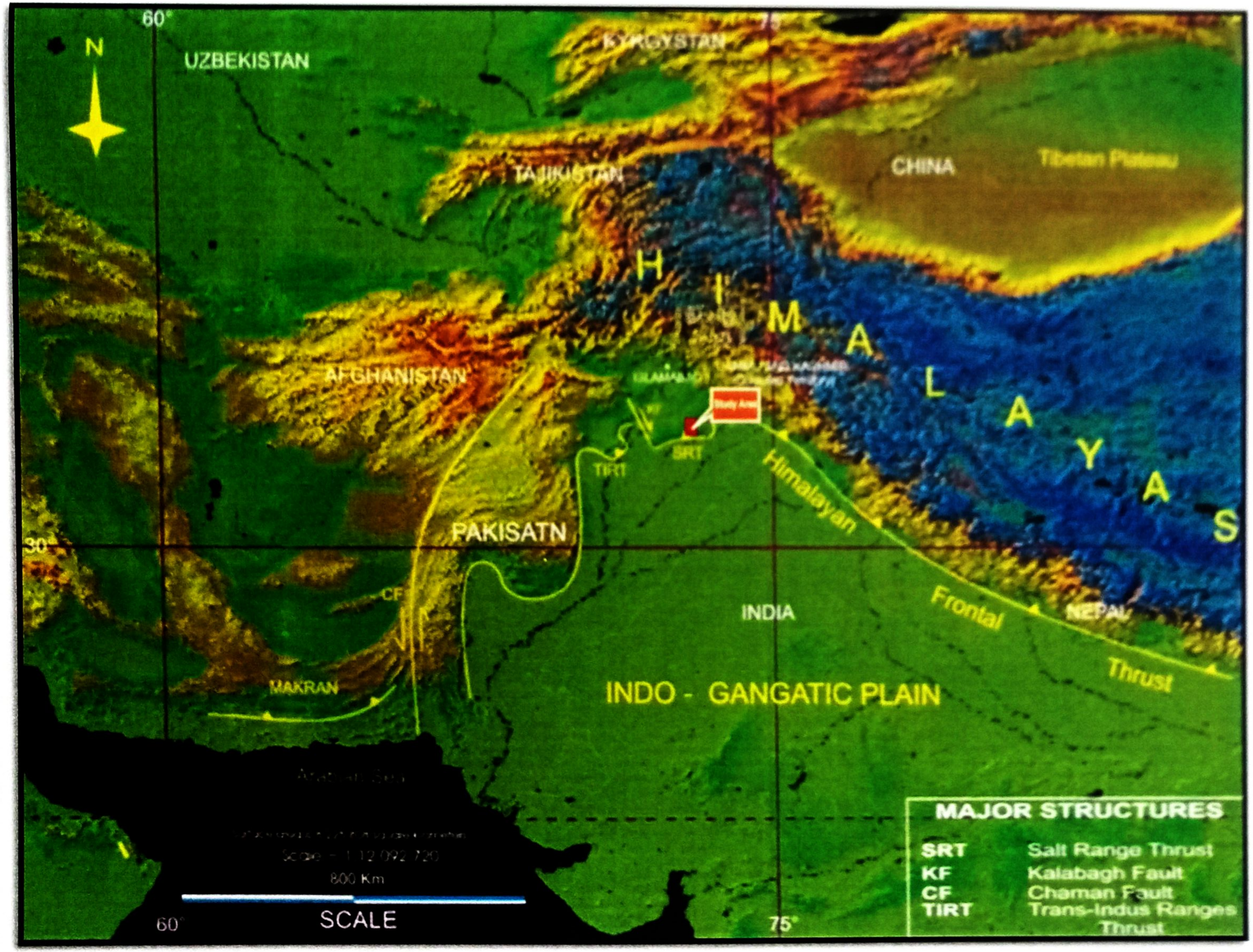


Figure 2. 1. Satellite image showing the Himalayas and Indo-Gangetic Plain. Rectangular inset shows the study area.

The western transform boundary of the Indo-Pakistani Plate is considered as Chaman Fault which extends northward from Kharan to Kabul for about 850 km (Molnar and Tapponnier, 1975; Stocklin, 1977). The Chaman Fault is a major left lateral strike slip active fault (Griesback, 1893; Kazmi, 1979; Lawerence and Yeats, 1979). It connects the Makran convergence zone with the Himalayan convergence zone where the Indo-Pakistani Plate is underthrusting Eurasia (Kazmi and Jan, 1997). In Pakistan this fault marks the boundary between the Chagai magmatic arc to the west and the Khojak flysch basin to the east.

2.3 Tectonostratigraphic subdivision and thrust system of the Pakistani Himalayas

Several different tectonostratigraphic terrains are recognized in the Himalayas, separated from one another and also from rocks of the Indian Plate by northward dipping fault zones, which provides natural basis for the subdivision of Himalayas in Pakistan, in north south direction (Gansser, 1964). The Himalayas in Pakistan can be divided into five litho-tectonic terrains, on the basis of fault system which are characterized by distinctive stratigraphy and physiography. These zones accommodated a large amount of crustal shortening through faulting, folding and thrusting in response to the compressive stresses, giving rise to Himalayas (Ahmed, 2003) as shown in figure 2.2. The subdivision of the Himalayas is given as follows.

Karakorum Block
Main Karakorum Thrust (MKT)
Kohistan Island Arc
Main Mantle Thrust (MMT)
Northern Deformed Fold and Thrust Belt (NDFTB)
Main Boundary Thrust (MBT)
Southern Deformed Fold and Thrust Belt (SDFTB)
Salt Range Thrust and Trans-Indus Ranges

2.3.1 Main Karakorum Thrust (MKT)

The MKT or Shyok Suture Zone was formed as a result of collision between the Karakorum Plate and the Kohistan Island arc (Tahirkheli, 1979, 1982) and was named as Northern Suture of the Himalayas (Pudsey et al., 1985). It was formed during Late Cretaceous (Coward et al., 1986). The Shyok Suture Zone is located to the south of the Karakorum batholiths along metasedimentary belt. The southern metasedimentary belt of the Karakorum block is thrust over Kohistan-Ladakh sequence along this suture zone. The structural horizon is characterized by grey to green slates, interbedded clastic sediments and blocks and exotic clasts of greenstone, limestone, red shale and minor ultramafic and is considered as olistrostome (Pudsey et al., 1985).

2.3.2 Main Mantle Thrust (MMT)

The MMT or Indus Suture Zone was formed as a result of the subduction and collision of Indian Plate at the southern margin of K.I.A during Eocene time (Tahirkheli, 1979, 1982; Gansser, 1981). The Indus suture terminates the Tethyan Himalaya on the north and marks the boundary between the Indian crustal plate and Kohistan Island arc (Tahirkheli and Jan, 1979). In Pakistan the Indus Suture is comprised of a complex sequence of imbricated mélanges, which consists of tectonic block of ophiolites, blueschists, greenschists, metavolcanics and metasediments in a matrix of shear sediments and or serpentines (Tahirkheli and Jan, 1979, 1982; Jan, 1980; Kazmi and Rana, 1982). The Indus Suture Zone borders a conspicuous structural feature called as the Nanga Parbat Syntaxes which interrupts the regional trend of Himalayas (Zeitler, 1985).

Gravity modeling data suggest that the MMT and MKT dip northward at 35° to 50° (Malinconico, 1989). The MMT is possibly correlative with the Indus suture in India. Following the collision along the MMT and its lateral equivalents during late Cretaceous to Early Tertiary time, thrusting generally progressed southward (Wells, 1984; Yeats and Hussain., 1987; Smith et al., 1994; Beck et al., 1995).

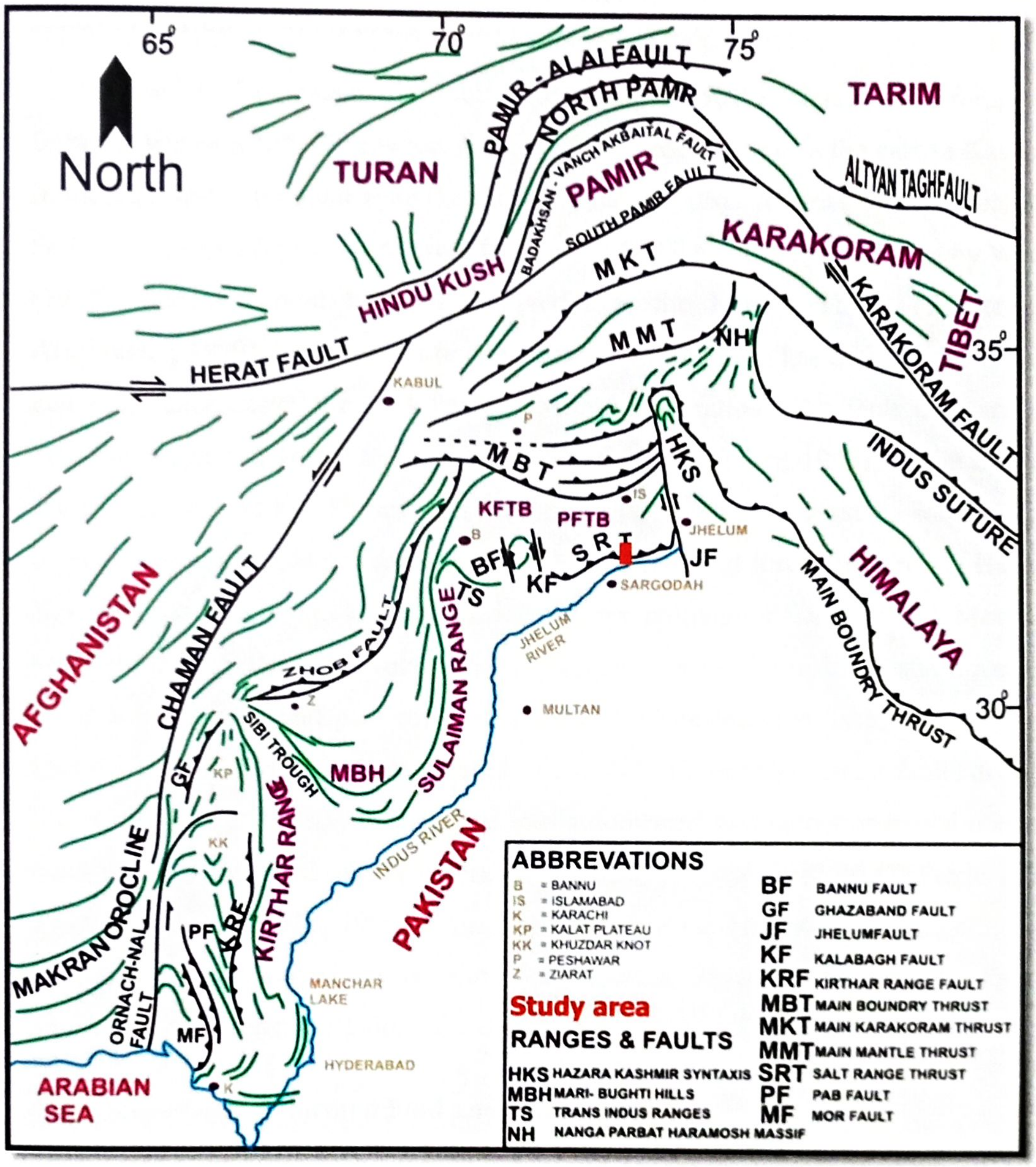


Figure 2.3. Distribution of major thrusts developed during the Himalayan Orogeny (after Sarwar and Dejong, 1979). Rectangular inset shows the study area.

2.3.5 Northern Deformed Fold and Thrust Belt

The northern deformed fold and thrust belt lies to the south of the MMT which is bounded by MBT towards south, separating it from the southern deformed fold and thrust belt (Fig. 2.3). It is about 300 km wide. This belt comprises of heavily deformed metasedimentary, sedimentary and igneous rocks. This belt stretches from Kurram area in the west near Afghan border up to Kashmir basin in the east.

2.3.6 Main Boundary Thrust (MBT)

The MBT represents the southward migration of the Himalayan deformation from the site of MMT. It runs for about 1500 km from Assam in the east to Kashmir in the west in the foreland zone (Lisa and Khwaja, 2005). A series of nearly parallel faults in sub-Himalayas, which were later called MBT were first recognized by Wadia (1957). The outermost fault of this series is the Murree Thrust (Seeber and Armbruster, 1979). This distinct tectonic feature in Pakistan, has thrusted the Eocene and older rocks over the Mid-Tertiary Murree Formation. The fault dips are not constant varying from 50 to nearly vertical (Kazmi and Jan, 1997). In the east the fault loops around the Hazara Kashmir Syntaxes. From northeast to southwest, it extends along the front of the northern deformed fold and thrust belt around Hazara-Kashmir Syntaxis (Fig. 2.2). It carries the pre-collision Paleozoic and Mesozoic sedimentary and metasedimentary rocks of the northern deformed fold and thrust belt in its hanging wall and post-collision folded Miocene foreland basin deposits in its foot wall. The MBT zone is comprised of parallel or enechelon thrust faults dividing the northwestern Himalayan sequence into a deformed and metamorphosed northern zone or the Hinterland, and a deformed southern zone or foreland (DiPetrio et al., 1996; Pivnik and Wells, 1996), (Fig. 2.3). It has been suggested (LeFort, 1975; Bird, 1978) that after movement on the Main Central Thrust and MMT continental shortening was transferred along the detachment of the MBT.

2.3.7 Southern Deformed Fold and Thrust Belt

The southern deformed fold and thrust belt rims the Himalayan mountain belt from Ganga delta in India up to the South Waziristan agency in Pakistan. It is oriented east west and is underlain by a thick pile of fluvial sediments. This belt was the main depocenter of the synorogenic sediment influx, which started in early Miocene.

This belt is bounded in the north by the Main Boundary Thrust (MBT) (Sarwar and Dejong, 1979; Yeats et al., 1984, Coward and Butler, 1985), and the Salt Range Thrust (SRT) and Trans Indus Range Thrust (TIRT) marks the southern boundary of this deformed fold and Thrust belt which separates it from Indo-Gangetic Foredeep in the south (Fig. 2.3).

2.3.8 Salt Range Thrust (SRT) and Trans Indus Ranges

The Salt Range Thrust (SRT) or the Himalayan Frontal Thrust (HFT) runs along the southern margin of the Salt Range, between Jhelum and Indus rivers, and it has pushed the older rocks of the Salt Range over the less deformed Tertiary sequence of the Jhelum Plain. The Thrust Zone is largely covered by the recent fanglomerate and alluvium (Kazmi and Jan, 1997) however at places the thrust is exposed and shows the Paleozoic rocks overlying the Neogene or Quaternary deposits of Jhelum plain (Gee, 1945, 1989; Yeats et al., 1984). Seismic reflection profile, gravity and drill-hole data indicates that the Salt Range and Potwar Plateau are underlain by a décollement zone within Eocambrian evaporites. Along the Salt Range Thrust, significant decoupling of sediments from the basement along the Salt layer has led to southward transport of the Salt Range and Potwar Plateau in the form of a large slab over the Jhelum Plain. Thus the Salt Range is the surface expression of the leading edge of the décollement Thrust (Lillie et al., 1987). The frontal thrust system has accommodated ≥ 20 km of shortening in Salt Range (Lillie et al., 1987; Baker et al, 1988) and approximately 10km in the Trans Indus Ranges (Blisniuk, 1996). The TIRT represents the active deformational front along which the Surghar Range (Meissener et al., 1974) and the Cambrian Jhelum Group rocks in the Khisor Range are thrust southward on to Indo-Gangetic Foredeep (Hemphill and Kidwai, 1973) (Fig. 2.3).

2.4 Salt Range

Upper Proterozoic to recent succession occurs in the Salt Range marking the southern Thrust front of the Himalayan mountain chain. During Quaternary time, the effects of the Himalayan orogeny extended southward, accentuated by movement within the Eocambrian saliferous formation, the Salt Range developed as a complex anticlinorium, emplaced southward along a major thrust which has recently been determined by seismic reflection measurements to have involved a décollement of at least 20 km. The Salt Range bridges the angle between the outermost ranges of the northwestern Himalaya and of the Sulaiman Arc to the west with its Trans Indus extension, (Gee, 1989).

Rising abruptly out of the alluvial plain, it forms impressive scarps, usually 750 to 1000m in altitude, although Sakesar Mountain rises some 1,500 m. The hill slopes and plateaus are relatively barren of vegetation. Rock exposure are usually excellent within scarps and gorges, complete section of the older formations are often exposed, whereas in the dip slope to the north, the younger Tertiary sequence is in continuity with that of the Soan basin of the Potwar Plateau (Gee, 1989).

Structurally, the Salt Range resulted in response of tectonic forces imposed during the later phases of the Himalayan Orogeny in late Cenozoic time. The occurrence of the thick, incompetent Salt Range Formation at the base of the sedimentary sequence has strongly influenced the structures (Gee, 1989). The Salt Range is a complex Salt anticlinorium within which the Salt Range Formation is tectonically repeated by Cenozoic subsurface flow to attain a thickness of more than 2,000 m in some anticlines. The Salt Range anticlinorium is actually a series of salt anticlines of the "Salt Pillow" type (Trusheim, 1960) in which the saline sequence has not penetrated the overlying non-saliferous formations, but diapirism has been a major factor at a few localities namely Kallar Kahar, Vasnal, and strikingly at Mari Indus and Kalabagh near the Indus. Recent interpretation of seismic reflection profile across the Potwar, Salt Range and alluvial plains to the south (Baker, 1987; Baker et al., 1988; Lillie et al., 1987) combine with drill hole, gravity (Farah et al., 1977) and paleomagnetic data (Johnson et al., 1979, 1986), indicates the presence of décollement along which the Eocambrian and overlying Paleozoic-Cenozoic sequence is displaced southward at least 29 km in the Central Salt Range, Eastward the Salt Range bifurcates into two northeast trending ridges (the Dil Jabba and Chambal-Jogi Tilla ridge) which are also folded (Gee, 1989). Westward, the Kalabagh Fault separates the Salt Range from Trans Indus Ranges (McDougall and Khan, 1990). Southward the Salt Range is truncated by The Salt Range Thrust (Fig. 2.3).

2.5 Tectonics of the study area

The study area lies in the central Salt Range which has been greatly influenced by the deformation associated with the Salt Range Thrust. The Kallar Kahar and adjoining areas are characterized by steep angle fault zones, running obliquely to the general east-west structural trend of the Salt Range. The movement along the fault zones is accompanied by the diapiric intrusion of the Eocambrian Salt Range Formation in these areas (Gee, 1989).

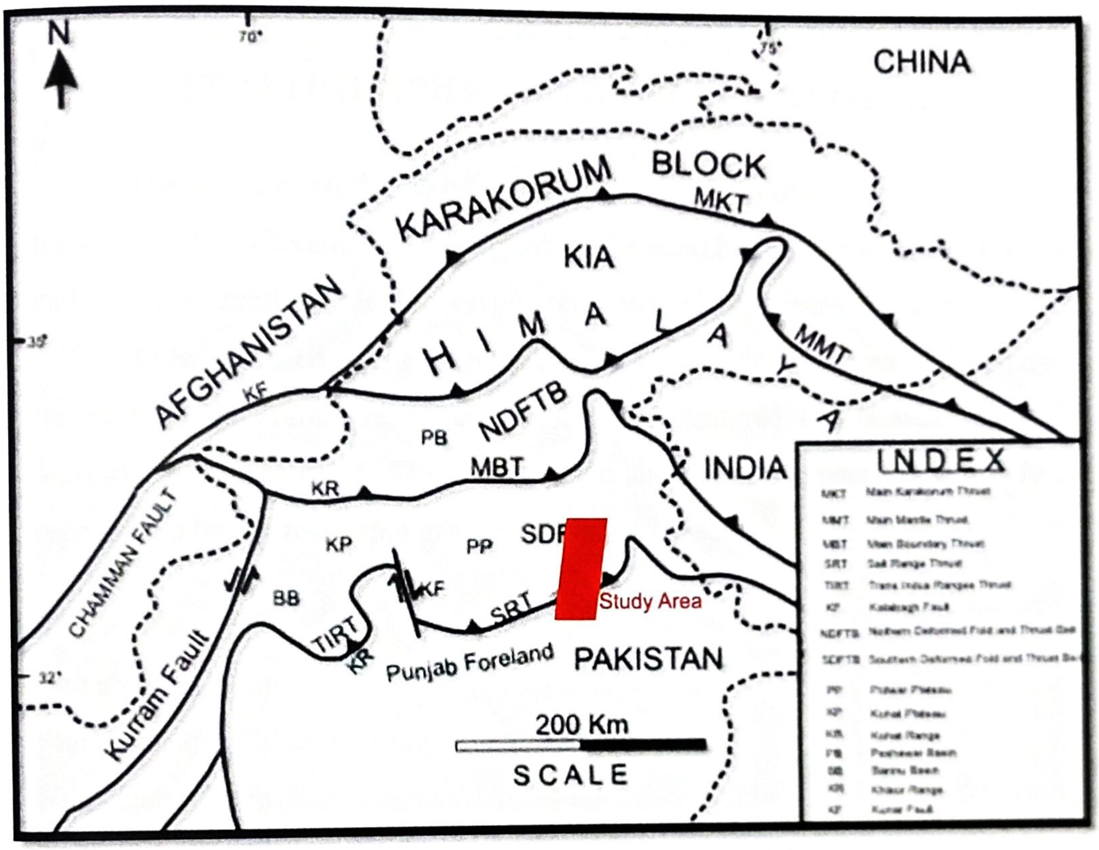


Figure 2.4. Tectonic map of north Pakistan, showing major structural features (after Kazmi and Rana, 1982). Rectangular inset shows the study area.

CHAPTER 3
STRATIGRAPHY OF THE SALT RANGE AREA

The rock description is based on the observation of exposed geology, the well top data of the different wells and published researches on the study area of different authors. The stratigraphic succession presented in this research is categorized into different groups based on their ages. The oldest formation exposed in the study area is the Salt Range Formation. Unconformities encountered in the succession are also represented in figure 3.1. The stratigraphic succession exposed in the study area is represented by the following groups from top to base.

Siwalik Group
Rawalpindi Group
Makarwal and Chharat Group
Nilawahan Group
Jhelum Group
Pre-Cambrian Strata

These stratigraphic successions are discussed in the forthcoming sections.

3.1 Precambrian

3.1.1 Salt Range Formation

History

Wynne (1878) has named the formation as 'saline series'. Later Gee (1945) named the same unit as 'Punjab Saline Series'. Asrarullah (1967) given the now using names as 'Salt Range Formation' after the Salt Range.

Lithology

The lower part of the Salt Range Formation contains the red gypseous marl in association with thick seams of salt, beds of gypsum; while dolomite, greenish clay and low-grade oil shale are present in the upper part.

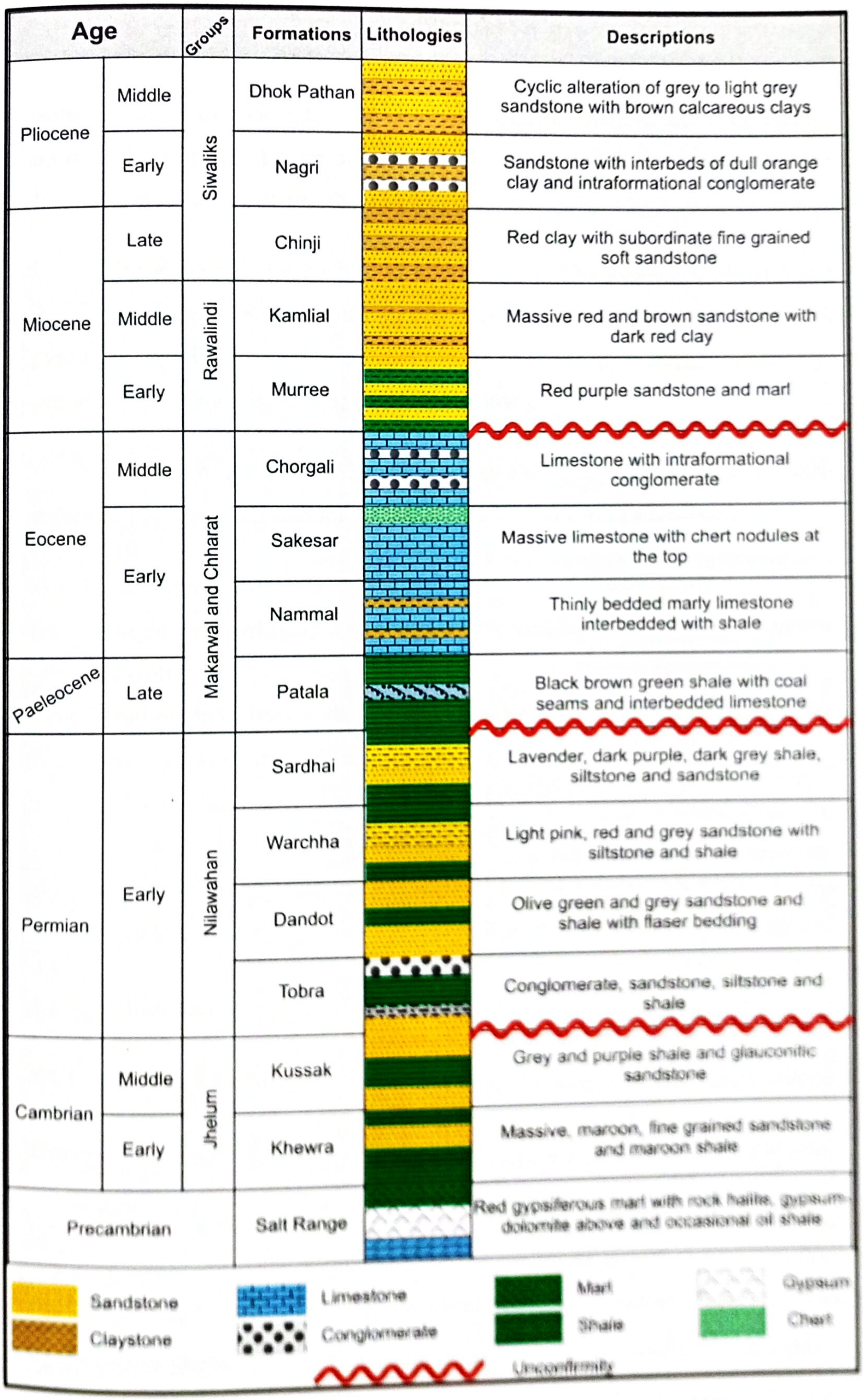


Figure 3.1. Generalized stratigraphy of the study area (modified after Gee et al., 1989).

The red colored marl consists mainly of clay, gypsum and dolomite with occasional grains and quartz crystals of variated sizes. Thick-bedded salt is in different shades of pink color and well developed laminations and color banding are up to a meter thick. Lesser amounts of potassium and magnesium sulfate ae also found in association with the shale beds.

The gypsum is pure white to gray in color. The gypsum is about 5 m thick, massive and is associated with bluish grey, clayey gypsum and earthy, friable gypsious clay. The dolomite is usually light in color, it is flaggy and cherty. It is combined with dolomitic shale, oil shale and low grade oil shale.

Asrarullah (et al., 1967) studied the Salt Range Formation in detail and separated the formation into three members in the following succession.

a) Sahwal Marl Member:

i) Bright red marl beds with irregular gypsum, dolomite beds and Khewra Trap (3-100 m).

ii) Dull red marl beds with a number of salt seams and 10 m thick gypsum bed at the top; (more than 40 m).

b) Bhandar Kas Gypsum Member: Massive gypsum with minute beds of dolomite and clay; (more than 80 m).

c) Billianwala Salt Member: Ferruginous red marl with thick seams of salt (more than 650 m).

3.2 Cambrian

3.2.1 Khewra Sandstone

History

The name "Khewra group" was initially proposed by Noetling (1894). Then Wynne (1878) named the formation "Purple sandstone series". Latter the name was used until recently, when the formation was officially called as "Khewra Sandstone" by the Stratigraphic Committee of Pakistan (Fatmi, 1973).

Lithology

The type locality is near Khewra town in Khewra Gorge, Salt Range. The formation mainly consists of purple to brown fine grained sandstone. The lowermost part of the formation consists of red, flaggy shale. The sandstone is generally thick-bedded to massive. Sedimentary features like ripple marks; mud cracks etc. are frequent in the formation. The formation is mainly sandstone in the Khewra Gorge; however, in the Khisor Range the upper part of the formation grades upward into glauconitic sandstone, which marks the base of the overlying Kussak Formation. The formation has recorded trace fossils in the Salt Range which are interpreted as trilobite.

Figure 3.2. Sahiwal Marl Member of the Salt Range Formation exposed in the study area.

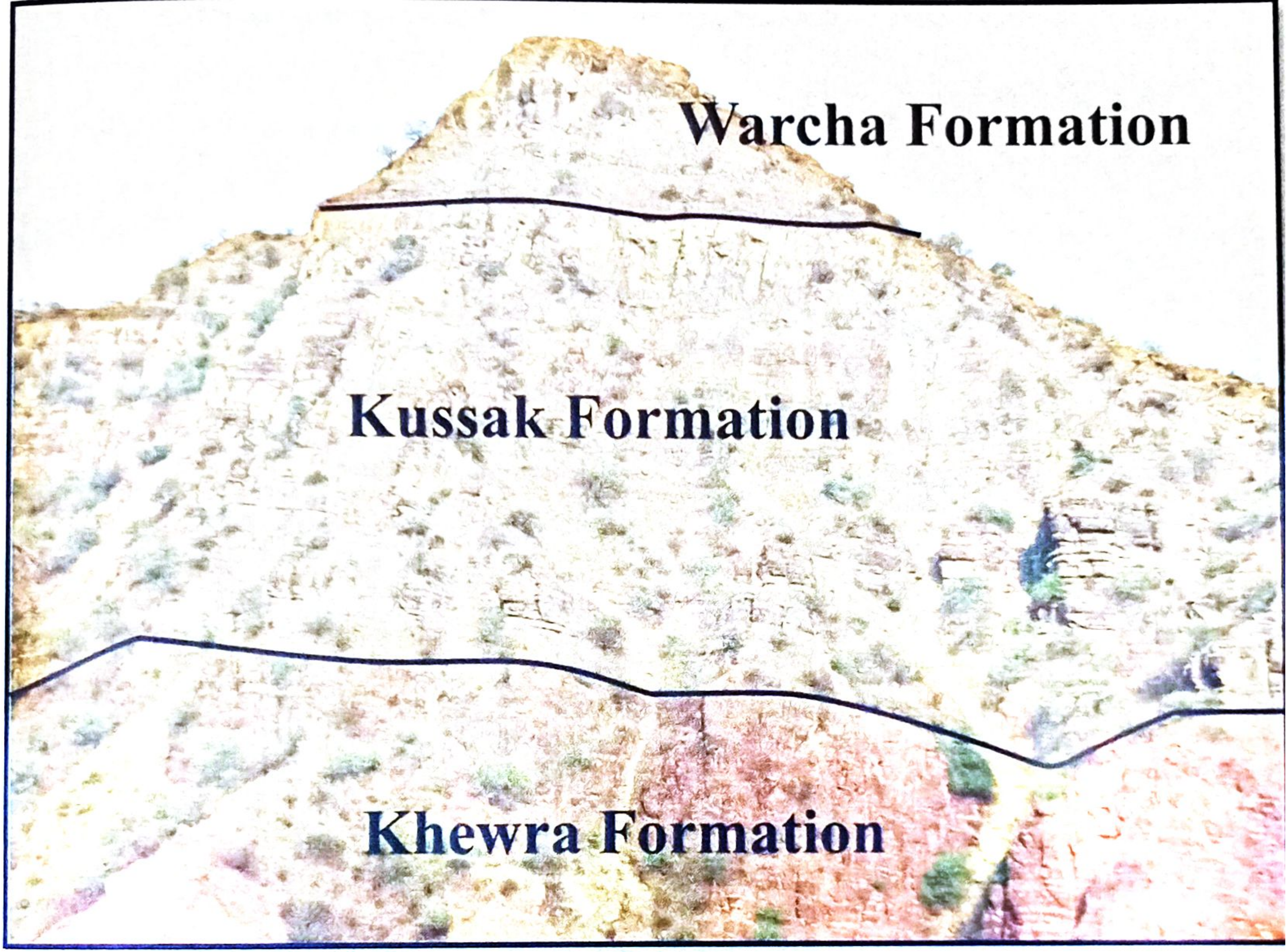
3.2.2 Kussak Formation

History

Wynne (1878) named it as “Obolus beds” or “Siphonotrata beds” to a mainly greenish-grey, glauconitic, micaceous sandstone and siltstone. Waagen and Wynne (1895) then use the name “Neobolus beds” for the same unit. Later, Noetling (1894) named it as “Kussak group” and the Stratigraphic Committee of Pakistan officially named the unit as Kussak Formation (Fatmi, 1973).

Lithology

The type locality is near Kussak Fort in the eastern part of the Salt Range. At the type locality, the formation consists of greenish-grey, glauconitic micaceous sandstone; greenish-grey siltstone is interbedded with light grey dolomitic and some oolitic, arenaceous dolomite. Several layers of intraformational conglomerate are also encountered. Pink gypsum lenses are also present near the top. The formation contains 5 to 25 cm long thin lenses of fossil asphalt (Gilsonite). The formation is widely distributed throughout the Salt Range with its best exposures in the eastern part. Thickness at the type locality is 70 m but it varies from 6 to 53 m at other places.


Warcha Formation
Kussak Formation
Khewra Formation

3.3.1 Sardhai Formation

History

The name Sardhai Formation was given by Gee (Pascoe, 1959) which is formalized by the Stratigraphic Committee of Pakistan. Gee had also called it as "Lavender clay stage". Wynne (1878) had called it "Lavender clays" and Noetling (1901) called the same unit as "upper part of Warchha Group".

Lithology

The type locality by Gee is in the Sardhai Gorge in the eastern Salt Range. The formation consists of bluish and greenish grey clay with minute sand and siltstone beds. It also has some carbonaceous shale. The clay has lavender color and contains some copper mineral. The formation is 42 m thick at the type locality. The formation is largely unfossiliferous, occasional plant remains and fish scales are found.

3.3.2 Warchha Formation

History

The name Warchha Sandstone was given by Hussain (1967), which was then accepted by the Stratigraphic Committee of Pakistan. The other names were used as "Warchha Group" of Noetling (1901). "Speckled sandstone" of Gee (1945) and middle speckled sandstone of Waagen (1879).

Lithology

Its type section is Warchha Gorge in the Salt Range. The Formation has medium to coarse grained cross bedded sandstone, conglomerate and interbedded shale. The sandstone is red, purple or light pink. The sandstone is arkosic. The formation is locally speckled so called "speckled sandstone". Its thickness is about 26 to 180 m. some plant remains have been reported from this formation.

Figure 3.4. Gently dipping Warchha Formation beds of Nilawahan Group.

3.3.3 Dandot Formation

History

The name Dandot Formation is formalized after the "Dandot Group" of Noetling (1901) and the "Olive Series" "Eurdesma beds" and "Conularia beds" of Wynne (1878) and Waagen (1879) named it as "Speckled sandstone".

Lithology

The type locality is near Dandot Village in eastern Salt Range. The lithology at type locality is composed of light grey to olive green yellowish sandstone. The Dandot Formation is well developed and exposed in the eastern Salt Range. The maximum thickness is recorded in the Makrach Valley which is about 50 m. The Dandot Formation is fossiliferous and the basal part in the eastern Salt Range has brachiopods, bivalves and many species of bryozoa and ostracoda.

3.3.4 Tobra Formation

History

The Tobra Formation is the lowest stratigraphic unit of Nilawahan Group that is previously known in the literature as "Talchir Boulder Bed" or "Talchir Stage" of Gee (Pascoe, 1959) and also the "Salt Range boulder bed" of Teichert (1967).

Lithology

The type locality is the eastern Salt Range near Tobra Village. The Tobra Formation is a mixed lithology in which the following three facies are present (Teichert, 1967).

1. Tillitic facies is exposed in the eastern Salt Range. This unit of rock grades into marine sandstone containing Eurydesma and Conularia fauna (Dandot Formation)
2. Freshwater facies without boulders. It is an alternating facie of siltstone and shale which contains spore flora. This is characteristic of central Salt Range.
3. This is the complex facies of diamictite, sandstone and boulder bed which increases in thickness in the western Salt Range and Khisor Range.

In the eastern Salt Range, the Tobra Formation consists of true tillite. The rock unit has boulders of granite with fragments of quartz, feldspar, magnetite, garnet, claystone, siltstone, quartzite, bituminous shale, diabase and gneiss. In the central Salt Range, the Tobra Formation consists mainly of freshwater facies comprising of siltstone and shale. It has flora and fauna including glossopteris, gangamopteris and several bivalves and ostracodes freshwater species (Reed, 1936). However in the western Salt Range, the Tobra Formation consists of three units.

1. Lower part which have brownish green, massive clastic material
2. Middle part have medium to coarse grained, thick bedded, dark to light olive grey sandstone.
3. Upper part consists of dark green, grey clay and sandstone with pebbles and boulders.

3.4 Paleocene

3.4.1 Patala Formation

History

The term Patala Formation was formalized for the "Patala Shale" of Davies and Pinfold (1937) by the Stratigraphic Committee of Pakistan.

Lithology

The section is exposed in Patala Nala in the Salt Range and is its type section. The formation consists of shale and marl with subordinate limestone and sandstone. The Shale is dark greenish grey, carbonaceous and calcareous in places. The limestone is white to light grey and nodular. In the upper part calcareous sandstone is present. The formation is 27 m thick at Khewra and 90 m thick in Patala Nala. The formation contains abundant foraminifers, mollusks and ostracodes. This formation is not exposed in our designated area however there were extensive mining for coal is carried out from the formation.

3.5 Eocene

3.5.1 Nammal Formation

History

The name Nammal Formation has been accepted by the Stratigraphic Committee of Pakistan for the "Nammal Limestone and Shale" of Gee (Fermor, 1935) and "Nammal Marl" of Danilchik and Shah (1967) occurring in the Salt and Trans-Indus Ranges.

Lithology

The type locality is in the Nammal Gorge. The formation comprises shale, marl and limestone. The shale is grey to olive green, while the limestone and marl are light grey to bluish grey. The limestone is argillaceous in places. In the Surghar Range, the lower part of the formation is composed of bluish grey marl with subordinate interbedded calcareous shale and minor limestone. The upper part consists of bluish grey to dark limestone with intercalations of marl and shale (Cheema et al., 1977). There are many fossils reported from this formation that includes mainly foraminifers and mollusk.

3.5.2 Sakesar Limestone

History

The term Sakesar Limestone was introduced by Gee (Fermor, 1935) for the Eocene limestone unit in the Salt and Trans-Indus Ranges.

Lithology

The Sakesar Peak in the Salt Range is the type of the Sakesar Formation. The group consists mainly of limestone with subordinate marl. Limestone is cream to gray, ductile, usually solid. Significant development of flint in the upper part is observed, the marl is light cream to light and forms a continuous horizon in the upper part. Near Daud Khel in the western Salt Range, limestone grades into white to grey and massive gypsum.

Figure 3.5. Beds of nodular limestone of Nammal Formations.

3.5.3 Chorgali Formation

History

The name “Chorgali beds” of Pascoe (1920) has been official as Chorgali Formation by the Stratigraphic Committee of Pakistan. The formation also represents the “Passage beds” of Pinfold (1918) in the Attock area “Badhrar beds” of Gee and Evans (Davies and Pinfold, 1937) in the Salt Range and “Lora Formation” of Latif (1970) in the Hazara area.

Lithology

The section exposed in the Chorgali Pass in the Khir-e-Murat Range, has been chosen as the type section. According to Cheema et al. (1977), the formation consists of shale and limestone. In the Khair-e-Murat Range, it is divisible into two distinct units.

The lower unit has dolomitic limestone and shale. The dolomitic limestone is white to light grey and yellowish grey, medium-bedded while the shale is grey to greenish grey, calcareous and is interbedded in upper part of the unit. The upper part of the formation is composed mainly of shale with thick bed of dark limestone. A bed of nodular argillaceous limestone is observed near the top. The shale is greenish grey, red, occasionally calcareous. Some grit beds are also intercalated.

In the Salt Range, the formation is divisible into two parts. The lower part has shale and limestone, while the upper part is mostly limestone. The shale of the lower part is greenish grey and is calcareous, and the limestone is light grey and argillaceous. In the upper part, the limestone is white or cream color, porcellaneous and well-bedded.

3.6 Miocene-Pliocene

3.6.1 Murree Formation

History

The "Mari Group" of Wynne (1874), "Murree Beds" of Lydekker (1876) and "Murree Series" of Pilgrim (1910) had been formally named Murree Formation by Stratigraphic Committee of Pakistan.

Lithology

The formation has monotonous sequence of dark red and purple clay, purple grey and greenish grey sandstone with intraformational conglomerate. The basal part has light greenish grey calcareous sandstone and conglomerate with abundant foraminifers of Eocene age. This formation is not exposed in our designated area.

3.6.2 Kamlial Formation

History

The "Kamlial beds" of Pinfold (1918) have been formally established as Kamlial Formation by the Stratigraphic Committee of Pakistan. The formation is equivalent to the "Kamlial Stage" of Pascoe (1963).

Lithology

A section wouthwest of Kamlial, Attock district is referred to as its type locality. The formation consists of purple-gray and dark brick-red sandstone, which is a medium to coarse grained. It contains interbeds of hard purple shale and yellow and purple intraformational conglomerate. This formation is poorly fossiliferous and some fossil remains of plants are reported.

3.6.3 Chinji Formation

History

Pilgrim (1913) proposed the name "Chinji zone" to designate the upper faual subdivision of his "Lower Siwalik". Lewis (1937) upgraded it to formational level and named it as "Chinji formation" which later on accepted by the Stratigraphic Committee of Pakistan. The formation also offers the "Karghocha formation" by Morris (1938), the red Wynne (1878) and "Chinji" and "Alternation beds" Eames (1952).

Lithology

The section south of Chinji (Kotehra) village in the Attock District has been designated as type section.

By Pilbeam (1977, 1979), the formation have red clay with subordinate ash gray or brown gray sandstone. The sandstone is fine to medium grained, soft, sometimes sandy and cross-bedded. Scattered pieces of quartzite and thin lenses of intraformational conglomerate are found at different horizons in the formation.

Figure 3.6. Cross bedded sandstone of Chinji Formation.

3.6.4 Nagri Formation

History

The "Nagri Formation" by Lewis (1937) is accepted as such by the Committee stratigraphy of Pakistan. Formation is the "Nagri zone" or "Nagri stage" by Pilgrim (1913, 1926), the "Dandot sandstone" of Wynne (1877), "Marwat formation" by Morris (1938), the "Lower Manchhar" of Blanford (1876), part of the 'Sibi group "and "Urak group "Hunting survey corporation (1961) and "Uzhda Pusha formation" of Kazmi et al. (1970).

Lithology

The village Nagri is designated in the district of Attock as the type of place. The Nagri Formation has sandstone with minor clay and conglomerate. The sandstone is greenish gray medium to coarse grained, cross-bedded and massive. In some places, the sandstone is bluish grey dull red with "salt and pepper" texture, calcareous and moderately to weakly cemented. The clay is sandy or silty chocolate brown or reddish grey and pale orange, the proportion of which varies from section to section. The conglomerate beds contains pebbles of Eocene limestone. The formation has fairly rich vertebrate remains.

Figure 3.7. Beds of Nagri Formation dipping in the North.

3.6.5 Dhok Pathan Formation

History

The name "Dhok Pathan" was introduced by Pilgrim (1913) during his biostratigraphic analysis for the upper subdivision of the Middle Siwalik in the northeast Punjab. Cotter in 1933 redefined the unit as Dhok Pathan Formation, which was adopted as such by the Stratigraphic Committee of Pakistan for application in the Kohat-Potwar Basin.

Lithology

The village of the Dhok Pathan, Attock District has been designated as the type section. The Formation is typically represented by monotonous cyclic alterations of sandstone and clay beds. The sandstone is commonly grey, light grey, glossy white or reddish brown and occasionally brownish grey, greenish grey brown or buff colored; thick bedded, calcareous and sandy. Minor intercalations of yellowish brown siltstone are common. Conglomerate in the form of lenses and a layer is an essential character of the upper part. The thickness of one sandstone-clay cycle varies from 6 to 60 m. Rich vertebrate fauna is recorded from the Dhok Pathan Formation.

CHAPTER 4
STRUCTURAL GEOLOGY OF THE AREA

4.1 Geological map

Revised geological map of the study area is prepared at 1:50,000 in ArcGIS 9.3, by integrating Google Earth imagery, existing geological maps and extensive field work.

The location and orientation data of different structures as well as stratigraphic units is acquired during the field visits using Global Positioning System (GPS) and Brunton Compass. This data is plotted over Google Earth software which is easily available in public domain. The published maps of E.R Gee, (1989), particularly sheet 4 and 5 of Salt Range are also draped over the field data within the software to confirm the acquired field data. The stratigraphic units are then segregated into different groups on the basis of their depositional characteristic such as age of deposition and lithology. The resulting metadata file is exported into Esri ArcGIS (version 9.3) in Keyhole Markup language Zipped (kmz) file format where revised geological map of the study area is prepared at 1:50,000 scale (Fig.4.1).

4.2 Faults and folds in study area

Series of anticlines and synclines are present in central part of fault bend fold. Faults and folds exposed in this area are described in detail as follows:

4.2.1 Bulah syncline (BS)

This is a gentle syncline with Rawalpindi group formations in its core and Eocene and Paleocene strata at its southern limbs.

4.2.2 Nurpur anticline (NA)

Nurpur anticline is north south oriented anticline with salt range formation in its core and Eocene and Paleocene strata at its limbs. Eastern limb of the anticline is inclined at an angle of 40°.

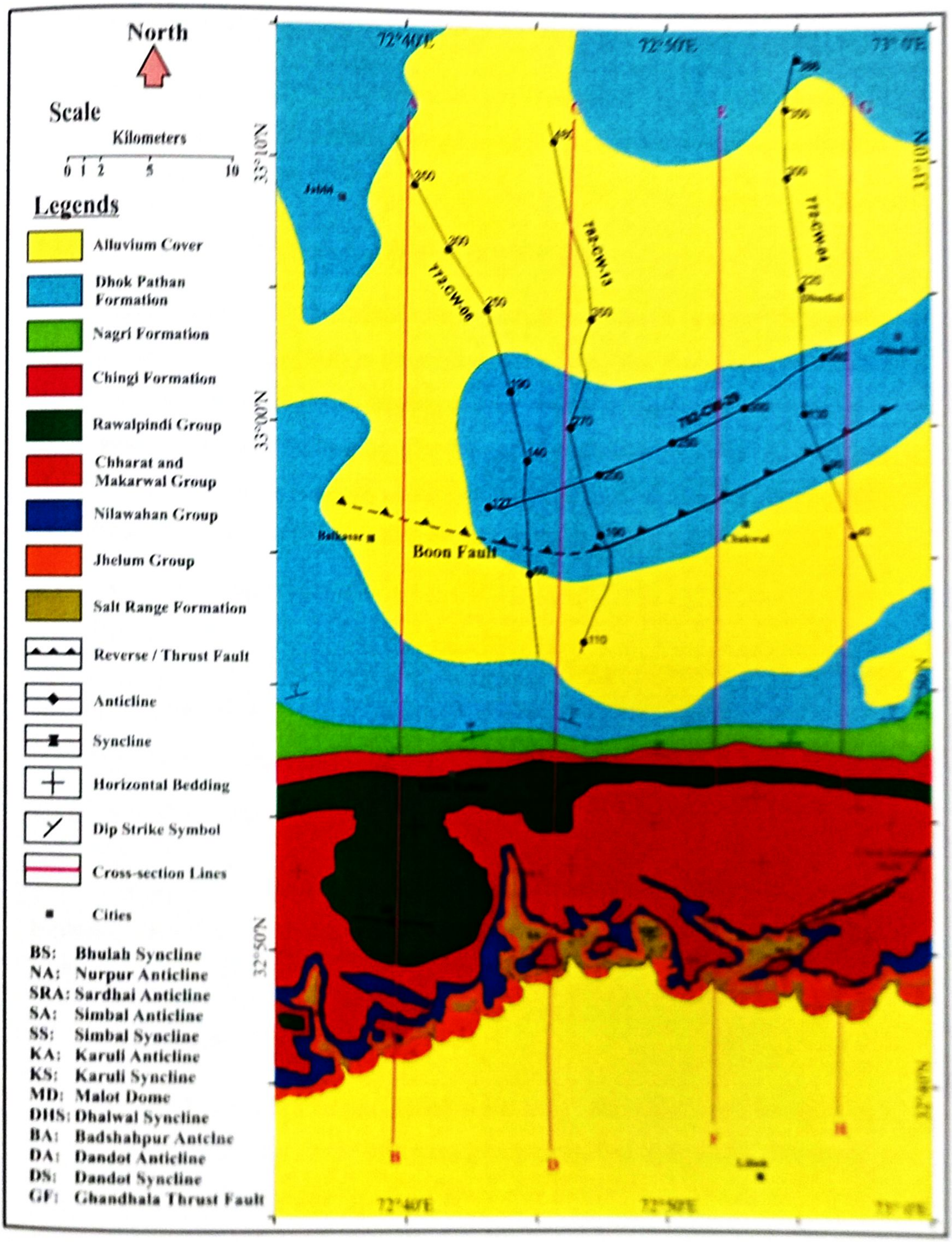


Figure 4.1. Geological map of the study area (modified after Gee et al., 1989)

4.2.3 Sardhi anticline (SRA)

Sardhai anticline is lying parallel to Nurpur anticline with salt range formation in its core and Eocene and Paleocene strata at its limbs. It's both limbs are inclined at 30°in east-west direction.

4.2.4 Simbal anticline (SA) and Simbal syncline (SS)

Simbal anticline lies in south of the Sardhai anticline. It is more like a gentle dipping dome having Salt Range Formation in its core. The Paleocene and Eocene strata are at its limbs which are dipping at 35°in NE-SW direction. Simbal syncline lies in south of the Simbal anticline. The core of this anticline contains Paleocene and Eocene strata whereas the Jhelum group formations are at its limbs. Its north western side dips at 40° whereas south eastern side dips gently at 20°.

4.2.5 Karuli anticline (KA)

Its lies parallel to Simbal ayncline with Salt Range Formation in its core and Nilawahan group at its limbs. It is NE-SW oriented anticline with both limbs at 40° (Fig. 4.2).

4.2.6 Karuli syncline (KS)

Further east to the Karuli anticline there lies the Karuli syncline is located. It possess Eocene and Paleocene strata in its core whereas Jhelum group formation at its limbs.

4.2.7 Malot dome (MD)

Malot Dome is the largest folded structure of the study area containing salt range formation in its core and Nilawahan group formation at its limbs. The strata at the eastern and northern sides dips 30° toward east and 35° toward north respectively. However, western and southern sides dip gently (15-20°) toward west and south respectively (Fig. 4.3 and 4.4).

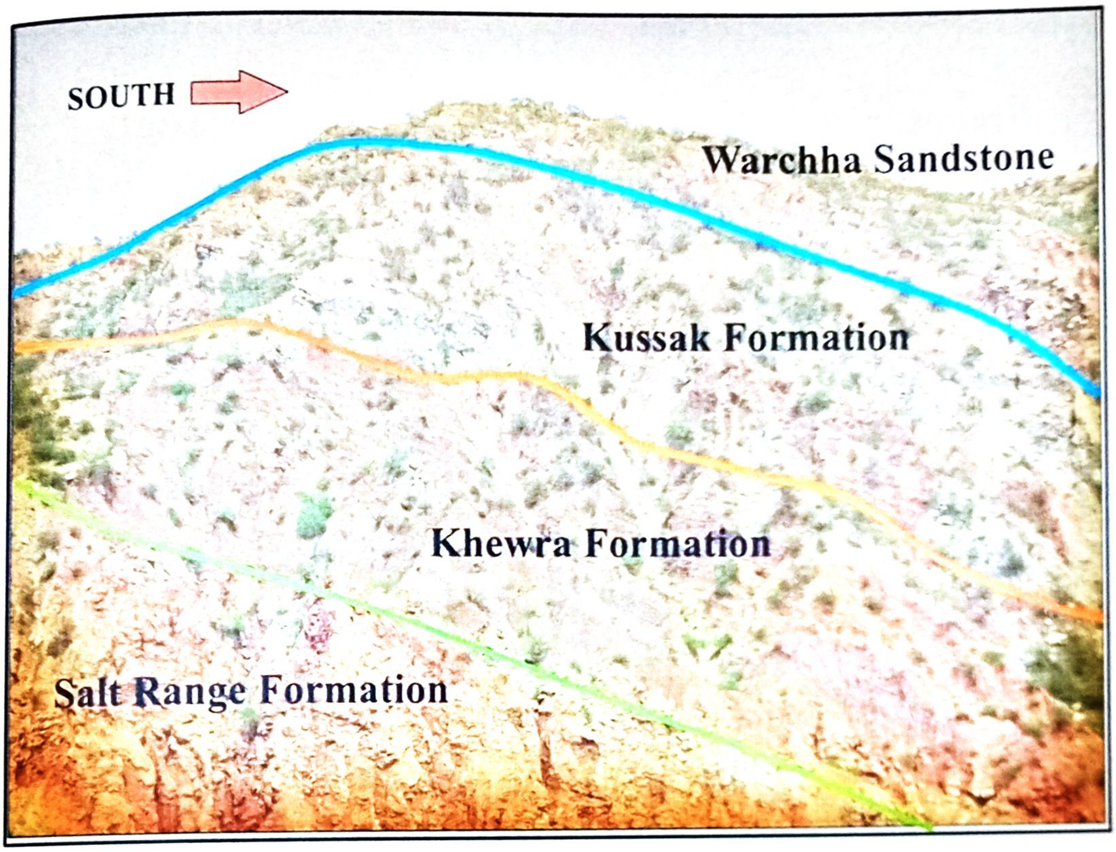


Figure 4.2. Eastern limb of Karuli anticline with Salt Range Formation in its core.

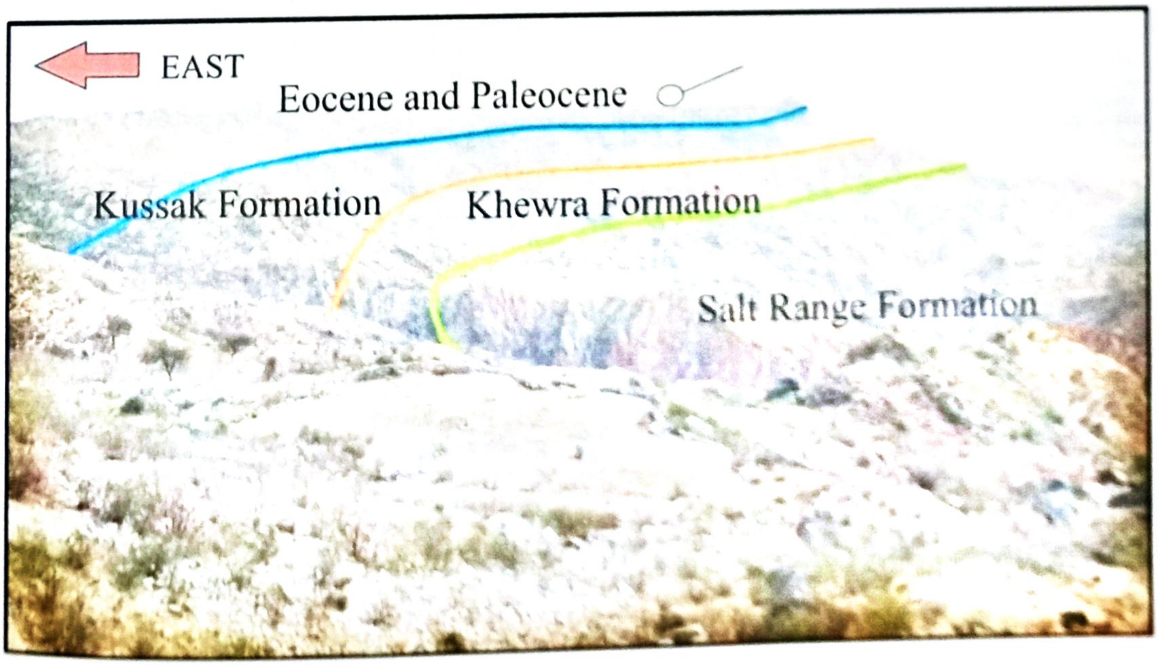


Figure 4.3. Northern limb of the Malot dome with the Salt Range Formation in its core.

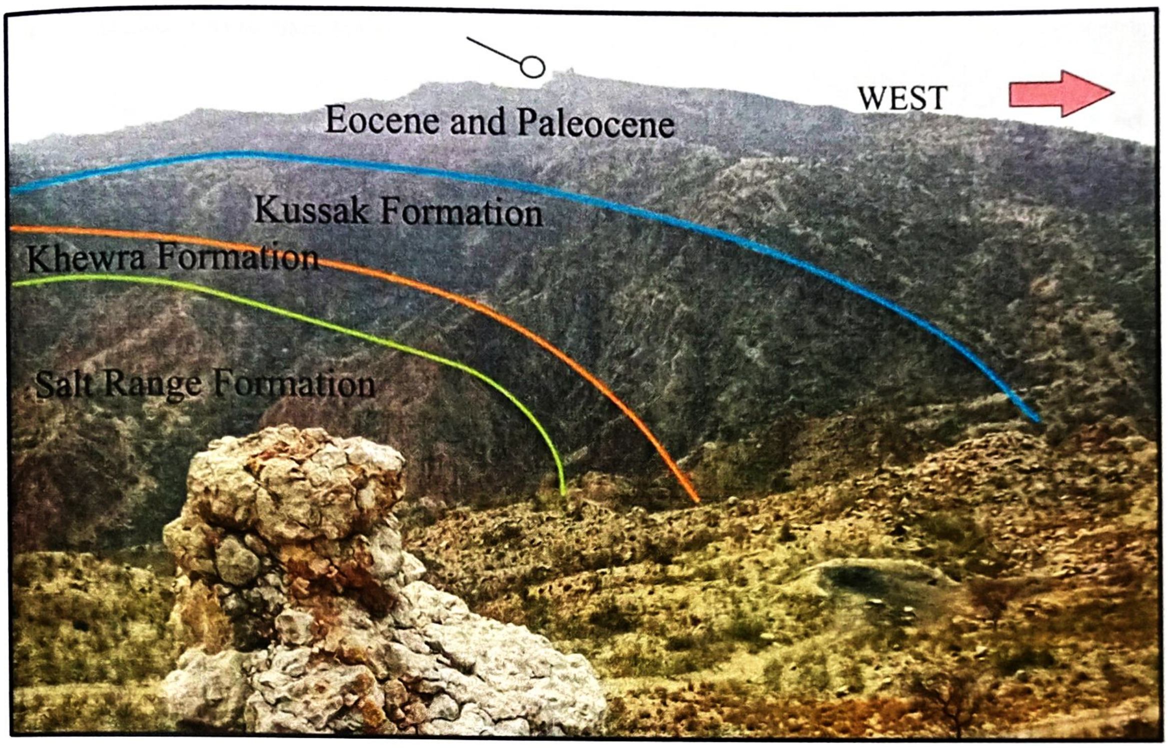


Figure 4.4. Southern limb of the Malot dome with the Salt Range Formation in its core.

4.2.8 Dhalwal syncline (DHS)

Dhalwal syncline is sandwiched between the Badshahpur anticline and the Malot dome. It contains Paleocene and Eocene formation in its core whereas the Jhelum group in its limbs. Both limbs are inclined at 35 ° toward north-east and south-west respectfully.

4.2.9 Badshahpur anticline (BA)

Badshahpur anticline is east west oriented anticline with the Salt Range Formation in its core whereas Eocene and Paleocene strata is present at its limbs. It's both limbs are inclined at 25NE and 30SW respectively.

4.2.10 Dandot anticline (DA)

Dandot anticline is a dome containing the Salt Range Formation in its core and Nilawahan group at its limbs. All the sides are inclined at 30°.

4.2.11 Dandot syncline (DS)

Dandot syncline is a small syncline containing Eocene and Paleocene in its cores and Jhelum group formations at its limbs. It is east-west oriented and both limbs are inclined at 30° (Fig. 4.5).

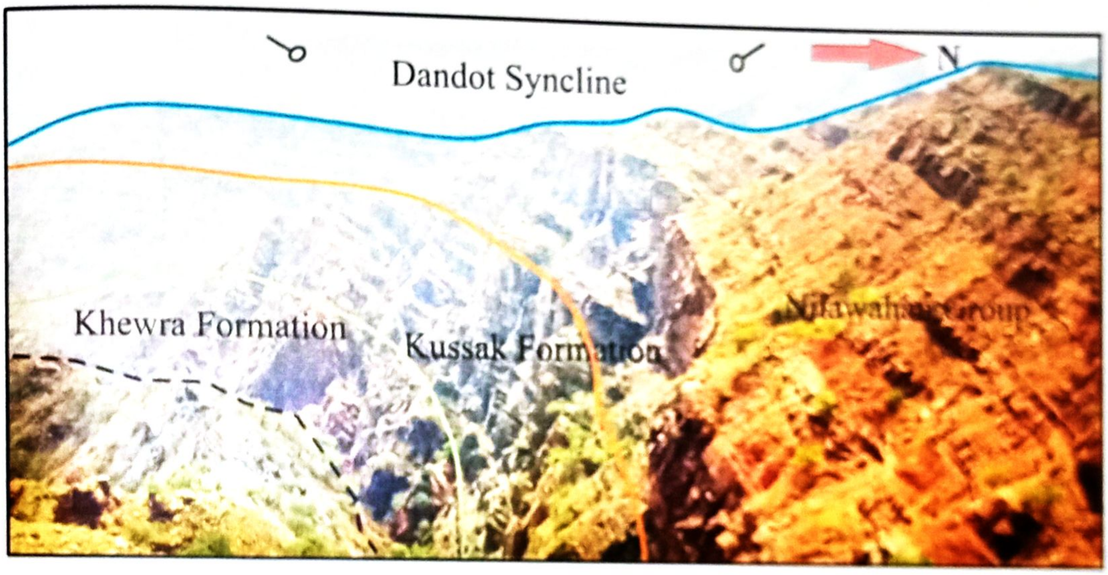


Figure 4.5. Western limb of Dandot syncline.

4.2.12 Gandhala thrust fault

The Gandhala thrust fault is north dipping thrust fault that had thrusted the Jhelum group formation over the Rawalpindi group in the vicinity. This fault is named after the Gandhala Nala located nearby (Fig. 4.6).

Figure 4.6. Western extension of the Gandhala fault named after the Gandhala Nala.

4.3 Methodology of cross sections construction

Four N-S oriented cross sections were prepared to understand subsurface structure pattern and its role in deformation of the strata at the surface. Methodology and explanation of cross section is given in the following text. In southern part of research area, exposed strata provide orientation data to interpret subsurface. In northern part, due to poor exposure of strata, orientation data was not available. In order to interpret subsurface area available public domain seismic lines (772-CW-04, 772-CW-06 and 772-CW-13) were used (Fig. 4.7). Basement is marked on seismic data at 4km depth with 2° taper toward the north which is in accordance with the previous work of (Baker et el., 1988). The reflector of the basement can be easily recognized due to density contrast at igneous and sedimentary interface. Two abandon wells Balkasar-1 and Lillah-01 used for placement of stratigraphic sequence in subsurface.

The partial availability of seismic data for subsurface control over behavior of strata, the most significant constrain used through the construction of cross-section is that the deformed-state cross sections must be in consistent with seismic and well data (where available) and with surface dip data and geological map. The surface data are extrapolated to depth using models of fault related folding (Suppe, 1983; Suppe and Medwedeff, 1984). Kink method is adopted for construction of fold profiles because of internally less and homogeneous deformation of strata (Suppe, 1983). In kink method, the major data type required are elevation data, contact relation data of various stratigraphic groups and orientation data (dip). Elevation data was easily acquired from the google earth which was also in accordance with the GPS data acquired from field as well as DEM data acquired from the open data website of USGS. However the dip and contacts of various strata are acquired during field visits. Then by using kink method, all the four cross section are constructed manually in graph paper which were then scanned and imported in Midland Valleys move for interpretation.

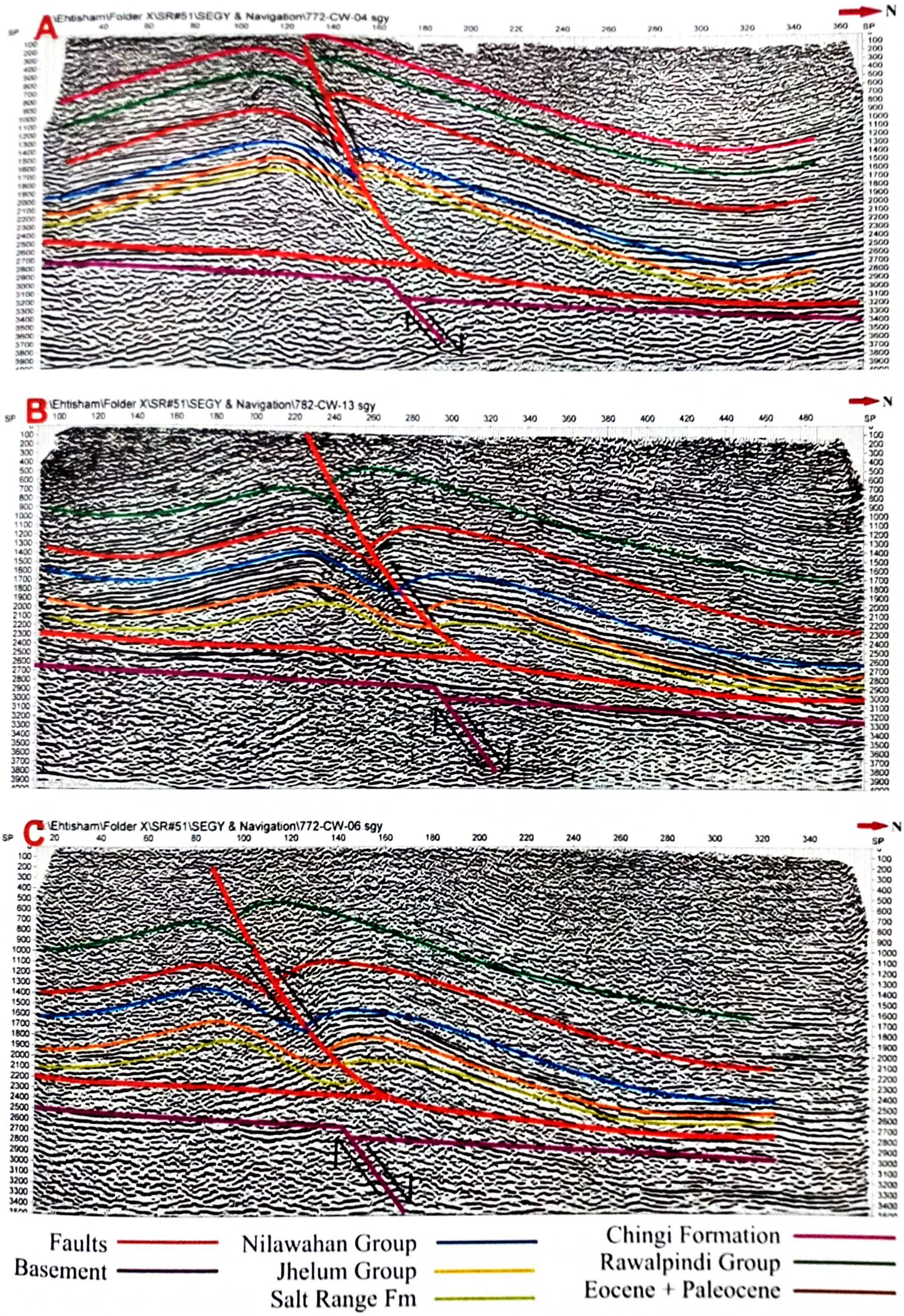


Figure 4.7. Interpreted seismic lines; a) 772-CW-04, b) 772-CW-013 c) 772-CW-06 (Stratigraphic boundaries are marked same as in sections).

4.4 Cross Sections

All four cross sections are approximately 72 km in length. Structures were not projected above the erosional surface to portray the real picture of the field. However they were constructed during the manual construction of cross sections. The dashed lines are marked above the erosional surface to observe the complete geometry of the thrusts and related folds. No fault zone is exposed in the vicinity of SRT trace. The dip domain data of Precambrian to Miocene data suggests presence of ramp anticline which can be modeled as fault-bend fold (Suppee, 1983; Mukhopadhyay, 2004). The geometry of the fault bend fold is comprised of secondary anticlines and synclines at its leading edge which are also exposed in the study area. These secondary anticlines and synclines at leading edge of fault bend fold shows its variance from the typical fault bend fold model (Fig. 4.8, 4.9, 4.10 and 4.11).

Seismic Lines demarcate the presence of an east-west trending Boon Fault dipping in the north that outcrops in section CD, EF and GH. In section AB Boon thrust is not exposed rather it terminates in subsurface as blind thrust. The presence of a normal fault in basement with overlying decollement zone favors the generation of this fault. Dip data acquired from above the fault area suggests the presence of an anticlinal structure that validates this folded structure to be associated with fault propagation fold geometry. This Boon Fault is the older fault than the Salt Range Thrust because of its location with respect to series of thrust present in the region from north to south. Further south their lies the Salt Range Thrust (SRT) that is the major general fault in the study area. The presence of a normal fault in basement rocks acted as a ramp from where SRT cuts upsection and forms fault bend fold geometry. This geometry of fault bend fold could only be explained by uniformly tapering layers with sufficient room for the structure to develop and restore back to their pre-deformational phase. The SRT is thus modeled as a blind thrust with ramp flat geometry buried below the Precambrian-Recent deposits with tip line along the hanging wall cut off of the Ramp anticline. Further southward, a series of anticlines and synclines including Bulah Syncline(BS), Nurpur Anticline (NA), Sardhi Anticline (SRA), Simbal anticline(SA), Simbal Syncline (SS), Karuli Anticline (KA), Karuli Syncline (KS), Malot Dome (MD), Dhalwal Syncline (DHS), Badshahpur Anticline (BA), Dandot Anticline (DA) and Dandot Syncline (DS)are present that are already discussed. In section GH, a thrust fault is outcropped at the surface known as Gandhala Fault (GF) that has thrusted the Khewra Formation of Jhelum Group over Kamlial Formation of Rawalpindi Group. This thrust fault is a splay of Salt Range Thrust that is generated to adjust the overlying sedimentary veneer. The strata in footwall of SRT is plotted in conjugation with well bore data of Lilla-01 well. Most of the formations were not reported in the well for which the layers which are not encountered in the well or tapered in the footwall of SRT to make the data in relevance with the well data. The room problem in the footwall is overcomed by plotting the normal fault in the subsurface which is providing the ramp for SRT (Suppe, 1983; Suppee and Medwedeff, 1984).

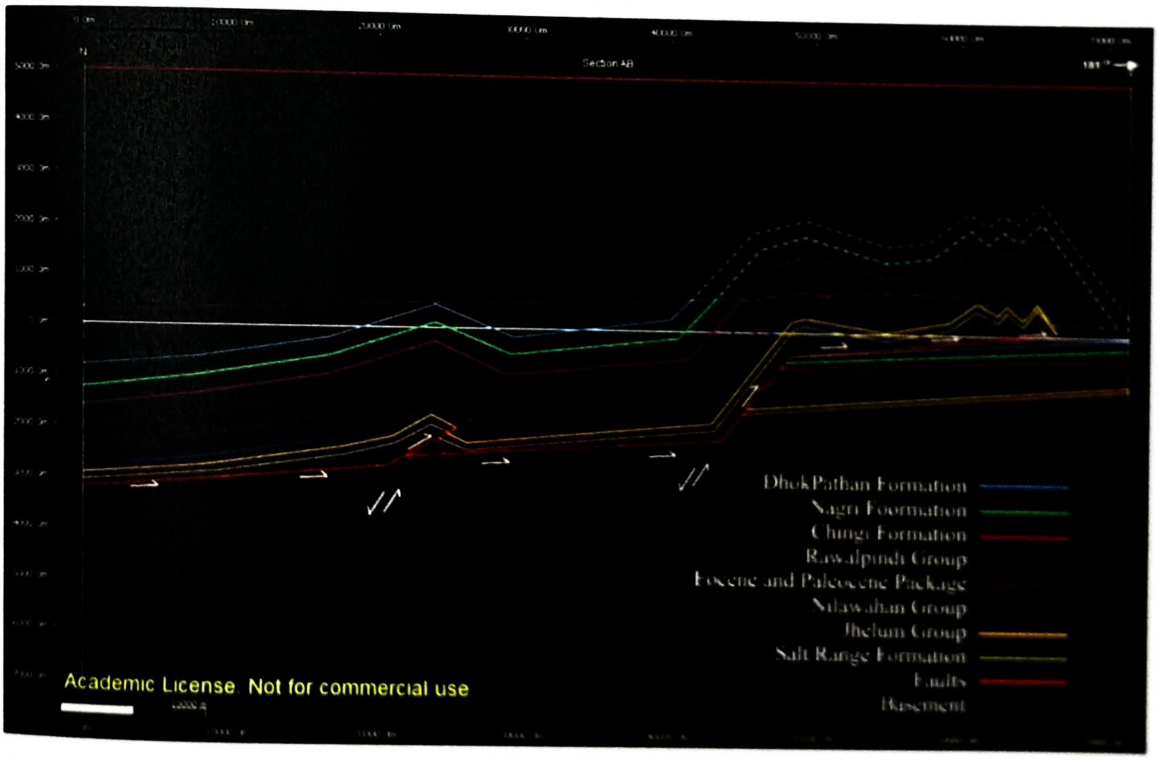


Figure 4.8. Geological cross section AB.

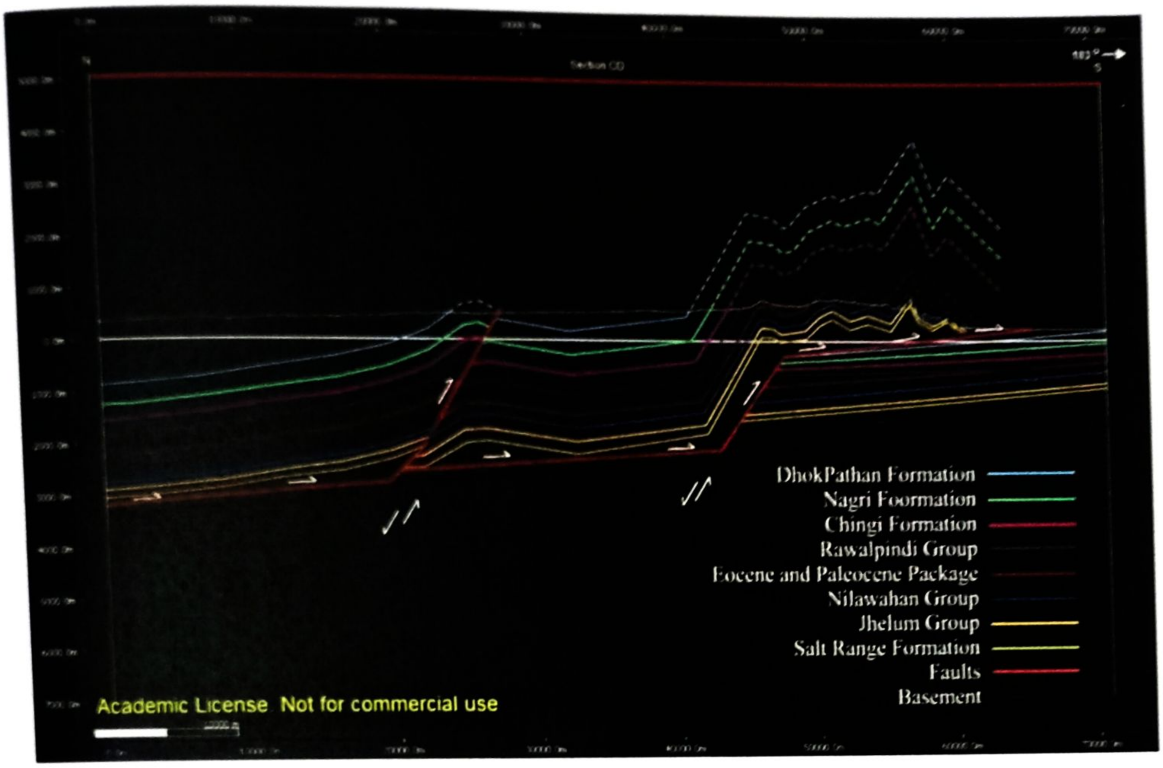


Figure 4.9. Geological cross section CD.

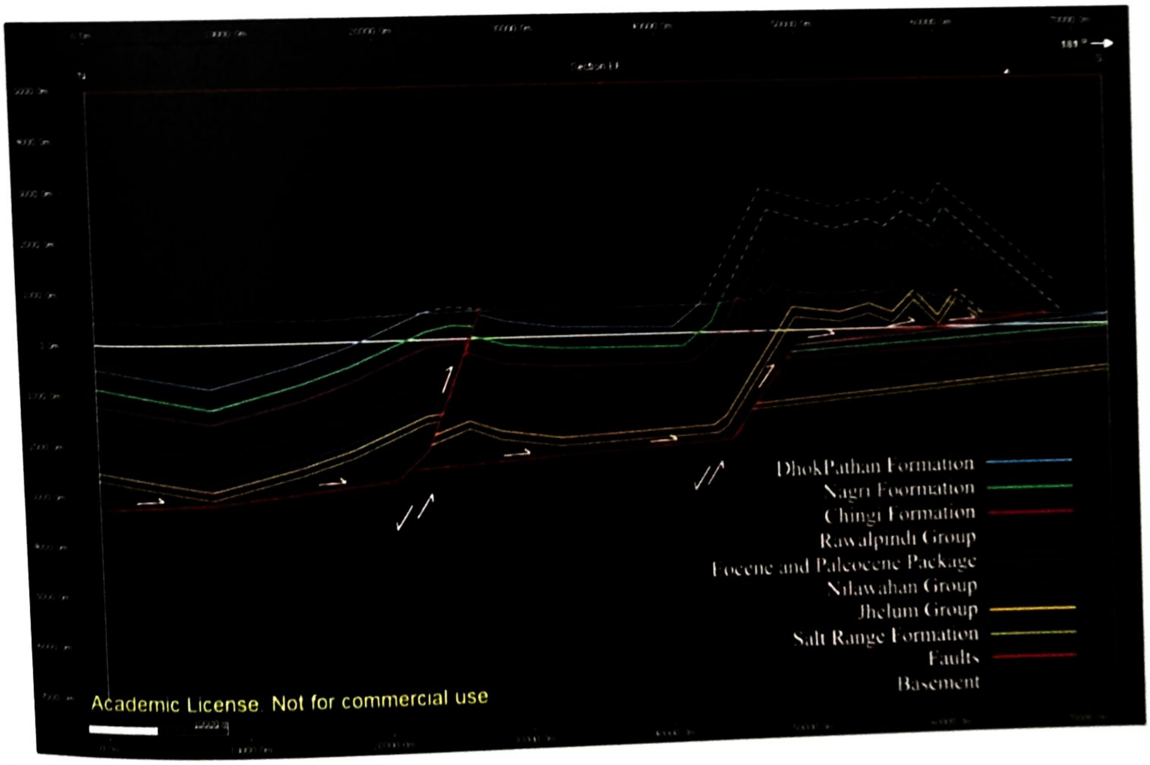


Figure 4.10. Geological cross section EF.

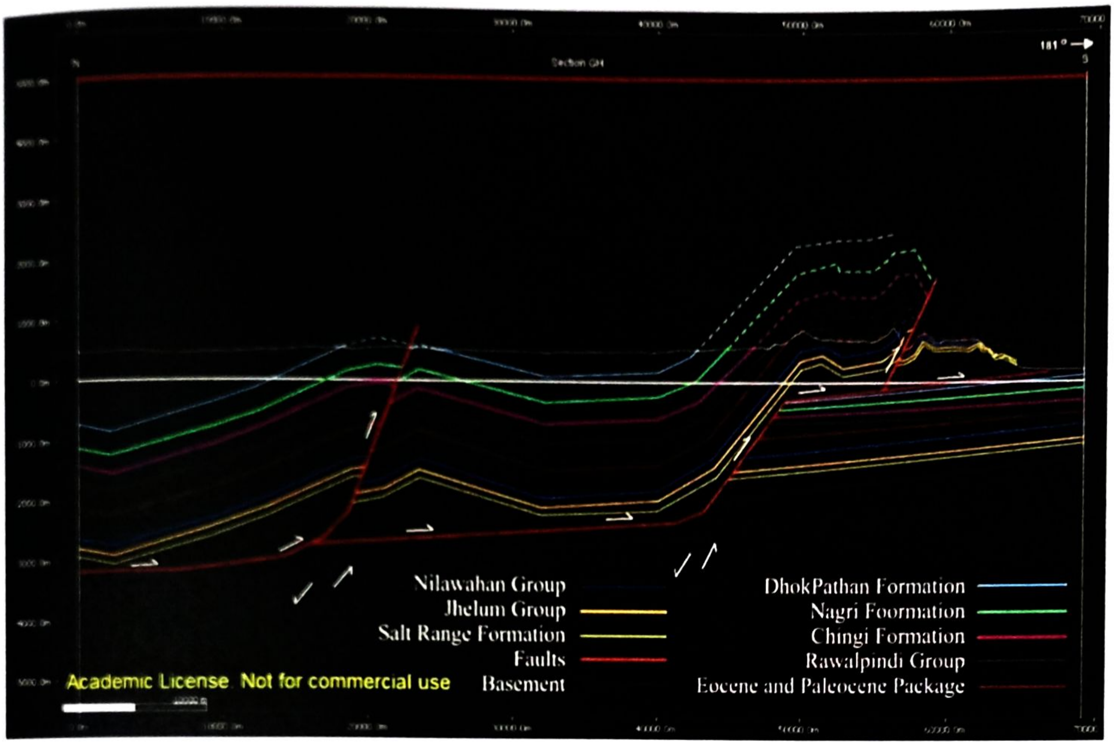


Figure 4.11. Geological cross section GH.

4.5 3D model of area

For interpretation, cross section construction, cross section digitization and 3D model building, Midland Valley Move 2014.2 was used. First of all, geological map of the study area was imported into the Move Platform as shown in figure 4.12.

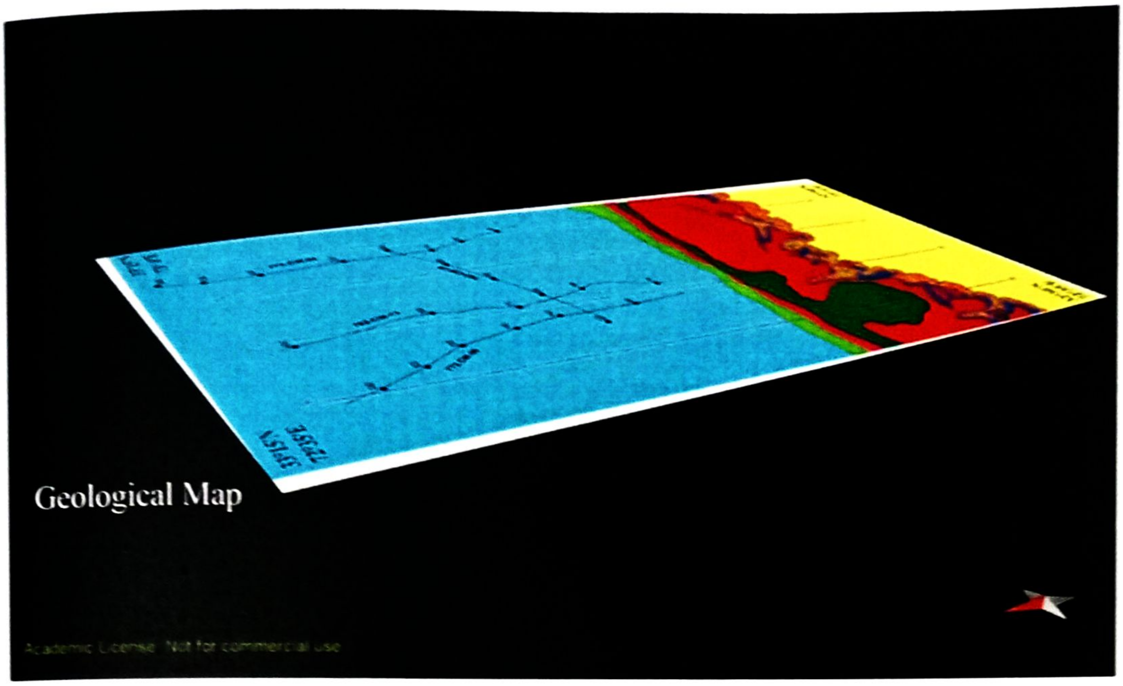


Figure 4.12. Geological map of the study area imported in Midland's Move Workplace.

Then Digital Elevation Model (DEM) of the study area was downloaded from the open data source of USGS website and overlaid onto the geological map already imported in the move software (Fig 4.14).

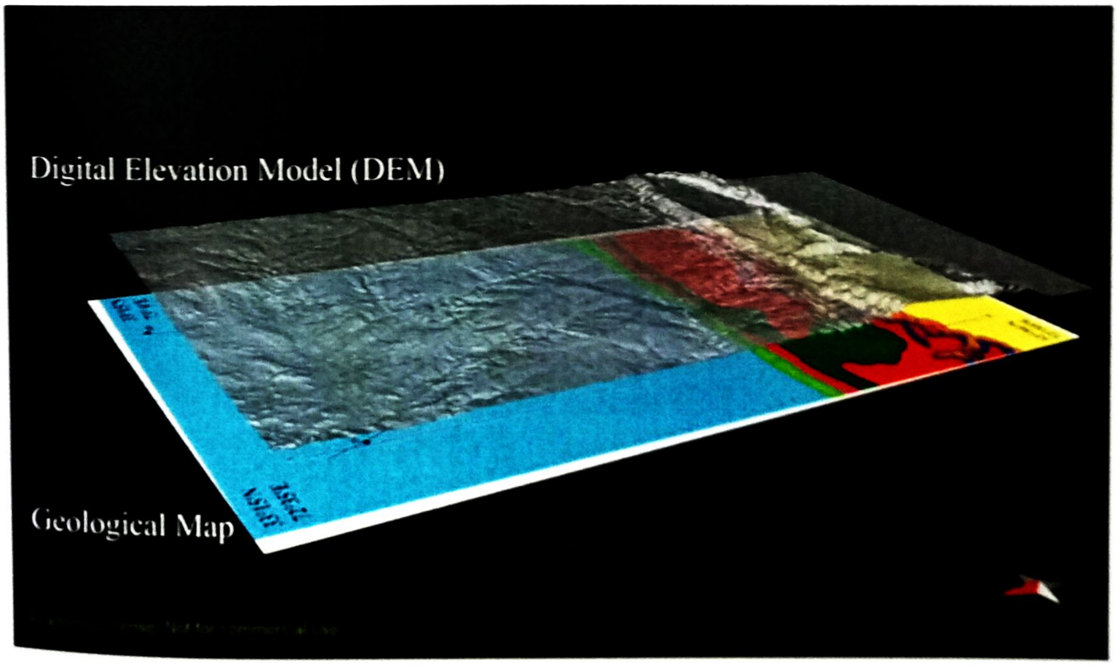


Figure 4.13. Digital elevation model of the study area with underlying geological map.

The geological map of the study area is then draped over DEM (Fig 4.15) which resulted in a model that incorporates the altitude profile (Fig 4.16).

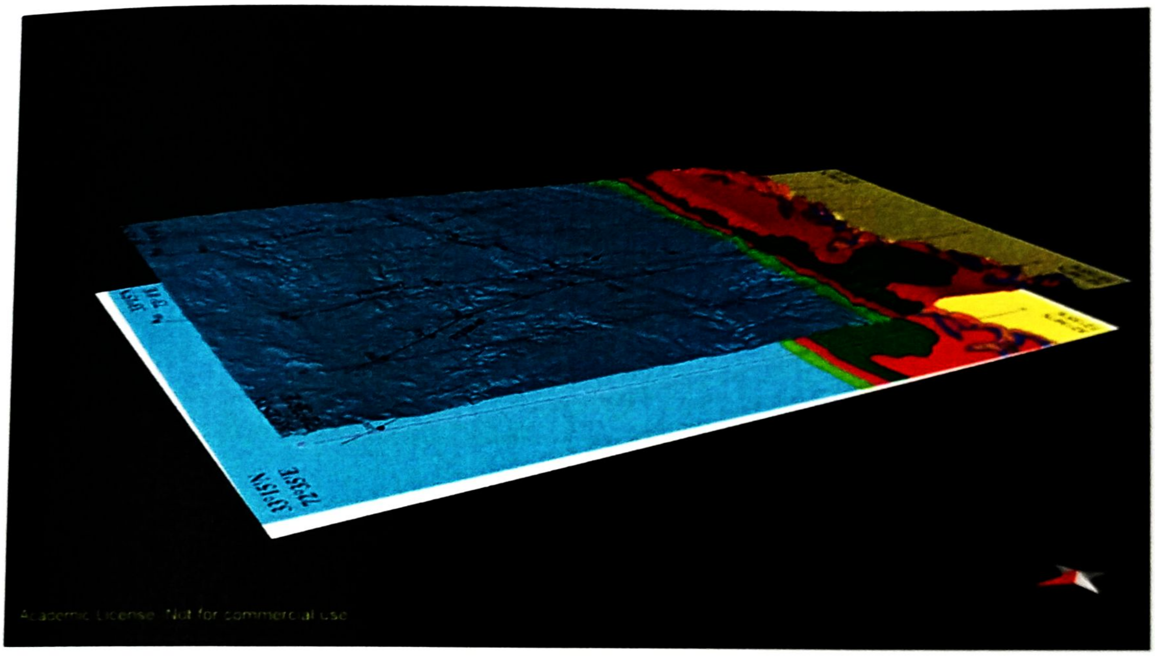


Figure 4.14. Draped geological map over DEM.

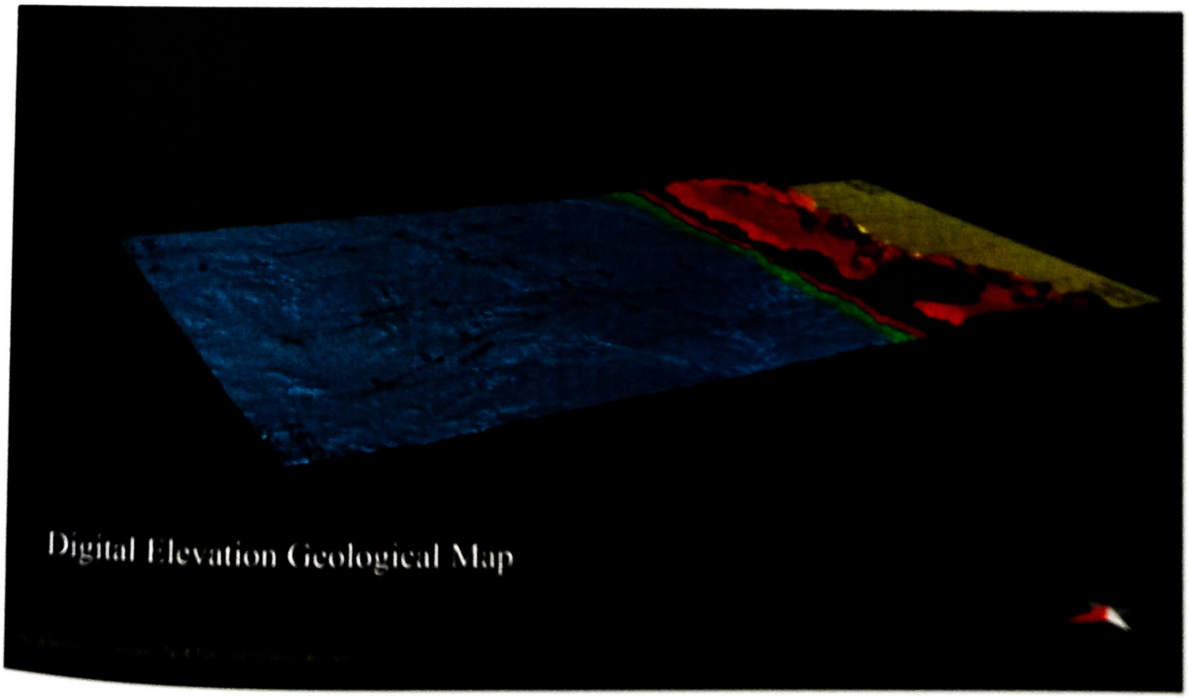


Figure 4.15. Geological map of the study area with elevation attribute.

Next step was to incorporate the available interpreted seismic lines, 772-CW-04, 772-CW-013 and 772-CW-06 in the model to observe the subsurface faults and basement in the northern extremity of the study area (Fig. 4.17).

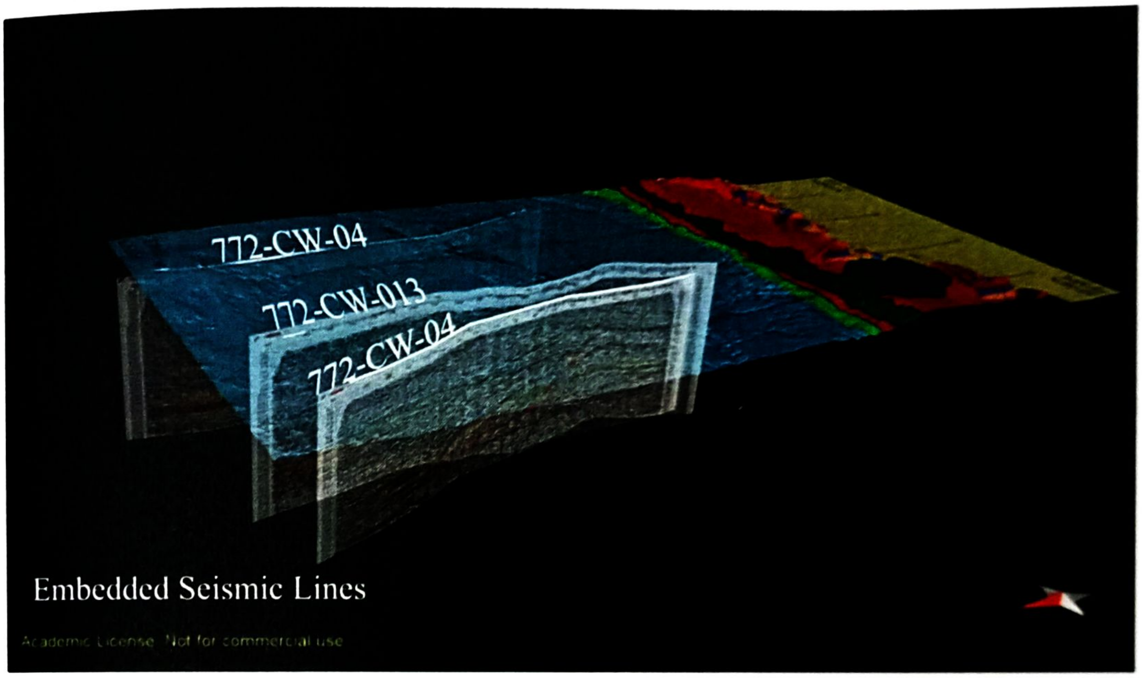


Figure 4.16. Embedded seismic lines in 3D geological model of the study area.

Further, trace lines and geological cross section were inserted into this model and elevation profile was projected along each section as shown in figure 4.18.

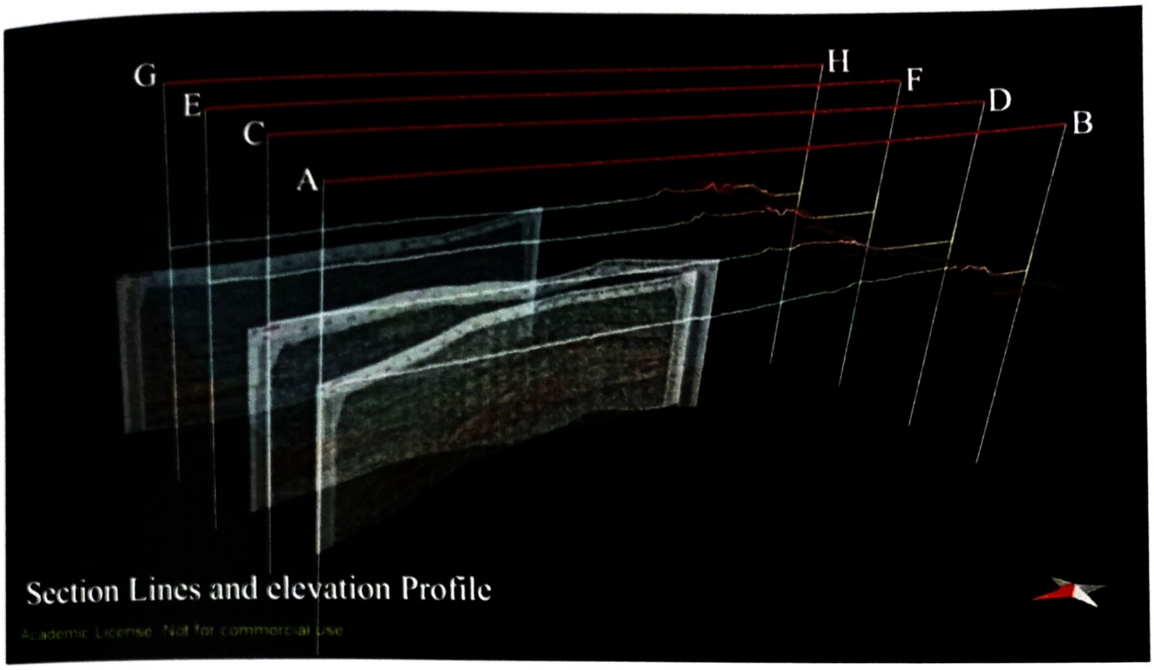


Figure 4.17. Section lines, posts and elevation profile embedded in 3d model.

The placement of faults and basement was aided by the seismic lines in the northern part whereas research work of Ghani et al; (2012), was used in the southern part of the study area as shown in figure 4.19.

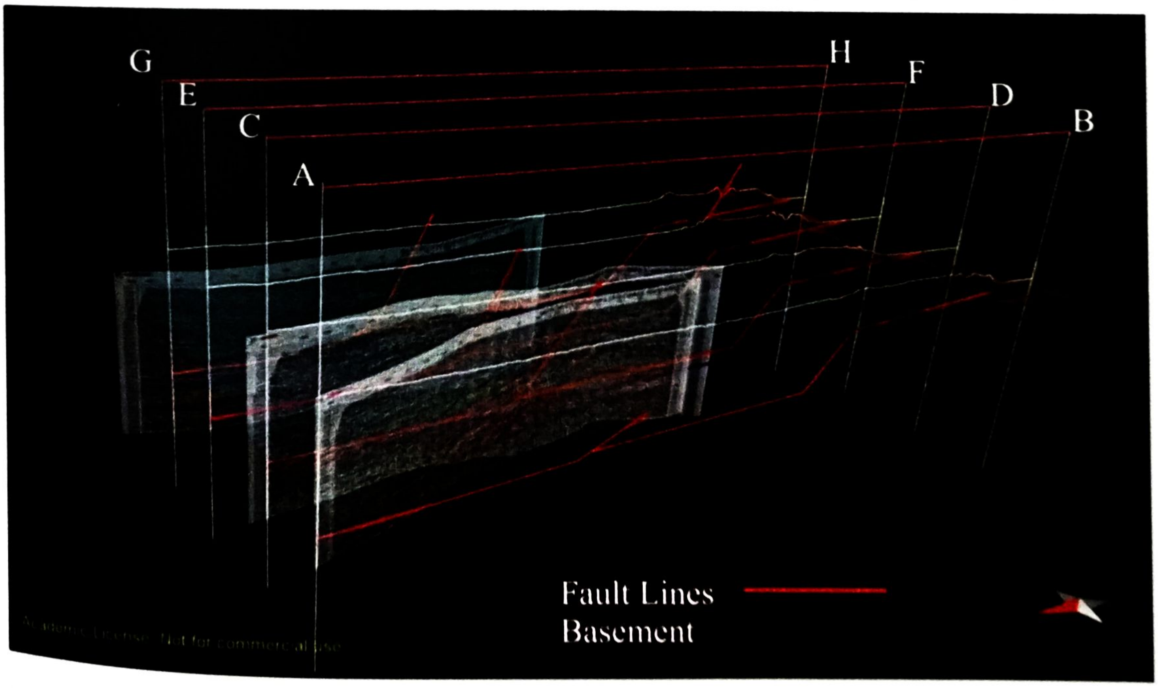


Figure 4.18. Placement of faults and basement trace line in sections.

In next step, 3D fault surface and basement surface was generated from these fault lines and basement lines of the cross sections termed as 3D meshed surfaces (Fig 4.20).

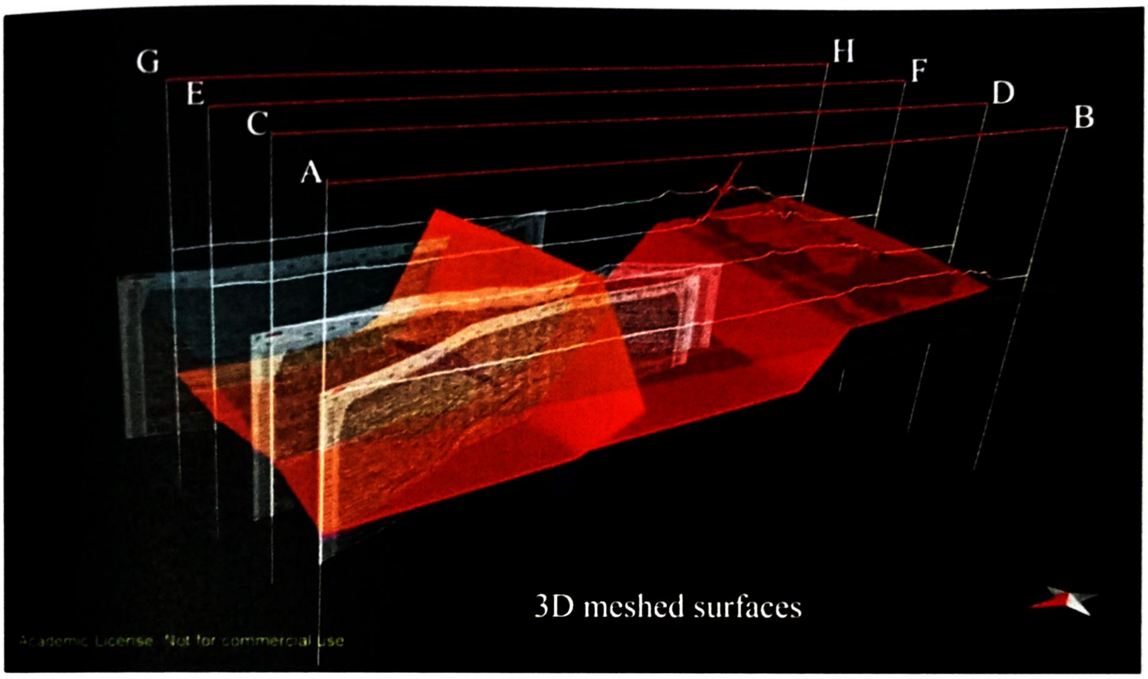


Figure 4.19. Generation of 3D surfaces from section traces.

The resultant 3D model of the study area is as shown in figure 4.21. The orange surface demarcate the Boon Fault that is at surface in the vicinity of section CD, EF and GH where as in section AB it die out in the subsurface. The red 3D surface is the Salt Range Thrust that has thrusted all the geological sequence onto the footwall. The underlying purple surface demarcates basement which is tapered about 2^{o} in the north.

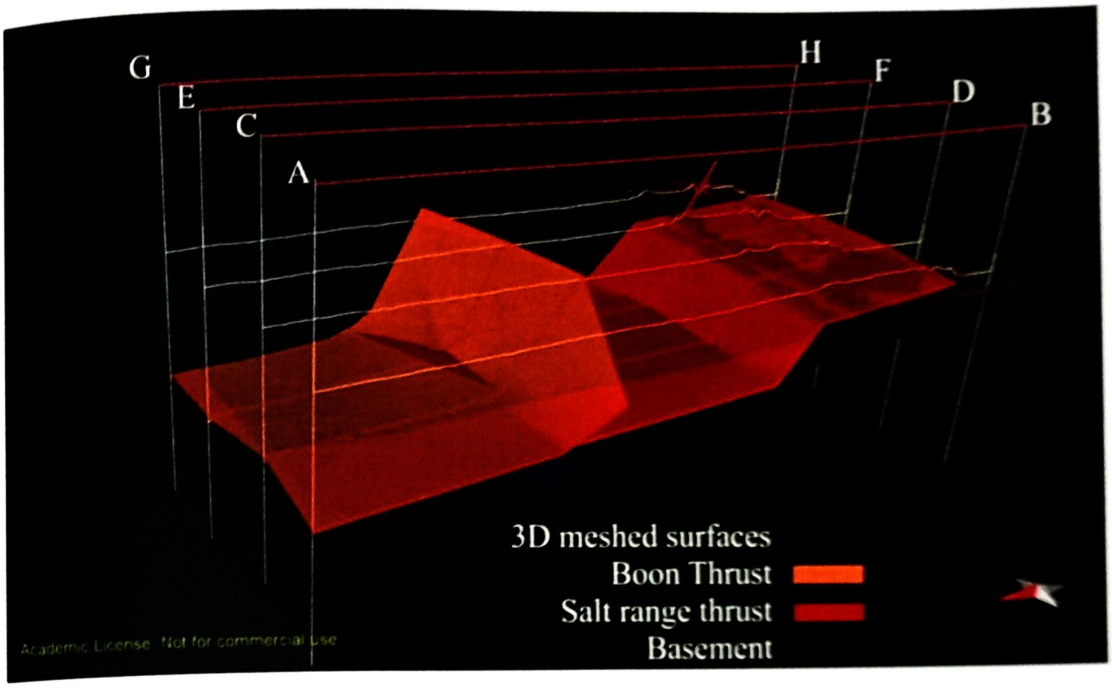


Figure 4.20. 3D surfaces of boon fault (orange), Salt Range Thrust (red) and basement (purple).

Then stratigraphy is keenly placed along each geological section in according with the fault surfaces as well as geological succession obtained from the well data of Balkasar 01 in the north and Lillah 01 in the south (Fig 4.22).

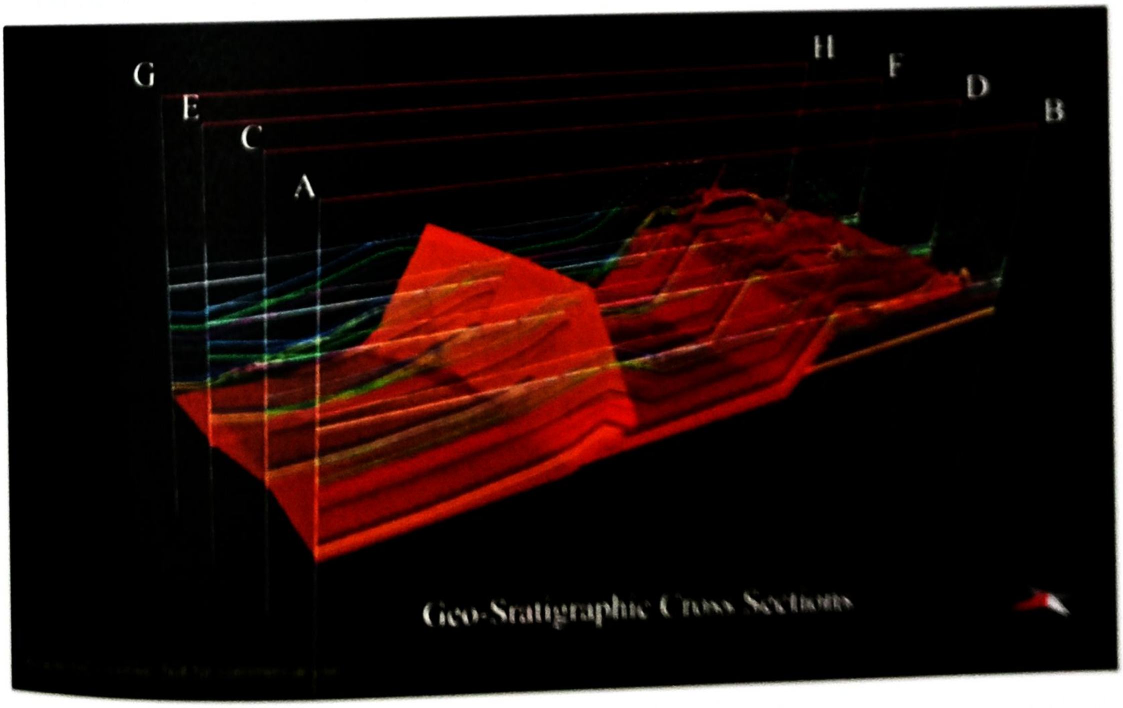


Figure 4.21. Stratigraphy of the geological sections imported at their relevant position.

The end product of the study area (Fig 4.23) gives a complete insight of the major faults and stratigraphic behavior in the subsurface.

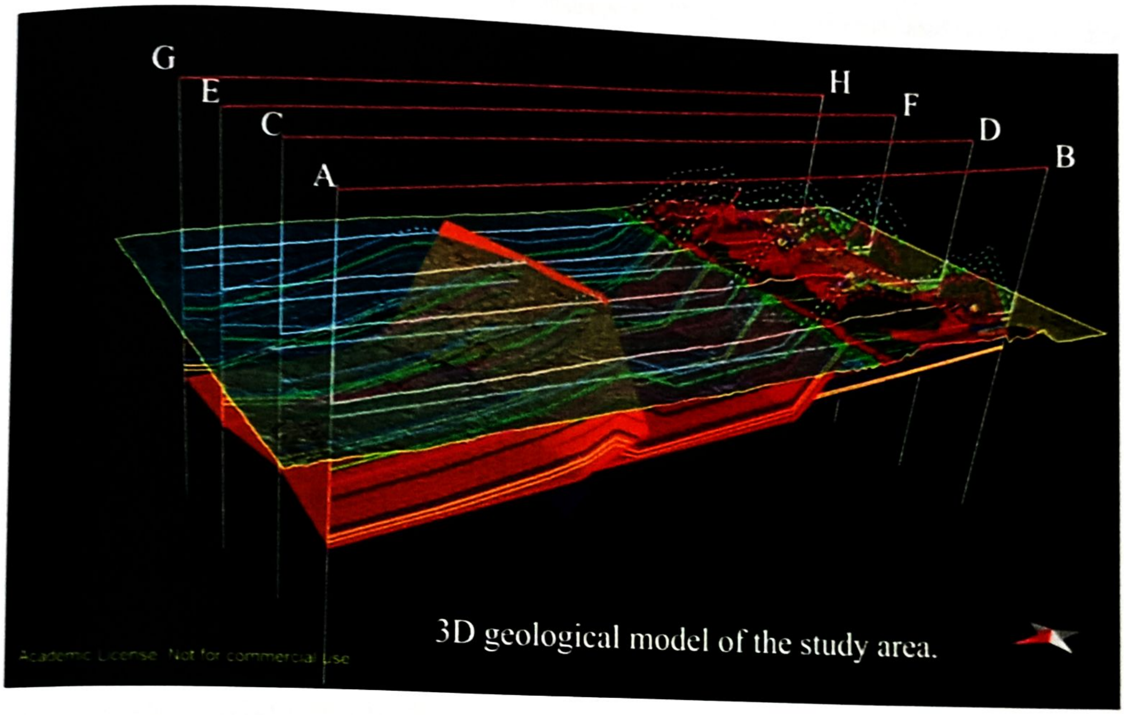


Figure 4.22. 3D geological model of the study area.

DISCUSSION

The Salt Range Thrust (SRT) represents the outermost boundary of Himalayan foreland fold and thrust system in Pakistan. The Precambrian and younger strata overrides the recent Punjab plane deposits along the SRT which extends from Jalalpur in the East and to Kalabagh in the west. The stratigraphic succession exposed in the study area varies from Precambrian to Quaternary. In Eastern and Central Salt Range area, thrusts and associated salt diaprism brought strata to the surface including Precambrian evaporates (Gee, 1980, 1989). These ductile evaporates lie beneath the Potwar Plateau and form a zone of decollement for regional thrusting. Two previous models (Pennock, 1989; Warwick, 1992) and presented for the Kinematics of Salt Range Thrust show two different pathways for SRT initiation. The first model explains deformation along SRT is controlled by thin skinned tectonics; SRT moves as décollement in pre-Cambrian evaporites sequence which ramps upward through Cambrian to Siwalik succession and bring Pre-Cambrian Salt Range Formation over Punjab plane deposits (Pennock et al., 1989). The second model suggested that deformation across the SRT is controlled by thick skinned tectonics in which SRT ramps across pre-existing normal fault in the basement (Warwick et al., 1992). The Salt Range Thrust propagates to the surface bringing Salt Range Formation over the Punjab plane deposits across this ramp. Both models show that the SRT is imbricated to the surface however in our study area the southward dipping Cambrian to Siwalik strata across the previously proposed SRT trace at surface contrast with the previously proposed imbricated nature of SRT. Four cross section were constructed in integration with seismic, well and surface dip domain data through conventional structural geological techniques. 3D structural model in this research show thrust trajectories, hanging wall fold geometries in order to validate the structural style which is in close accordance to the field signatures of strata at the leading edge of SRT. 3D surfaces of fault and basement were generated in 2D move and stratigraphic succession of each cross section is placed at their precise location. The resultant 3D model of the study area showed that the Salt Range Thrust is evolved as décollement thrust along the Salt Range Formation, ramps up section across the pre-existing normal fault in basement and terminate as a blind thrust with tip line within the Siwaliks. The resultant fold in the hanging wall of SRT, formed as multiband fault bend fold. There were no strike slip component of the Salt Range Thrust encountered however previous literature suggest the presence of such deformation in extreme south that are not so far covered by the research area.

CONCLUSIONS

The integration of field data and seismic lines into a 3D model of the study area helped thoroughly in understanding the structural evolution of the salt range thrust. Following points are concluded from this research.

a) Series of anticlines and synclines formed on crustal portion of fault bend fold are formed because of progressive shortening along Salt Range Thrust.

b) Ghandhala thrust splays out from SRT as a splay fault along upper flat of Salt Range Thrust.

c) Salt Range thrust in this area act as a blind thrust.

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