STRUCTURAL EVOLUTION THROUGH BALANCED STRUCTURAL CROSS-SECTION OF NORTH EASTERN POTWAR BASIN, KAHUTA, KALAR AND SURROUNDING AREAS, PUNJAB, PAKISTAN.

By

NADEEM AHMAD USMANI

Department of Earth and Environmental Sciences
Bahria University, Islamabad

2014

STRUCTURAL EVOLUTION THROUGH BALANCED STRUCTURAL CROSS-SECTION OF NORTH EASTERN POTWAR BASIN, KAHUTA, KALAR AND SURROUNDING AREAS, PUNJAB, PAKISTAN.

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

NADEEM AHMAD USMANI

Department of Earth and Environmental Sciences
Bahria University, Islamabad

2014

CERTIFICATE OF ORIGINALITY

This is to certify that the intellectual contents of the thesis

Structural Evolution through Balanced Structural Cross-section of North Eastern Potwar Basin, Kahuta, Kalar and Surrounding Areas, Punjab, Pakistan.

are the product of my own research work except, as cited properly and accurately in the acknowledgements and references, the material taken from such sources as research papers, research journals, books, internet, etc. solely to support, elaborate, compare and extend the earlier work. Further this work has not been submitted by me previously for any degree, nor shall it be submitted by me in future for obtaining any degree from this University, or any other university or institution. The incorrectness of this information, if proved at any stage, shall authorize the University to cancel my degree.

Signature:__________________ Date: _________

Name of the Research Candidate: Nadeem Ahmad Usmani

ACKNOWLEDGEMENT

I would like to dedicate this research project especially to my parents, my brothers, my teachers and all those friends who have kept me motivated and supported me throughout my MS Program. I thank them for being the source of constant encouragement which has given me the strength to undertake this very task in the first place. This thesis would not have been possible without the encouragement and generosity of number of people including my teachers, supervisors, colleagues and family members.

My special thanks to Dr. Muhammad Zafar (Head of Department, Earth and Environmental Sciences, Bahria University, Islamabad) for their unending support and perpetual guidance which provided me inspiration needed throughout my study at this department. He really provided me all the opportunities throughout all the semesters.

First of all, I would like to pay my special thanks to my supervisors Mr. Fahad Mahmood and Hammad Ghani (Lecturer), for their encouragement, guidance, criticism and intellectual advice throughout my research work.

I would like to acknowledge my best friends, Mr. Raja Waqas Satti (Assistant Director, GSP), Mr. Sohaib Iqbal (Assistant Director, GSP), Raza Abbasi and Khawaja Waqas Ahmed (Mudlogger, Petroservices) as this work would have not been completed without their thoughts provoking ideas, and guidance.

I would like to express my deepest gratitude to my parents, brothers and sisters and all those people who have cooperated with me directly or indirectly especially Dr. Tehseenullah Khan Bangash for developing my presentation skills, technical writing and his guidance throughout my MS Program.

My sincere appreciation and thanks for my friends, Syed Ahsan Gardezi (Assistant Director, GSP), Atif Ali Hassan (Assistant Director, GSP), Syed Faraz Gillani, Ahtsham Ahmad (Lecturer, BU), Taseer Ahmad (Assistant Director, GSP), Asad Jhangir (Assistant Director, GSP), Syed Ahtsham Jafri, and all of my class fellows for their encouragement, moral and technical support, company and interest in seeing this research complete.

ABSTRACT

The study area covers the Kahuta and Kalar areas in the Potwar Fold-and -Thrust Belt (PFTB), which demonstrates the Himalayan Foreland Fold-and-Thrust Belt situated at the western boundary of the Sub-Himalayas. The surface and subsurface rocks range in age from Precambrian to Recent. The Dhok Pathan and Soan formations of Pliocene to Pleistocene marks unconformity with Quaternary Terrace gravel deposits in the study area. The structural evolution of a part of the northeastern PFTB is interpreted through balanced structural cross-sections constructed by integrating seismic section of PR-92-26, structural data and well data of Kalar X-1. The cross-sections revealed the subsurface folds geometries and kinematics of thrusts which represents the deformational history of the study area. The basement was marked as prominent reflector picked at time 4.1 s or 4100 ms in seismic section PR-92-26, the equivalent depth of which is 9020 meters after time to depth conversion. The balanced cross-sections demonstrate that the folded and faulted structures present in the subsurface are formed as a result of back thrust and blind thrusts present below these structures. The anticlinal and synclinal structures are formed as detachment folds cut by thrust faults along the limbs of folds which states that these folded structures are formed prior to faulting. A 3D structural model has been generated to better understand the variation in subsurface structural geometry. The model depicts the deformation style, variation and the termination of structures across the section lines. The 3D structural model explains that the regional structures extends upto the depth of 09 km in the subsurface. The restored cross-sections shows that the average amount and percentage of shortening accommodated by structures in the study area are approximately 6 km and 29%.

CONTENTS

Page

ACKNOWLEDGEMENT i

ABSTRACT ii

LIST OF FIGURES vi

LIST OF TABLES ix

CHAPTER 1

INTRODUCTION

1.1 General Statement 1

1.2 Location and Accessibility and Climate 3

1.3 Previous work 3

1.4 Aims and Objectives 4

1.5 Methodology 5

1.5.1 Field work 5

1.5.2 Laboratory work 6

1.5.2.1 Preparation of Geological Map 6

1.5.2.2 Preparation of Geological Cross-section 6

CHAPTER 2

REGIONAL TECTONICS

2.1 Introduction 8

2.2 Pangaea 8

2.3 Geodynamic Setting of the Himalayas 8

2.4 Northward Movement of Greater India 9

2.5 Regional Fault System in Northern Mountainous area of Pakistan 10

2.5.1 Karakoram Block 13

2.5.2 Main Karakorum Thrust (MKT) 13

2.5.3 Kohistan Island Arc (K.I.A) 13

2.5.4 Main Mantle Thrust (MMT) 13

2.5.5 Main Central Thrust (MCT) 14

2.5.6 Northern Deformed Fold and Thrust Belt (NDFTB) 14

2.5.7 Main Boundary Thrust (MBT) 14

2.5.8 Kohat Fold and Thrust Belt (KFTB) 15

2.5.9 Potwar Fold and Thrust Belt (PFTB) 15

CHAPTER 3

STRATIGRAPHY

3.1 Introduction 18
3.2 Rawalpindi group 18
3.2.1 Murree Formation 19
3.2.2 Kamlial Formation 19
3.3 Siwalik group 20
3.3.1 Chinji Formation 21
3.3.2 Nagri Formation 22
3.3.3 Dhok Pathan Formation 24
3.3.4 Soan Formation 24
3.4 Quaternary deposits 25
3.4.1 Terrace Gravel 25
3.4.2 Sand, Silt and Clay 25
3.4.3 Alluvium 26

CHAPTER 4

STRUCTURAL GEOLOGY

4.1 Faults 29
4.1.1 Rawat Fault 29
4.1.2 Kahuta Fault 31
4.2. Folds 32
4.2.1 Anticlines 32
4.2.1.1 Kalar Anticline 32
4.2.1.2 Nagial Anticline 32
4.2.1.3 Jawa Antiform 33
4.2.2 Synclines 33
4.2.2.1 Batala Syncline 33
4.2.2.2 Alliot Syncline 34
4.2.2.3 Mori Syncline 34
4.2.2.4 Kalial Synform 35
4.3 Cross-section 35

4.3.1 Methodology of time to depth conversion 36
4.3.2 Section AA/ 36
4.3.3 Section BB/ 38
4.3.4 Cross-section Restoration 38
4.4 3D Structural Model of the study area 42
4.4.1 3D Fault Modelling 42
4.4.2 3D Horizon Modelling 42

CHAPTER 5

DISCUSSION AND CONCLUSIONS

5.1 Discussion 45
5.2 Conclusions 46

REFERENCES 48
APPENDIX-I 53
APPENDIX-II 54

LIST OF FIGURES

Page

Fig 1.1. Generalized structural map of Potwar Plateau showing location of study area in box (after Khan et al., 1986). 2

Fig 1.2. Location map of the study area Kahuta, Punjab (shown by orange box), accessible through road network from major cities. 4

Fig 2.1. Breakup of Pangaea about 200 Ma and different positions of the Gondwanian and Laurasian palates with respect to time (Scottess C. R. 1990). 9

Fig 2.2. Positions of greater India with respect to the Africa and Madagascar fixed in their relative motion since 80 Ma. The stage positions are derived by magnetic anomalies and the absolute time scale as proposed by LaBrecque and others (1977).The cross hatched strip is the present doubled up Indian crust between the Himalayan crust and Indus ophiolite belt. The dotted line represent the position of Arabia before the Neogene opening of the Red Sea from Powell and Conaghan (1979). 11

Fig 2.3. Map showing location and major tectonic trends on and around the north-west part of the Indo-Pakistan sub-continent (modified after Sarwar and Dejong 1979), (red box shows the study area). 12

Fig 2.4. Cross section extending from Peshawar basin to north eastern Kohat Plateau (after McDougall et al., 1991). 16

Fig 2.5. Balanced cross-section along central/ eastern Potwar sub-Basin (after Moghal et al., 2007). (a) Balanced cross-section through central/ eastern Potwar sub- Basin along Chak Beli Khan, Tanwin-Bains, Gungri-Qazian, Mahesian and Rothas structures (after Moghal et al., 2007). (b) Balanced cross-section through central/ eastern Potwar sub-Basin along Chak Beli Khan, Tanwin-Bains, Adhi and Bhubar structures (after Moghal et al., 2007). 17

Fig 3.1. Cross beds in Murree sandstone near Panjar area. Stratigraphic younging direction is indicated by word “Up” (Pencil for scale). 19

Fig 3.2. Clay balls in the Kamlial Formation near Kahuta area (Pencil for 20

scale).
Fig 3.3. Wood fossil in sandstone of the Kamlial Formation near Panjar area (Pencil for scale). 21
Fig 3.4. Beds of the Chinji Formation dominantly composed of red-purple clays and buff gray sandstone. 22
Fig 3.5. Sandstone of the Nagri Formation near Mawara area (Camera pouch for scale). 23
Fig 3.6. Sandstone of the Dhok Pathan Formation having flaser bedding near Thoa Khalsa area. 24
Fig 3.7. Sandstone of the Soan Formation having bentonite clay near Batala area (File for scale). 25
Fig 3.8. Terrace gravel deposits exposed near Mori area. 26
Fig 4.1. Geological map of the study area. 30
Fig 4.2. Shearing and crushing along Rawat Fault near Mohri village. S-type drag fold is seen in the middle right corner of the photograph (File for scale). 31
Fig 4.3. Shearing and crushing zone along Kahuta Fault near Bata village in sandstone of the Chinji Formation. 31
Fig 4.4. View of Kalar Anticline in Landsat 8 OLI image. Red circle marking the anticlinal structure. 33
Fig 4.5. Photograph illustrating the Chinji Formation exposed in the core of the Jawa Antiform near Jawa village. 34
Fig 4.6. (A) Uninterpreted seismic line PW15 across the portion of Eastern Salt range/Potwar Plateau. (B) Interpreted seismic line PW15 across the portion of Eastern Salt range/Potwar Plateau used for balanced cross-section (Pennock et al., 1988). 36
Fig 4.7. Seismic section PR-92-26 across the study area. (A) Uninterpreted seismic section PR-92-26. (B) Interpreted seismic section PR-92-26. 37
Fig 4.8. (A) Balanced cross-section along line AA$^{/}$. (B) Restored section AA$^{/}$ showing approximately 6.5 km of shortening. 40
Fig 4.9. (A) Balanced cross-section along line BB$^{/}$. (B) Restored section BB$^{/}$ showing approximately 5.5 km of shortening. 41
Fig 4.10. 3D model of study area showing the interaction between surface 43

geology and structural cross-sections.
Fig 4.11. 3D model showing the structural cross-sections across the lines A-A´ and B-B´. 43
Fig 4.12. 3D fault model of the study area showing a regional thrust system. 44
Fig 4.13. 3D model of horizon at the level of the Murree Formation intersected by thrust faults. 44

LIST OF TABLES

Page

Table 3.1. Generalized stratigraphy of Eastern Potwar Basin (after Peanock et al., 1988). 27

Table 3.2. Stratigraphic column proposed for study area based on surface measurements and well bore data; column is also used in construction of cross-sections (Figs 4.8 and 4.9). 28

CHAPTER 1

INTRODUCTION

1.1 General Statement

The Potwar Fold and Thrust Belt (PFTB) demonstrate the Himalayan foreland fold and thrust belt in Pakistan and is located at the western boundary of the Sub Himalayas. The Potwar Plateau is bounded by the Kala Chitta and Margala Hills ranges to the north, the Indus River and Kohat Plateau to the west, and the Jhelum River and the Hazara-Kashmir Syntaxis to the east. Physiographically, it is a surface of low relief, except where dissected by major rivers. Salt Range Thrust terminates at its southern boundary (Fig 1.1). The PFTB has recorded deformation in sedimentary strata and preserving continental molasse sequence resulting from Himalayan orogeny. The deformational structural style revealed by numerous structures at surface represent extreme deformation in Potwar basin (Pennock et al., 1988).

The Potwar Plateau is composed of three domains. The Northern Potwar Deformed Zone (NPDZ) exposed in the northern part of the Potwar Plateau, the central Soan Syncline, and in the south the area is fringed by the Salt ranges. It has been estimated that ~55 km of horizontal shortening has been accommodated from the central Soan Syncline to northern part of the NPDZ during 5.1 to 2.0 Ma, whereas, 20 km of horizontal shortening has occurred along the Salt ranges after 2.0 Ma (Jaswal et al., 1997). Seismic reflection lines from the eastern Potwar Plateau reveal a variety of structural styles which may be related to several factors, including: 1) changes in distribution and thickness of a basal evaporite sequence; 2) basement faults and flexures; and 3) low dip of the basement (Pennock et al., 1988).

The study area is located near Kalar, Kahuta and Doberan areas District Rawalpindi, Pakistan (Fig 1.2). The study area is situated in the Sub-Himalayas of Pakistan. The study area falls on the Survey of Pakistan topographic sheet number 43G/6 and 43G/7 on 1:50,000 scale. The study area lies between longitudes 73^o 15' E to 73^o 30' E and latitudes 33^o 28' N to 33^o 38' N. Murree and Kamlial formations of Miocene age are the oldest rock units exposed in the study area.

The profiles from the eastern Potwar provide important subsurface constraints in the area that is structurally unique in the Himalayan foreland of Northern Pakistan,

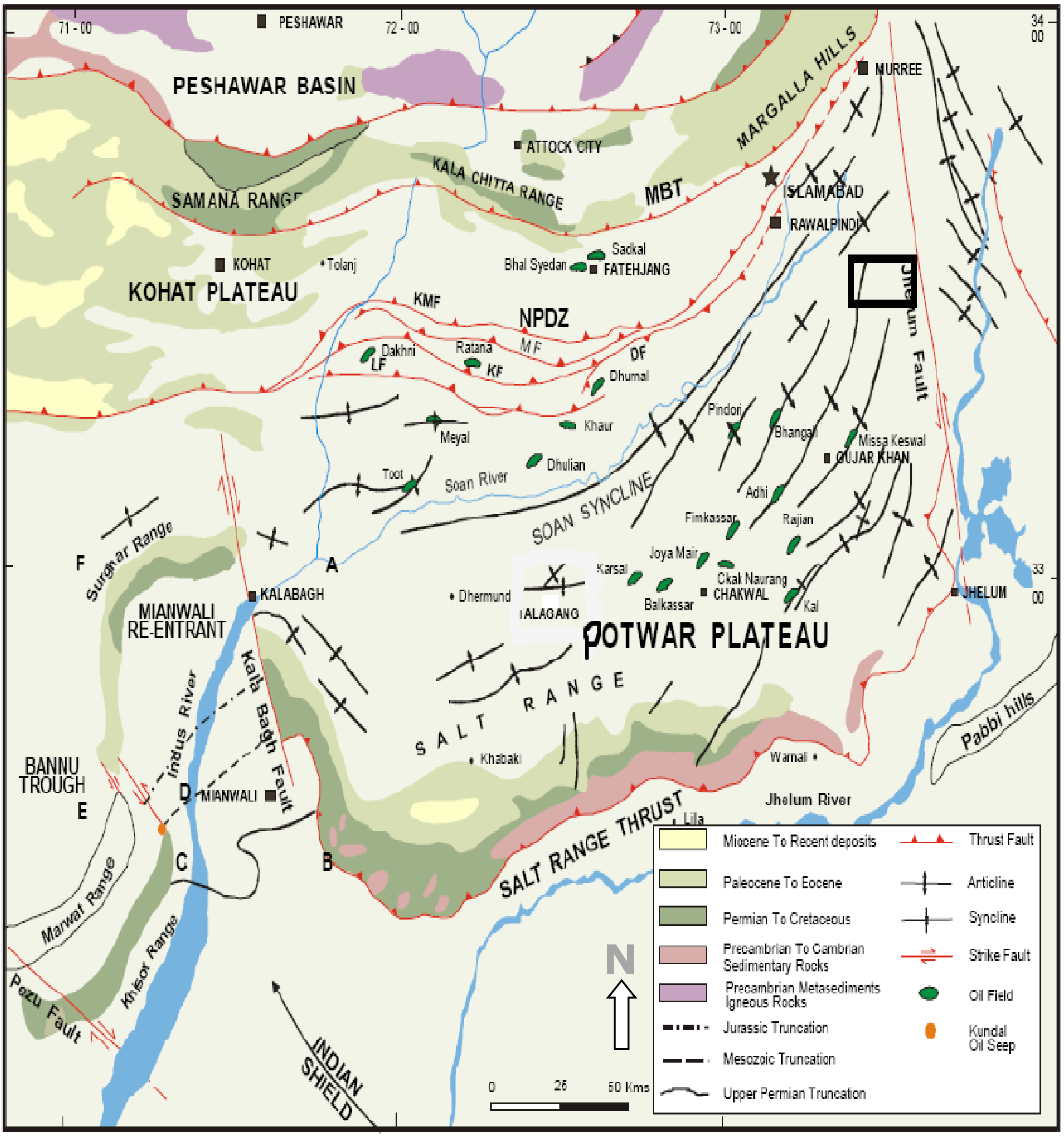


Fig 1.1 Generalized structural map of the Potwar Plateau showing the location of the study area in box (after Khan et al., 1986).

and of considerable economic importance in the light of recent oil and gas discoveries (Fletcher and Soeparjadi, 1984; Khan et al., 1986). Exploration wells south of the Soan Syncline have never drilled repeated section. Due to severe and dangerous overpressures within the molasse, some of these wells never reached the primary Cambrian to Eocene objectives. Other wells, which penetrate the targeted Cambrian to Eocene strata is generally regarded as economic basement for this part of the fold-and-thrust belt (Pennock et al., 1988).

As the study area is present in compressional regime due to which structure are present for traps and good reservoirs. This research work will enhance the understanding for structural evolution of the North Eastern Potwar fold-and-thrust belt around the Kalar and Kahuta areas.

1.2 Location, Accessibility and Climate

The study area is approximately 50 km east of Islamabad and easily accessible through GT- Road from Islamabad and Rawalpindi (Fig 1.2). In addition, many small roads, stream courses and fair weather tracks/paths connecting local villages provide an easy access to study the rocks and sections from different views which are quite helpful in structural interpretation of the study area.

Climatically the study area is semi-humid with moderate to intense summer and winters. The average temperature during summer is 35°C. The suitable time to carry out geological field work in the study area is from October to March.

1.3 Previous Work

Potwar Plateau was mapped by various geoscientists, for example, Butler et al., 1987; Leather, 1987; Baker et al., 1988; Jaumé and Lillie, 1988; Pennock et al., 1988; Jaswal et al., 1997. McDougall and Hussain, 1991 have combined seismic-reflection profiles, petroleum exploration well logs, Bouguer gravity anomaly maps and surface geological maps to construct regional structural cross sections along the Potwar Plateau.

The structural interpretations and the detailed timing of structural events in the Potwar Plateau were determined by Raynolds (1980), Burbank et al (1986), and Johnson et al (1986). Duroy (1986), Khan et al (1986), Butler et al (1987), Leather (1987), Baker et al (1988), and Jaume and Lillie (1988) also worked on the structural interpretations of the Potwar Plateau by making the subsurface structures more precisely beneath the eastern Potwar Plateau. This study helps in understanding the Himalayan foreland fold-and-thrust belt and also provides important constraints which are commonly absent in ancient collisional mountain belts (e.g., topographic slope, basement slope, detailed timing information).

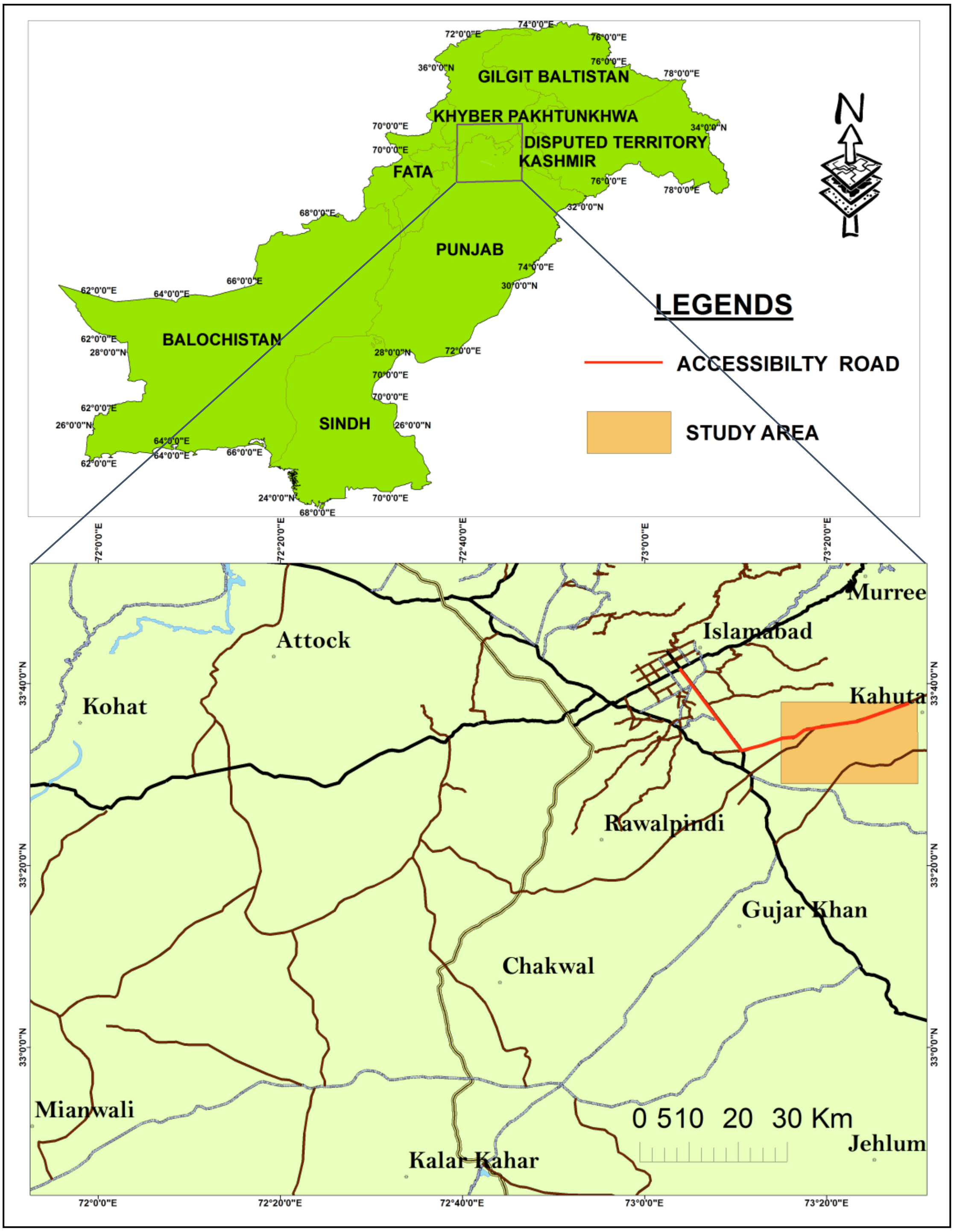


Fig 1.2. Location map of the study area Kahuta, Punjab (shown by orange box), accessible through road network from major cities.

1.4 Aims and Objectives

This research work aimed with the following objectives.

1. To carry out detail geological mapping of the study area with the help of aerial photographs, satellite images and field traverses at 1:50,000 scale.
2. To evaluate subsurface structures of the area through seismic data.

3. To develop a comprehensive model for the structural evolution of the area with the help of surface geology, subsurface seismic and well bore data.
4. To construct balance structural cross sections of the study area to interpret the structural evolution of the area with the help of surface and subsurface folds and thrusts geometries and their sequence and kinematics.
5. To work out the nature of tectonics responsible for structuration of the area and the total amount of shortening accommodated by structures in the study area with the help of restored balance cross sections.
6. To develop a 3D structural model of the study area in order to understand the geometry of structures in the subsurface.

1.5 Methodology

Reconnaissance study of the area was done by studying satellite images using computer software's like Erdas Imagine 8.4 and ArcGIS 10.1 combined with published geological maps of Geological Survey of Pakistan. The satellite image analysis was used to delineate the major fold and fault structures, and stratigraphic units before going to the field work.

1.5.1. Field Work

Field work was carried out in the area from Rawat to Kahuta along the Rawat Fault, from Kahuta to Panjar along the Kahuta Fault, from Mandra to Batala and Kalar along Batala Syncline and Kalar Anticline and along Ling Nala to cover the area between the Rawat Fault and Nagial Anticline. Traverses were also made to study the structural features along those streams which are running across the regional strike.

Two geological field visits were made to the area. First field work was carried out from 1st to 8th March, 2014. This visit was intended to identify the important areas for comprehensive studies. Second field work was planned from 12th March to 19th March 2014. In this field excursion, detailed study was carried out to delineate the structural and stratigraphic features in the study area. The evidence of the existing faults i.e. fault gouge, breccia, shearing, were also recorded during the field work.

1.5.2. Laboratory Work

Prior to beginning the field work, satellite images were first studied in the laboratory to delineate the regional scale structural trend of the area. After collecting data in the field, it was transferred to computer and various components were selected for further work. Following is a general procedure that was adopted in the laboratory work:

1. The collected field data was gathered and interpreted in the laboratory.
2. The interpretation of seismic section of PR-92-26 was extrapolated from previous research work, which marked as base for interpretation of structures in the study area.
3. Geological map and cross-sections were prepared from data collected in the field.
4. The results interpreted from maps, 3D models, cross-sections and diagrams were written in final report.

1.5.2.1 Preparation of Geological Map

Detailed geological map of the area was prepared using published geological maps of Geological Survey of Pakistan as base maps. Regional geological map of eastern Potwar Plateau by Pennock et al., (1988) was used as base map to delineate the geology and structure of the study area. Final layout of geological map with proper scale and legend was prepared in ArcMap 10.1 software by incorporating the collected field data and satellite image analysis.

1.5.2.2 Preparation of Geological Cross-section

Geological cross-section was constructed across the structures in mapped area to understand the subsurface geometry. Following are the general steps that were followed for the construction of cross-section.

1. A section line was selected on the map that crossed maximum geological formations and structures at right angle.
2. Profile of section line was constructed from Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEM) file by using the Move 14.0 software.

3. Cross section was finally constructed using Move 14.0 software.
4. Thicknesses of different geological formations were taken from the well tops of LMKR Kalar X-1 and published previous work of the study area.
5. Dip data used for the construction of cross-section shows an integration of data from already published maps and the field observations.
6. 3D structural model is generated in order to observe the structural geometry and variation of structures along trend in Move 14.0.
7. Cross sections were restored by using software Move 14.0 to calculate the total amount of shortening accommodated by structures in the study area.
8. The total amount of shortening is calculated upto basement and the average shortening percentage was determined from restored cross-sections.

CHAPTER 2

REGIONAL TECTONICS

2.1 Introduction

Pakistan is situated between Indo-Pak and Eurasian plates and its structure are effected majorly by past and present positions of Indian and Eurasian plates. The primary structural and stratigraphic setting of Indian plate is greatly affected by the events of plate movements which occurred during the Late Paleozoic to the present. In Permian to the Jurassic time the location of Indo-Pak plate was southern hemisphere, which was in-between Africa, Antarctic and Australia (Wandrey et al., 2004).

2.2 Pangaea

The supercontinent Pangaea was occurred in the Paleozoic time and start of Mesozoic time. It shaped approximately before 300 Ma and then start to split apart about 200 million years ago (Scottess, C. R 1990), (Fig 2.1). Pangaea the first rebuild supercontinent was bordered by a mega ocean, called Panthalassa (Condie, K. C, 2002).

Eurasia composed of three geological separations which may be called as the Laurasian, Tethyan, and Gondwanian domains. The origin dated to the late Paleozoic time, when all the landmasses had floated to form an uninterrupted landmass which continue together for about 100 Ma (Irving et al., 1979). In late Triassic time, Pangaea splited into two major supercontinents, Laurasia in the North and Gondwana in the South while the Tethys shaped a slice between the northern and southern divisions of Pangaea (Du Toit, 1937). Pakistan is lying on the connection of Gondwanian and Tethyan domain (Kazmi and Jan, 1997).

2.3 Geodynamic Setting of the Himalayas

The Himalayas and the Indian Ocean are two most important and well developed features bordering the Indo-Pakistani subcontinent. Drifting of the continents and collisional type tectonics are initiated due to sea floor spreading. Extensive sea floor spreading caused the Indo- Pakistan plate moved away from the Gondwana land, and Indian Ocean opened.

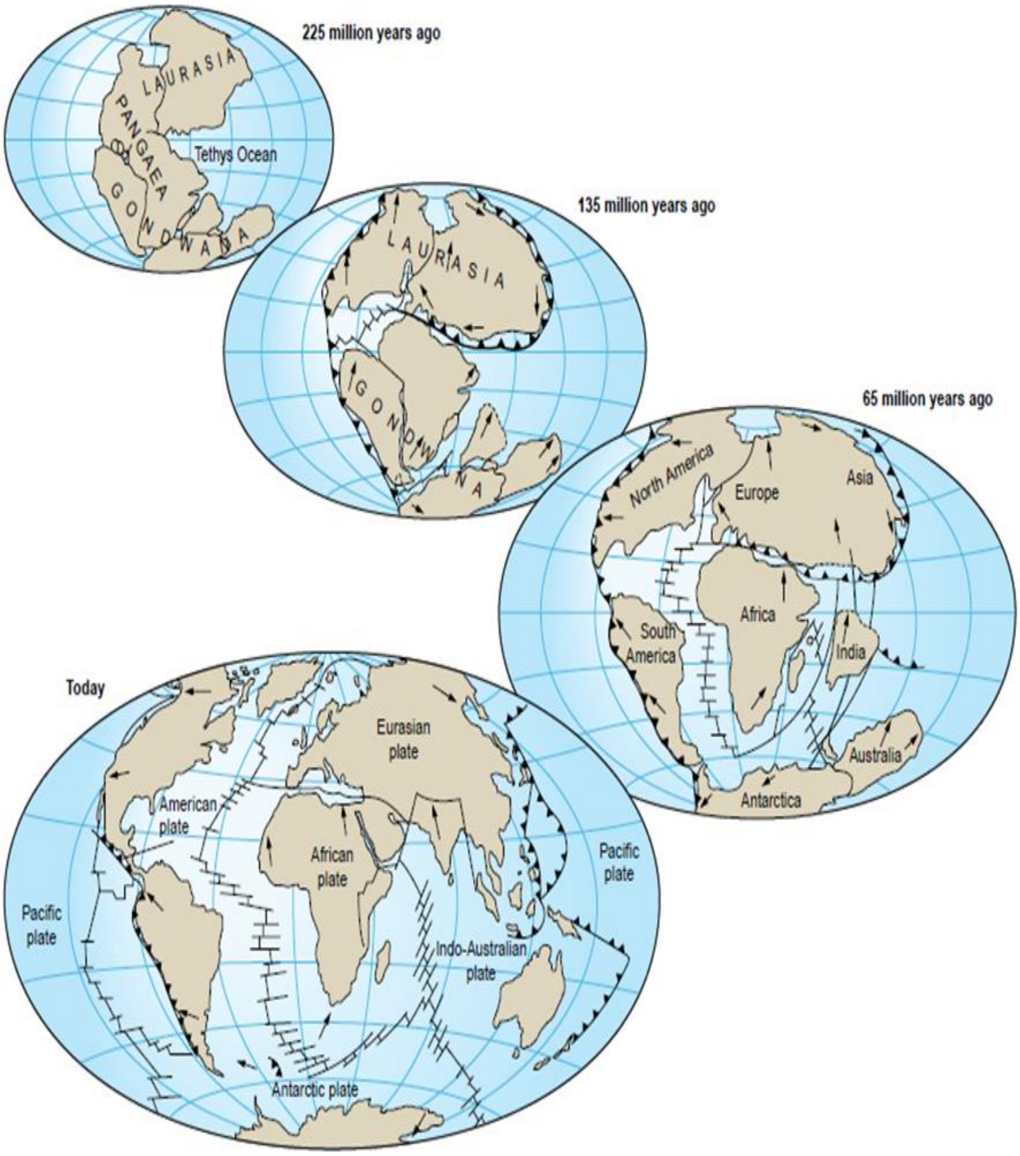


Fig 2.1 Breakup of Pangaea about 200 Ma and different positions of the Gondwanian and Laurasian plates with respect to time (Scottess C. R. 1990).

Indian plate travelled a distance of 5,000 km North and then collided with Eurasia as a result of geo dynamic forces. Himalayas and their adjacent mountain ranges are formed as a result of this collision (Kazmi and Jan, 1997).

2.4 Northward movement of greater India

Supercontinent Pangaea has been divided into its two parts i.e., Laurasia and Gondwanaland in Early Permian about 300 Ma ago. Among the Gondwana continents, Indian plate started its movement towards north-west relative to Australia and Antarctica form late Cretaceous to early Eocene, and then collided with Kohistan Island Arc (Chaudhary et al., 1999; Valdiya, 1980).

According to Powell and Conaghan (1979) Kohistan Island Arc (KIA) collided with the Eurasian plate. The Himalayas emerged along the boundary of the Indian Plate due to collision of Indian and Eurasian plates (Spenser, 1993). Pakistan is located at the boundary of these three tectonic blocks and its structures are formed due to these collisional events. Positions of the Indian plate with respect to time relative to Madagascar, from 80 Ma to present is shown in Figure 2.2.

The subducted part of the Indian shield collided with the Eurasian block and has been detached into two slices, the frontal mass collided with Eurasian plate along the southern suture zone but the rare block of Indian plate has under thrusted beneath the frontal block and Eurasian plate. This collision has obducted large masses of the ophiolites and melanges in the suture zone. Upper part of the detached frontal block form the basement and transported toward the south as a result of the collisional forces from the Eurasian plate. This detachment leads to the formation of the thrust faults i.e. Main Boundary Thrust (MBT) and Main Central Thrust (MCT) in the Indian plate (Powell and Conaghan, 1979).

Continued under thrusting of the rare block has scraped off the Phanerozoic sediments from the sea floor as well as some of the basement rocks and showed southward as tectonised blocks and metamorphosed masses, thrust napes and thrust slices. These southward shifted and sliced sediments commonly known as the Himalayan Shuphen Zone and Lesser Himalayas (Kazmi and Jan, 1997).

In Miocene time the deposition of the Siwaliks in the Upper Indus Basin is due to erosion which was started with the upheaval of the Himalayas in the Eocene time. Fluvial environments starts in Upper Indus Basin from onward to the Miocene. In this time the Neo-Tethys was closed and the foredeep axis has been started further moving toward south with time (Lillie et al., 1987).

2.5 Regional Fault System in Northern Mountainous Area of Pakistan

The north western part of Indo-Pakistan subcontinent has been divided into litho-tectonic domains of different geological and physiographical features (Sarwar and Dejong, 1979), (Fig 2.3).

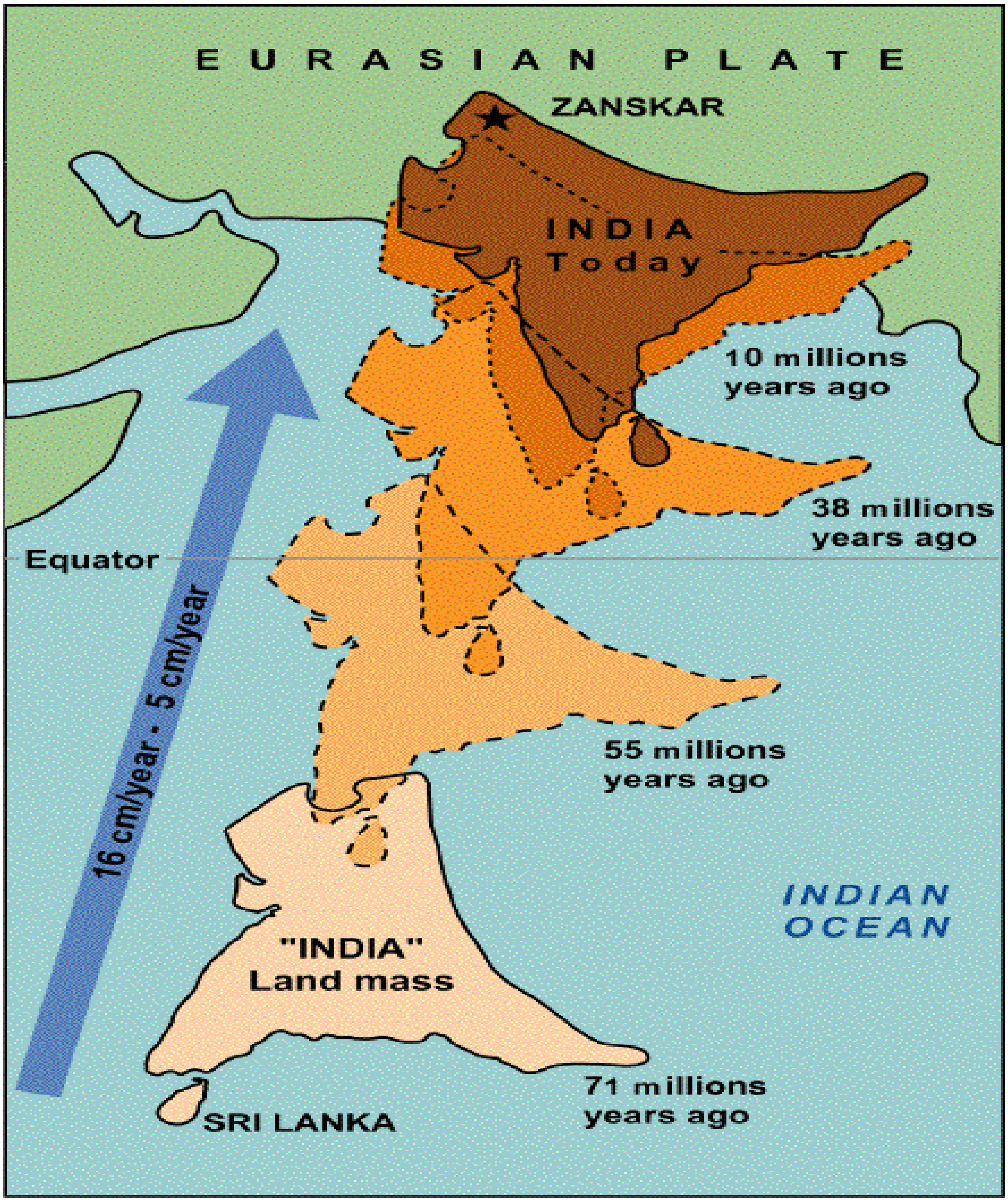


Fig 2.2. Positions of greater India with respect to the Africa and Madagascar fixed in their relative motion since 80 Ma. The stage positions are derived by magnetic anomalies and the absolute time scale as proposed by LaBrecque and others (1977).The cross hatched strip is the present doubled up Indian crust between the Himalayan crust and Indus ophiolite belt. The dotted line represent the position of Arabia before the Neogene opening of the Red Sea from Powell and Conaghan (1979).

Regional fault system in Northern area of Pakistan is comprised of five thrust faults of large extent both in their length and crustal shortening. If we move toward south from Northern side of mountainous area, these faults divides the hilly area into the following geological divisions (Ahmad et al, 2004).

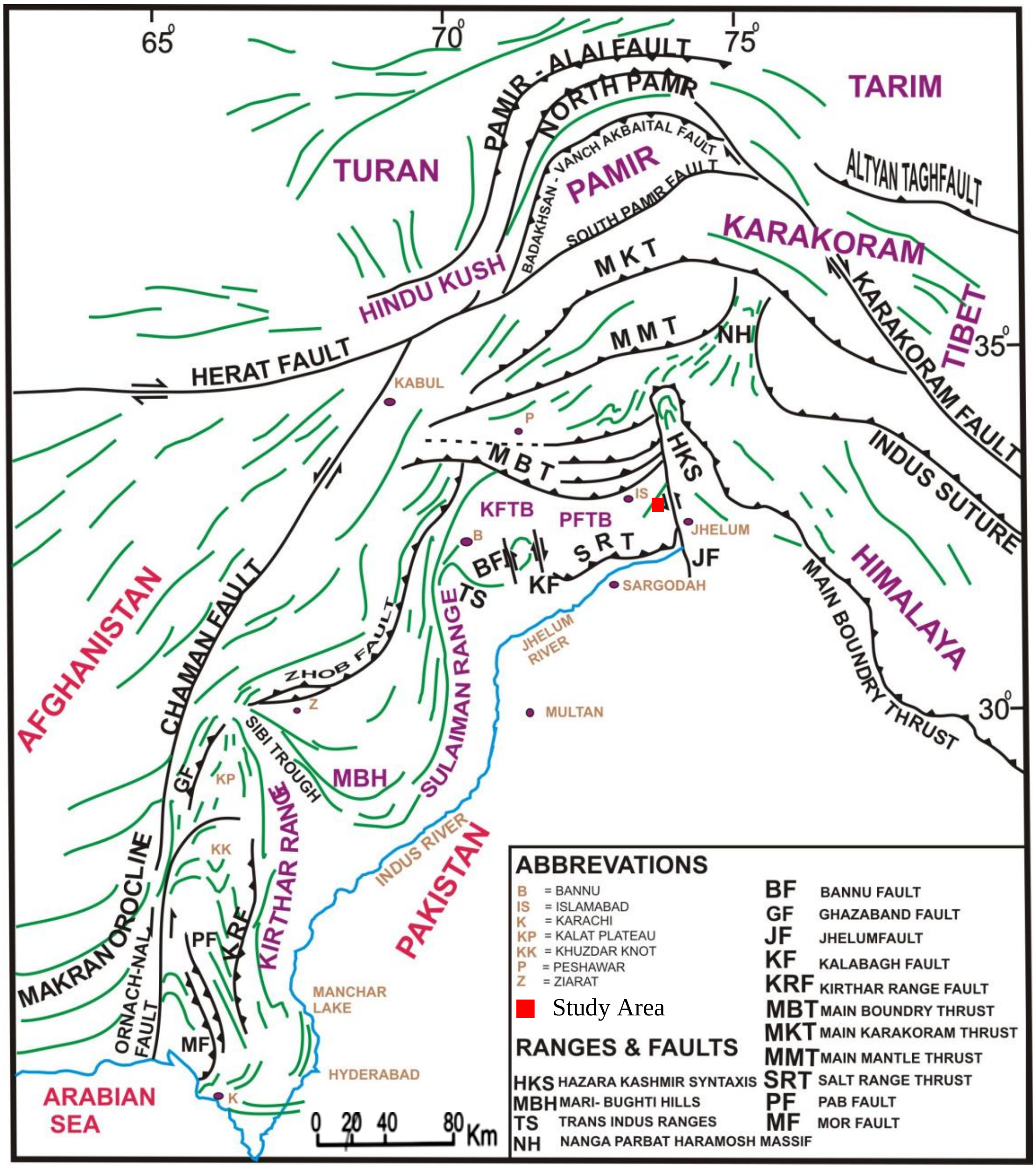


Fig 2.3. Map showing location and major tectonic trends on and around the north-west part of the Indo-Pakistan sub-continent (modified after Sarwar and Dejong 1979), (red box shows the study area).

a) Sandwiched block between Eurasia and Indian Plate, Kohistan Island Arc (KIA).

b) Metamorphosed rocks of Northern Deformed Fold and Thrust Belt (NDFTB).

c) Sedimentary and metasedimentary succession of Southern Deformed Fold and Thrust Belt (SDFTB).

d) The mountainous foothill, Punjab Foredeep.

2.5.1 Karakoram Block

All the strata of the Karakoram Block is of the Asian plate and is comprised of sedimentary, metasedimentary and igneous rocks. Kohistan Island Arc (KIA) is lying in the south of the Karakoram Block while Pamir lies in the north. In the Cretaceous time period the collision of these two blocks occurred (Treloar et al., 1989; Yoshida et al., 1997).

2.5.2 Main Karakorum Thrust (MKT)

Kohistan Island Arc and the Karakoram Block collided along the line which is now called Main Karakorum Thrust (MKT) in Northern Pakistan (Tahirkheli, 1979; 1982). The name “Northern Suture” also given to the MKT by (Pudsey et al., 1985). It was formed in late cretaceous according to Coward et al., 1986.

2.5.3 Kohistan Island Arc (K.I.A)

Neo-Tethys shrink with the movement of greater India toward the Eurasia around 130 Ma ago. Intra oceanic subduction is generated when the oceanic front of greater India collided with the Eurasian plate and a series of volcanic arcs generated during the Cretaceous time period i.e., Kohistan Island Arc, Ladakh, Nauristan and Kandhar. The Kohistan Island Arc is consist of the mafic to ultramafic sequence related to subduction type. Pre collision (102 ma) magmatism intruded in this arc (Trelar et al, 1989, and 1991) whereas, intra arc rifting and magmatism followed this event (Khan et al, 1993).

This arc magmatism event was continued almost about 40 Ma, after this Kohistan Island Arc collided with the southern margin of the Karakoram plate and back arc basin was closed (Khan et al, 1993).

2.5.4 Main Mantle Thrust (MMT)

Main Mantle Thrust is the boundary between Kohistan-Ladakh Island Arc in the North and Higher Himalayas in the South. It also demarcate the northern boundary of the Indian crustal plate.

Back to 65 Ma ago collision between the Indian plate and Kohistan Island was occurred. A complex assemblages of imbricated melange’s are found which are composed of the ophiolites, blueschists, greenschists, metavolcanics, and meta sediments. The eastern zone is comprised of the pre collision basinal sedimentary strata which is composed of shale's, turbidities, deep water radiolarian cherts and ophiolitic melanges (Kazmi et al., 1997 and Majid et al., 1991).

2.5.5 Main Central Thrust (MCT)

It is intra-continental thrust, developed within the Indian Plate which is north dipping and south-verging and is characterize by abrupt break in metamorphic facies. Pecher (1978) introduced the notation of "Main Central Thrust Zone" considering the fact that MCT is not only a thrust plane but reflects whole column of rocks with ductile deformation on the both sides of the fault within several kilometers. Crustal scale thrusting along this fault has produced inverted grade metamorphism passes upward from barovian type sequence to the chlorite biotitic zone.

According to the Lefort, (1975) the inverted metamorphism is produced as collision, but within the Indian crustal plate the crustal shortening and thickening occur. This inverted metamorphism may be the result of emplacing hot slab of the Higher Himalayas over the cool slab of the Lower Himalayan sediments (Windley, 1983).

2.5.6 Northern Deformed Fold and Thrust Belt (NDFTB)

A 300 km wide Northern Deformed Fold and Thrust Belt (NDFTB) lies in south of Main Mantle Thrust (MMT). This belt is comprised of intensely deformed sedimentary, metasedimentary and igneous rocks extending from Kashmir basin in the east upto the Kurram area in the west near Afghan border. The NDFTB is bounded to the south by Main Boundary Thrust (MBT) separating it from the SDFTB (Ahmad et al, 2004).

2.5.7 Main Boundary Thrust (MBT)

Lesser Himalaya is bounded on south by the thrust fault called Main Boundary Thrust (MBT). Main Boundary Thrust is the northern limit of the Sub Himalayas. On the eastern, northern and western side it cuts the Murree Formation with hair pin shape structure. The Panjal Fault run parallel to this fault in the vicinity of 1-5 km, along which Precambrian sequence has been thrusted over the Paleozoic and Mesozoic rocks (Wadia, 1931). In south of the Margalla hills, Murree Fault run in east-west direction and meet another fault namely Parachinar Fault. Therefore most of the recent worker named these two faults as Murree-Parachinar Fault. Some recent workers name the Murree Thrust on both limbs of the syntaxes as the Main Boundary Thrust (Treloar et al., 1989, 1991 and Greco, 1991).

2.5.8 Kohat Fold and Thrust Belt (KFTB)

The Kohat Fold and Thrust Belt (KFTB) is located on the southern part of the Himalayan and Karakorum orogenic belt and is a result of compressional tectonics after the Indo-Eurasian collision (Fig 2.3). It is about 85 km wide and extends for about 200 km. It is located in the west of Potwar Plateau and is comprised of Eocene and younger sedimentary rocks in a tectonically restricted basin. Evaporates (Bahadur Khel Salt and Jatta Gypsum) are present in the southern part of the plateau. These rocks are east-west trending, gentle to steeply dipping and deformed into doubly plunging and overturned folds of tens of kilometer long (Pivnik et al., 1993).

The tectonic rotational activities have occurred because of the unbalanced tectonic forces acting on western and eastern parts of the plateau (Paracha, 2004). Structures in the northern part are different from those of the southern part (Fig 2.4). There are tight overturned folds, syncline folds and several thrust faults in the northern region. In the north the evaporate sequence is reduced or missing. In the anticlinal cores Panoba shale is exposed. In the southern part east-west trending folds and north and south dipping reverse faults are present in the Kohat Plateau. Most of the faults are fault propagation folds (McDougall et al., 1991).

In the anticlinal cores Bahadur Khel Salt is exposed whereas Jatta Gypsum is imbricated and folded with slices of Panoba Shale. In this region, Lower Eocene rocks have been thrusted over the molasses at several places (Pivnik et al., 1993).

2.5.9 Potwar Fold and Thrust Belt (PFTB)

The PFTB is east-west oriented and is overlain by a thick sequence of fluvial molasse sediments. The PFTB is internally less deformed and approximately 150 km wide in north-south direction (Kazmi and Rana, 1982). Salt Range Thrust (SRT) forms the southern boundary while MBT marks the northern boundary along Margalla/Kala-Chitta ranges.

The PFTB is subdivided into Northern Potwar Deformed Zone (NPDZ) and South Potwar Platform Zone (SPPZ). Soan Syncline marks the boundary between

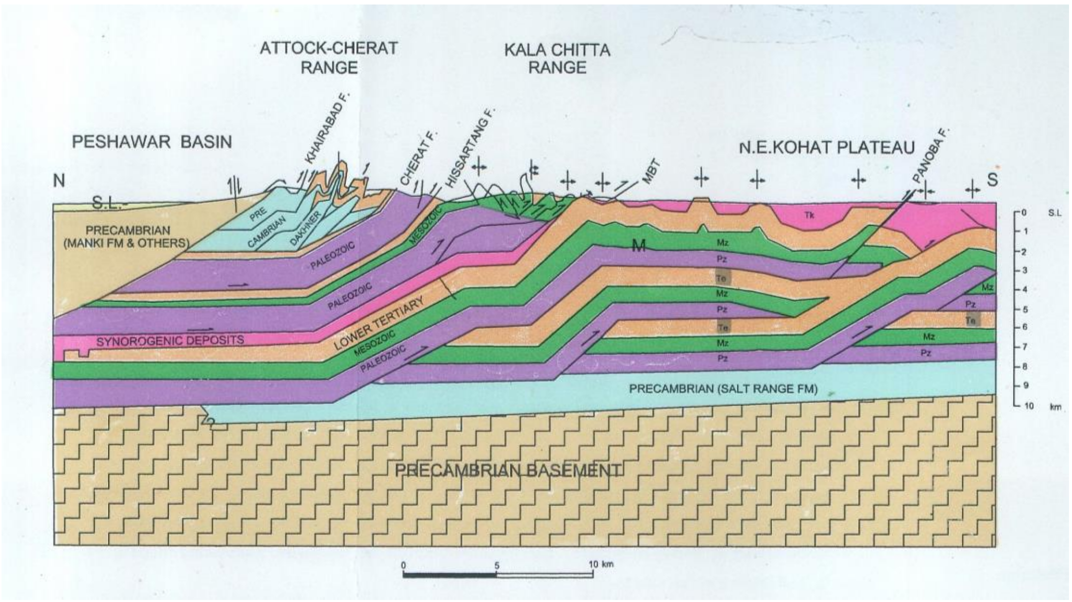


Fig 2.4. Cross section extending from Peshawar basin to north eastern Kohat Plateau (after McDougall et al., 1991).

these two zones. Most of the deformation is concentrated in the northern part of the fold-and-thrust belt, which is called the Northern Potwar Deformed Zone (NPDZ) (Leather, 1987; Baker et al., 1988).

On the basis of the structural style, the Potwar basin may be divided into central, western and eastern parts. The western and central parts are deformed by south verging thrusting. The structures in western and central part are generally east-west oriented. The deformation in the eastern part is in northeast to southwest direction and are mainly bounded by thrusts and back thrusts (Fig 2.5). The differences in direction may be due to lesser amount (or thickness) of salt in the Infra-cambrian. In the eastern part there is very low dip of the basement (1°–1.5°) as compared to central part with dip amount ranges from (2°–3°) (Moghal et al., 2007).

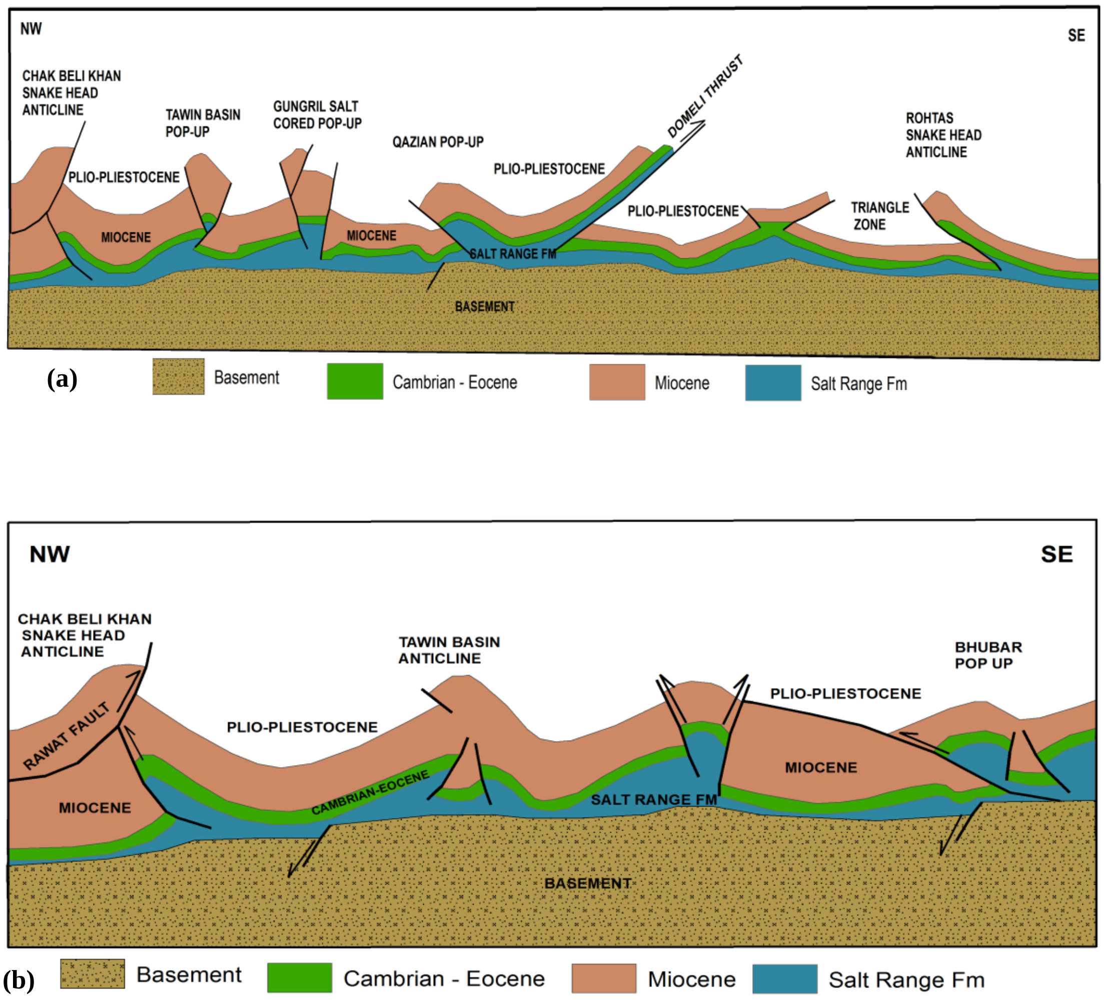


Fig 2.5. Balanced cross-section along central/ eastern Potwar sub-Basin (after Moghal et al., 2007). (a) Balanced cross-section through central/ eastern Potwar sub-Basin along Chak Beli Khan, Tanwin-Bains, Gungri-Qazian, Mahesian and Rothas structures (after Moghal et al., 2007). (b) Balanced cross-section through central/ eastern Potwar sub-Basin along Chak Beli Khan, Tanwin- Basins, Adhi and Bhubar structures (after Moghal et al., 2007).

CHAPTER 3

STRATIGRAPHY

3.1 Introduction

The Eastern Potwar basin is occupied mostly by the sedimentary rocks of continental origin and Quaternary deposits, which was deposited in subsiding basin on the southern flanks of rising Himalayas (Pennock et al, 1988) (Table 3.1). The rocks exposed in the study area are of sedimentary origin which range in age from Miocene to Recent whereas the exploration history for hydrocarbons and seismic data along the study area suggest that Salt Range Formation is oldest unexposed rock (Moghal et al., 2007) (Table 3.1).

The rock types present in the study area are comprises of sandstone, claystone, siltstone and conglomerate. The lithology of the Murree Formation is mainly sandstone, siltstone and claystone which suggests mix environment of brachish to fluviatile during early Miocene. The fluviatile condition begins towards early-middle Miocene as indicated by predominant sandstone of the Kamlial Formation. The Chinji, Nagri and Dhok Pathan formations consisting of sandstone and clays suggest flood plain deposits accumulating during late Miocene to middle Pliocene time. The conglomerates which is sub-ordinate to the interbeds of sandstone, siltstone, claystone and boulders of older deposits indicate fresh water conditions which prevailed during upper Pliocene time (Pennock et al, 1988).

Unconformities exist between the Dhok Pathan, Soan Formations and Terrace gravel deposits. The Quaternary deposit of sand, silt, clay and alluvium are mostly capping the bed rock. Stratigraphic column for study area is generated with help of surface measurement and well bore data for incorporating formations thicknesses in construction of cross-sections (Table 3.2).

3.2 Rawalpindi Group

Rawalpindi Group belongs to Miocene age and it is comprises of the Murree Formation and Kamlial Formation.

3.2.1 Murree Formation

It is exposed in the northern part of the study area. Thickness cannot be measured as lower contact is not exposed. The formation comprises sandstone alternating with siltstone and mudstone. Two types of sandstone have been recognized in this Formation. One is loose, friable dirty white to light gray and the other is hard, compact and dark gray. The mudstone is red to maroon and medium bedded. The sedimentary structure present in sandstone of Murree Formation is cross bedding (Fig 3.1).

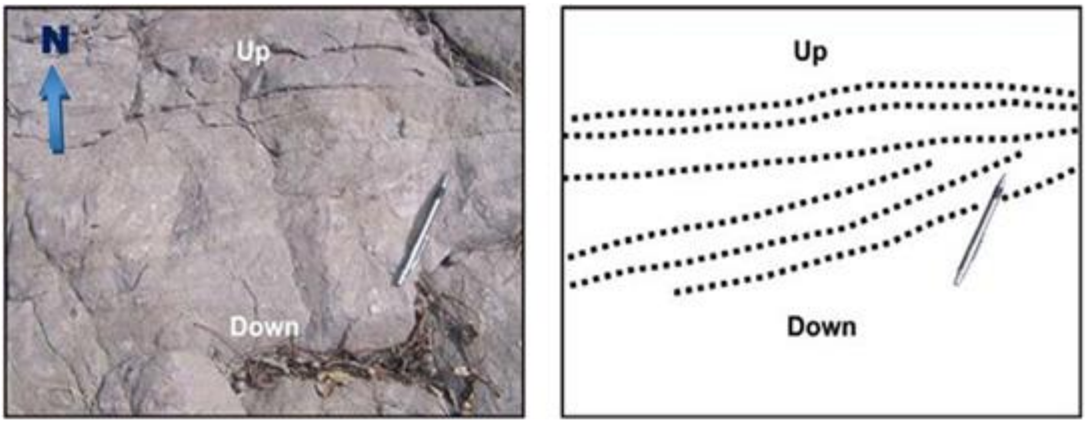


Fig 3.1. Cross beds in the Murree sandstone near Panjar area. Stratigraphic younging direction is indicated by word “Up” (Pencil for scale).

Texturally the sandstone is fine to medium grained, with angular to subangular grains. The essential minerals are quartz, feldspars and calcite. The accessory minerals include amphibole, mica, biotite, chlorite, epidote, tourmaline and iron ore. The lower contact is not exposed and the upper contact is gradational with the Kamlial Formation.

3.2.2 Kamlial Formation

It is exposed in the northern part (Khad Nar) in the mapped area. It is 400 meters thick and comprises of sandstone interbeded with siltstone. The sandstone is light gray, greenish gray, medium bedded and at many places it has a salt and pepper pattern of quartz grains mixed with mica flakes and ferromagnesian minerals. Because of its strength it outcrops at the surface as resistive ridges. Pseudoconglomerates are very frequently interbedded with the sandstone units. These are confined to the basal as well as the upper portions in the sandstone sequences. The clasts are sedimentary, mostly clay balls which range in size from small pebbles to cobbles (Fig 3.2). The clasts are weathered and limonitic and give the conglomeratic beds pale, yellowish brown colour.

The siltstone is reddish to brown and thin to medium bedded. Gypsum stringers are presesnt in the claystone beds. Texturally the sandstone is fine to medium grained and is poorly sorted with angular to sub-angular grains. The essential minerals are quartz, feldspars and calcite.

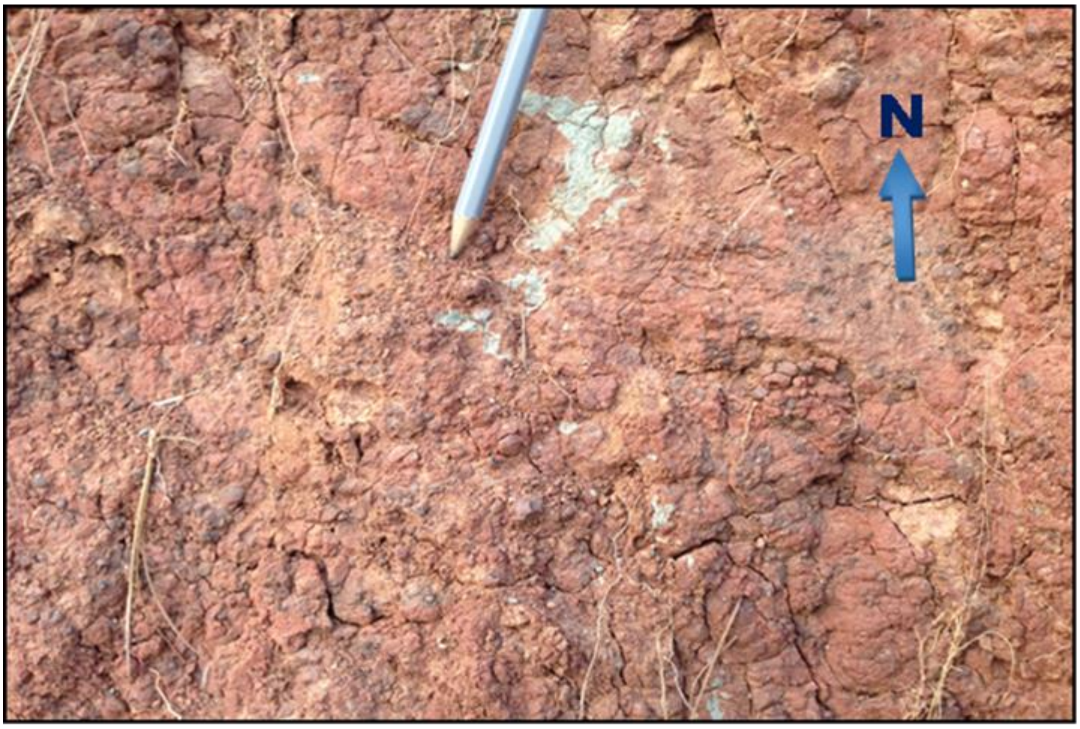


Fig 3.2. Clay balls in the Kamlial Formation near Kahuta area (Pencil for scale).

The calcite percentage includes carbonates as cementing material. The accessory minerals include muscovite, biotite, chlorite, epidote, tourmaline and iron-ore. It is distinguishable from the Chinji Formation usuallly on the basis of presence of spheroidal weathering and wood fossils or leaf imprints (Fig 3.3). It has gradational contact with the Murree Formation and the Chinji Formation.

3.3 Siwalik Group

The Miocene-Pliocene sequence in the Potwar Plateau consists of Siwalik Group rocks (Fatmi, 1973, Meissner et al., 1974). The Siwalik Group is comprised of the following formations:

Fig 3.3. Wood fossil in the sandstone of the Kamlial Formation near Panjar area (Pencil for scale).

- Soan Formation
- Dhok Pathan Formation
- Nagri Formation
- Chinji Formation

The Siwalik Group has thickness of several thousand meters and shows a coarsening upward molasse sequence in the Indo-Pakistan sub-continent (Meissner et al., 1974). All formations of the Siwalik group are present in the study area.

3.3.1 Chinji Formation

It is exposed in the central part of the study area. It is more than 600 meters thick and comprises of variegated clays with subordinate sandstone. The Formation is covered with alluvium at various places. Two distinctive types of sandstone have been noticed in the observed sequence i.e. blue gray sandstone and buff sandstone. The blue gray sandstone is well sorted, clean and is consists of quartz, feldspar, garnet, muscovite, biotite and schists clasts. The sandstones extend as sheets which laterally merge into claystone over long distances. The conglomeratic layers are present in this type of sandstone. The buff sandstone is typically buff to gray brown, more mature in composition with quartz, feldspar and calcite. The conglomerates of carbonate nodules and weathered rock fragments are common in buff sandstone. These conglomerates occurs as sheets and lenses that thickens or thins out abruptly.

The sandstone is softer, easily erodible and also shows patchy weathering at certain places. The sandstone units grade upward into the much thicker claystone beds. The claystone beds are poorly sorted and have light gray, brown and orange red color. The sandstones of the Chinji Formation are generally moderately sorted with sub-angular to sub-rounded grains. The sedimentary structures like ripups, load cast and cross bedding are also present in this Formation.

The essential minerals of sandstone are quartz and feldspar whereas the accessory minerals are biotite, chlorite, garnet and tourmaline. The clays are reddish, maroonish, purplish and brick red (Fig 3.4). These clays are soft and easily erodible. The lower contact with the Kamlial Formation is gradational but upper contact with the Nagri Formation is sharp.

Fig 3.4. Beds of the Chinji Formation dominantly composed of red, purple clays and buff gray sandstone.

3.3.2 Nagri Formation

It is exposed in the southern part of the study area and mostly occupies the limbs of Batala syncline. It is 450 meters thick and comprises of sandstone and clays.

The sandstone of the Nagri Formation is of two types i.e. blue grey sandstone and buff sandstone. The blue gray sandstone consisting of quartz, feldspar, garnet, muscovite, biotite and calcite. The buff sandstone is yellowish brown, fine to medium grained, at places silty. It is cross bedded and contains conglomerates of carbonate nodules (Fig 3.5). The intraformational pseudoconglomerates composed of mud pellets, pebbles of volcanic rocks, and balls of sandstone and clay in the sandy matrix are common in the lower and upper part of the formation. These conglomerates occur as thin beds, lenses or stringes. The clays are reddish, orange and olive gray at places and weathers into sub-rounded to angular irregular blocks.

Fig 3.5. Sandstone of the Nagri Formation near Mawara area (Camera pouch for scale).

The sandstones of Nagri Formation are moderately sorted having sub-angular to sub-rounded grains. The sandstone is fine to medium grained and is characterized by salt and pepper texture. The essential minerals are quartz, feldspar and carbonate whereas the accessory minerals are biotite, muscovite, chlorite, epidote, garnet and iron ore. The lower contact with the Chinji Formation is sharp while the upper contact with the Dhok Pathan is gradational.

3.3.3 Dhok Pathan Formation

It is exposed at the limbs of Batala syncline and Kalar anticline. It is 300 meters thick and comprises cyclic alteration of sandstone, siltstone and claystone. The sandstone is greenish gray to gray, thin bedded to medium; fine to medium grained with igneous and volcanic pebbles scattered in the upper part of the formation. The upper part of the sandstone is soft and friable having hard and compact conglomeratic levels. Claystone is orange red, thin bedded to medium bedded. The Dhok Pathan Formation has ribbed topography and flaser bedding (Fig 3.6). The lower contact with the Nagri Formation is gradational while the upper contact with the Soan Formation is disconformable.

Fig 3.6. Sandstone of the Dhok Pathan Formation having flaser bedding near Thoa Khalsa area.

3.3.4 Soan Formation

It is exposed in the core of Batala Syncline and southeastern limb of Kalar Anticline. It comprises of alternating sandstone, conglomerate and subordinate claystone. The sandstone is gray to greenish gray while the claystone is orange red. The conglomerate consists of pebbles and cobbles of gneiss, quartzite and diabase. The bentonite clay is present at the basal part of the Formation (Fig 3.7). The lower contact with the Dhok Pathan Formation and upper contact with terrace gravel deposits are unconformable.

3.4 Quatenary Deposits

Quatenary deposits includes terrace gravel, sand, silt, clay and alluvium in the study area.

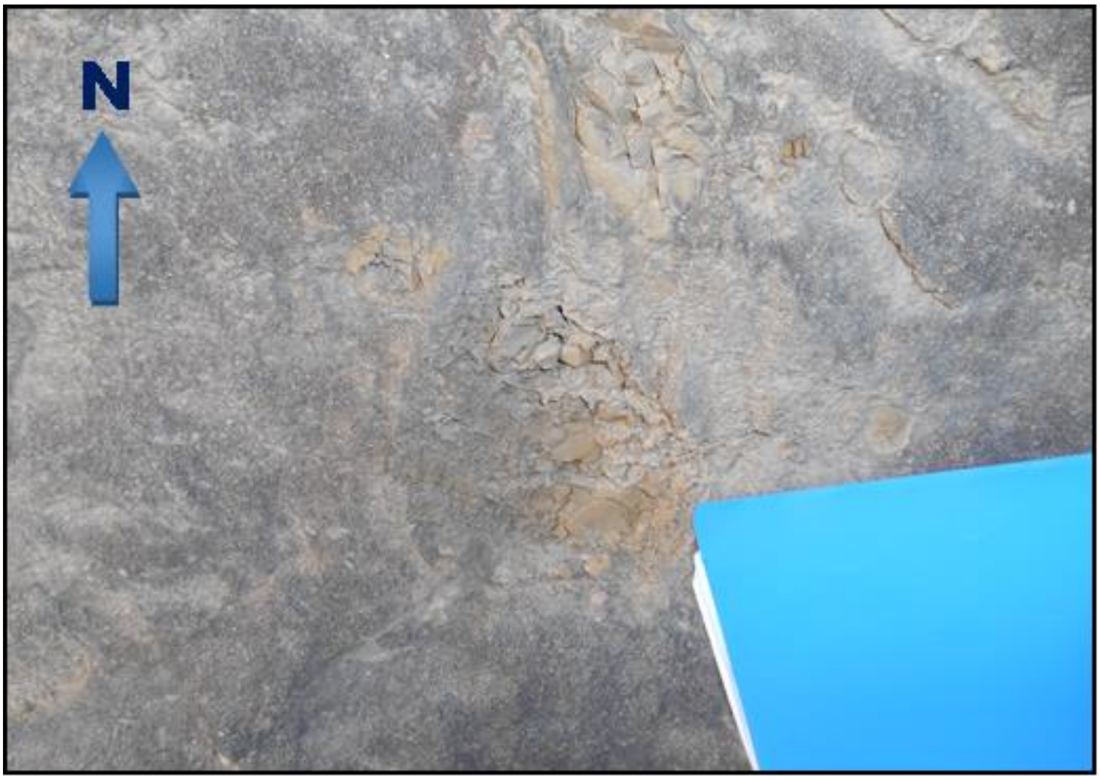


Fig 3.7. Sandstone of the Soan Formation having bentonite clay near Batala area (File for scale).

3.4.1 Terrace Gravel

It is exposed in the southeastern part of the study area and comprises of semi consolidated pebbles and boulders of limestone, quartzite, gneiss, schist and diabase (Fig 3.8).

3.4.2 Sand, Silt and Clay

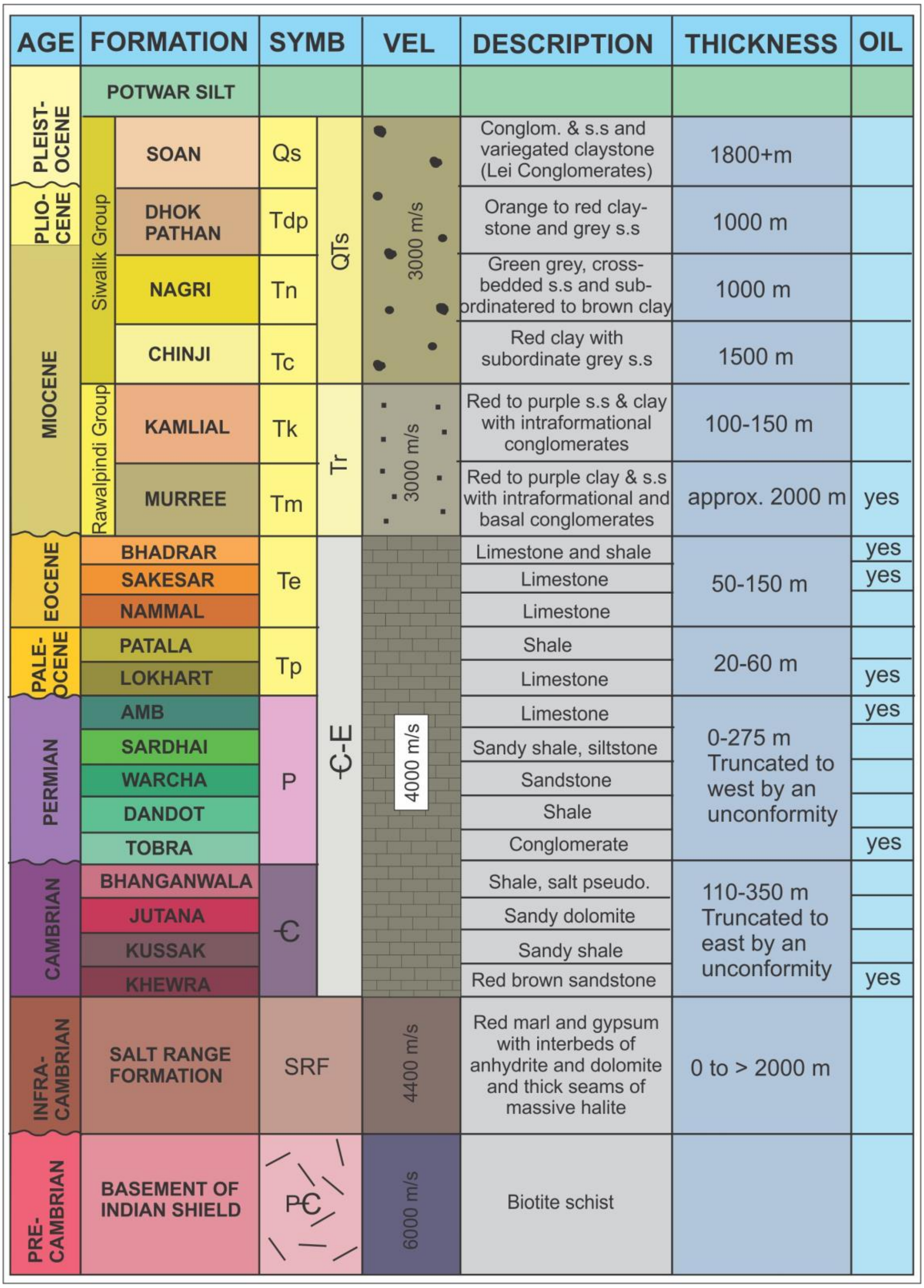
These include unconsolidated alluvial and fan deposits, composed of poorly sorted gravel with matrix of sand, silt and clay with coarse sandy matrix.

Fig 3.8. Terrace gravel deposits exposed near Mori area.

3.4.3 Alluvium

The alluvium deposits comprises of coarse gravel to boulders and are mostly accumulated along streams beds.

Table 3.1. Generalized stratigraphy of Eastern Potwar Basin (after Peanock et al., 1988).



AGE	FORMATION		SYMB		VEL	DESCRIPTION	THICKNESS	OIL
PLEISTOCENE	POTWAR SILT							
		SOAN	Qs	QTs	3000 m/s	Conglom. & s.s and variegated claystone (Lei Conglomerates)	1800+m	
PLIOCENE	Siwalik Group	DHOK PATHAN	Tdp			Orange to red claystone and grey s.s	1000 m	
MIOCENE		NAGRI	Tn			Green grey, cross-bedded s.s and subordinatered to brown clay	1000 m	
		CHINJI	Tc			Red clay with subordinate grey s.s	1500 m	
	Rawalpindi Group	KAMLIAL	Tk	Tr	3000 m/s	Red to purple s.s & clay with intraformational conglomerates	100-150 m	
		MURREE	Tm			Red to purple clay & s.s with intraformational and basal conglomerates	approx. 2000 m	yes
EOCENE	BHADRAR		Te	Ꞓ-E	4000 m/s	Limestone and shale	50-150 m	yes
	SAKESAR					Limestone		yes
	NAMMAL					Limestone		
PALEOCENE	PATALA		Tp			Shale	20-60 m	
	LOKHART					Limestone		yes
PERMIAN	AMB		P			Limestone	0-275 m Truncated to west by an unconformity	yes
	SARDHAI					Sandy shale, siltstone		
	WARCHA					Sandstone		
	DANDOT					Shale		
	TOBRA					Conglomerate		yes
CAMBRIAN	BHANGANWALA		Ꞓ			Shale, salt pseudo.	110-350 m Truncated to east by an unconformity	
	JUTANA					Sandy dolomite		
	KUSSAK					Sandy shale		
	KHEWRA					Red brown sandstone		yes
INFRA-CAMBRIAN	SALT RANGE FORMATION		SRF		4400 m/s	Red marl and gypsum with interbeds of anhydrite and dolomite and thick seams of massive halite	0 to > 2000 m	
PRE-CAMBRIAN	BASEMENT OF INDIAN SHIELD		PꞒ		6000 m/s	Biotite schist		

Table 3.2. Stratigraphic column proposed for study area based on surface measurements and well bore data; column is also used in construction of cross-sections (Figs 4.9 and 4.10).

AGE			FORMATION	LITHOLOGY	THICKNESS (m)
Era	**Period**	**Epoch**			
CENOZOIC	TERTIARY	PLIOCENE	SOAN FORMATION	Conglomerate, sandstone and claystone	1800
			DHOKPATHAN FORMATION	Claystone and sandstone	1000
		MIOCENE	NAGRI FORMATION	Sandstone , conglomerate and clay	1300
			CHINJI FORMATION	Variegated clays and sandstone	1800
			KAMLIAL FORMATION	Sandstone and clay	400
			MURREE FORMATION	Sandstone, siltstone, mudstone and clay	2000
CAMBRIAN-EOCENE			CAMBRIAN-EOCENE UNDIFFERENTIATED	Limestone, shale, sandy dolomite and red brown sandstone	1500
PRE-CAMBRIAN			SALT RANGE FORMATION	Marl, gypsum ,anhydrite and thick seems of halite	<600
			BASEMENT OF INDIAN SHIELD	-	-

CHAPTER 4

STRUCTURAL GEOLOGY

The study area is folded and faulted and is predominantly controlled by thrust tectonics. Imbricated thrust faults and back thrust present in the subsurface are bisecting and uplifting the structures at surface. The broad asymmetrical synclines and tight anticlines are present at surface. The structures developed in the study area are result of collision between Indian and Eurasian plates. A revised geological map of the study area was prepared at 1:50,000 in Arc GIS 10.1 using previous published geological maps, field observations and satellite imageries (Fig 4.1). A balanced structural cross-section of study area was prepared using seismic data, well data and surface geologic data. The general strike direction of structures in the study area is northeast-southwest.

This chapter describe fold and fault structures of the study area in detail together with structural analysis using 2D and 3D modelling to delineate the structural geometries of the study area.

4.1 Faults

The major faults exposed in the study area are Rawat Fault and Kahuta Fault (Fig 4.1) .These faults are of thrust nature and have been briefly explained below.

4.1.1 Rawat Fault (RF)

The Rawat Fault extends from Mohri village to Dadochha village in the study area (Fig 4.1). It occurs between the Murree, Kamlial, Chinji, Nagri and Dhok Pathan formations. In the northeastern side of the study area, the Murree Formation is thrusted over the Chinji Formation while in southwestern part the Chinji Formation is in the hanging wall and Nagri and Dhok Pathan formations lies in the footwall block of the Rawat Fault. The Kamlial Formation is thrusted over the Chinji Formation at the eastern flank of the Alliot Syncline.

The general strike of Rawat Fault is northeast-southwest with dip amount ranges from 30^o -60^o towards northwest. In the northeastern part of the Rawat Fault the dip amount ranges from 50^o - 60^o while in the southwestern side the amount of dip

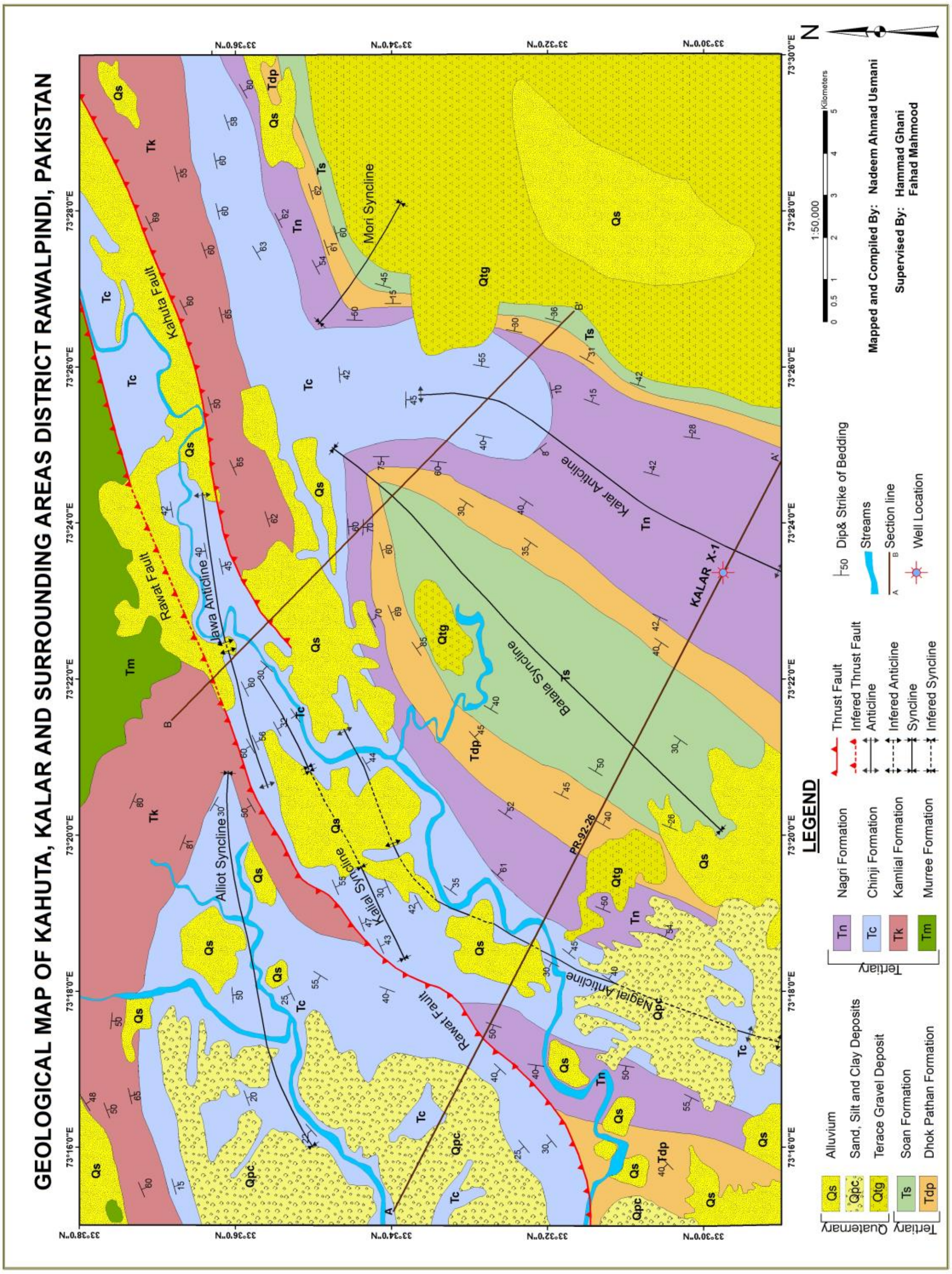


Fig 4.1. Geological map of the study area.

changes from 30° - 40°. The Rawat Fault is identified in the field on the basis of stratigraphy, slickensides, shearing and crushing.

The drag folds are seen in the Chinji Formation in the footwall block of the Rawat Fault (Fig 4.2). On the basis of observed features, the Rawat Fault is marked as thrust and reverse fault.

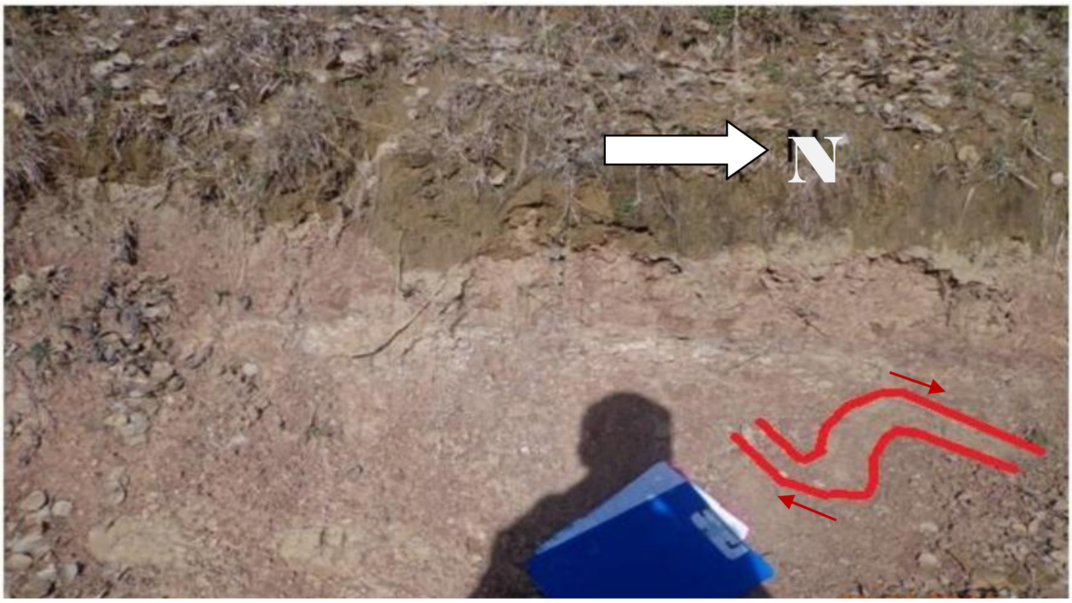


Fig 4.2. Shearing and crushing along Rawat Fault near Mohri village. S- type drag fold is seen in the middle right corner of the photograph (File for scale).

4.1.2 Kahuta Fault (KF)

The Kahuta Fault is northeast-southwest trending reverse fault. It is the splay of the Jhelum Fault. The Kamlial Formation is thrusted over the Chinji Formation along this fault. The Jawa Antiform is developed along the footwall block of Kahuta Fault. The dip amount ranges from 50°- 60° towards southeast. The shearing and crushing zone of 05 meter is present along the fault zone (Fig 4.3).

Fig 4.3. Shearing and crushing zone along Kahuta Fault near Bata village in sandstone of the Chinji Formation.

The fault breccia and gouge can be identified in the study area along the Kahuta Fault. The drag folds are common along this fault in the study area. The Kahuta Fault is transecting the southeastern limb of the Jawa Antiform in the study area.

4.2 Folds

The folds in the study area are open to tight. The folded structures controlled the geomorphic features of study area. The broad syncline has developed valleys while the tight anticlines are making ridges in the area. At the surface the limbs of folds are cut by the thrust faults while in subsurface the limbs are cut by blind thrusts. The major folds of the study area are discussed as under:

4.2.1 Anticlines

4.2.1.1 Kalar Anticline

The Kalar Anticline is exposed at the Kalar Syedan village and nearby localities in the study area. The shape of this anticlinal structure can be seen through satellite imagery (Fig 4.4). The Kalar Anticline is running in northeast to southwest direction in the study area. The anticlinal structure is formed by the folding of Chinji, Nagri, Dhok Pathan and Soan formations. On the northeastern side, the Chinji Formation is present in the core while Nagri and Dhok Pathan formations lies at the limbs. The southwestern flank of the anticline comprises of the Nagri Formation in the core whereas the limbs consists of Dhok Pathan and Soan formations. The attitude of southeastern limb is N40^{o}E - N55^{o}E and 28^{o}SE - 55^{o}SE whereas the attitude of northwestern limb is N30^{o}E - N45^{o}E and 40^{o}NW - 42^{o}NW. The southeastern limb is steeper than northwestern limb. The plunge of the anticline is in northeast direction in the study area.

4.2.1.2 Nagial Anticline

The Nagial Anticline is exposed in the footwall block of Rawat Fault. The Chinji Formation is present in the core while the Nagri Formation is present at the limb (Fig 4.1). The northwestern flank of the Nagial Anticline is transected by Rawat Fault. The attitude of southeastern limb is N42^{o}E – N54^{o}E and 40^{o}SE - 45^{o}SE whereas the attitude of northwestern limb is N35^{o}E - N44^{o}E and 30^{o}NW - 42^{o}NW.

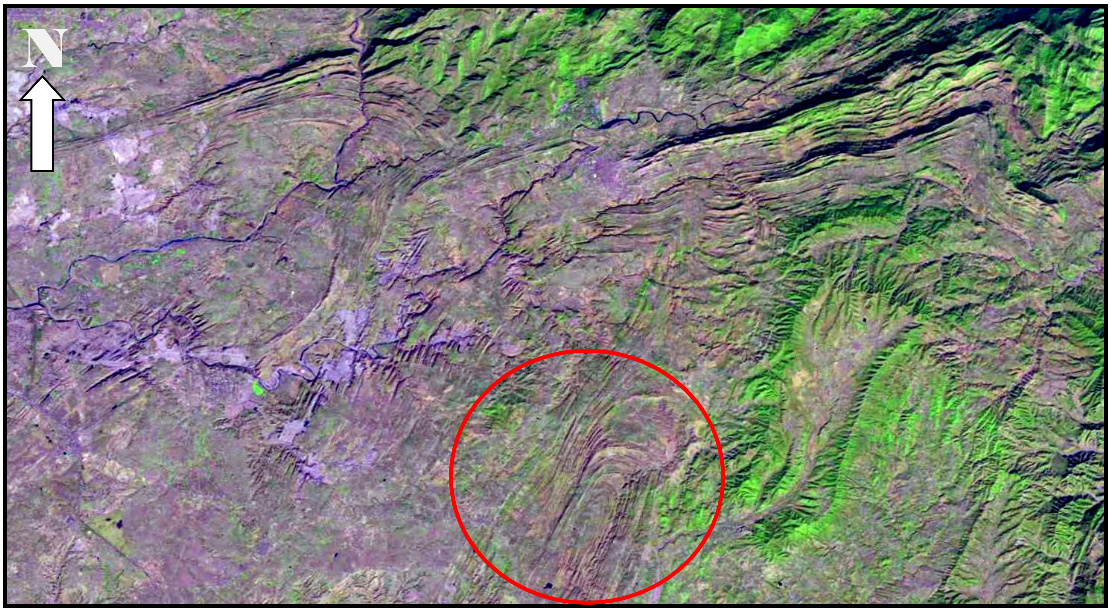


Fig 4.4. View of Kalar Anticline in Landsat 8 OLI image. Red circle marking the anticlinal structure.

4.2.1.3 Jawa Antiform

The Jawa Antiform is exposed at the Jawa village and nearby localities in the study area. This is intraformational fold formed by folding of the Chinji Formation (Fig 4.5). The southeastern limb is transected by the Kahuta Fault and northwestern limb is cut by the Rawat Fault. The attitude of southeastern limb is N40°E - N58°E and 45°SE - 56°SE whereas the attitude of northwestern limb is N38°E - N42°E and 40°NW - 60°NW.

4.2.2 Synclines

4.2.2.1 Batala Syncline

The Batala Syncline is a major synclinal structure present in the study area. It is exposed at Batala village and Channi village. The Batala Syncline is trending northeast-southwest while it is plunging towards the northeastern side of the study area. The Soan Formation is located at the core while Nagri and Dhok Pathan formations are exposed at the limbs of the syncline. The attitude of northwestern limb is N50°E - N46°E and 40°SE - 60°SE whereas the attitude of southeastern limb is N40°E – N34°E and 30°NW - 65°NW. The southeastern limb is relatively steeper than the northwestern limb.

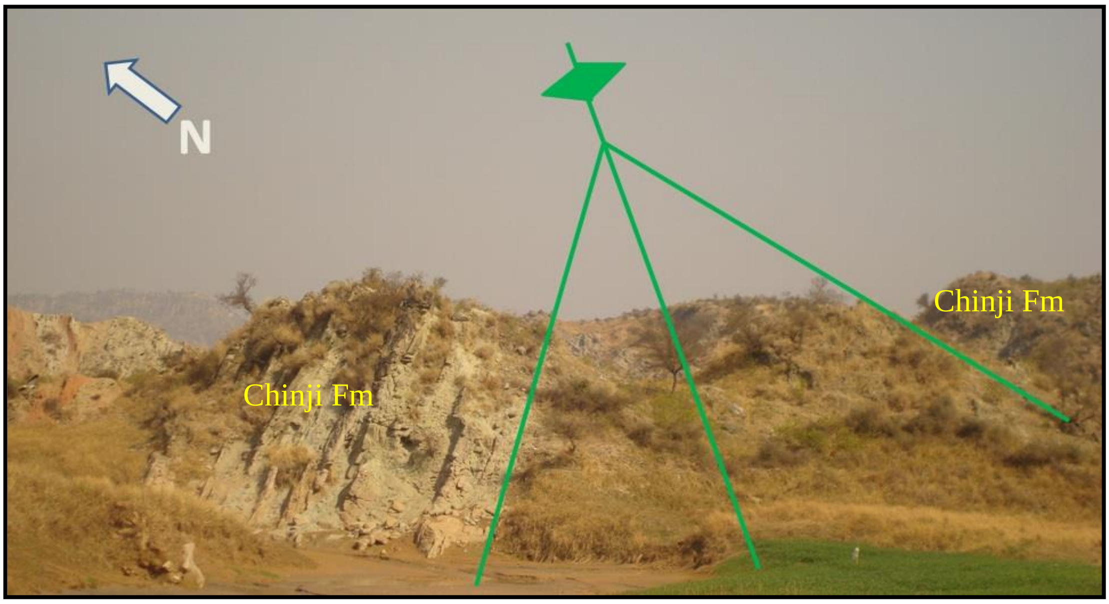


Fig 4.5. Photograph illustrating the Chinji Formation exposed in the core of the Jawa Antiform near Jawa village.

4.2.2.2 Alliot Syncline

The Alliot Syncline is exposed along the northwestern side of the study area and extending from Alliot village to surroundings of the Pathrian village. The Alliot syncline is trending in ENE to WSW. It is formed by folding of the Chinji Formation and Kamlial Formation. The Chinji Formation is present in the core while Kamlial Formation lies at the limbs. The southeastern limb of syncline is terminated against the Rawat Fault (Fig 4.1). The attitude of northwestern limb is N28^{o}E – N35^{o}E and 50^{o}SE - 81^{o}SE whereas the attitude of southeastern limb is N30^{o}E – N37^{o}E and 25^{o}NW - 50^{o}NW. The northwestern limb is relatively steeper than the southeastern limb. It is plunging in northeast of the study area.

4.2.2.2 Mori Syncline

The Mori syncline is third major syncline extending from Mori village to Toa Khalsa in the study area. It is northwest to southeast trending structure and its fold axis is plunging towards northwest. The Soan Formation and Quaternary terrace gravel deposits are exposed in the core, while Dhok Pathan, Nagri and Chinji formations are present at limbs (Fig 4.1). The Quaternary terrace gravel deposit covers most of the area of syncline. The dips on the northeastern flank of the syncline are steeper as compared to the southwestern flank.

4.2.2.4 Kalial Synform

The Kalial Synform lies in the footwall of the Rawat Fault having Chinji Formation in the core as well as at the limbs (Fig.4.1). The strike of axial plane is northeast-southwest. Its northwestern limb is cut by the Rawat Fault whereas its southeastern limb is terminated against the Nagial anticline. The attitude of northwestern limb is N42^{o}E - N48^{o}E and 47^{o} SE - 60^{o}SE, whereas, the attitude of southeastern limb is N30^{o}E – N45^{o}E and 30^{o}NW - 32^{o}NW. The northwestern limb is relatively steeper than the southeastern limb due to transecting of the Rawat Fault.

4.3 Cross Sections

Two cross sections are constructed along the lines AA$^{/}$ and BB$^{/}$ to understand the surface and subsurface structural geometries and transition of structural style along trend. The cross sections are constructed upto the depth of 9 km by the integration of seismic, well (Kalar X-1) and structural data. Tectonically, the study area is complex and the quality of seismic section is poor for interpretation. Section line AA$^{/}$ is constructed along seismic line PR-92-26 while section BB$^{/}$ is constructed across the surface structural trend. The seismic line PR-92-26 is only used to interpret structures in subsurface and to mark the depth of basement. The prominent reflector was marked as basement in PR-92-26. The time for basement reflector was picked at 4.1s in PR-92-26 with reference to shot point location at surface. The character of this prominent basement reflector was traced throughout the section and time was picked accordingly. The time section for basement reflector is prepared and later on converted into depth section. The depth values under the corresponding shot point’s location at surface were incorporated into structural cross section AA$^{/}$.

The structural interpretation in the seismic section was extrapolated from interpreted seismic section PW-15 of (Pennock et al., 1988), which marked as base for interpretation of structures in the study area (Fig 4.6). The faults in the subsurface were marked on the seismic section by picking offsets in reflectors while faults exposed at the surface were marked on the seismic section in relation with shot points at surface (Fig 4.7). Section AA$^{/}$ and BB$^{/}$ are restored up to the basement and the amount of shortening is calculated for the overlying sequence.

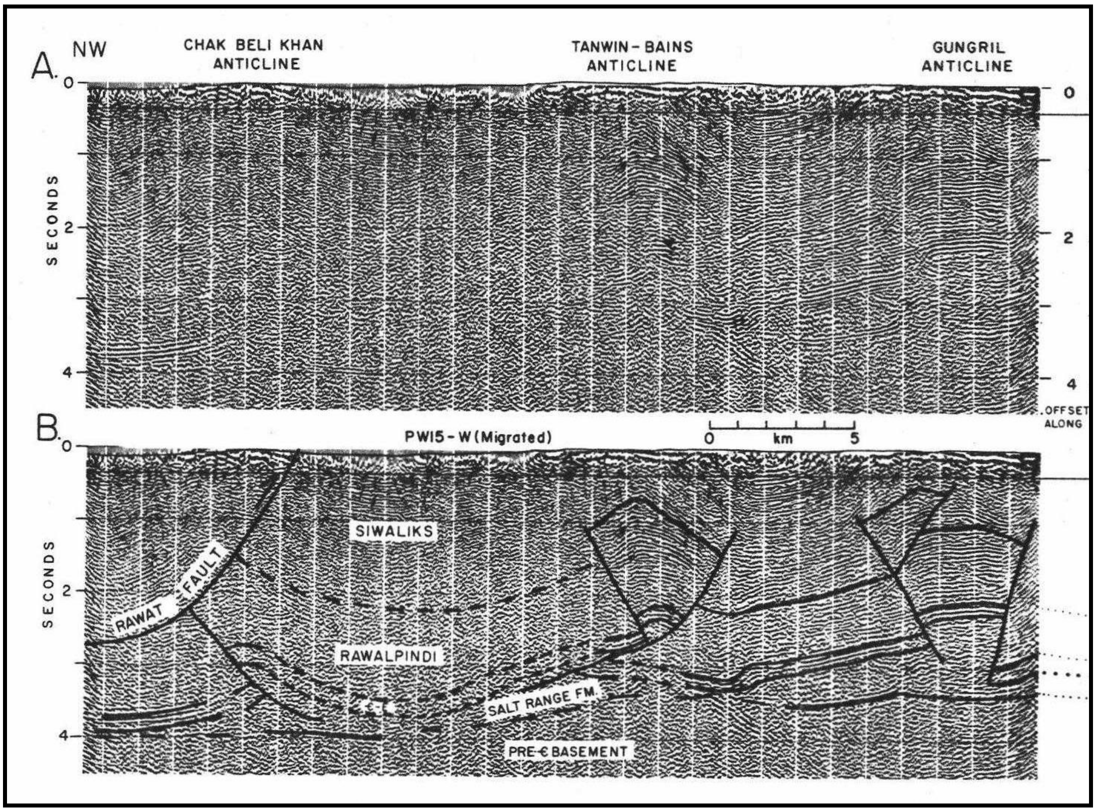


Fig 4.6. (A) Uninterpreted seismic line PW15 across the portion of Eastern Salt range/Potwar Plateau. (B) Interpreted seismic line PW15 across the portion of Eastern Salt range/Potwar Plateau used for balanced cross-section (Pennock et al., 1988).

4.3.1 Methodology of Time to Depth Conversion

The time to depth conversion of basement reflector was used for its interpolation into the geo-seismic cross-sections. The methodology used for this conversion include picking of time of different reflectors from seismic section. Against those time the velocities at different shot points from velocity windows was picked and plotted in MS excel sheets. The depth of the reflector was calculated by the given formula:

$$\text{Depth} = \text{Time} * \text{Velocity}/2$$

The reflector at the shotpoint 620 against time 4.1 second or 4100 millisecond was considered as basement reflector and the calculated depth of basement was 9020 meter. This depth of basement was later used in the construction of balanced structural cross section.

4.3.2 Section AA$^{/}$

It is 17 km long and oriented WNW-ESE in the southwestern part of the study

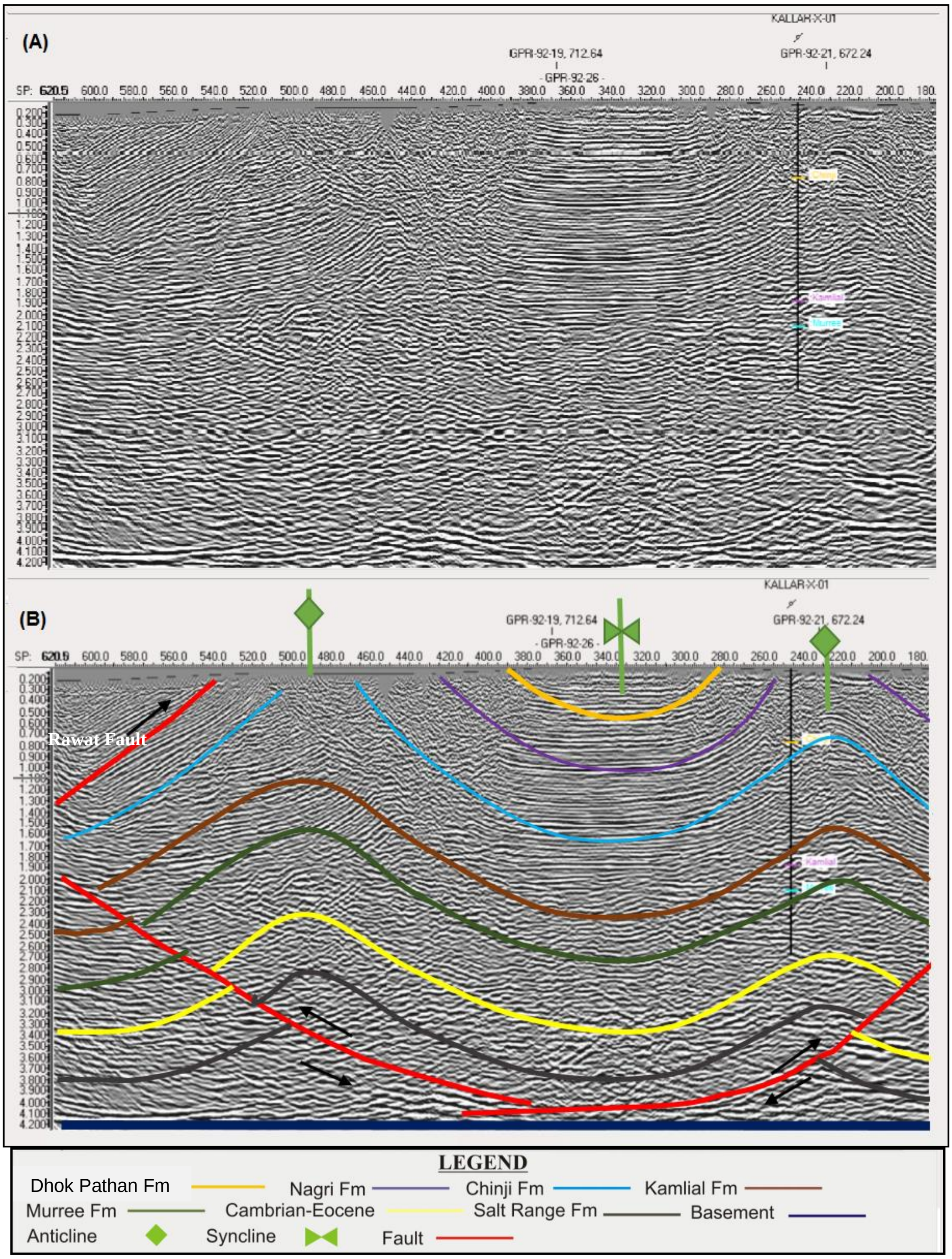


Fig 4.7. Seismic section PR-92-26 across the study area. (A) Uninterpreted seismic section PR-92-26. (B) Interpreted seismic section PR-92-26.

area (Figs 4.1 and 4.8). The cross-section is prepared along seismic line PR-92-26 and well Kalar X-1 lies on it. The interpreted seismic section used as base for constructing cross section. The selected section line cuts across the major structure present in the study area. The Kalar Anticline is present in the ESE of this section with Nagri

Formation in the core and Dhok Pathan Formation at the limbs. The Kalar X-1 well is drilled in the northwestern limb of Kalar Anticline which shows the anomalous thickness of Murree Formation. The Batala Syncline is an open synclinal fold in west of the Kalar Anticline exposing Soan Formation in the core and Nagri and Dhok Pathan formations at the limbs. A tightly folded Nagial Anticline is exposed in west of the Batala Syncline.

The subsurface structural style illustrates the Rawat Fault originating from basal detachment. The Rawat Fault is a high angle thrust fault cutting the limb of Nagial Anticline which is present in the footwall block of Rawat Fault. During progressive deformation, the back thrust and blind thrusts present in subsurface had uplifted and folded the structures above them.

4.3.3 Section BB$^{/}$

The section BB$^{/}$ is 12.5 km long and is located northeast of section AA$^{/}$. The cross-section is constructed across the surface attitude data and is oriented NW- SE which helps to understand the structural variations in the study area (Figs 4.1 and 4.9). The major structures that lie along this section line includes the Rawat Fault, Jawa Antiform, Kahuta Fault, Batala Syncline and Kalar Anticline. The Kalar Anticline is located to the southeast of the section having the Chinji Formation in the core whereas Nagri, Dhok Pathan and Soan formations at the limbs. The Batala Syncline is exposed in west of the Kalar Anticline having the Soan Formation in core and Chinji, Nagri and Dhok Pathan formations at the limbs. The Jawa Antiform exists in the footwall of the Kahuta Fault. Both limbs of the Jawa Antiform are transected by thrust faults. The Rawat Fault cuts the northwestern limb of the Jawa Antiform while the southeastern limb is cut by the Kahuta Fault.

The Rawat Fault is dipping steep in this section at surface. The Kahuta Fault is high angle back thrust fault in this section which originates from a blind thrust in the subsurface. It cuts the upsection of both the Kalar Anticline and Batala Syncline towards north in the subsurface.

4.3.4 Cross Section Restoration

The cross-sections along the line A-A´ and B-B´ are restored to their undeformed state up to basement in order to calculate the amount of shortening accommodated by the rocks in the study area. The undeformed average line length (L) for both cross-sections was determined by using the relation:

$$L=A/T$$

Total deformed area for Murree and Kamlial formations was measured (A) from restored cross section. The regional undeformed thickness (T) for these formations was then assessed from regional studies (Pennock et al, 1988, Jaswal et al., 1997). The actual length of the cross-section A-A´ is 17 km and after restoration along the folds and faults it increases upto approximately 23.5 km. The amount of shortening along section A-A´ reveals approximately 6.5 km and percentage of shortening is 27.6% (Fig 4.8). The cross-section B-B´ is 12.5 km in length whereas its restored length changes to approximately 18 km. The amount and percentage of shortening along B-B´ is approximately 5.5 km and 30.5% respectively (Fig 4.9). The average shortening percentage accommodated by the deformational structures in the study area along the sections A-A´ and B-B´ is 29%.

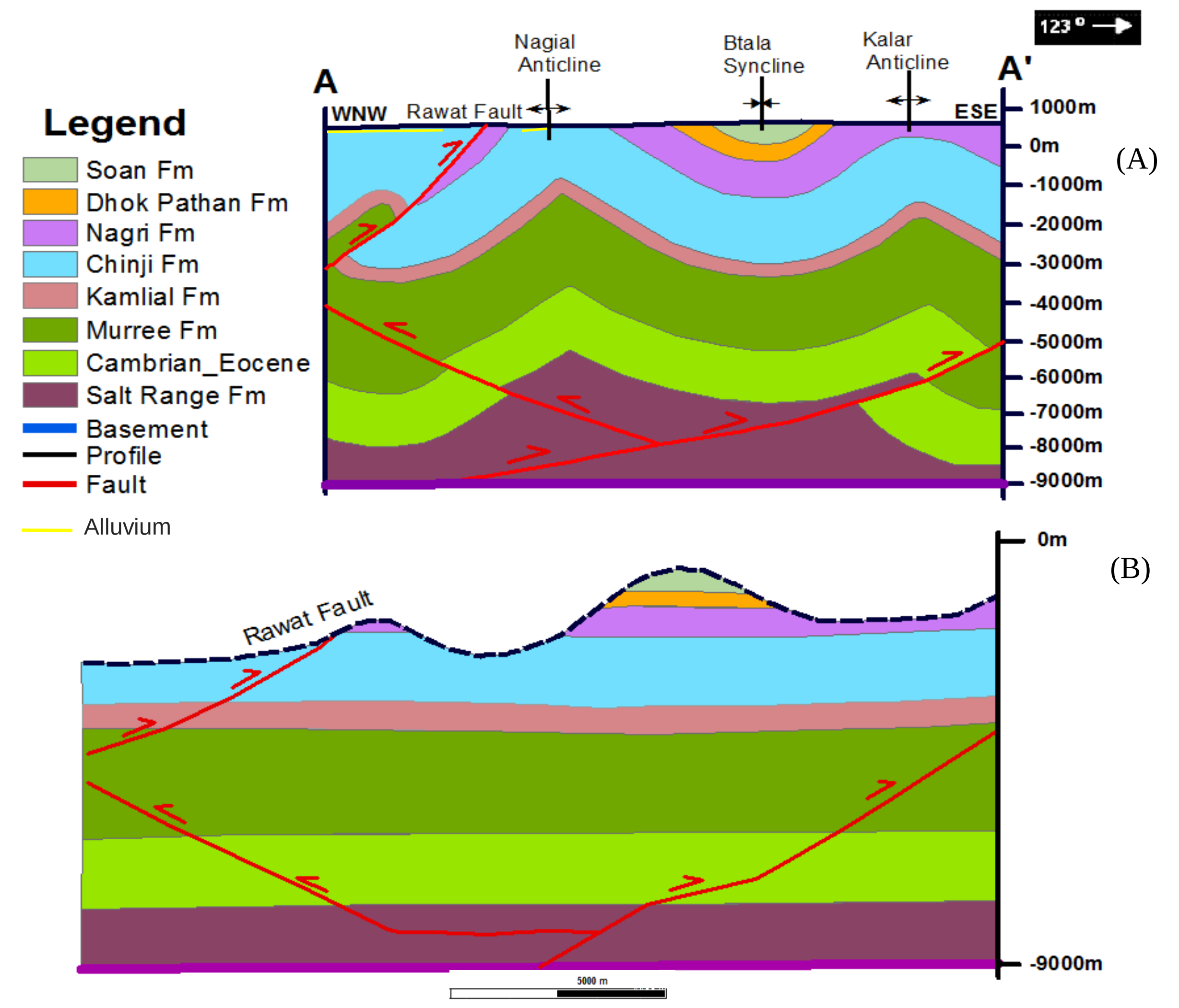


Fig 4.8. (A) Balanced cross-section along line $AA^{/}$. (B) Restored section $AA^{/}$ showing approximately 6.5 km of shortening.

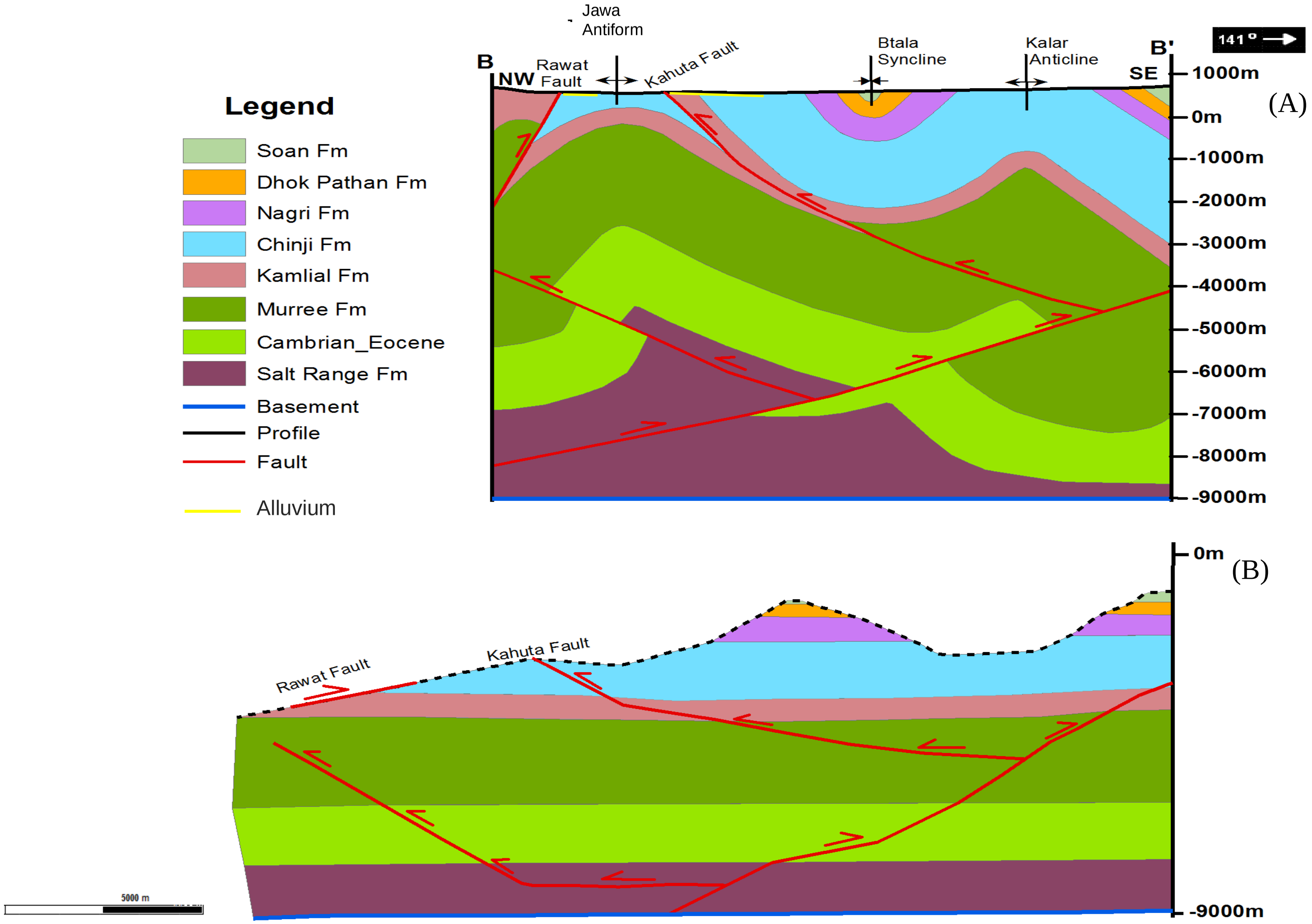


Fig 4.9. (A) Balanced cross-section along line BB/. (B) Restored section BB/ showing approximately 5.5 km of shortening.

4.4 3D Structural Model of the study area

The subsurface structural geometry of the study area is demonstrated by the projected three dimensional (3D) structural model by using software Move 14.0 (Fig 4.10). The structural model of the study area is discussed in relation with kinematics of fold and thrust present in the area. It is constructed along the lines A-A´ and B-B´ by the integration of field data, geological map and structural cross-sections. The 3D model explains the extension of the regional structures in the subsurface upto the depth of 09 km, in correlation with surface data. The model depicts the deformation style, variation and the termination of structures across the lines A-A´ and B-B´ (Fig 4.11). The 3D model is prepared by generating 3D surfaces of main faults and folds present in study area.

4.4.1 3D Fault Modeling

A 3D fault model is generated by connecting fault planes, which were constructed in the cross-sections A-A´ and B-B´ (Figs 4.11 and 4.12). The Rawat Fault in both cross sections depicts a regional thrust (Fig 4.12). The model was constructed to delineate the behavior of faults in the subsurface along and between the cross-sections. Some of these faults are listric, north or south verging fore and back thrusts originating from basal detachment (Fig 4.12).

Among these four faults, two are blind in nature while other two are exposed on the surface. The 3D model of these faults demonstrate variation from east to west in the trend of fault planes. The Kahuta Back Thrust and Rawat Fault cuts the surface along the cross-section B-B´, while along the line A-A´ only Rawat Fault is exposed at the surface (Figs 4.11 and 4.12). The deformation and displacement of strata along the faults exposed at the surface is indicating more vertical displacement towards NW and is decreasing towards SE in the study area.

4.4.2 3D Horizon Modeling

A 3D horizon model is generated to describe the kinematics of folds along and between the lines A-A´ and B-B´. The model is prepared to interpret the horizon cut by the faults at the level of the Murree Formation with respect to its present geometry between the lines A-A´ and B-B´ (Fig 4.13). The closure of folds present in the study area and their orientation can be seen through this model. The 3D model is shown in

Figure 4.13, which illustrate that the folds are trending northeast-southwest and plunging towards northeast.

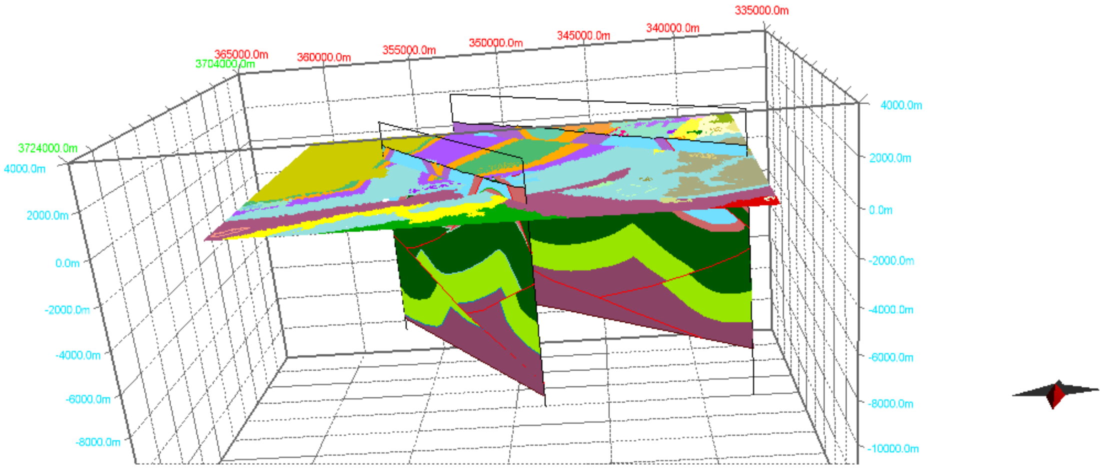


Fig 4.10. 3D model of study area showing the interaction between surface geology and structural cross-sections.

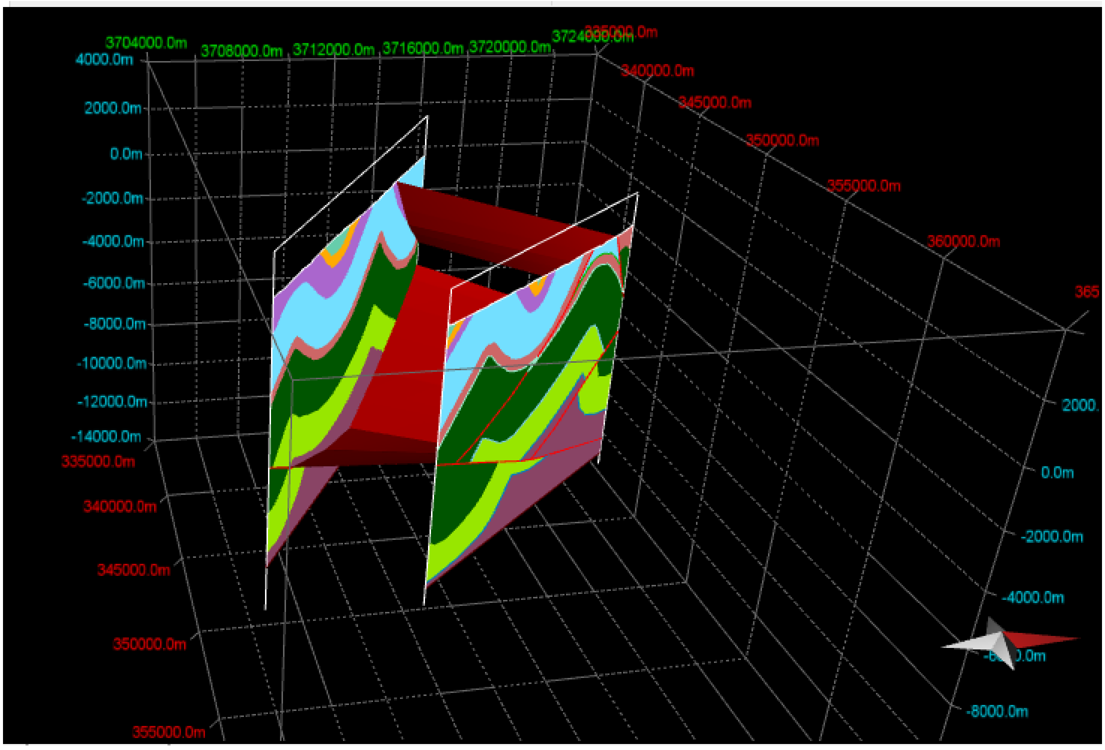


Fig 4.11. 3D model showing the structural cross-sections across the lines A-A´ and B - B´.

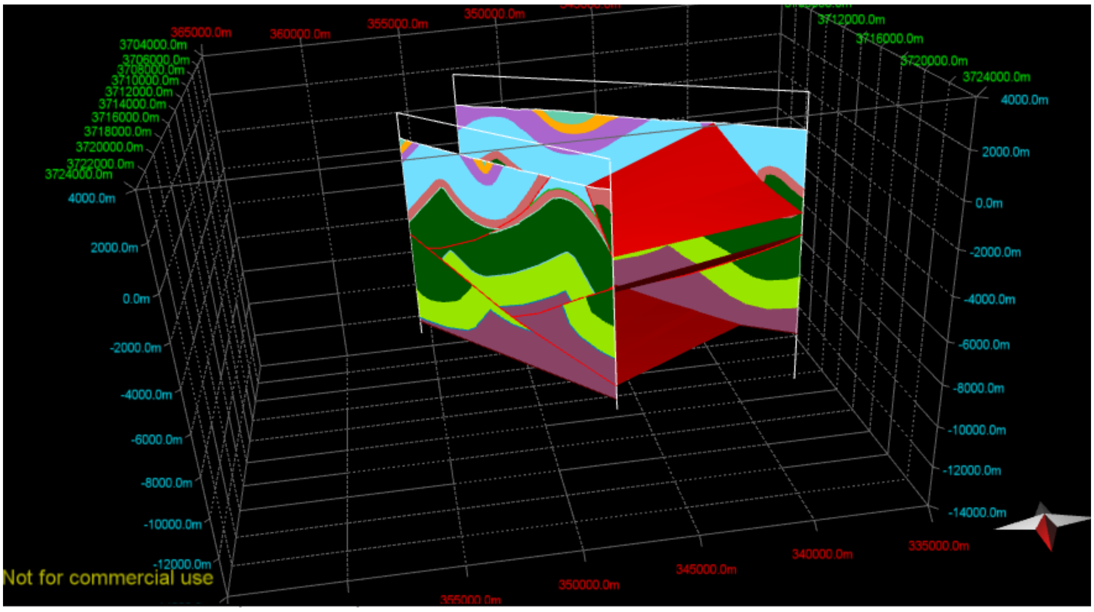


Fig 4.12. 3D fault model of the study area showing a regional thrust system.

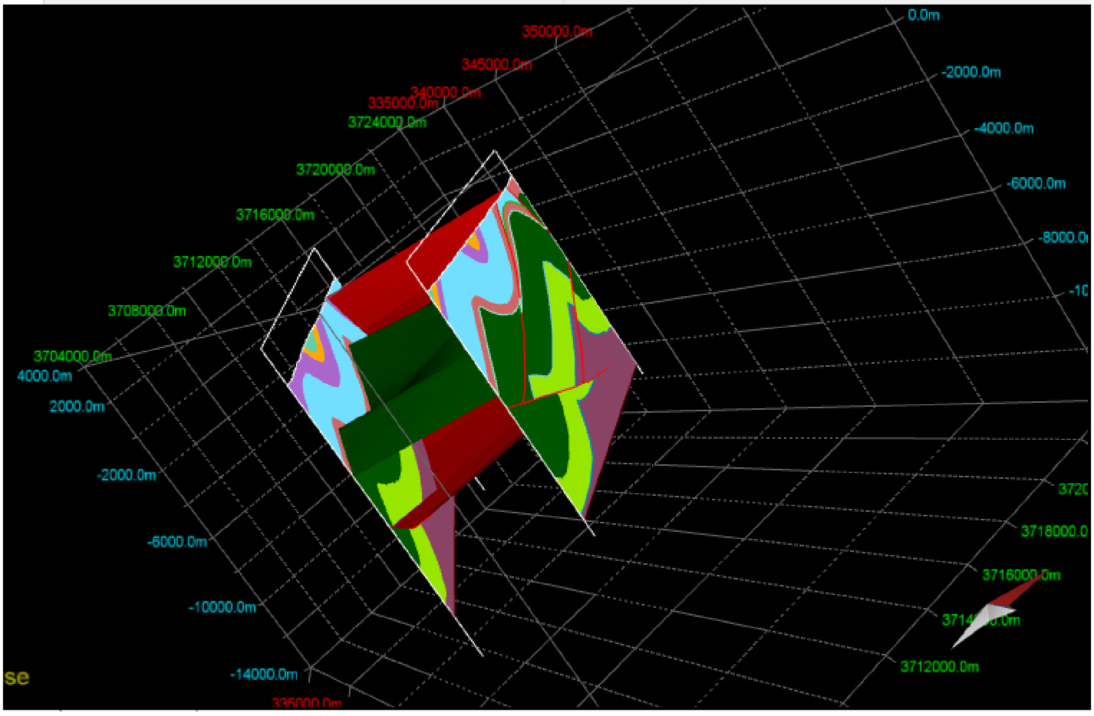


Fig 4.13. 3D model of horizon at the level of the Murree Formation intersected by faults.

CHAPTER 5

DISCUSSION AND CONCLUSIONS

5.1 Discussion

The PFTB is located at the western boundary of the sub Himalayas and exhibits the foreland fold and thrust belt in Pakistan. As a result of Eocene collision of the Indian plate with the Eurasian plate, the fold and thrust belt had gone through the extensive deformational phase. The PFTB has recorded deformation in sedimentary strata and preserving the continental molasse sequence resulting from Himalayan orogeny. The structural style revealed by numerous structures represents extreme deformation in the Potwar Basin/Plateau.

The purpose of present research is to understand the structural geometry of surface and subsurface structures and to develop a comprehensive model for structural evolution of the area with the help of surface geology, seismic and well bore data. The 2D and 3D modeling of the study area are main objectives to know the nature of tectonics responsible for structuration of area and the amount of shortening accommodated by structures in the area through restored balance cross-sections.

The study area is occupied by the sedimentary rocks which range in age from Miocene to Recent. The observed geological formations in the study area are Murree, Kamlial, Chinji, Nagri, Dhok Pathan and Soan formations. Unconformities exist between the Dhok Pathan Formation, Soan Formation and Terrace gravel deposits. The Quaternary deposits are typically composed of sand, silt, clay, alluvium and are mostly capping the bed rock.

Structurally, the study area exhibits intense folding and faulting of the strata, and is mainly controlled by thrust tectonics. Imbricated thrust faults and back thrust present in the subsurface are bisecting and elevating the structures at the surface. The faults present in the study area are the Rawat Fault and Kahuta Fault, which are thrust and reverse in nature and trending in northeast-southwest. The Rawat Fault is formed due to thrusting of the Murree and Kamlial formations over the Chinji Formation whereas in Kahuta Fault the Kamlial Formation is thrusted over the Chinji Formation. These faults are identified in the field on the basis of stratigraphy, slickensides, drag folds, shearing and crushing.

The folds in the study area are trending northeast-southwest and open to tight in nature. The synclines are broad and wide forming the valleys whereas the anticlines are close to tight making ridges in the area. The folds are limb faulted at the surface whereas in the subsurface these folds are present as core faulted by blind thrust faults resulting in the complex deformational style.

The cross-sections demonstrate that the back thrust and blind thrusts present in the subsurface are the main cause which had uplifted and folded the structures above them. The cross-sections were restored to their undeformed state upto basement and the average amount and percentage of shortening accommodated by the rocks in the study area were calculated which is approximately 6 km and 29%.

The 3D model was prepared to understand the structural geometries of the study area with the help of software Move 14.0. The 3D surfaces of main faults and folds are created which shows thrust tectonics in the area and it delineates the northeast-southwest oriented plunging folds.

5.2 Conclusions

As a result of detailed structural analysis carried out along the study area, the conclusions drawn from this thesis work are as follows.

1. This research has resulted in the preparation of detailed geological map on 1:50,000 scale from Kahuta in north to Kalar in south.
2. The surface lithology in the study area is of sedimentary nature which ranges in age from the Miocene to Recent.
3. The detail structural analysis in the area suggests that only detachment folding and thrust tectonics are responsible for structural evolution of the northeastern PFTB.
4. The study area is categorized by northeast-southwest trending, open to tight and plunging folds.
5. The displacement along the faults in the study area is changing laterally and blind thrust faults present in the subsurface had uplifted and folded the rocks intensely.
6. The structural variations along the strike depends on variable amount of throw exhibited by thrust faults.

7. The average amount and percentage of shortening accommodated by structures in the study area are approximately 6 km and 29%.

REFERENCES

Ahmad, S., Hamidullah, S., Irfan, M., and Ali, A., (2004) Structural transect of the western Kohat Fold and Thrust Belt between Hangu and Basia Khel, NWFP, Pakistan. PAPG, ATC 2004, conference proceedings.

Baker, D.M., Lillie, R.J., Yeats, R.S., Johnson, G.D., Yousaf, M., Zaman, A.S.H., (1988) Development of the Himalayan thrust zone: Salt Range, Pakistan, Geology 16, 3-7.

Butler, R. W. H., M. P. Coward, G. M. Harwood, and R. J. Knipe, 1987, Salt, its control on thrust geometry, structural style and gravitational collapse along the Himalayan mountain front in the Salt Range of northern Pakistan: in I. Lerche and J. J. O'Brien eds., Dynamical Geology of Salt and Related Structures, Academic Press Inc., p. 339-418.

Burbank, D. W., R. G. H. Raynolds, and G. D. Johnson, 1986, Late Cenozoic tectonics and sedimentation in the northwestern Himalayan foredeep: II. Eastern limb of the northwest syntaxis and regional synthesis: in P. Allen and P. Homewood, eds., Foreland Basins: International Association of Sedimentologists Special Publication 8, p. 293-306.

Chaudhry, M.N., N. Ahsan, 1999. Sedimentological constraints on India-Asia Collision. In: Terra Nostra, 14th Himalaya-Karakoram-Tibet Workshop, Germany, 22-23 Sep, 1999.

Condie, K. C., 2002. The supercontinental cycle: are there two patterns of cyclicity? Journal of African Earth Sciences, 35(2), 179– 183.

Coward, M. P., Windley, B. F. et al. 1986. Collision tectonics in the NW Himalayas. In: Coward, M. P. & Ries, A. C. (eds) Collision Tectonics. Geological Society, London, Special Publications, 19, 203– 219.

Duroy, Y., 1986. Subsurface densities and lithospheric flexure of the Himalayan foreland in Pakistan interpreted from gravity: M. S. thesis, Oregon State University, Corvallis, Oregon, 74 pp.

Du Toit, A. L., 1937. Our wandering continents. London: Oliver and Boyd.

Fatmi, A. N., 1973. Lithostratigraphic units of the Kohat-Potwar province, Indus basin, Pakistan. Geol. Surv. Pak., Memo. 10: Atp.

Fletcher, G. L., and R. A. Soeparjadi, 1984, Oil and gas developments in Far East in 1984: AAPG Bulletin, v. 68, p.1622-1675.

Greco, A., 1991, Stratigraphy, metamorphism and tectonics of the Hazara-Kashmir syntaxis area; Kashmir Journal of Geology, v,8-9,p, 39-65.

Irving, E. and McGlynn, J.C. (1979). Paleomagnetism in the Coronation Geosyncline and arrangements of continents in the middle Proterozoic. Geophysical Journal of the Royal Astronomical Society 58: 309-336.

Jaswal, T. M., Lillie, R. J., Lawrence, R. D., 1997. Structure and evolution of the northern Potwar deformed zone, Pakistan. AAPG Bulletin, 81, 308-328.

Jaume, S. C., and R. J. Lillie., 1988, Mechanics of the Salt Range-Potwar Plateau, Pakistan: a fold-and-thrust belt underlain by evaporites: Tectonics.

Johnson, G. D., R. G. Raynolds, and D. W. Burbank, 1986, Late Cenozoic tectonics and sedimentation in the northwestern Himalaya foredeep: I. Thrust ramping and associated deformation in the Potwar region: in P. Allen, and P. Homewood, eds., Foreland Basins: International Association of Sedimentologists Special Publication 8, p. 273-291.

Kazmi, A.H., and Rana, R.A., 1982, Tectonic map of Pakistan: Ministry of Petroleum and Natural Resources, Geological Survey of Pakistan, scale 1:2,000,000.

Kazmi, A. H. and M.Q. Jan, 1997, Geology and Tectonics of Pakistan; Graphic Publishers, Karachi. Pakistan.

Khan, M.A., R. Ahmed, H. A. Raza, and A. Kemal, 1986, Geology of petroleum in Kohat-Potwar depression, Pakistan: AAPG Bulletin, v. 70, p. 396-414.

Khan, M. A., Jan, M. Q. &L Weaver, B. L., 1993. Evolution of the lower arc crust in Kohistan, N. Pakistan: temporal arc magmatism through early, mature and intra-arc rift stages. In: Himalayan Tectonics (P. J. Treloar & M. P. Searle, eds.), Spec. Publ. Geol. Soc. London, 74,123- 138.

Khan, T., Khan, M. A. &Jan, M. Q., 1993. Kohistan, a collage of island arc and back-arc basin assemblages in the HimalayaofN. Pakistan. Geol. Soc. Amer. Abstracts with Programs, A- 122.

Khan, I. A., Bridge, J. S., Kappelman, J., Wilson, R., 1997. Evolution of Miocene fluvial environments, eastern Potwar plateau, northern Pakistan. Sedimentology, 44, 221-251.

LaBrecque, J. L., Kent, D. V., and Cande, S. C., 1977. Revised magnetic polarity time scale for Late Cretaceous and Cenozoic time: Geology, v.5, no. 6, p. 330-335.

Leather, M., 1987, Balanced structural cross-section of the western Salt Range and Potwar Plateau: Deformation near the strike-slip terminus of an overthrust sheet: M. S. thesis, Oregon State University, Corvallis, Oregon, 271 pp.

Lefort, P, 1975, Himalayas: The collided range, present knowledge of the continental arc. Am , J, Sci, 275A:1-44.

Lillie, R.J., Johnson, G.D., Yousaf, M., Zamin, A.S.H. and Yeats, R.S., 1987. Structural development within the Himalayan Foreland fold and thrust belt of Pakistan. *In*: Beaumont, C. and Tankard, A.J. Eds, Sedimentary Basins and Basin-Forming Mechanism. Canadian Soc. *Petrol. Geol. Mem.*, **12**, 379-392.

Majid, M., Danishwar , S. and Hamidullah, S., 1991. Petrographic and Chemical Variations in the Rift-Related Basic Dykes of The Malka Area (Lower Swat), NWFP, Pakistan. Geological Bulletin, University of Peshawar, 24, 1-23.

McDougall, J.W., and Hussain, Ahmad, 1991. Fold and thrust propagation in the western Himalaya based on a balanced cross section of the Surghar Range and Kohat Plateau, Pakistan: American Association of Petroleum Geologists Bulletin, v. 75, no. 3, p. 463–478.

Meissner, C. R., Master, J.M., Rashid, M.A. and Hussain M., 1974. Stratigraphy of Kohat quadrangle, Pakistan. United States Geological Survey professional paper, 716 D.

Moghal M. A., Saqi, M. I., Hameed, A., Bugti, M. N., 2007. Subsurface geometry of Potwar sub basin in relation to structuration and entrapment. Pakistan Journal of Hydrocarbon Research, 17, 61-72.

Paracha, W. 2004. Kohat Plateau with Reference to Himalayan Tectonic General Study, p.4651. 2004 Can. Soc. Expl. Geophysicist Conf.

Pecher, A. (1978), Déformation et métamorphisme associes à une grande zone de cisaillement, exemple du grand chevauchement central Himalayen (MCT), transversales des Annapurnas et du Manaslu, Népal, thèse d'état thesis, 310 pp., Univ. de Grenoble, Grenoble, France.

Pennock, S. Edward, Lillie, J. Robert, Agha Sher Hamid Zaman and Muhammad Yousuf, 1988, Structural Interpretation of Seismic Reflection Data from the Eastern Salt Range and Potwar Plateau, Pakistan, submitted to AAPG Bulletin, 15 April1988.

Pivnik, D.A., and Sercombe, W.J., 1993. Compression and transgression-related deformation in the Kohat Plateau, NW Pakitan. In: Treloar, PJ.& Searle, M.P. (eds.). Himalayan Tectonics. Geol. Soc. Lond., Spec. Publ. 74: 559-580.

Powell, C., and Conaghan, P., 1979, Plate Tectonics and the Himalayas, Earth Planet. Sci. Letters 20, p. 1-12.

Pudsey, C. J., Schroeder, R. and Shelton, P W., 1985: Cretaceous (Aptian - Albian) Age for Island Arc Volcanics, Kohistan, N. Pakistan. - In: GUPTA, V. J. (Ed.), Contributions to Himalayan Geology. 3, 150-168, Hindustan Publishing Comp., Delhi.

Raynolds, R. G., 1980, The Plio-Pleistocene structural and stratigraphic evolution of the eastern Potwar Plateau, Pakistan: Ph.D. thesis, Dartmouth College, Hanover, New Hampshire, 265 pp.

Sarwar, G. and DeJong. K. A., 1979. Arcs, oroclines, syntaxsis. The curvatures of mountain belts in Pakistan. In: Farah, A. & DeJong, K. A. (Eds.). Geo. Dynamics of Pakistan. Geol. Surv. Pak., Quetta, 341-350.

Scotese, C. R and Mckenow W. S., 199. Revised world maps and introduction. In: Mcknew, W. S and Scotese, C. R (eds) Paleozoic Paleogeography and Biogeography, Geological Society, London, Memoir, 12, 1-21.

Spencer, D.A. 1993. Tectonics of the higher and Tethyan Himalaya, Uer Kaghan Valley, NW Himalaya, Pakistan: Implications of an early collisional, high pressure eclogite facies metamorphism to the Himalayan belt. Doctoral dessert. ETH, Zurich.

Tahirkheli, R.A., et al., 1979, The India-Eurasia suture zone in northern Pakistan: synthesis and interpretation of recent data at plate scale, in Farah, A. and DeJong, H., eds., Geodynamics of Pakistan, Geol. Surv. Pakistan, Quetta, p.125-130.

Tahirkheli,R.A.K.& Jan, M. Q. (eds.), 1982. Geology of Kohistan, Karakoram Himalaya, north Pakistan. Geol. Bull. Uni. Peshawar, 11, 187p.

Treloar, P.J., Broughton, R.D., Williams, M.P., Coward, M.P., Coward, M.P. and Windley, B.F., 1989. Deformation, metamorphism and imbricatin of the Indian Plate, south of the Main Mantle Thrust, north Pakistan. Jour. Met. Geol., 7,111- 125.

Treloar, P.J., G.J. Potts, J. Wheeler, and D.C. Rex, 1991. Structural evolution and asymmetric uplift of the Nanga Parbat syntaxis, Pakistan. Himalaya. Geol. Rund., 80 411-428.

Valdiya, K.S., (1980). Two Intracontinental boundary thrusts of Himalaya: Tectonophysics, Vol. 66, p. 323-348.

Wadia, D.N., 1931. The syntaxis of the North-west Himalaya, its rocks, tectonics, and orogeny. India Geol. Surv. Recs., 65, Pt. 2, . 189-220.

Wandrey, C.J., B.E. Law, and H.A. Shah, 2004, Patala-Nammal Composite Total Petroleum System, Kohat-Potwar Geologic Province, Pakistan: USGS Bulletin 2208-B, US Department of Interior, 20 p.

Windley, B. F., 1983, Metamorphism and tectonics of the Himalaya: Journal of the Geological Society of London, v. 140, p. 849-865.

Yoshida, M., 1997 Paleomagnetic synthesis of three phases collision in the himalay-Karakoram belt and surrounding terranes. In: extended Abs. international seminar on Paleomagnetic Studies in Himalaya-Karakoram collision Belt and surrounding countries. Geosci. Lab., geol. Surv. Pak., Islamabad, 23-26.

APPENDIX-I

WELL TOPS OF KALLAR X-01:

KALLAR-X- 01
LOCATION: 033.495556 073.389162
UWI000988
6417.0000
654.0000 KB

FORMATIONS	**WELL TOPS (meters)**
FF NAGRI	000000.0
FF CHINJI	001273.0
FF KAMLIAL	003096.0
FF MURREE	003486.0
FF KULDANA	006090.0

APPENDIX-II

Published Geological Map of Punjab Pakistan: