STRUCTURAL AND STRATIGRAPHIC FRAMEWORK OF THE MARWAT-KHISOR RANGES, N-W.F.P., PAKISTAN.

BY

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THIS WORK IS DEDICATED TO MY BELOVED MOTHER

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ABSTRACT

The Marwat-Khisor ranges define an east to northeast-trending fold-thrust belt flanking the mobile perimeter of the Bannu Basin in the south. Detailed mapping in this belt has led to well understanding of its stratigraphy and structural architecture. The stratigraphy of the Khisor Range consists of Paleozoic to Mesozoic platform sedimentary rocks unconformably overlain by Plio-Pleistocene sediments of Siwalik Group rocks whereas the Marwat Range is entirely composed of Siwalik Group rocks of Plio-Pleistocene age. Structures produced by ongoing Himalayan tectonics are well recorded in these ranges and are represented by regional to local scale, parallel to en cehelon folds and thrust faults. Key structural elements of the Khisor Range are the Paniala, Saiyiduwali, Mir Ali, and Khisor anticlines along with a frontal thrust named the Khisor Thrust. The Marwat Anticline constitutes the main structure of the Marwat Range. At the surface, most of these folds have southward-facing asymmetry except the Paniala Anticline, which is north facing. The Khisor Thrust fault is partially exposed along the southern slopes of the Khisor Range where it places Permian strata in its hanging wall over the Siwalik Group rocks in the footwall. Several interpretive structural transects are constructed across the Marwat-Khisor ranges in order to analyze its subsurface style. Projecting surface structures to depth using kink plane bisecting angle techniques, it is found that in Marwat-Khisor ranges basement is not involved in deformation and there is a through-going sole fault at the base of Jhelum Group rocks which separates basement from the overlying sedimentary sequence. Shortening above this basal decollement is the consequence of sequential up-section ramping. The Marwat Anticline is the earliest response to shortening related to a simple structural process-fault-bend folding and its evolution is concurrent with the underlying ramp. It was subsequently followed by gradual southward migration of deformation till enough critical taper was achieved to initiate the next frontal ramp from the basal decollement that emerged at surface as Khisor Thrust that accomplish

most of the shortening in the frontal boundary of the Khisor Range. Major folds in the Khisor Thrust sheet such as the Paniala, Saiyiduwali, Khisor, and Mir Ali anticlines accommodate bending in the underlying thrust ramp. Orientation of both large and small-scale structures indicate that the Marwat-Khisor structural province is characterized by thin skinned deformed fold-thrust assemblages that define a south-southeast vergent structural system impinging upon the Punjab Foreland. Attitude data on the fold limbs suggest that the prominent fold structures have been evolved as fault-bend folds, being the consequence of contractile deformation related to southward progression of Himalayan deformation. Deformation in the region post-dates the deposition of Plio-Pleistocene Siwaliks indicating that the age of compressional deformation is post Pleistocene. Prerequisites for hydrocarbon generation, accumulation and entrapment such as source, reservoir, seal, and fault related anticlinal culminations are present throughout the study area that proves the hydrocarbon potential of the surrounding region.

CHAPTER 1

Introduction

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INTRODUCTION

1.1 GENERAL STATEMENT

The Trans-Indus extension of the Salt ranges is composed of Surghar-Shinghar, Marwat-Khisor, Pezu and Manzai ranges which form an "S" shaped double re-entrant and surrounds the Bannu Basin (Fig. 1.1). These ranges represent the western part of the northwestern Himalayan foreland fold-and-thrust belt that formed by progressive south- directed decollement-related thrusting of the sedimentary cover of Indian Plate crust during the ongoing collision between India and Eurasia. Following the convergence of the Kohistan Island arc and the Indian Plate at the site of the Main Mantle Thrust and its lateral equivalents during latest Cretaceous to Early Tertiary time (Wells, 1984; Yeats and Hussain, 1987; Smith et al., 1994; Beck et al., 1995), deformation generally shifted southward with time. The southern most and latest thrusting has occurred along the frontal thrust system bordering the Trans-Indus ranges (Khan et al., 1988), (Fig. 1.2).

The study area covers about 1300 square kilometers of the Marwat-Khisor ranges in the central part of the Trans-Indus ranges (Fig. 1.1). These ranges lie within the Survey of Pakistan topographic sheets number 38 L/15, 38 L/16, 38 P/3 and 38 P/4, located between longitudes 70° 50′00″ to 71° 15′00″ E and latitudes 32° 10′00″ to 32° 30′00″ N. Geographically the Marwat-Khisor ranges are marked by the Bannu Basin in the north, D.I. Khan Plain in the south, Indus River in the southeast, and Bhittani Range to the northwest (Fig. 1.2). Low to moderate relief ranging from 200 m at the valley floor to 1300 m at the Kingriali peak characterizes these ranges. The Marwat-Khisor ranges stretches from Paniala in the west up to Dara Tang in the east (Fig. 1.2). The Marwat Range is an anticlinal feature largely covered by the Siwalik Group rocks. The Khisor Range that lies south of Marwat Range exposes the

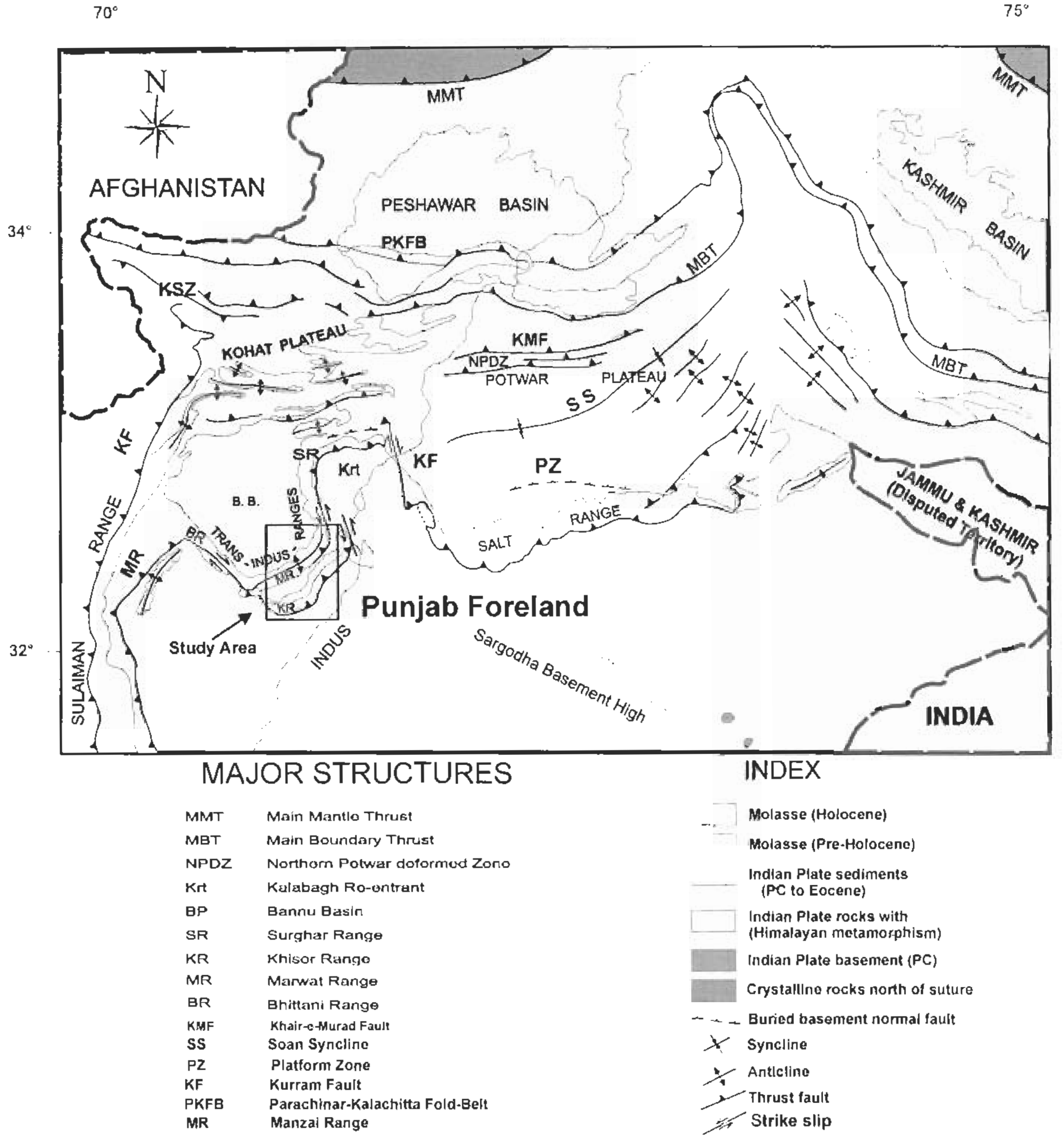


Figure 1.1. Generalized geologic map of the NW Himalayan foreland fold and thrust belt (modified after Kazmi and Rana, 1982; Lillie et al., 1987; Yeats and Lawrence, 1984; Coward et al., 1986). Red Box shows location the of study area.

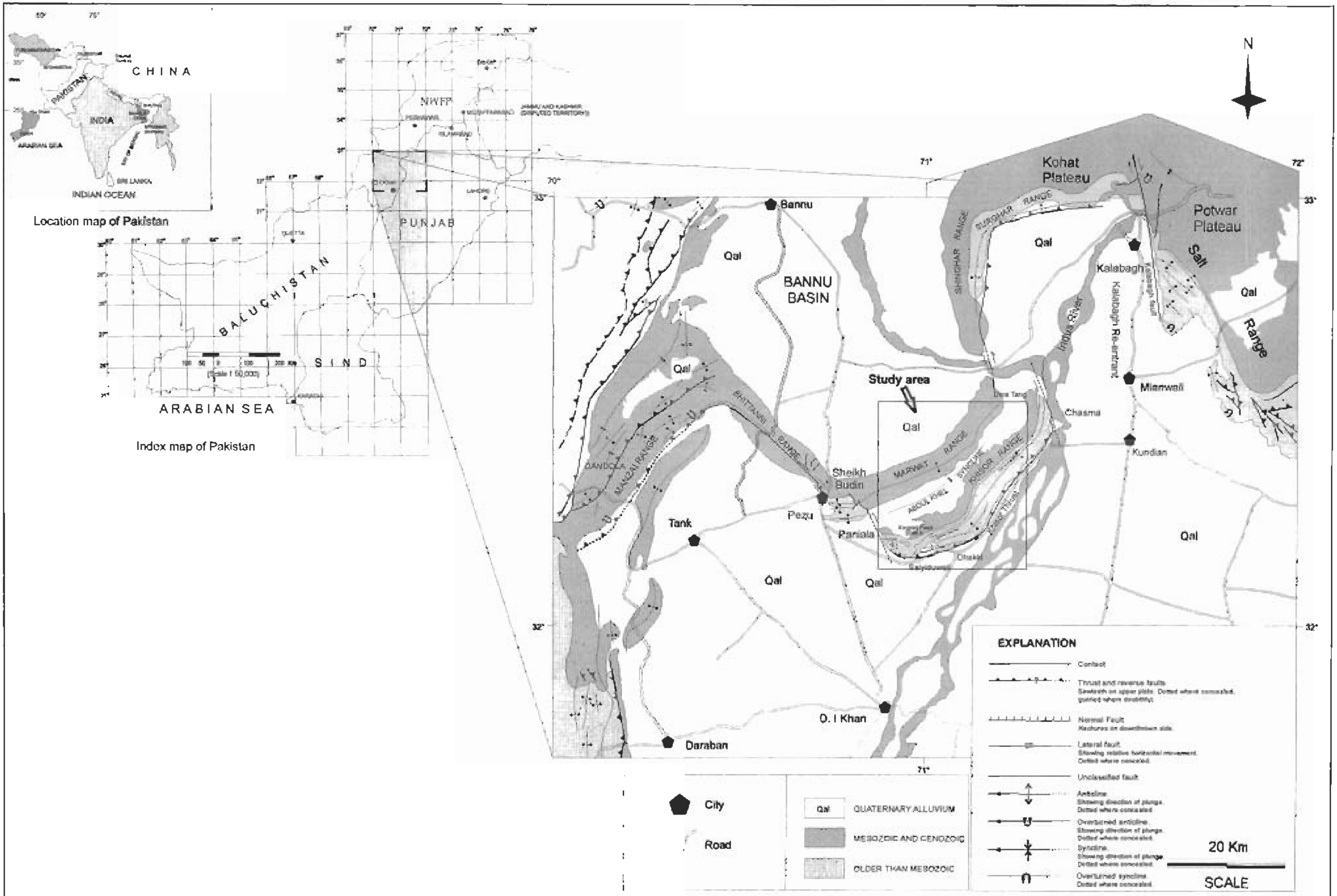


Figure 1.2. Generalized geological map, showing geology of the Trans Indus ranges between longitude 70° & 72° E and latitude 32° & 33°N. Rectangle shows location of the study area (modified after Wahid et a.,l 2004).

non-outcropping Cambrian to Triassic rocks underneath the Bannu Basin and Marwat Range at surface and is characterized by east to east-northeast structural trends. The structural style of the range includes parallel to en echelon fold trends detached at the base of Jhelum Group rocks of Cambrian age. The Cambrian to Plio-Pleistocene rocks of the Khisor Range are thrust southwards over the Punjab Foreland along the Khisor Thrust that is probably the western extension of the Salt Range Thrust (Gee, 1980). Cambrian to Triassic age shallow marine lithologies predominantly underlies the Khisor Range that is unconformably overlain by the Plio-Pleistocene Siwalik Group rocks (Fig. 1.3). The exposed stratigraphic sequence of the Khisor Range is broadly correlative with that of the Western Salt Range with the exception that rocks of the Rawalpindi Group (Miocene) are missing.

1.2 LOCATION

The study area is located about 250 Km south-southwest from Peshawar and about 120 Km from Bannu towards south-southeast. It is located 60 Km north of Dera Ismail Khan (D.I. Khan) towards north. It is easily approachable by a network of metalled roads from Bannu, Peshawar, Tank and D.I. Khan. It occupies an important geological position in understanding the structural evolution of the southern most Himalayan frontal thrust system of North Pakistan. There is a lot of potential especially in the western and central Khisor Range for the construction of underground openings and chambers that may be utilized for classified and non-classified projects for the national interest in future.

1.3 SCOPE OF STUDY

Since Hemphill and Kidwai (1973) produced a regional geological map of a part of the western Khisor Range no attempt has been made to map the central and western parts of the Marwat-Khisor ranges.

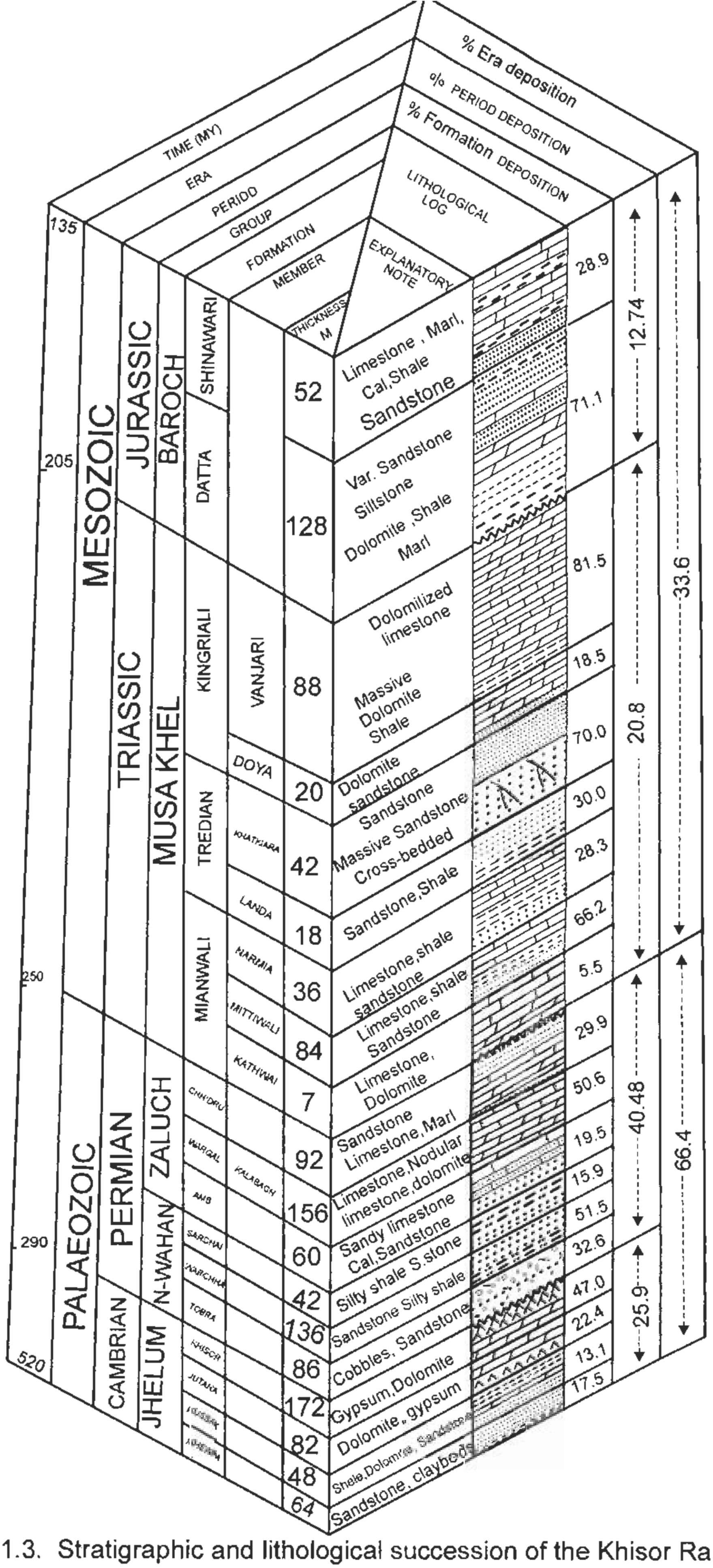


Figure 1.3. Stratigraphic and lithological succession of the Khisor Range.

There is a strong need to map the geological details of the area at 1:50,000 scale in the light of new scientific knowledge. This will help to resolve the stratigraphic and structural related problems for the future exploration and exploitation of hydrocarbons and would be helpful in formulating future excavation strategies for the construction of underground engineering facilities, such as various subsurface openings i.e. storage spaces, repository closures for waste nuclear fuel, protective shelters, shaft and adits.

This study is intended to be carried out with the following objectives:

i) To carry out detailed field investigation in order to prepare a detailed geological map of the region at 1:50,000 scale.
ii) To recognize key structural elements their local and gross regional patterns and structural style.
iii) To construct a consolidated structural model of the area that will help in assessing the hydrocarbon potential of the region.
iv) To confirm structurally self-supported locations for underground excavation should be utilized for the development of subsurface facilities.

1.4 HISTORICAL REVIEW

Previously little consideration has been reward to the tectonic perceptive of this significant Himalayan anterior thrust zone. As far as geological mapping is concerned nothing has been published except a geological map in the extreme west of Khisor Range near Paniala village (Hemphill and Kidwai, 1973). Structural sketch of the Marwat-Khisor ranges was published by Blisniuk et al., 1996. Previous studies in the study area have been mainly concentrated on the understanding of its stratigraphic framework.

Wynne, (1880) subdivided the Jurassic sequence of the Khisor Range and Sheikh Budin Hills into a lower "Variegated Group" and an upper "Jurassic limestone" and recorded a number of fossils from these rock units. Coulson, (1938) reported bouleiceras species from Wynne's lower Variegated Group about 2 km southeast of Paniala in the western end of the Khisor Range. Later on Gee, (1945) and Pascoe (1959) subdivided the Jurassic sequence of the Trans-Indus ranges into a lower "Variegated Stage" and an upper "Baroch Limestone" (Wahid et al., 2004). The later worker reported the presence of "golden oolites" without defining their stratigraphic position from his Baroch Limestone and Variegated Group in the Sheikh Budin Hills. Wadia, (1961) divided the Jurassic sequence of the Trans-Indus ranges into Late and Middle Jurassic; however, his description is confusing and he presumably considered rocks of Early Jurassic age to be absent from the area.

Detailed geological studies of the Bannu and Dera Ismail Khan areas were carried out by Hemphill and Kidwai (1973). They described the lithostratigraphic units of the Marwat-Khisor ranges and parts of the Suleiman Range and the Waziristan area. Siddiqi, (1973) studied the silica sand deposits of the Khisor Range and Sheikh Budin Hills and estimated reserves of about 20 million tons. Hussain, (1973) concluded that about 31 million tons of silica sand was workable at a depth of 200 feet in the Marwat-Khisor ranges.

Fatmi and Cheema, (1972) and Fatmi, (1977) described the cephalopods of Early Jurassic age from the upper marine "Wazir Wal Member" (now Shinawari Formation) of the Datta Formation in Khisor Range near Paniala village. They discussed in detail the biostratigraphy of the Jurassic sequence on the basis of fossil evidence.

Blisniuk (1996) presented a regional structural outline of the Khisor Range while conducting paleomagnetic studies of the Siwalik Group rocks. He interpreted that south verging thrusting and normal faulting are responsible for the tectonic evolution of the Khisor Range thrust front. Blisniuk et al., (1998), also noted that the area along the present day thrust front was affected by synorogenic normal faulting within the foreland basin before thrusting began.

Fold-thrust styles has been interpreted in the Marwat-Khisor ranges by Alam et al.,(2005) on the basis of outcrop structural data and proposed that the structural form is thin-skinned involving decollement thrust-fold assemblages, kinematically interrelated to a provincial basal decollement being observed at the base of Jhelum Group rocks.

Ahmad et al., (2007) have tinted the petroleum prospectivity and structural interpretation of fraction the of the Bhittini and Northern Suleiman ranges.

1.5 METHODOLOGY

Before performing fieldwork relevant literature was extensively reviewed to acquire knowledge regarding the geological setup of the proposed study area. In the field we have studied the lithologic sections of the exposed stratigraphic succession and conducted several stratigraphic/structural traverses across the Marwat-Khisor ranges for the preparation of structural geological map of the area. Traverses were planned in the north south direction in the western domain and northwest approximately right angle to the trend of the outcrops in the eastern domain in the Khisor Range. Similar technique for traverses has been adopted in the Marwat Range.

1.5.1 Fieldwork

- Reconnaissance fieldwork was carried out in the summer season 2003 and was followed by a detailed study during the winter season 2004.

- Two months period was spent in the field, (Marwat-Khisor ranges) between the Bannu Basin to the north and Punjab Foreland to the south (Fig. 1.2), to acquire field data regarding structure and stratigraphy.

- During the fieldwork attitudes of planar structures and their GPS locations were collected across the Marwat-Khisor ranges.

- Besides studying the physical properties of the exposed rock units, detailed structural data regarding strike and dip of bedding and, faults and attitudes of the fold axes were collected and correlated with each other in order to establish the pattern of the various structures.

1.5.2 Laboratory Work

- Four detailed geological cross-sections have been constructed across the structural trends for the better understanding of the structural style of the area.
- Two stratigraphic columnar sections have been constructed to understand the stratigraphic profile of the study area.
- Computer software i.e., corel draw 12 was used for the preparation of geological map and cross-sections.

1.6 GEOLOGICAL SETTING OF PAKISTAN

Pakistan contains the northwestern boundary of the Indian lithospheric plate (Fig. 1.4). Underthrusting of the Indian plate beneath the Eurasian Plate has produced compressional thin-skinned tectonic features since Eocene time on the northern and northwestern fringes of the Indian Plate. Continued underthrusting of the Indian Plate since the Cretaceous produced the spectacular mountain ranges of the Himalaya and a chain of foreland fold-and-thrust belts as thick sheets of sedimentary rock were thrust over the Indian Craton (Kemal, 1991).

Foreland fold-and-thrust belts throughout the world are conspicuous features of convergent plate tectonics. The Kohat-Potwar fold and thrust belt along with the frontal ranges of the northwestern Himalayas is one of these. The Salt and Trans-Indus ranges constitute the mobile flank of the Kohat and Potwar fold and thrust belt which is mostly characterized by decollement thrust-fold assemblages. Thrusting along with associated folding is certainly the main method of accommodating shortening within these orogenic belts. The most recent thrusting occurred along the frontal thrust system in the Salt Range to the east and in the Trans-Indus ranges to the west (Blisniuk et al., 1998). The Trans-Indus ranges represent the leading deformational front of the Kohat fold and thrust belt and Bannu Basin in North Pakistan. Underneath the Potwar Plateau and the frontal Salt ranges, the Precambrian Salt Range Formation forms a laterally extensive basal decollement at the basement-cover interface. As a result, the structural style is mainly thin-skinned and the basement is convex upward and gently north-dipping. Similar basement geometry has been interpreted for the basement underneath eastern Kohat Plateau and Bannu Basin (McDougall & Hussain 1991; Parwez, 1992). The geometry of the thrust front along the Salt ranges appears to be controlled by north-dipping basement-involving normal faults that localize thrusting (Pennock et al., 1989). Similar deformational style has been interpreted for the Surghar-Shinghar Range and possibly also along the Khisor Range and the Sheikh Budin Hills (Blisniuk, 1996).

1.7 GEOTECTONIC SETTING OF PAKISTAN

The Eurasian Plate is composed of three broad geological domains, which from north to south are the Laurasian, Tethyan and Gondwanian domain. During the late Paleozoic all these domains were part of the super continental mass called as Pangaea (Wegner, 1924; Smith and Hatton, 1970; Irving, 1979; Smith, 1981) that was surrounded by a universal ocean, the Panthalassa. An arm of this ocean, the Tethys

(SueS, 1893) formed a wedge between the northern and southern parts of the Pangaea. By Late Triassic, Pangaea has split into two super continents, Laurasia to the north and Gondwanaland to the south (Fig. 1.4), separated by the Tethys seaway (Du Toit, 1937).

Several lithospheric blocks of Gondwana affinity, which detached from the mother continent, drifted northward and finally accreted to the Laurasian domain beginning in the Carboniferous (Burret, 1974; Sengor, 1984; 1988; Fig. 1.4). Present day Eurasia is composed of the initial Laurasian landmass and the accreted assemblages of the former fragments of Gondwanaland. According to Sengor (1988) the accreted terrain has been termed as the Tethyan domain. Pakistan is located at the junction of the Gondwanian and Tethyan domains.

1.8 GEODYNAMIC SETTING OF PAKISTAN

The geodynamic processes of sea floor spreading, continental drift, and collision tectonics resulted in the formation of the Indian Ocean and the Himalayas surrounding the Indo-Pakistani subcontinent (Fig. 1.4 and 1.5). Both of these features evolved when a plate of the earth crust carrying the Indo-Pakistani landmass rifted away from the super continent Gondwana about 130 Ma ago (Johnson et al., 1976). As a consequence, the Neo-Tethys that was located between the Indian continent in the south and Asian plate in the north started shrinking. This shrinkage and continental drift was facilitated by the consumption of Neo-Tethys, opening up of the Indian ocean behind, the transform motion along Owen Fracture Zone located towards southwest of the Indo-Pakistani subcontinent and Ninety East Ridge located towards southeast of Indo-Pakistani subcontinent. Propelled by the geodynamic forces, the Indian plate traveled 5000 km northward and eventually collided with Eurasia. The subduction of the northern margin of the Indian plate finally closed the Neo-Tethys and the Indian Ocean assumed its present widespread expanse. This collision formed the Himalayas and the adjacent mountain ranges (McKenzie and Sclater, 1976). During the closure of

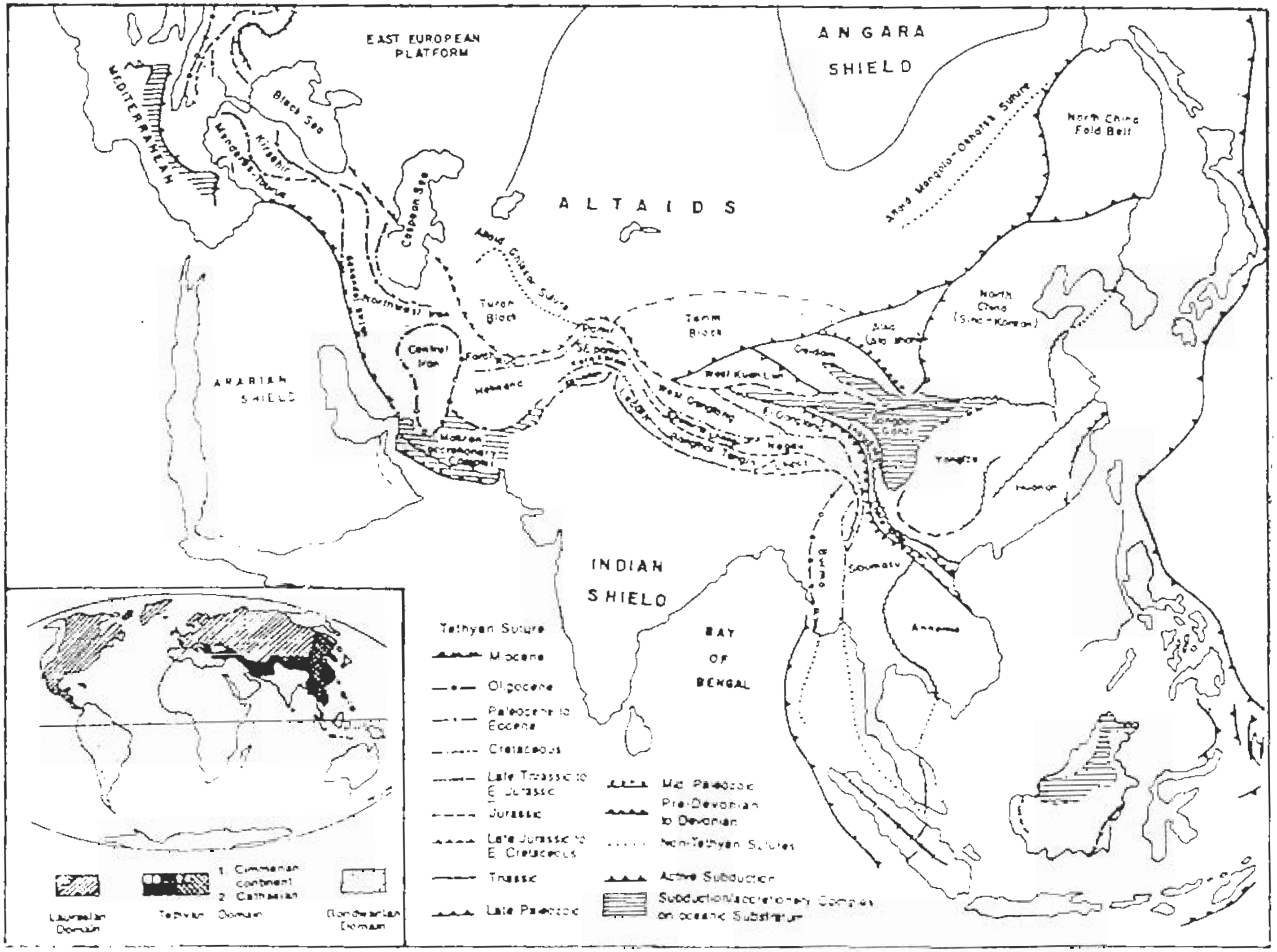


Figure 1.4- Map showing broad tectonic zones of Eurasia and the major suture and accretionary blocks of the Tethyan Domain (after Sengor et al., 1988).

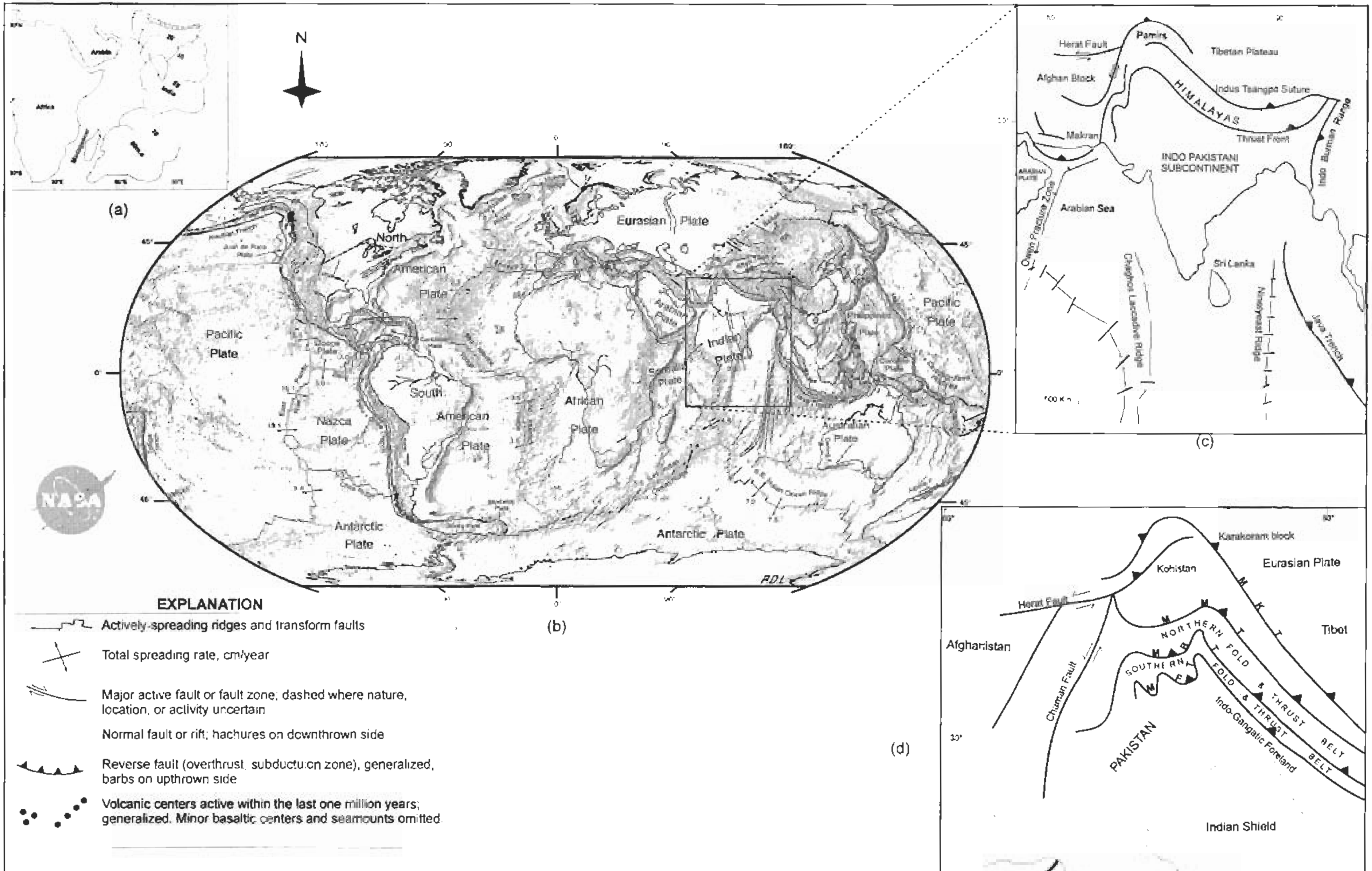


Figure 1.5. (a). Relative motion of Indian subcontinent to the Africa and Madagascar since 80 m.y. (After Powell, 1979).
(b). Digital tectonic activity map of the earth, showing tectonism and volcanism of the last one million years (From NASA, October 2002).
(c). Tectonic map of India-eurasia collision zone (modified after Qayyum et al., 1996).
(d). Tectonic map of NW Pakistan (modified after Powel, 1979, Trelor and Izzat,1993, reproduced after Wahid et al., 2004).

the Neo-Tethys Ocean, intraoceanic subduction generated a series of arcs, namely Kohistan–Ladakh, Nuristan and Kandhar (Fig. 1.6 and 1.7), (Searle, 1991; Treloar and Izatt, 1993). The arc magmatism occurred for a period of 40 Ma (Petterson *et al.*, 1985), after which the back-arc basin was finally closed and the Kohistan–Ladakh Arc was accreted onto the Eurasian plate forming an Andean type continental margin. The collisional boundary is referred to as the Main Karakoram Thrust (MKT) where the collisional event began in the Late Cretaceous (102~75 Ma) (Coward, 1986; Patriate and Achache, 1984; Powell, 1979). This collisional time is also supported by the fact that Indo-Pakistani subcontinent was rapidly drifting at a rate of 15 cm per year northwards relative to Australia and Antarctica about 80 Ma ago. From 53 Ma to the present, the Indo-Pakistani subcontinent seemed to have moved northward at much slower rates of 4 to 6 cm per year (Powell, 1979). The abrupt slowing is considered to be a consequence of the collision with Eurasia during the Early Tertiary (Le Fort, 1975; Molnar and Tapponier, 1975; Klootwijik et al., 1992).

After the Kohistan–Ladakh Arc docked with the Eurasian plate to the north, the subduction of the Neo-Tethys beneath Kohistan–Ladakh Arc was still continued and resulted in the complete consumption of the leading edge of the Indian plate that finally collided with the remnants of Kohistan–Ladakh Arc (Powell, 1979). The collision between the Indian plate and the Kohistan–Ladakh arc occurred during the Eocene and is marked by the Main Mantle Thrust (Tahirkheli, 1979). The southwards, migration of Himalayan deformation from the site of the Main Mantle Thrust is represented by the Main Boundary Thrust (MBT) along which the northern deformed fold and thrust belt is thrust southwards over the molasse sediments of the Potwar and Kohat plateaus (Fig. 1.6).

1.9 STRUCTURAL SETTING OF PAKISTAN

On the basis of four regional fault systems the Pakistani Himalayas can be divided into five litho-tectonic terrains, which are characterized by distinctive stratigraphy and physiography. From north to south these gross geological belts and the major fault system separating them are as given and described respectively below:

Karakoram Block

Main Karakoram Thrust

Kohistan Island Arc

Main Mantle Thrust

Northern Deformed Fold and Thrust Belt

Main Boundary Thrust

Southern Deformed Fold and Thrust Belt

Salt Range Thrust and Trans-Indus ranges thrust

Punjab Foredeep

1.9.1 Karakoram Block (KB)

The Karakoram block consists of complex assemblages of heavily deformed sedimentary, metasedimentary and igneous rocks of the southern Asian plate. It lies between the Pamirs in the north and the Kohistan–Ladakh Arc in the south. The collision between the Karakoram block and the Kohistan-Ladakh arc occurred along the MKT during the Cretaceous (Treloar et al., 1989; Zaman and Torii, 1996; Yoshida et al., 1997). This collage of arcs, the Kohistan Island Arc (KIA) and Ladakh arc, collided with the northern margin of the Indian plate along the MMT in the Early Tertiary (Beck et al., 1995; Yoshida et al., 1997). The Main Karakoram Thrust (MKT) marks the southern boundary of the Karakoram block (Fig. 1.6).

1.9.2 Main Karakoram Thrust (MKT)

The Main Karakoram Thrust (MKT) is a major tectonic feature in northern Pakistan formed as a result of the collision between the Karakoram block in the north and the Kohistan Island Arc in the south (Tahirkheli, 1979; 1982; 1983). The MKT was

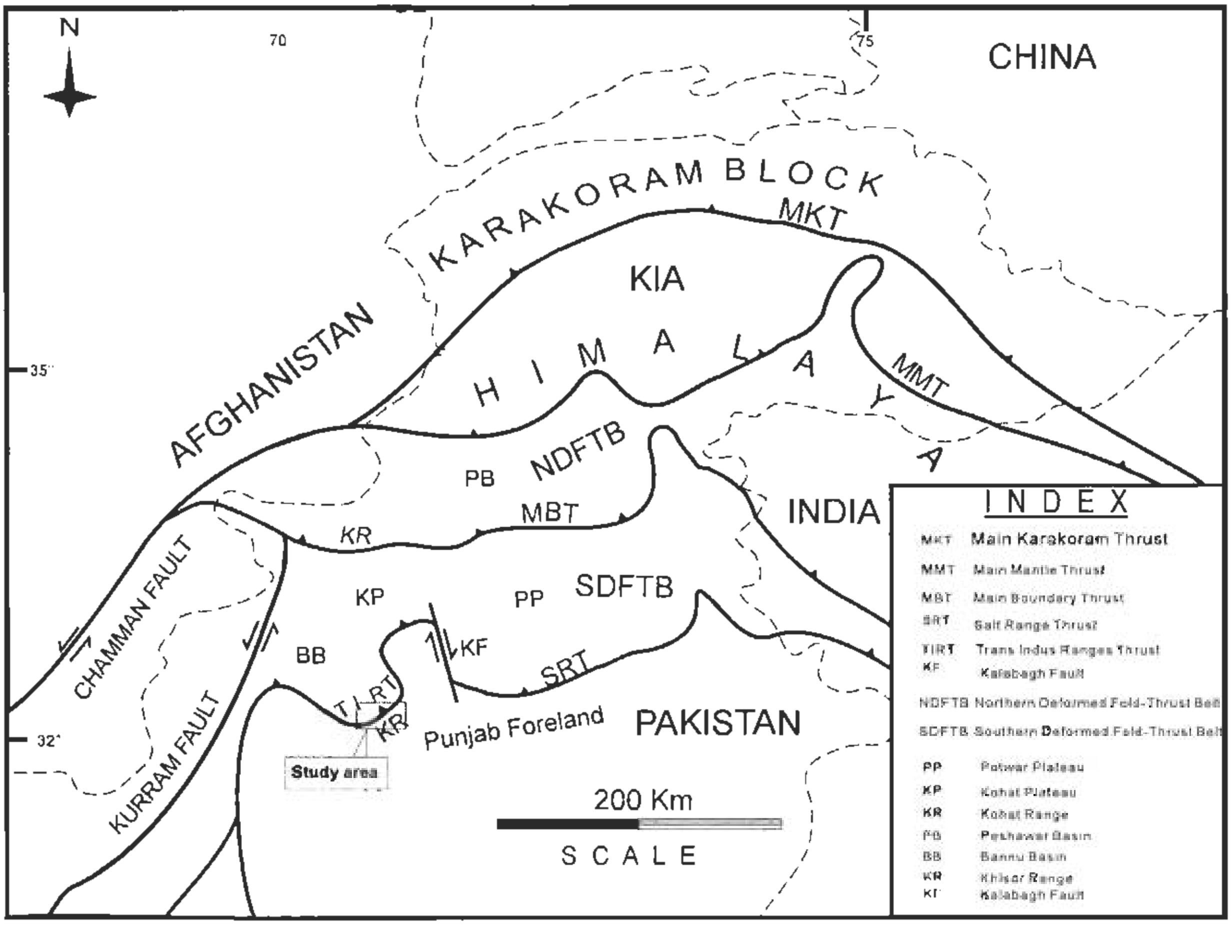


Figure 1.6. Tectonic map of North Pakistan, showing major structural features, (modified after Kazmi & Rana, 1982).

previously named as the Northern Suture (Pudsey et al., 1986). The Arc-Karakoram contact, sometime called the northern megashear (Tahirkheli, 1979), or MKT (Bard et al., 1980), corresponds to the reactivation of the Shyok Suture by the thrust. According to (Tahirkheli, 1979; 1982 and Ganser, 1981) it formed during Late Cretaceous.

1.9.3 Kohistan Island Arc (KIA)

The (KIA) developed in response to northward-directed subduction of the Neo-Tethys underneath Asia during Late Jurassic to Cretaceous time (Tahirkheli, 1979; Searle, 1987; Hamidullah and Onstot, 1992). In the NW Himalaya, collision between continental India and the KIA is interpreted as having occurred at between 50~55 Ma (Treloar, 1997). Rocks within the suture zone, which separates the Indian Plate from the structurally overlying Kohistan Arc include blueschist facies rocks, metamorphism of which is dated by Ar-Ar techniques at ca. 80 Ma (Anczkiewicz et al., 2000). The KIA is a 40 km thick pile of mafic, ultamafic and calc-alkaline plutonic and volcanic rocks and has been widely accepted as a vertical section through an intra-oceanic island arc (Hamidullah and Onstot, 1992). It covers 36000 Km^2 in the western Himalayas, Karakoram, and eastern Hindukush. The arc is oriented east west and comprises a variety of volcanic and plutonic rocks and subordinate sedimentary rocks that have undergone varying degree of deformation and metamorphism. It is divided into Ladakh and Kohistan Arc by the north trending Nanga Parbat Haramosh massif and is underlain by the Indian crustal plate (Seeber and Armbuster, 1979). The MKT towards north and MMT towards south bound the Kohistan island Arc which merges laterally in India and Tibet to form a single suture, namely such as the Indus Tsangpo suture. In Afghanistan, towards west of the KIA the MKT and MMT join one another and merge with the left lateral Kunar Fault (Fig. 1.6).

1.9.4 Main Mantle Thrust (MMT)

The MMT bounds the KIA to the south and the Indian Plate to the north. It formed as a result of collision and subduction of Indian Plate underneath the KIA during Eocene time (Tahirkheli, 1979; 1982 and Ganser, 1981). The Main Mantle Thrust dips northwards, between 25° and 45° (Malinconico, 1986) and is the southernmost thrust involving lower-crust crystalline rocks of the Indo-Pakistani shield (Le Fort, 1975; Bard, 1983a). The MMT, which borders its northern margin, exhibits major swing in its trend towards northeast giving rise to a reentrant within the (KIA) sequence. This reentrant is called as Nanga Parbat-Haramosh massif and is composed of more than 15 km thick Proterozoic gneisses and schists (Madin, 1986).

1.9.5 Northern Deformed Fold and Thrust Belt (NDFTB)

The northern deformed fold and thrust belt lies south of Main Mantle Thrust and is a belt of heavily deformed sedimentary, meta-sedimentary and igneous rocks. This belt stretches from Kurram area in the west near Afghan border up to the Kashmir basin in the east. The northern fold and thrust belt is bounded by Main Boundary Thrust separating it from the southern deformed fold and thrust belt.

1.9.6 Main Boundary Thrust (MBT)

The Main Boundary Thrust (MBT) represents the southwards migration of Himalayan deformation from the site of MMT. From northeast to southwest, it extends along the front of the northern fold and thrust belt around Hazara-Kashmir Syntaxes. It carries the pre-collision Paleozoic and Mesozoic sedimentary and meta-sedimentary rocks of the northern deformed fold and thrust belt in its hanging wall and post-collision folded Miocene foreland-basin deposits in its footwall. The MBT zone is comprised of a series of parallel or en-echelon thrust faults dividing the northwest Himalayan sequence into a deformed sedimentary southern zone or foreland zone, and a

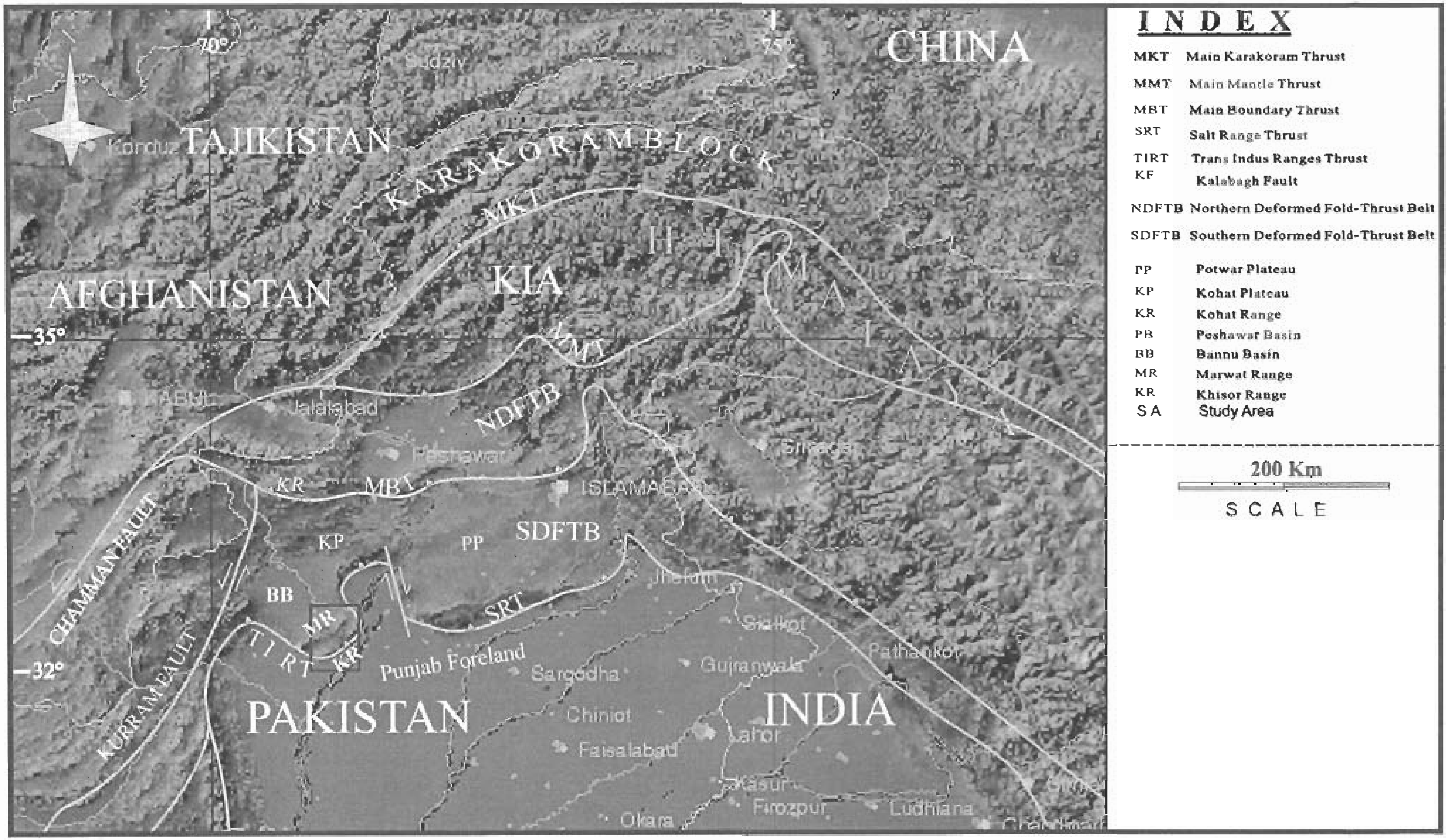


Figure 1.7 Digital Satellite Image showing major tectonomorphic terrains of North Pakistan. Inset shows the study area of Fig.4.1 (modified after Wahid et al., 2004) .

deformed and metamorphosed northern zone or the hinterland zone (Di Pietro et al., 1996; Pivinik and Wells, 1996).

1.9.7 Southern Deformed Fold and Thrust Belt (SDFTB)

The southern deformed fold and thrust belt rims the Himalayan mountain belt from Gange delta in India up to the South Waziristan Agency in Pakistan (Fig. 1.5 and 1.7). It is oriented east west and is underlain by a thick pile of fluvial sediments. This belt was the main depocenter of the synorogenic sediments influx, which started in the early Miocene. This fold and thrust belt can be divided into two tectonic provinces, the Potwar Plateau to the east and the Kohat Plateau to the west of Indus River, in the Trans-Indus-ranges (Fig. 1.2 and 1.8). The Potwar Plateau is a less internally deformed fold and thrust belt having a width of approximately 150 km in a north-south direction (Kazmi and Rana, 1982). It is bounded to the south by the Salt Range Thrust and to the north by the Hazara / Kalachitta ranges. Most of the deformation is concentrated in the northern part of the plateau, which is called the Northern Potwar Deformed Zone (NPDZ) (Leather, 1987; Baker et al., 1988). The Kohat Plateau is the westernmost of the southern deformed fold and thrust belt and was located far off southwards of the shelf margin at the time of collision and suturing in the north. The Salt ranges and the Potwar Plateau form an allochtonous block of passive margin carbonates and thick Miocene foredeep sequence which has been thrust over the foreland along a weak basal decollement being observed in the Eo-Cambrian evaporates of the Salt Range Formation that overlies a metamorphic basement (Yeats et al., 1984; Lillie et al., 1987).

The SDFTB had been influenced by the southward progression of deformation during late Miocene. The plateau is bounded to the north by the Main Boundary Thrust, which brings highly deformed Mesozoic rocks of the Kohat Range over the Eocene-Miocene sediments of Kohat Plateau (Yeats and Hussain, 1987). Towards the west, the Kurram Fault juxtaposes highly deformed Mesozoic rocks of Samana, Darsamand, Thal and North Waziristan Agency with the Eocene to Miocene sediments of the Kohat Plateau. The Kurram Fault is believed to be a left lateral transpressive boundary. The southeastern boundary of the Kohat Plateau is the Surghar Range where Mesozoic rocks were emplaced southwards onto the Indo-Gangatic foredeep in the south. Towards south, the undeformed sediments of Bannu Basin form the southern boundary of the Kohat Plateau (Fig. 1.6).

1.9.8 Salt Range Thrust (SRT) and Trans-Indus Ranges Thrust (TIRT)

In northern Pakistan most of the youngest thrusting has occurred along the frontal thrust system in Salt Range along Salt Range Thrust (SRT) in the east and in Trans-Indus ranges thrust (TIRT) in the west (Blisniuk et al., 1998). The frontal thrust system has accommodated about ≥ 20 km of shortening in Salt Range (Lillie et al., 1987; Baker et al., 1998) and ~ 10 km in the Trans-Indus ranges (Blisniuk, 1996). Along this thrust front the Eocambrian Salt Range Formation in the Salt Range (Gee, 1980); Permian rocks in the Surghar Range (Meissener et al., 1974) and the Cambrian Jhelum Group rocks in the Khisor Range, (Hemphill and Kidwai, 1973) are thrust over the Punjab Foredeep in the south (Fig. 1.8).

1.9.9 Punjab Plain (PP)

The Punjab Plain lies south of the Salt and Trans-Indus ranges and overlain by unconsolidated Quaternary sediments and is the present day depocenter for the eroded debris of the Himalayan chains in the north. A prominent element in the Punjab Plain is the Sargodha High, a basement ridge that trends obliquely to the Salt Range, but parallel to the overall Himalayan trend (Fig. 1.5 and 1.8). Its trend is defined by both the exposed basement rocks of the Kirana Hills and by a series of gravity anomalies that extends from the foot of Khisor Range to at least the Pakistan-India border (Farah et al., 1977). It is an expression of a recently activated intracontinental thrust (Le Fort, 1975). The Sargodha Ridge has been described both as a Mesozoic

Figure.1.8. Index map of Pakistan, showing major structural features. Triangle represents the oil well locations in the region.

basement high and a gentle basement uplift of a peripheral lithospheric bulge, developed as an elastic response to the northward underthrusting of the Indian Shield (Molnar, 1976; Duroy, 1986 and Duroy et al., 1989).

1.10 HISTORICAL STRATIGRAPHY

The stratigraphy of the area is well established from the outcrop exposures in both the Marwat-Khisor ranges and Shaikh Budin Hills. Fatmi et al, 1999 has studied the stratigraphy of the area and drawn two columnar sections. One section of the Cambrian, Permian and Triassic rocks of the western Khisor Range near Saiyiduwali and the other section of the Permian and Mesozoic rocks at Pungi Wand, Shaikh Budin Hills. The Saiyiduwali section revealed rocks exposed at the base is Jhelum Group and the top is marked by the Kingriali Formation of Triassic age. The Pungi wand section of Shaikh Budin Hills exposed the Wargal Limestone of Permian age at the base and Samana suk Formation of Jurassic age at the apex. Oil well drilled in the Marwat Range disclosed the subsurface stratigraphic sequence of the study area. The stratigraphic sequence encountered in the well is comparable with the columnar section measured in the western Khisor Range by Fatmi et al, 1999, with the exception of Siwalik Group rocks being encountered in the Marwat Range. Stratigraphic profile of the surface outcrop along the Khisor frontal thrust sheet in the vicinity of Saiyiduwali and Paniala sections suggest that it is similar to the other parts of the range except the Jhelum Group rocks of Lower Cambrian age which exposed along the Saiyiduwali section. The Stratigraphic sequence of the Marwat-Khisor ranges and along the present day thrust front can be subdivided into three major, unconformity-bounded stratigraphic horizons, which are given from bottom to top as:

1. Precambrian Crystalline Basement rocks

The Precambrian Crystalline Basement rocks are not exposed in the study area, but exposed towards the south and southeast of the Trans-Indus and Salt ranges in the form of Kirana Hills and Nagar Parker granite. The Nagar Parker is understood to encircle the northwestern fraction of the Indian Shield and describes the spreading out of Precambrian rocks of the Indian Peninsula. Kirana Hills exposes the Precambrian rocks of the Indian Shield about 100 km towards south of the Khisor Range near the Sargodha town.

2. Shallow Marine Cambrian, Permian and Mesozoic rocks

Cambrian rocks are well developed in the Salt and Khisor ranges. The pre-orogenic platform rocks of Permian age are located along the southern outskirts of the Kohat-Potwar Plateau. The Mesozoic sequence is also well developed in the southern perimeter of both the plateaus. The Permian system is well developed in the eastern portion; Mesozoic rocks have been mapped in the western portion and Cambrian sequence in the central portion of the Khisor Range.

3. Cenozoic, Late Tertiary i.e., Neogene to Quaternary

These syn-orogenic foreland basin sediments are coarse clastics dominantly conglomerate and molasse deposits are mapped in the entire Marwat Range. Similarly the northern flank of the Khisor Range is frequently composed of the clastic sediments of alternate beds of sandstone and argillaceous materials and the same lithology have been mapped at various locations in the frontal segments of the Khisor foothills.

Detailed stratigraphic columnar sections with lithological descriptions and findings during the present studies of various formations in the Marwat-Khisor ranges are given in the subsequent chapters under the heading of Paleozoic and Mesozoic stratigraphy of the Khisor Range and Cenozoic stratigraphy of the Marwat Range.

CHAPTER 2

Paleozoic-Mesozoic Stratigraphy

CHAPTER 2

PALEOZOIC AND MESOZOIC STRATIGRAPHY OF THE KHISOR RANGE

2.1 INTRODUCTION

Detailed field mapping in the Khisor Range led to well understanding of the stratigraphy of the area that includes Cambrian to Middle Jurassic platform sediments unconformably overlain by Plio-Pleistocene fluvial sediments of Siwalik Group (Table 2.1). The platform sediments become thicker and more complete from east to west in the Khisor Range.

In the western part of the Khisor Range, northwest of Saiyiduwali, an excellent section of Paleozoic and Mesozoic rocks ranging in age from Cambrian to Jurassic are exposed. The stratigraphic succession was studied along the Saiyiduwali and Paniala sections of the Khisor Range as shown in (Fig 2.1 & 2.2).

In the Saiyiduwali area, the base of stratigraphic succession is occupied by the rocks of Cambrian age that include Khewra Sandstone, Kussak Formation, Jutana Formation and Khisor Formation (Fig 2.1). The Khewra Sandstone consists of purplish-brown, thick-bedded sandstone with coarse clay bands and concretionary layers in the upper part. The overlying Kussak Formation is a sandy and dolomitic unit that is rich in glauconite. The Jutana Formation is predominantly gray, massive dolomite and is overlain by the Khisor Formation that is predominantly gypsiferous marl interbedded with shale along with minor oil-impregnated gypsum and dolomite layers. Overlying the Cambrian rocks is a sequence of Permian rocks that consist of the Nilawahan and Zaluch Group (Fig 2.1). The base of the Nilawahan Group begins at the Tobra Formation that is a tillitic deposit while overlying Warchha Sandstone contains siltstone and silty shale. The Sardhai Formation consists of carbonaceous, silty shale with minor sandstone bands. Local people have explored the carbonaceous layers for coal.

Chrono-stratigraphy			Litho-stratigraphy			[illegible]	[illegible]	
Time (M/Y)	ERA	Period	Group	Formation	Member			m
		Pleistocene	Siwalik	Soan		Massive conglomerate, sandstone, siltstone, claystone and clay.	Qs	44
10.0	CENOZOIC	Pliocene		Dhok Pathan		Cross-bedded Sandstone and clay beds.	Tdp	166
				Nagri		Cross-bedded and massive Sandstone, claystone and conglomerate.	Tn	962
	MESOZOIC	Jurassic	Baroch	Shinawari		Limestone, marl and shale.	Jss	52
20.5				Datta		Variegated sandstone, siltstone and shale.	Jsd	128
		Triassic	Musa Khel	Kingriali	Vanjari Doya	Massive dolomite, sandstone, marl and shale.	Tmk	88
				Tredian	Khatkiara Landa	Cross-bedded sandstone, shale.	Tmt	42
250.0				Mianwali	Narmia Mittiwali Kathwai	Marl, limestone, sandstone, siltstone and dolomite.	Tm m	127
	PALEOZOIC	Permian	Zaluch	Chhidru		Limestone, sandstone	Pzc	92
				Wargal L.st	Kalabagh Lower	Massive limestone, sandy limestone, dolo.	Pzw	156
290.0				Amb		Limestone, sandstone	Pza	60
			Nilawahan	Sardhai		Carbonaceous shale,	Pns	42
				Warchha S.stone		Cross-bedded Sandstone, shale, cobbles and pebbles.	Pnw	136
				Tobra		Sandstone, pebbles, cobbles, clay and silt.	Pnt	86
		Cambrian	Jhelum	Khisor		Gypsum, dolomite, shale, sandstone, siltstone	Cjk	172
				Jutana		Dolomite, sandydolo.	Cjj	82
520.0				Kussak		Conglomerate, shale, dolomite, glau.s.st.	Cjk	48
				Khewra		Thick-bedded s.st. Flaggy shale.	Cjk	64 +

Table 2.1. Stratigraphic framework of the Marwat-Khisor ranges (modified after Fatmi et al., 1999).

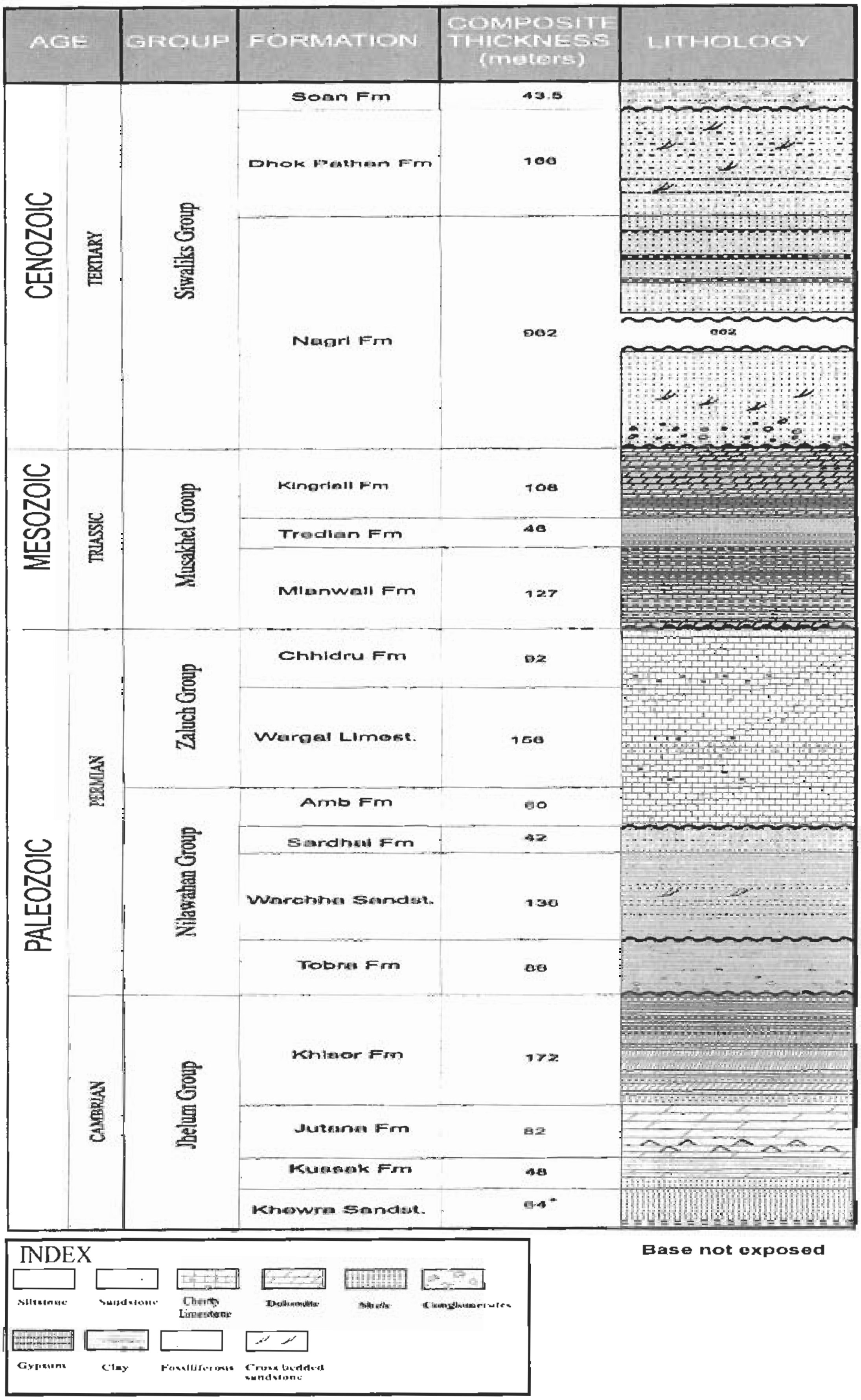


Figure 2.1. Generalized stratigraphic sequence of the Khisor Range exposed along Saiyiduwali section (modified after Wahid et al., 2004)

ERA	PERIOD	GROUP	FORMATION	MEMBER	Th/m
CENOZOIC	PLEISTOCENE	SIWALIK	SOAN		300
			DHOK PATHAN		500
	PLIOCENE		NAGRI		950
MESOZOIC	JURASSIC	BAROCH	SHINAWARI		196
			DATTA		344
	TRIASSIC	MUSA KHEL	KINGRIALI	VANJARI	262
				DOYAI	28
			TREDIAN	KHATHIARA	42
				LANDA	18
			MIANWALI	NARMIA	34
				MITTIWALI	80
				KATHWAI	4
PALEOZOIC	PERMIAN	ZALUCH	CHHIDRU		68
			WARGAL LIMESTONE	KALABAGH	40
				LOWER MEMBER	109

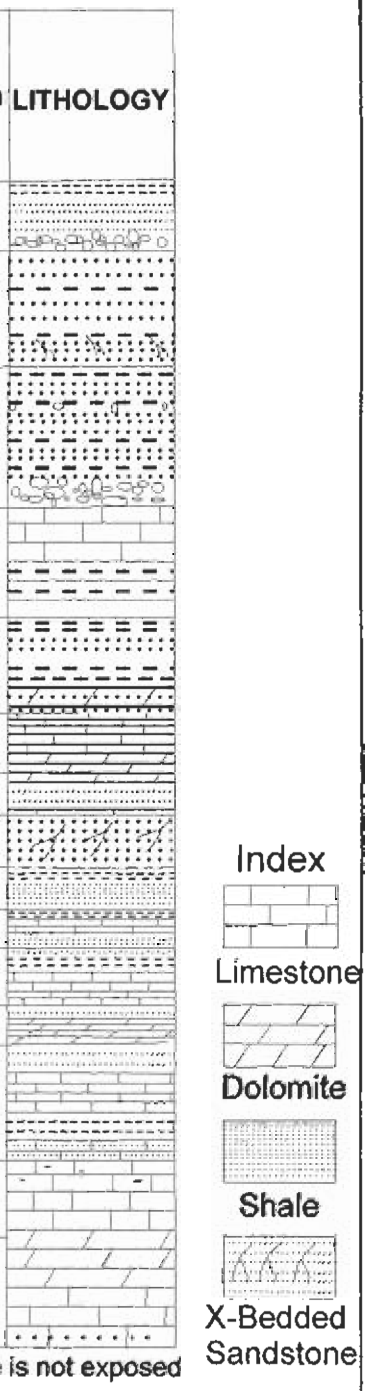


Figure 2.2. Generalized stratigraphic sequence of the western Khisor Range along Paniala section of sutdy area.

The overlying Zaluch Group consists of mixed sandy and carbonate units in the lower Amb Formation and upper parts of the Chhidru Formation but a thick carbonate cliff-forming unit i.e. Wargal Limestone, is present between these two. Brachiopods, crinoids, bryozoans, corals and other fossils are common in this group. The upper 20 m thick, gray, nodular marly limestone of the Wargal Limestone contains abundant brachiopods and bellerophan and underlies the Chhidru Formation. Sandy limestone is common in the upper part of the Chhidru Formation. The contact between the Permian Chhidru Formation and the Triassic Mianwali Formation (Kathwai Member) of the Musa Khel Group is well exposed in the Saiyiduwali area. The basal Kathwai Member of the Mianwali Formation is sandy and dolomitic in the lower part but is glauconitic in the upper part. It is overlain by interbedded limestone and shale with subordinate siltstone of the Mittiwali Member, which is overlain by shale, limestone and the silty and sandy sequence of the Narmia Member. The Tredian Formation overlies the Mianwali Formation, which is silty in the lower part (Landa Member) and thick-bedded sandstone (Khatkiara Member) in the upper part. The Kingriali Formation consists of dolomitic marl and shale, and is unconformably overlain by the Siwalik Group rocks in the Khisor Range. The Musa Khel Group is well exposed in the west and extends up to north of Saiyiduwali but further eastwards it does not make its way to the surface. Jurassic in the west, Triassic in the center and Permian rocks in the east are unconformably overlain by the Nagri, Dhok Pathan and Soan Formation of Siwalik Group.

2.2 PALEOZOIC ROCKS

The Paleozoic sediments in the study area consist of Cambrian Jhelum Group, Permian Nilawahan and Zaluch groups that are described as under:

2.2.1 Cambrian Succession

Only the Jhelum Group falls under Cambrian succession that is exposed in the central Khisor Range, north of Saiyiduwali village occupying the core of the Saiyiduwali

Anticline, Fig 2.2 a, represents the Jhelum Group rocks. The Jhelum Group consists of the following four formations from bottom to top:

2.2.1.1 Jhelum Group

This group is composed for the following four units:

Khisor Formation

Jutana Formation
Kussak Formation

Khewra Sandstone

2.2.1.1a Khewra Sandstone

The Khewra Sandstone only exposed in the north northwest of Saiyiduwali Village in the Saiyiduwali Anticline of the mapped area. The Khewra Sandstone is primarily of sandstone beds. The sandstone observed light brownish to reddish brown thick-bedded to massive in the upper part (Pate 2.1); while the lower part of the formation is comprised of thin bedded to sheeted reddish shale. Glauconitic sandstone observed in the upper portion of the formation, which is considered as the foundation part of the overlying Kussak Formation. The formation is more than 64 m thick in the Saiyiduwali section. The base of the formation is not exposed and its upper contact is disconformable with the Kussak Formation.

The formation contains some trace fossils in the Salt Range, which have been interpreted as trilobite trails by Schindewolf and Seilacher (1955) and are not indicative of any particular age. However, as the overlying Kussak Formation

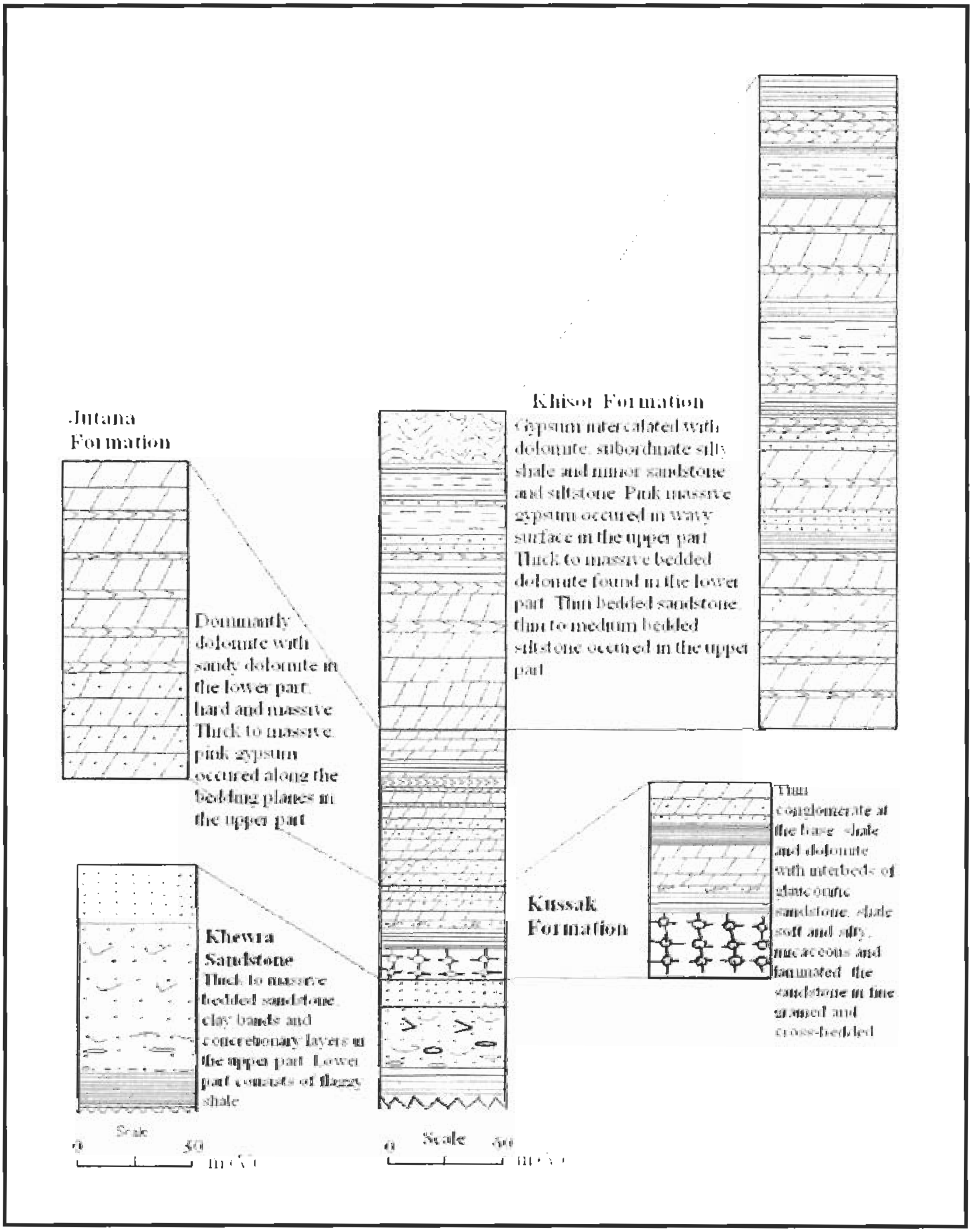


Figure 2.2 a Columnar section of the Cambrian rocks of Jhelum Group exposed in the Khisor Range, north of Saiyiduwali.

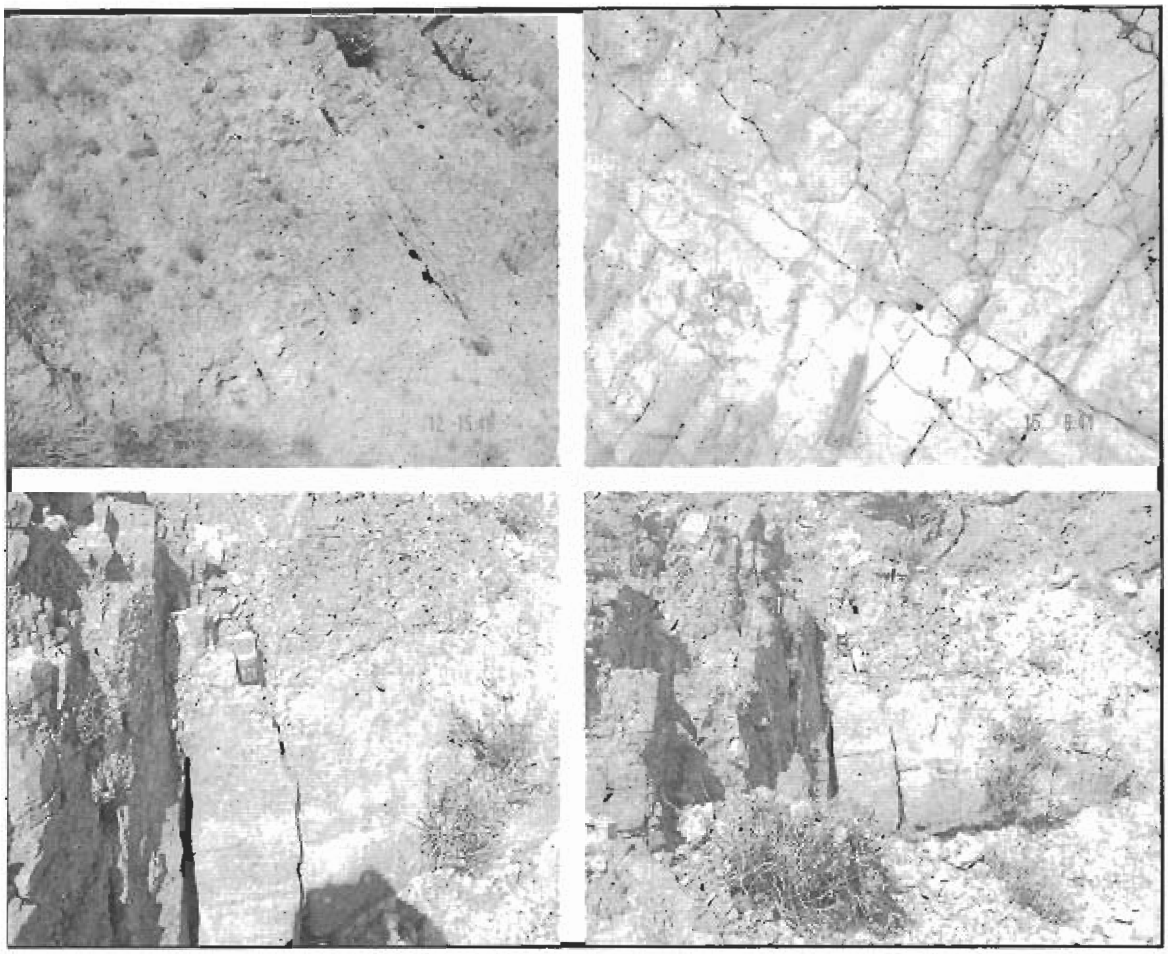


Plate 2.1 ENE looking view of thick-bedded to massive, purple-brown Khewra Sandstone, exposed along the Saiyiduwali Section, Central Khisor Range.

is not older than late Early Cambrian, therefore age assigned to the Khewra Sandstone as Early Cambrian (Table 2.1 & Plate 2.1).

2.2.1.1b Kussak Formation

The disconformity at the base of the Kussak Formation in the Khisor Range is marked by a widespread, thin conglomerate bed. In the study area the formation is only observed in the western Khisor Range north of Saiyiduwali Village. The formation is composed mainly of dolomite, shale and interbedded glauconitic sandstone (Table 2.1 & Plate 2.2).

The shale is thin bedded to laminated and observed fragile micaceous and soft. It is greenish gray to brownish gray and partly silty. The dolomite medium to thick bedded light to whitish gray and at places observed greenish gray to glauconitic. The grained size visually observed coarse in the outcrop. The sandstone is reddish gray to gray, and texturally observed fine-grained micaceous and cross-bedded. The sandstone beds partially composed of dolomitic pockets and lenses.

The formation is 48 m thick in the Saiyiduwali section (Fatmi et al., 1999). Its basal contact is disconformable with the underlying Khewra Sandstone and its upper contact with the Jutana Formation is conformable.

The age of the formation, based on paleontological information in the eastern part of the Salt Range, is late Early Cambrian or early Middle Cambrian (Teichert, 1964).

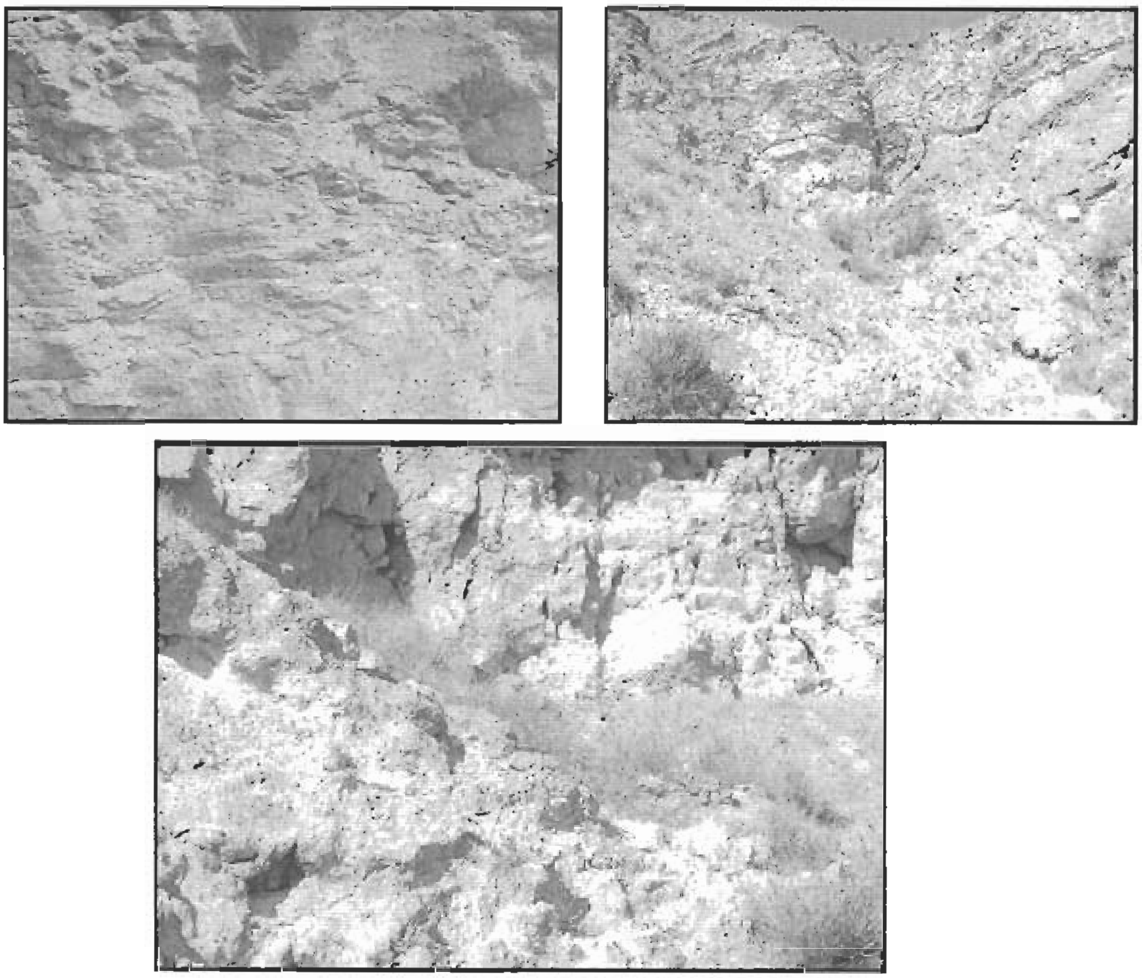


Plate 2.2 NNW looking view of the medium to thick-bedded dolomite within the Kussak Formation exposed along the Saiyiduwali section, Central Khisor Range

2.2.1.1c Jutana Formation

Jutana Formation of the Jhelum Group mapped only at the locality of Saiyiduwali section. The formation mostly comprised of dolomite to sandy dolomite beds particularly in the lower part of the formation in the Saiyiduwali section (Table 2.1 & Plate 2.3). Texturally the sandy dolomite observed medium to fine-grained solid thick bedded to massive. Where the dolomitic horizon is observed light gray to whitish gray and medium to thick-bedded and occasionally massive.

The Jutana Formation is 82 m thick in the Saiyiduwali section. Its contact with the underlying Kussak Formation and the overlying Khisor Formation (equivalent to the Baghanwala Formation of the Salt Rage) are conformable. Its age is late Early Cambrian or early Middle Cambrian (Teichert, 1964). The formation is fossiliferous. Schindewolf and Seilacher (in Teichert, 1964) collected and described some fossils from the shale units in the middle part of the formation exposed in the eastern Salt Range, including Lingulella fuchsi, Botsfordia granutala, Redlichia noetlingi and also gastropods.

2.2.1.1d Khisor Formation

Gee (1945) described a unit of rocks composed of gypsiferous dolomitic shale and dolomite lying between the Jutana Formation and the Tobra Formation in the Khisor Range as "Gypsiferous Series". Hussain (1960) named the formation as Khisor gypsiferous beds.

The Khisor Formation is only exposed and mapped north of Saiyiduwali village. It is mostly consists of gypsum, dolomite, clastic material such as silty shale, and slightly of sandstone and siltstone (Table 2.1 & Plate 2.4).

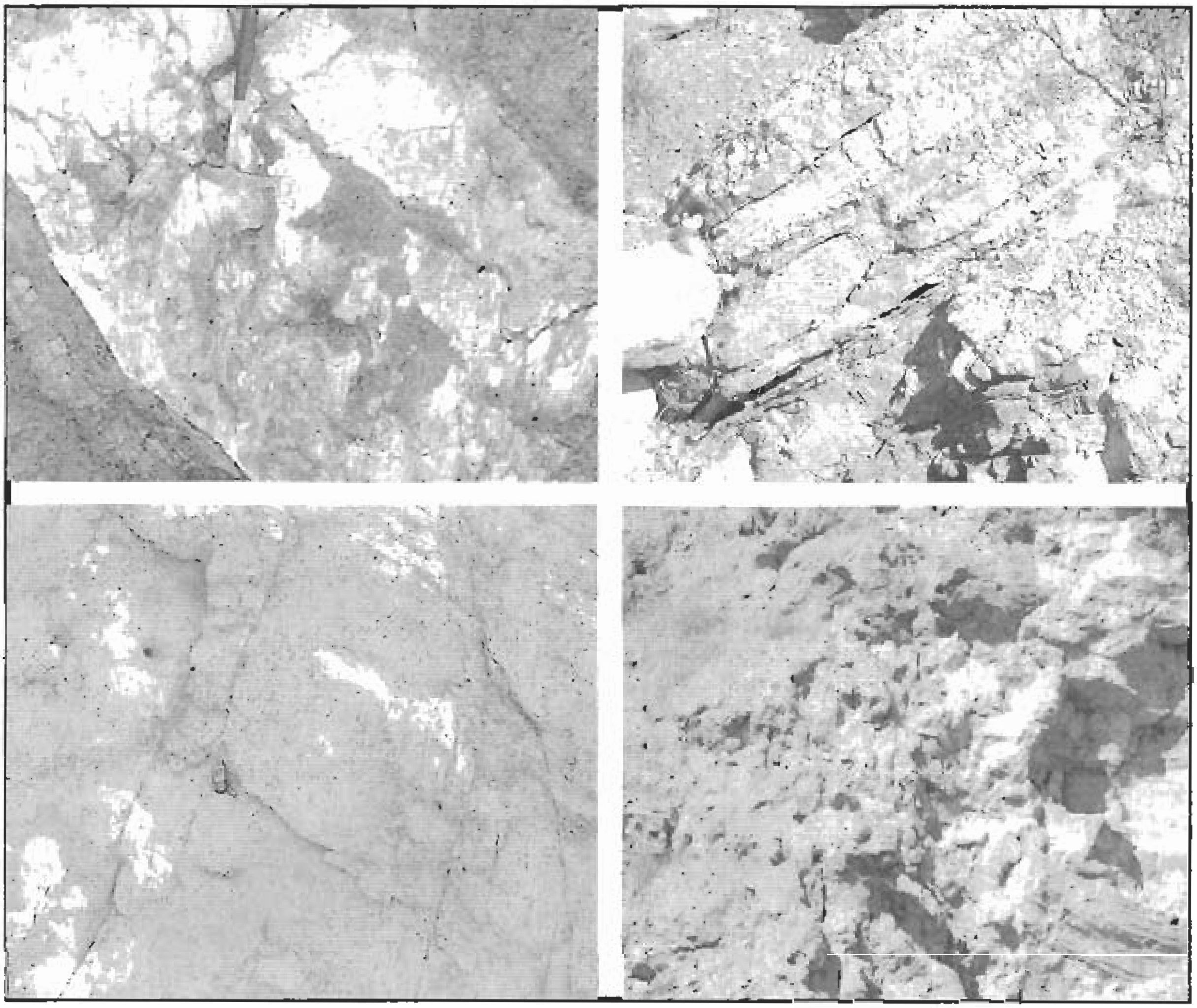


Plate 2.3 ESE looking view of the thick bedded to massive, gray to white gray dolomite interbedded with pink to whitish gypsum along the bedding planes within the utana Formation, exposed along Saiyiduwali section.

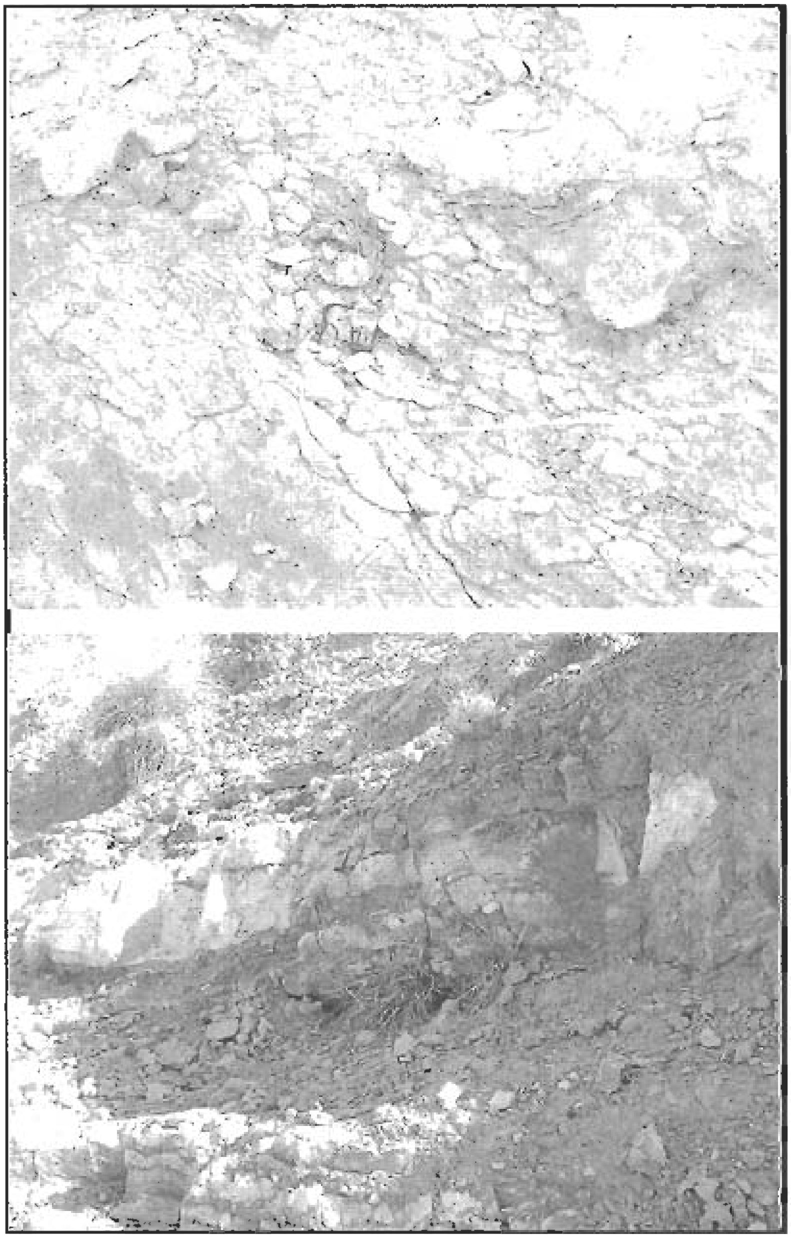


Plate 2.4 North and Southeast looking view of the outcrop of Khisor Formation showing gypsiferous beds and its intercalation with dolomite, silty shale and sandstone, exposed along Saiyiduwali section.

The dominant portion is whitish to light brownish and occasionally pinkish yellow gypsum in the upper part of the formation. The gypsum is thick-bedded to massive and formed crenulations faces at the top. Dolomite is the second dominant facies and observed its lateral extension in the formation. Texturally the dolomite is fine to very fine-grained and thick-bedded to massive. It is gray to dark gray, occasionally pinkish to weathering brownish gray. The shale is thin bedded to sheeted or laminated and infrequently gypsiferous at places. The gypsum is interbedded with gypsiferous shale. The sandstone formed the lower horizon of the formation. It is laminated to flaggy bedded where the siltstone is thin to medium bedded.

The Khisor Formation is 162 m thick in the Saiyiduwali section (Fatmi et al., 1999 and Wahid et al., 2004). Its contact with the underlying Jutana Formation is conformable whereas its upper contact with the Tobra Formation of Permian age is disconformable. The formation, which is composed of fossils, is regarded as a lateral facies equivalent to the Baghanwala Formation (Salt Pseudomorph beds) of the Salt Range, having a similar stratigraphic position. The Baghanwala Formation is developed in the Khisor Range. It is therefore assumed that the Khisor Formation to be of the similar early Middle Cambrian age.

2.2.2 Permian succession

The Permian sequence of the study area consists of the Nilawahan and Zaluch Group. The sequence is predominantly clastic, where siltstone intervals alternate with coarse sandstone and conglomerate horizon has been observed. The only significant limestone interval is the Wargal Limestone, but carbonates do tend to take place more extensively in the Zaluch Group.

The Nilawahan Group includes the Tobra, Warchha and Sardhai Formation.

2.2.2.1 Nilawahan Group

The following three formations occur in the Nilawahan Group:

Sardhai Formation

Warchha Sandstone

Tobra Formation

2.2.2.1 a Tobra Formation

The Tobra Formation along the Saiyiduwali and Dhupsari sections in the western and eastern Khisor Range respectively divisible into the following three units from bottom to top:

i) Upper unit: the upper unit is comprised of greenish to dark green medium to thick bedded siltstone and sandstone. The sandstone beds are containing pebbles and cobbles of igneous, metamorphic and clastic rocks (Plate 2.5).

ii) Middle unit: the middle unit is brownish to coffee brown, fine to medium-grained, thick-bedded to massive sandstone. The sandstone is comprised on pebbles and observed conglomerate at the base.

iii) Lower unit: the lower unit consists of brownish to greenish-brown and blackish, thick-bedded to massive. Poorly-sorted terrigenous / clastic material, fine to coarse-grained occasionally boulders observed in the lower part of the lower unit in the Saiyiduwali section.

Principally the formation is a tillite. It is 86 m thick along the Saiyiduwali section (Fatmi et al., 1999 and Wahid et al., 2004), (Table 2.1 and Plate 2.5). Kummel and Teichert (1970)

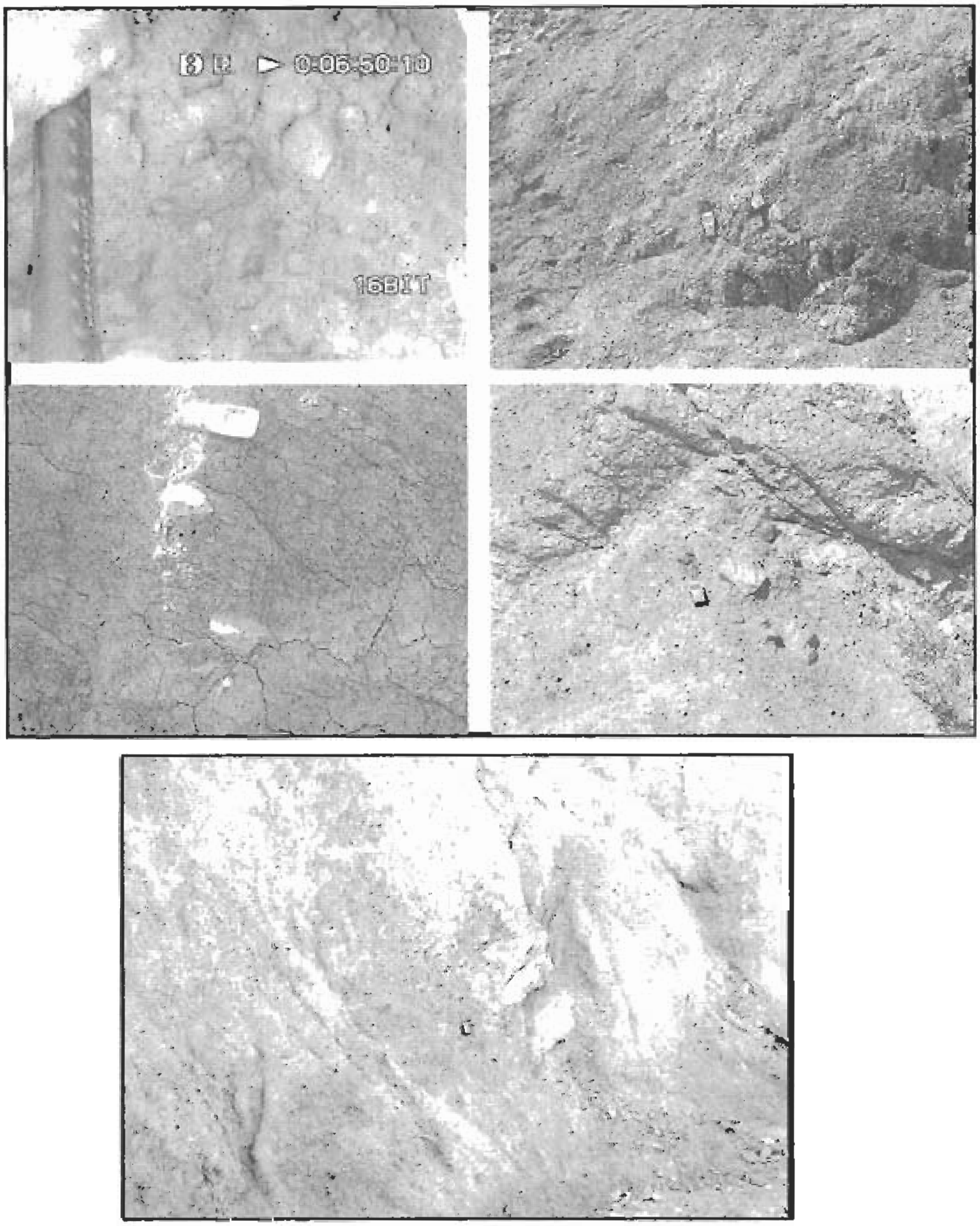


Plate 2.5 Northwest and southeast looking view of the Tobra Formation, show pebbles and cobbles of the igneous and clastic rocks within green and reddish sandstone beds.

Plate 2.6 NW looking view of the contact between Tobra Formation and Warchha Sandstone northwest of Saiyiduwali.

considered the Tobra Formation in the Khisor Range as a mixed facies of diamictite, sandstone, and boulder beds.

The Warchha Sandstone overlies the Tobra Formation conformably whereas its lower contact with the Khisor Formation is disconformable, marked by a sharp change in lithology and distinct wavy bedding of the underlying pink gypsum of Khisor Formation. On the basis of the presence of Striatopodocarpites and Protohaploxypinus, its age is considered to be Early Permian (Blame and Teichert, 1967).

2.2.2.1b Warchha Sandstone

Hussain (1967), named the Warchha Sandstone. Previously the unit was named "Warchha Group" Noetling (1901), "Speckled Sandstone" by Gee (1945), and middle Speckled Sandstone by Waagen (1881).

The Warchha Sandstone is exposed throughout the Khisor Range, particularly in the Saiyiduwali and Dhupsari sections. As the name represents, it is predominantly composed of fragile, soft medium to coarse-grained sandstone. There are no competent beds of the sandstone observed throughout the sandstone horizon. The sandstone some times interbedded with shale. The sandstone is massive and red to chocolate brown, and cross-bedded (Fig. 2.1 and Plate 2.7). The lower part of the sandstone is coarse while the upper part observed fine. The mass of the sandstone body comprised on fine to coarse fragments of the pre-existing crystalline rocks and observed upward fining depositional environments. The shale is soft, thin bedded and occasionally flaky, brownish to dark and partly chocolate brown.

The formation is 136 m thick in the Saiyiduwali section (Fatmi et al., 1999 and Wahid et al., 2004). It directly overlies the Tobra Formation and is overlain by the Sardhai Formation with a gradational contact. On the basis of its stratigraphic position with the overlying and underlying Early Permian formations, the same age has been assigned to it.

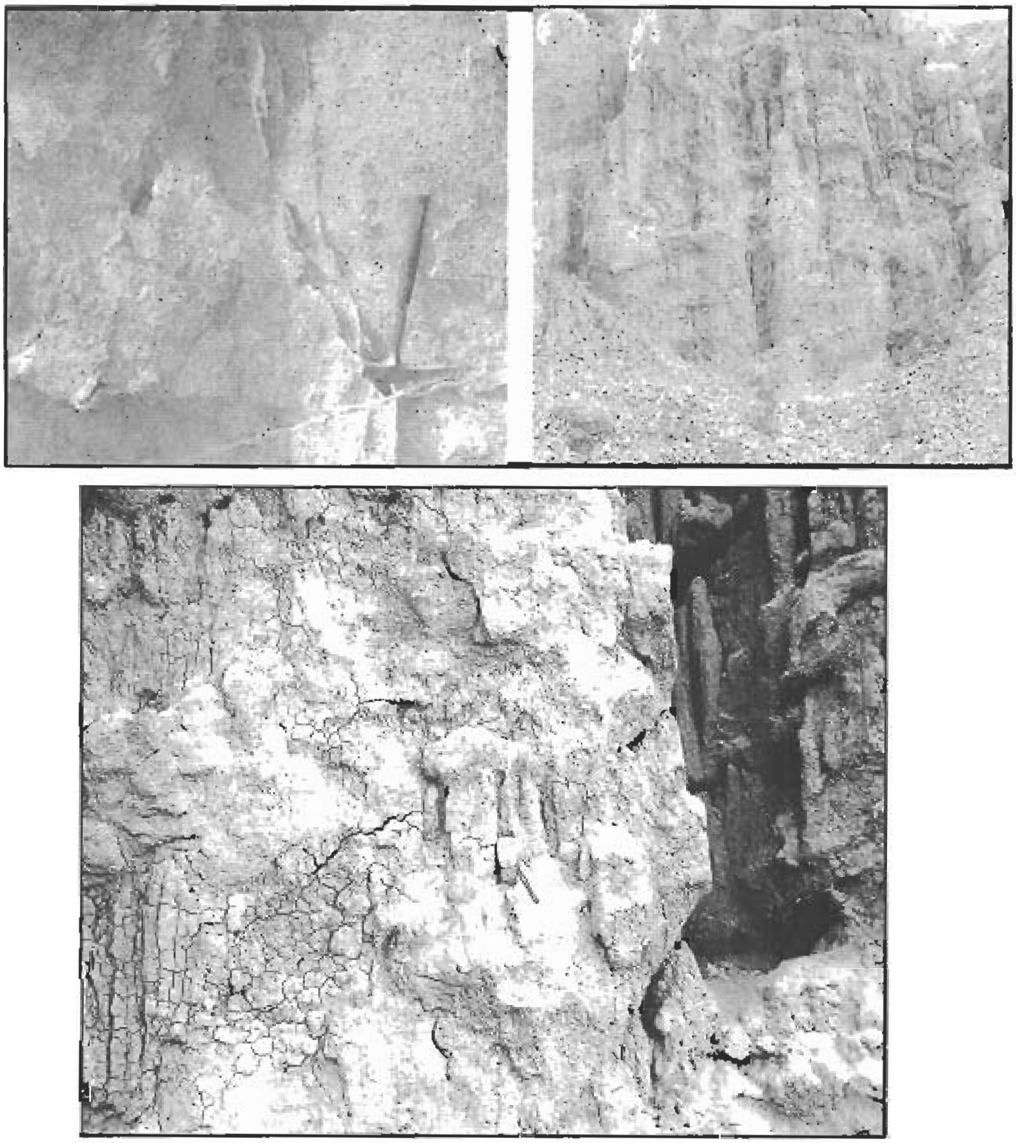


Plate 2.7 NE looking view of the Warchha Sandstone. The sandstone is red / purple, coarse grained and massive exposed in the central Khisor Range.

2.2.2.1c Sardhai Formation

The Sardhai Formation mapped in the Saiyiduwali and Dhupsari sections. The formation predominantly composed of blackish to dark black shale with insignificant sandstone in the said sections (Fig 2.1 and Plate 2.8). The shale is silty and most probably carbonaceous and occasionally interbedded with thin bedded whitish sandstone. Well developed thin to medium bedded limestone observed in the eastern Khisor Range.

The thickness of this formation is 42 m in the Saiyiduwali section (Fatmi et al., 1999 and Wahid et al., 2004). Gradational contact to the Warchha Sandstone has been observed while conformable contact has been seen with the Amb Formation in the Saiyiduwali and Dhupsari sections. The formation has been assigned an Early Permian age by Hussain (1967).

2.2.2.2 Zaluch Group

The Zaluch Group is subdivided into the following formations distinguished from each other by difference in limestone proportion:

Chhidru Formation

Wargal Limestone

Amb Formation

The Zaluch Group represents totally marine conditions, which prevailed over the Indus Basin and Punjab Platform areas of Pakistan in Late Permian times. It generally differs from the underlying rock sequences by it's predominantly carbonate lithologies. The onset of deposition above the Sardhai Formation is made up sandstone and marginal marine limestone of the Wargal Limestone. The boundary between these formations tends to be gradational. The Wargal Limestone is however distinctive, with well defined top and bottom

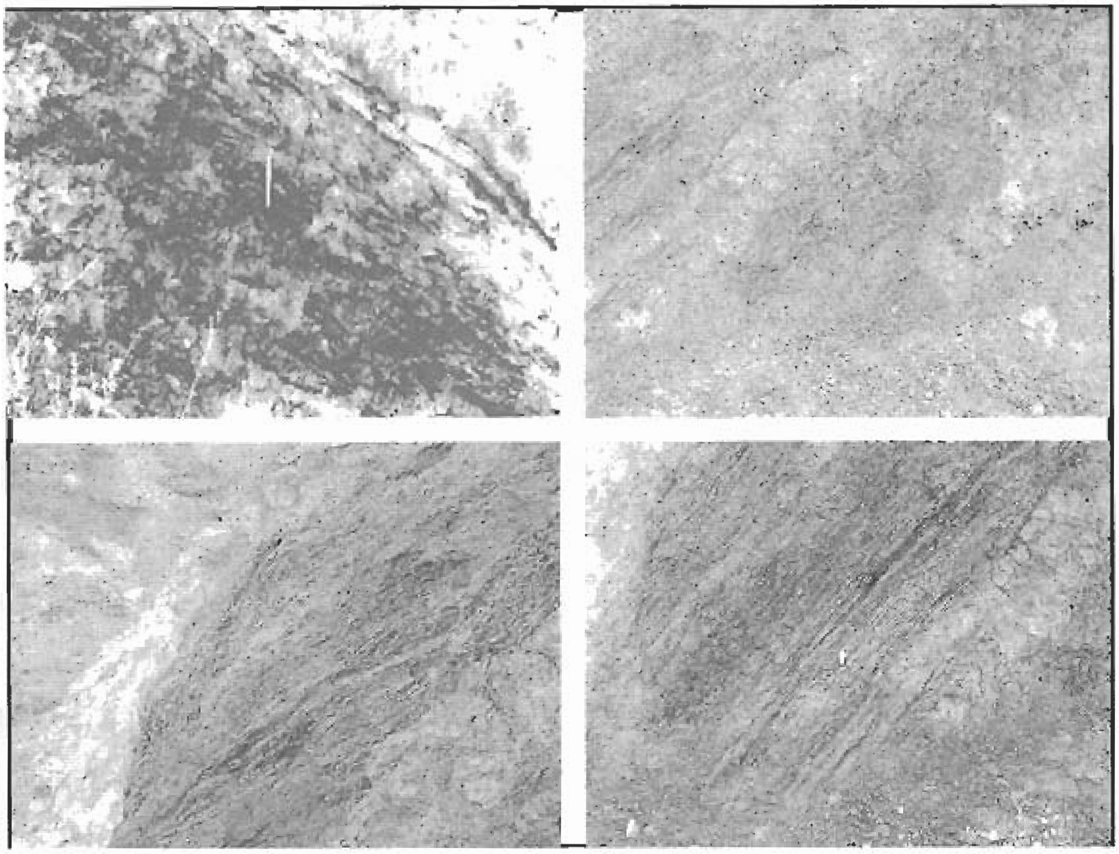


Plate 2.8 NNW looking view of the outcrop of Sardhai Formation that consists of blackish to dark black, silty and carbonaceous shale interbedded with sandstone, exposed in the eastern Khisor Range

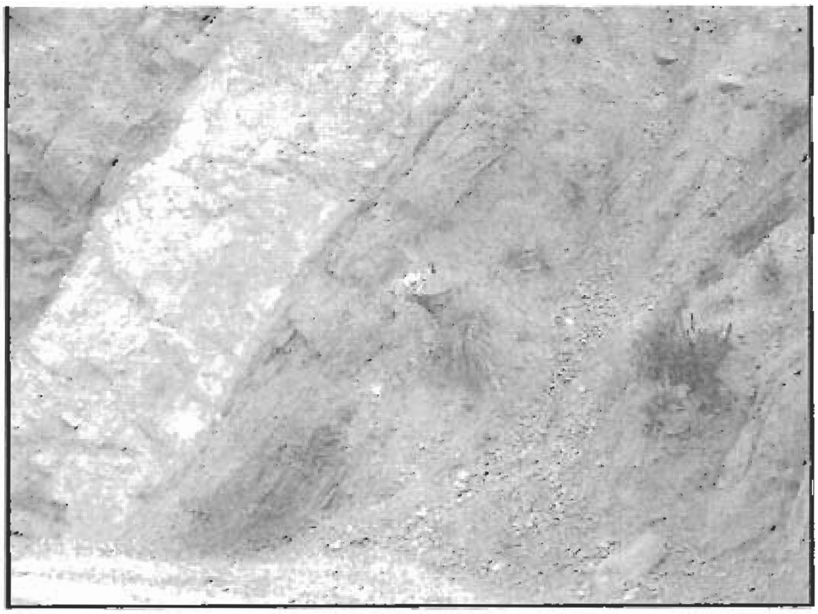


Plate 2.9 NW looking view of the contact between Sardhai and Amb Formation NW of Dhupsari village.

boundaries and a highly fossiliferous (mainly brachiopod) limestone lithology. The youngest formation of Permian age is the Chhidru Formation, consists of sandstone, shale and an occasional limestone horizon deposited in probably marginal marine, estuarine or lagoonal conditions. The uppermost unit of the Chhidru Formation, brownish white sandstone with Late Permian brachiopods, is unconformably overlain by a dolomite unit of the Triassic period.

2.2.2.2a Amb Formation

The Amb Formation is well exposed in the frontal margin of the Khisor Range except the Paniala section and primarily consists of limestone and sandstone (Fig 2.2 and Plate 2.10).

The lower part of the formation comprised of thick bedded to massive sandy limestone. The sandy limestone is gray to brownish gray and highly fossiliferous and the sandstone beds at the base of the formation observed medium to thick bedded and coarse grained (Plate 2.10). The lower most part of the formation composed of dark gray to blackish shale. The rich fauna of the calcareous sandstone and limestone indicates a shallow to very shallow marine paleo-environment, probably with intermittent periods of lacustrine conditions during which the carbonaceous shale and coal were deposited.

Both the lower and upper contact of the formation with Sardhai Formation and Wargal Limestone are conformable respectively. The thickness of formation as measured in the Saiyiduwali section is 60 m (Fatmi et al., 1999 and Wahid et al., 2004).

Based on the faunal assemblages such as fusulinids, bryozoans, brachiopods, bivalves and gastropods and index fossil Monodiexodina Kattaensis the formation has been assigned an Early Permian age (Pakistan-Japanese Research Group, 1985).

2.2.2.2b Wargal Limestone

The Wargal Limestone is extensively exposed in the Khisor Range except in the western part of the study area. The Wargal Limestone consists largely of limestone, dolomitic limestone and sandy limestone. Base is composed of sandy limestone of grayish to reddish brown and medium to thick-bedded wit thin beds of dark gray to blackish shale. The middle part of the Wargal Limestone is dolomitic limestone which is thick-bedded to massive and contains crinoids and bellerophon. The upper part of the formation consist of massive resistant limestone horizon which makes huge cliff throughout frontal Khisor Range, is gray to brown, weathers dark gray, with the existence of plentiful mega fauna in which the brachiopods are major contents (Plate 2.11).

The formation in the Saiyiduwali section comprises limestone and dolomitic limestone (Fig 2.2). The Dhupsari section composed of whitish limestone at the lower part while reddish nodular to thick bedded at the upper part (Plate 2.11). Colour variation observed throughout limestone horizon. Black to dark brown of glassy appearances chert nodules observed mostly along the bedding planes in the form of irregular lenses. The limestone is frequently nodular particularly is the characteristic of the lower part. The upper part is composed on thick bedded to massive limestone. The limestone is light reddish to whitish and observed oolitic.

The thickness of the Wargal Limestone is 156 m in the Saiyiduwali section (Fatmi et al., 1999 and Wahid et al., 2004) and 149 m in the Paniala section of Khisor Range. Its contact with the underlying Amb Formation is conformable whereas its upper contact with the Chhidru Formation is gradational and also conformable. Based on brachiopods, Ustritsky (1962) placed the formation in the Late Permian.

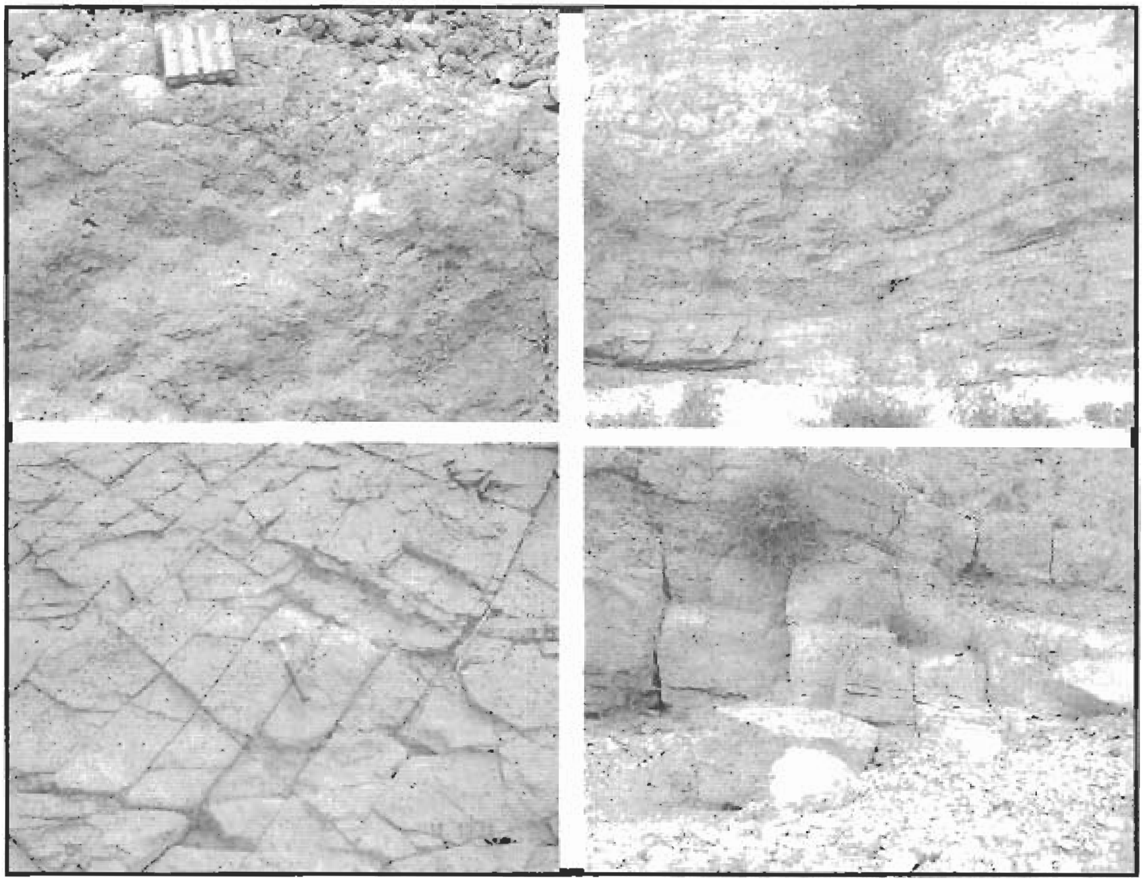


Plate 2.10 South looking view of the Amb Formation cross-joints developed in the sandy limestone beds, exposed along the central and eastern Khisor Range.

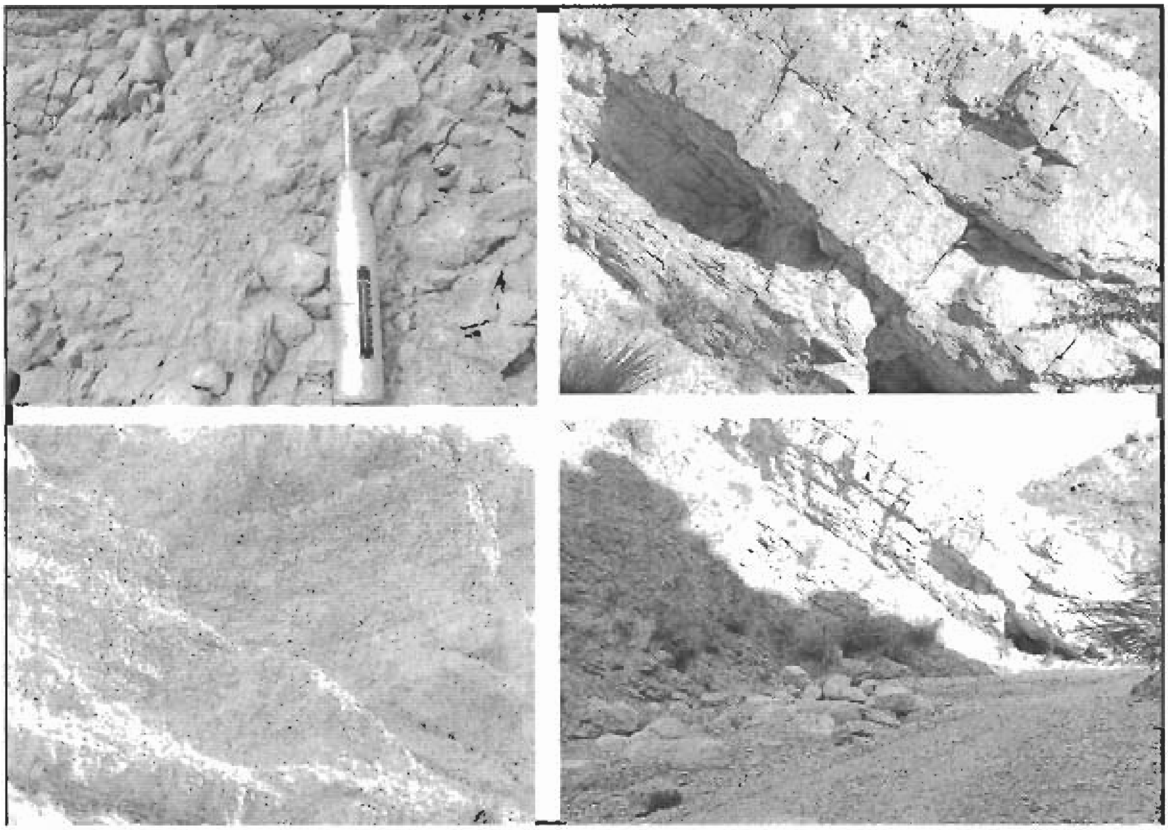


Plate 2.11 NE looking view of the fractured and thick bedded limestone of the Wargal Limestone exposed northwest of the Saiyiduwali and Dhupsari villages.

Plate 2.12 South looking view of the contact between Amb Formation and Wargal Limestone NW of Dhupsari Village.

2.2.2.2c Chhidru Formation

Waagen (1891) named the rocks overlying the Wargal Limestone as "Chhidru beds" and Noetling (1901) called them the "Chhidru Group". Dunbar (1932) introduced the name Chhidru Formation.

It consists predominantly of sandy limestone, limestone, sandstone and shale in the Saiyiduwali section. The formation comprised yellowish to gray shale at the base. This unit is overlying by weathered brown to dark brown calcareous sandstone. The limestone is gray to weathering brownish gray medium to thick bedded. It is argillaceous highly fossiliferous and observed black chart along the bedding planes (Plate 2.13). In the middle the formation comprised on thin bedded to medium bedded fractured sandy limestone and is overlain by calcareous sandstone and sandy limestone (Fig 2.2 and Plate 2.13). The sandstone is massive and medium to coarse-grained. The uppermost part of the formation comprised on whitish fine-grained friable sandstone bed of 2 m thick. Black to dark black hard and glassy chert occurs along the bedding planes is the characteristics feature of the upper portion of the formation. The chert content observed more in proportion than the Wargal Limestone. The thickness of the formation is 92 m in the Saiyiduwali section and 68 m in the Paniala section (Alam et al., 2003). The Wargal Limestone conformably underlies it and its upper contact is a well-defined paraconformity with the Mianwali Formation of Early Triassic age (Kummel and Teichert, 1970). The formation observed highly contains mega fossils at different horizons. It contains mostly brachiopods and corals in the lower horizon while crinoids and bellerophon have been seen in the upper most horizon of the formation. Brachiopods include Derbyia, Linoproductus, Spirifer and Spirigerella. The age assigned to the formation is Late Permian (Kummel and Teichert, 1970).

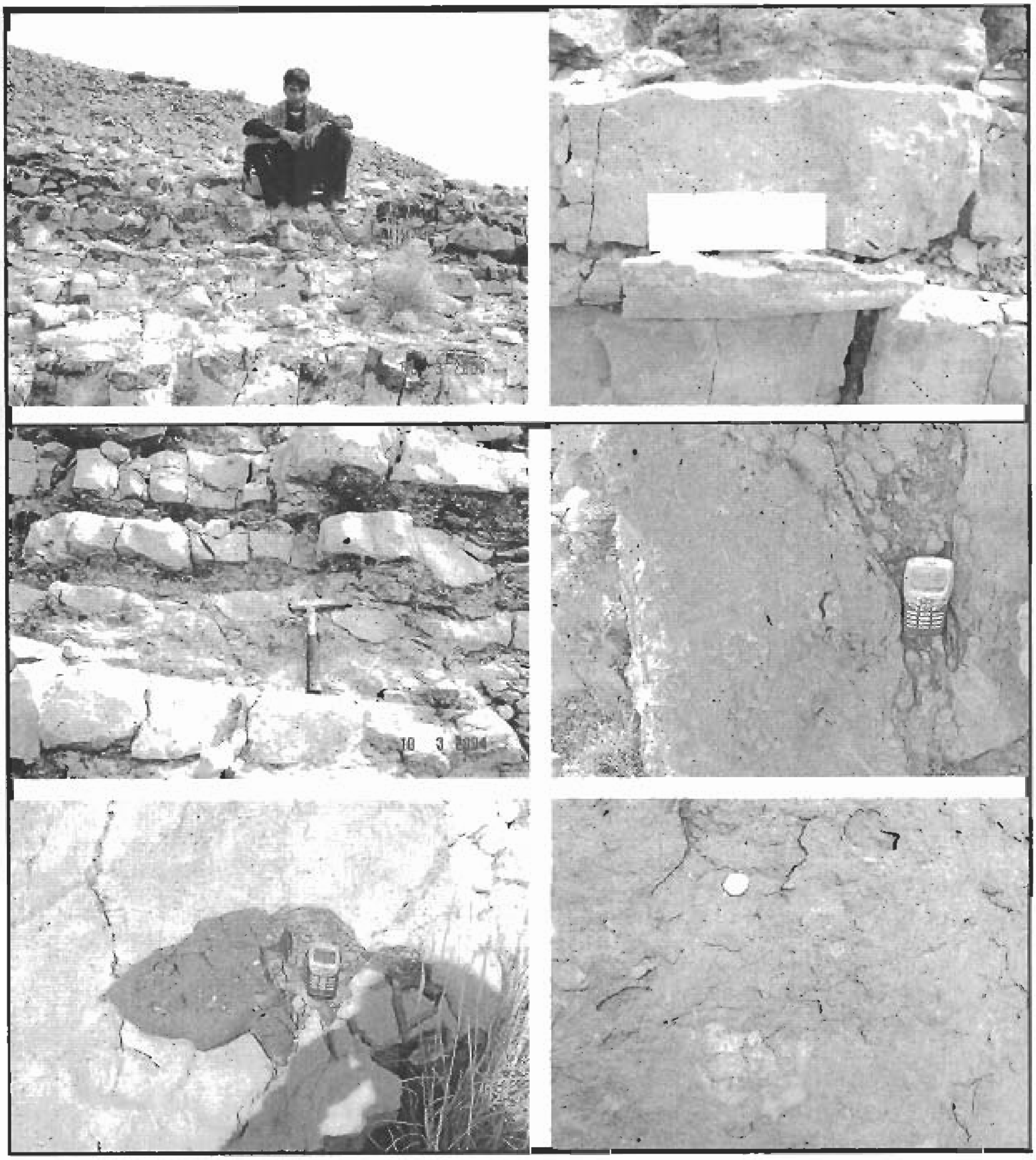


Plate 2.13 NNE looking view of the Chhidru Formation that consists of sandy limestone and shale. Boudinage features are found in the stiff layers of the formation.

2.3 MESOZOIC ROCKS

Mesozoic rocks are well developed in the western and central domain of the Khisor Range. Exposures of Jurassic rocks are limited and only occur in the vicinity of Paniala village whereas the Triassic rocks dominate in the western and central parts and have limited exposure in the eastern parts of the Khisor Range.

2.3.1 Triassic Succession

Rocks of the Musa Khel Group make up the Triassic sequence of the Khisor Range and include the following three formations from top to bottom:

Kingriali Formation
Tredian Formation
Mianwali Formation

2.3.1a Mianwali Formation

The Mianwali Formation is exposed and mapped throughout the Khisor Range. Lithologically the formation consists of varied facies of limestone, sandstone, dolomite and shale. The formation is well developed comparatively in the western Khisor Range rather than in the eastern Khisor Range. Its total thickness is 127 m in the Saiyiduwali section (Fatmi et al., 1999 and Wahid et al., 2004) and 118 m in the Paniala section (Table.2.1 and Plate. 2.14). The Mianwali Formation is distinguishable into the following three members in the Khisor Range.

iii) Narmia Member   ii) Mittiwali Member   i) Kathwai Member

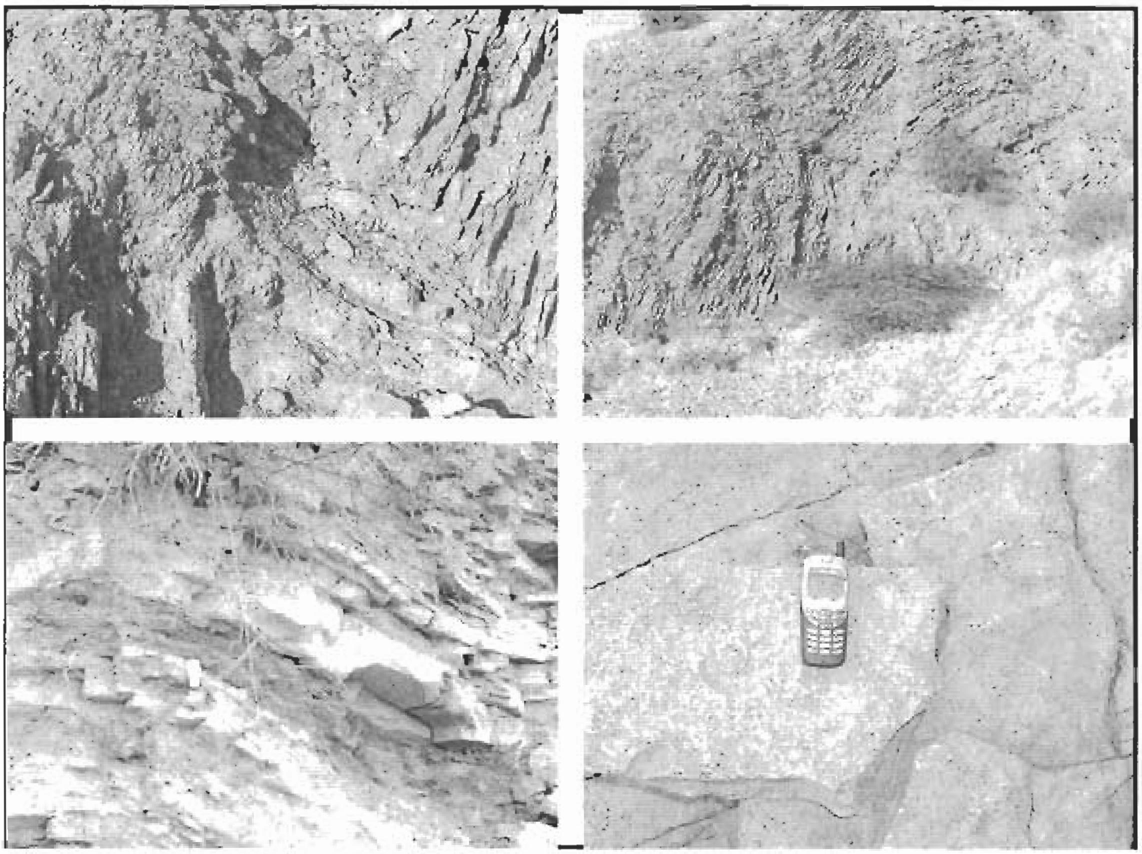


Plate 2.14 NNE looking view of the Mianwali Formation showing marl, limestone, sandstone, siltstone and dolomite within the formation, exposed along the western and central Khisor Range.

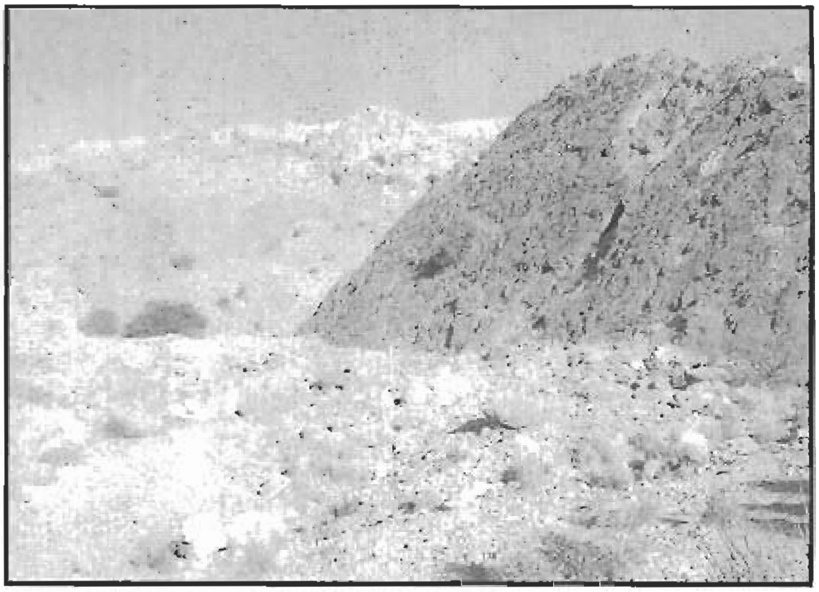


Plate 2.15 NW looking view of the contact of the Chiddru and Mianwali Formation SW of Paniala.

i) Kathwai Member

This member consists of dolomite unit in the lower horizon while limestone in the upper horizon. The dolomite is thin to medium bedded, brownish to greenish gray. The limestone is occupied the upper part. It is gray to brownish gray and observed glauconitic. Carbonaceous shale occurs in the lower part and is overlain by brown dolomite and glauconitic limestone that contains ammonites. This member is 7 m thick in the Saiyiduwali section, 4 m thick in the Paniala section (Alam et al., 2003), (Fig 2.2 and Plate 2.15).

ii) Mittiwali Member

This member consists of fine-grained, non-glauconitic limestone with rich ammonites contents. The basal unit is greenish to grayish, micaceous, pliable, silty and flaggy bedded shale. Interbeds of the silty shale and limestone with secondary sandstone are also observed. Crinoidal limestone is present in the uppermost horizon of the member (Alam et al., 2003).

High fossils content are observed in the Mittiwali Member as shown in the (Plate 2.14). Its thickness is 84 m in the Saiyiduwali section and 80 m thick in the Paniala section (Alam et al., 2003), (Table.2.1).

iii) Narmia Member

The lower part of the Narmia Member consists of gray to brownish gray fragmental limestone. The limestone is sandy in places and contained fauna like brachiopods and ammonides. The upper portion of the member comprised of gray to greenish gray shale with interbeds of sandstone. The uppermost horizon comprised of dolomite and limestone. The dolomite is gray to brownish gray and thick-bedded. It is 36 m thick in the Saiyiduwali section and 34 m thick in the Paniala section (Alam et al., 2003), (Fig 2.2 and Plate 2.11). The age assigned to the formation is Early Triassic (Kummel, 1966).

The lower contact of the formation with the Chhidru Formation of Late Permian age is marked by a paraconformity, whereas its upper contact with the overlying Tredian Formation is sharp and well defined.

2.3.1b Tredian Formation

The Tredian Formation is basically non-marine unit that overlying by the Mianwali Formation. The Tredian Formation is exposed in the western Khisor Range and is divisible into two members; the lower Landa Member and the upper Khatkiara Member (Danilchik and Shah 1967).

i) Landa Member

Two facies are recognized in this member such as sandstone and shale. The sandstone is non-calcareous, soft, fine-grained, micaceous medium bedded, and shows different colour. The shale is gray to greenish gray, soft, laminated to very thin bedded. It is 22 m thick in the Saiyiduwali section (Fig 2.1) and 18 m thick in the Paniala section (Alam et al., 2003), (Fig 2.2).

ii) Khatkiara Member

The Khatkiara Member is comparatively the massive of the two members and consists of whitish gray to weathering gray, medium to thick-bedded, medium to coarse-grained and cross-bedded sandstone in the lower part of the member. Light gray dolomitic beds observed on the top of the member. It is 24 m thick in the Saiyiduwali section (Fig 2.1) and 42 m thick in the Paniala section (Alam et al., 2003), (Fig 2.2 and Plate. 2.16).

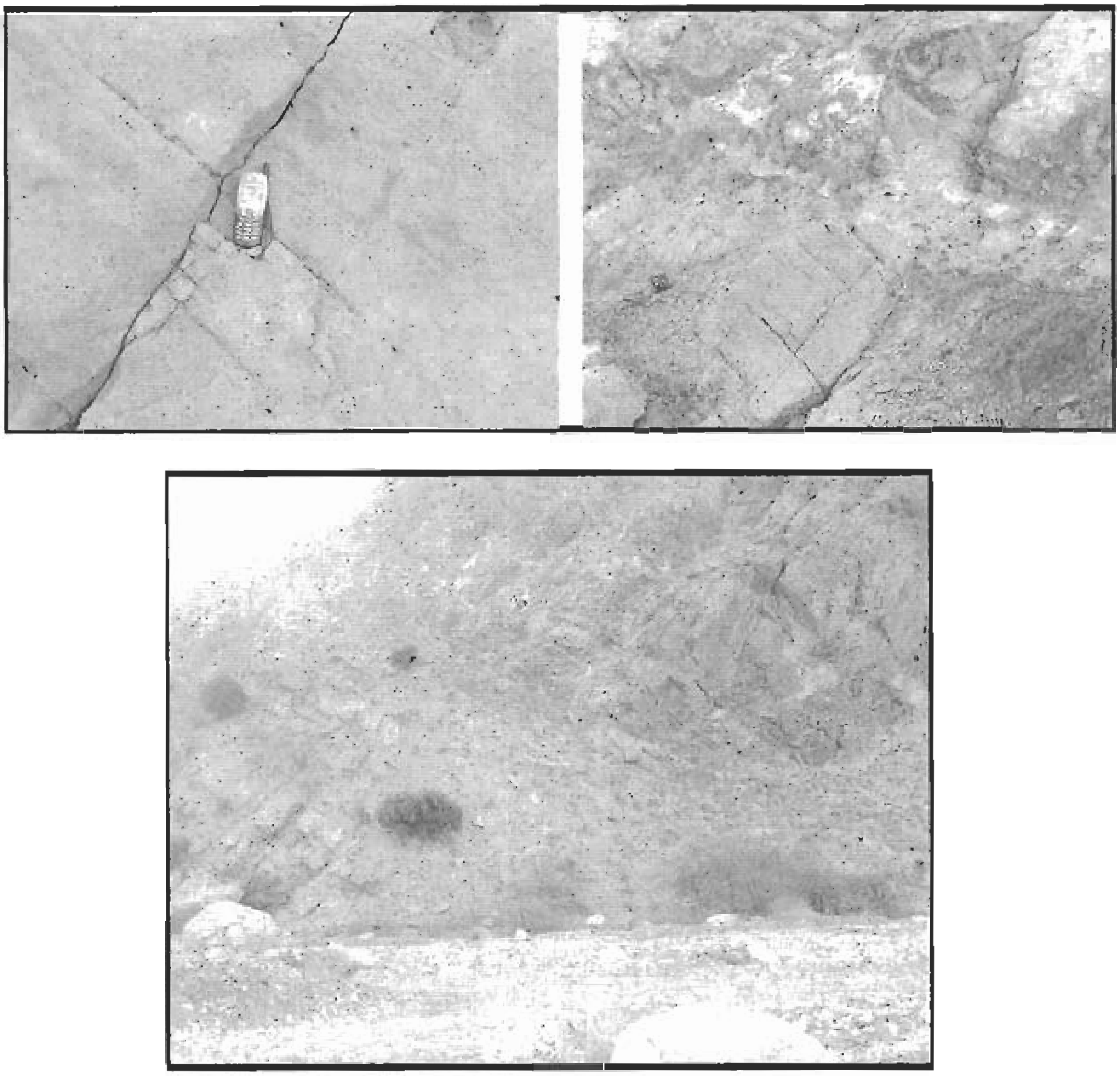


Plate 2.16 SE looking view of the thick to massive bedded sandstone of Tredian Formation exposed along the Paniala section. The sandstone is soft, fine grained and cross-bedded.

The Tredian Formation conformably overlies and underlies the Mianwali and the Kingriali Formation respectively. Its age is Middle Triassic, on the basis of its stratigraphic position overlying the Mianwali Formation of early Triassic age.

The total thickness of the Tredian Formation is 46 m in the Saiyiduwali section and 60 m in the Paniala section.

2.3.1c Kingriali Formation

The Kingriali Formation has been divided into two members, a lower Doya Member and an upper Vanjari Member in the Surghar Range (Fatmi et al., 1990).

i) Doya Member

The Doya Member is composed of medium to thick bedded dolomite and dolomitic limestone with interbedded greenish gray dolomitic shale. In the Ghori Tang Nala southwest of Paniala village the dolomite is light brownish gray, fine to coarse granular by textural array and marly in the upper part (Plate 2.17 and 2.18). The member is 33 m thick in the Saiyiduwali section and 20 m in the Paniala section (Alam et al., 2003), (Fig 2.1 and 2.2).

ii) Vanjari Member

The lower part of this member is comprised of thick-bedded to massive dolomite. The upper portion of the member dominantly composed of dolomitized marl and shale and both are interbedded with dolomite and dolomitic limestone in the top most horizon. The dolomite is gray to weathering brown, medium to thick-bedded. The dolomite is texturally fine to coarse-grained and visually observed solid, hard, dense and occasionally fractured. In the lower horizon the dolomite is sandy and thick bedded. The upper dolomitic horizon comprised of medium to

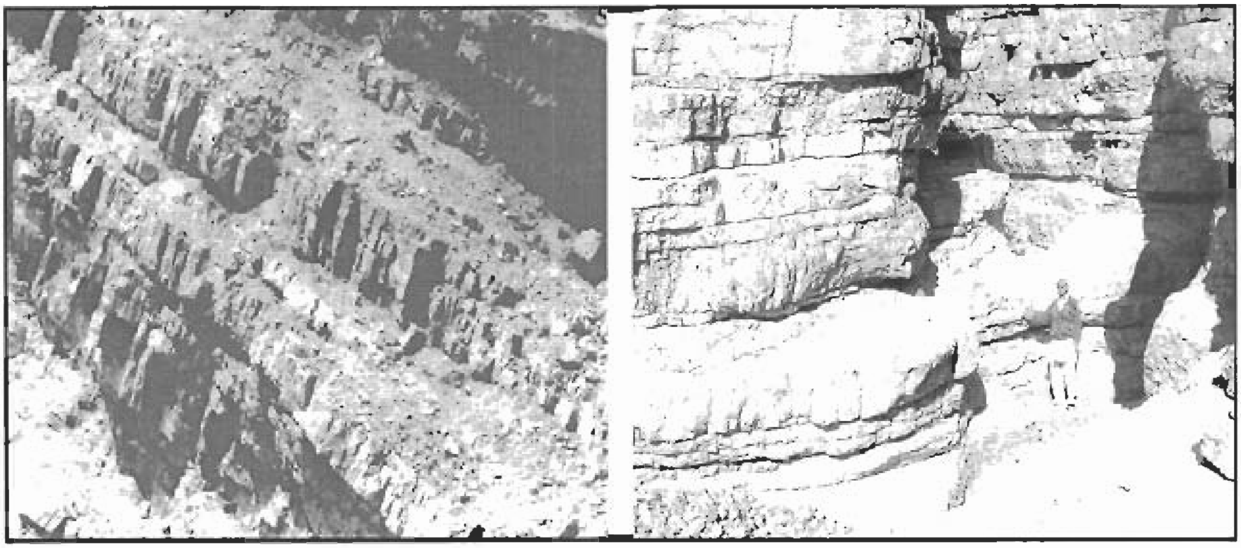


Plate 2.17 Photograph showing an interbedded sequence of dolomite and sandstone within Kingriali Formation, exposed along Paniala section looking towards NE.

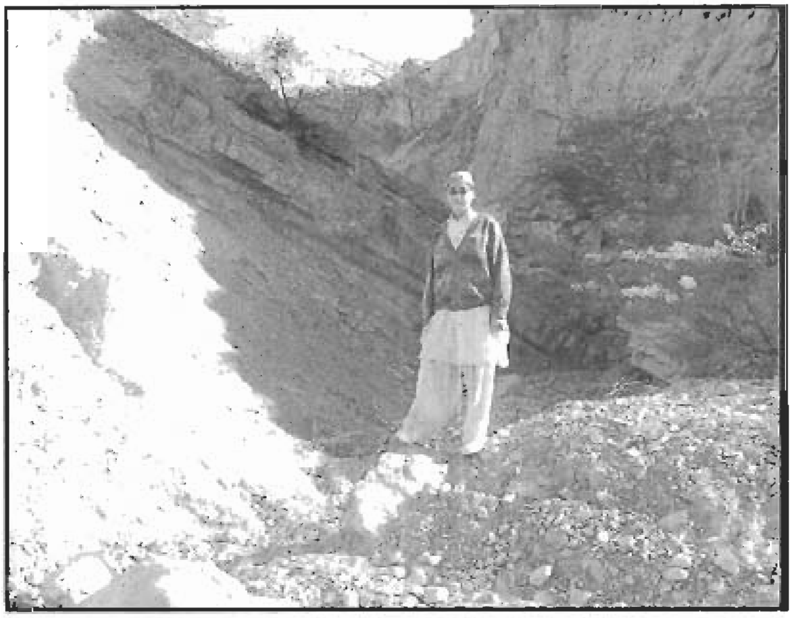


Plate 2.18 SW looking view of the contact between Datta and Kingriali Formation SE of Paniala.

thick bedded, where marly dolomite interbedded with dolomitized marl. The dolomitic limestone is white; fine grained, hard and medium bedded. Chert makes its way wide along the bedding planes. The exterior of the topmost dolomitic layer is observed uneven and rough.

The Vanjari Member is not fully present in the Saiyiduwali section, where it forms Kingriali Peak, but is well developed in the Paniala section (Fig 2.2).

The total thickness of the Kingriali Formation is more than 101 m in the Saiyiduwali section and 108 m in the Paniala section. Interbedded dolomite and sandstone marks its basal contact with the Tredian Formation, whereas the upper contact with the Datta Formation is disconformable as indicated by the development of rusty brown, ferruginous dolomite and an uneven surface at the contact. Fossils are rare and poorly preserved. Some brachiopods, bivalves and crinoidal remains have been recovered that indicate a Late Triassic age for the formation.

2.3.2 Jurassic Succession

Two formations, the Datta and Shinawari are exposed in the western Khisor Range in the vicinity of Paniala.

2.3.2a Datta Formation

The formation is primarily of continental origin and comprised of multicolored sandstone and shale with siltstone intercalations in the Paniala section. The sandstone is medium to thick bedded, fine to coarse-grained, comparatively soft, fragile and cross-bedded. The lower horizon of the formation consists of thin to thick bedded sandy dolomite. Lower part comprised of white, fine to medium grained silica sand while the upper part composed of different colour of medium to coarse-grained silica sand (Plate 2.19).

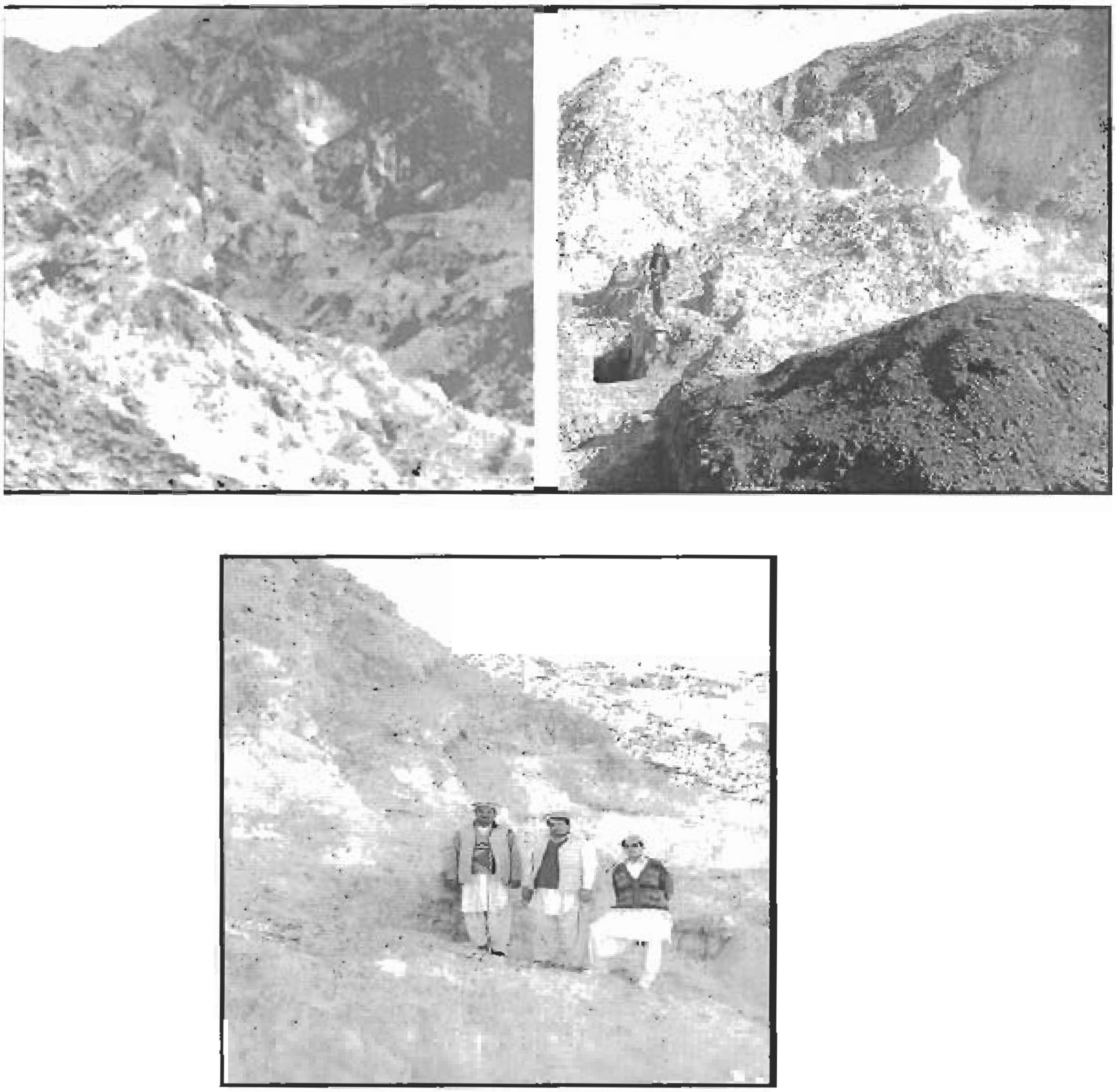


Plate 2.19 Photograph showing Datta Formation consists of variegated sandstone and siltstone with shale intercalations. The exposure of the formation is restricted to Paniala section of the Western Khisor Range.
Camera's trend towards SE.

Occasional coal seams are present at the lower part of the formation. Similarly Fire clay and laterite beds observed at the lower horizon of the formation. The upper part consists of carbonaceous shale and sandstone interbeds at places. Mining activities of the industrial raw material observed in progress in southwest of the Paniala village.

The thickness of the Datta Formation is 128 m in the Paniala section (Fig 2.2 and Plate 2.19). The formation rests unconformably on the Kingriali Formation and its contact with the overlying Shinawari Formation is gradational. The age is considered Early Jurassic, pre-Toarcian based on lower Toarcian ammonites (Early Jurassic ammonites) (Danilchik and Shah, 1967).

2.3.2b Shinawari Formation

Different lithological units have been observed in the formation. The Shinawari Formation is exposed and mapped in the northwestern margin of the Khisor Range near southwest of Paniala village. Dominantly lithologies observed thin to medium bedded greenish gray limestone, marl, calcareous to non-calcareous shale and thin to medium bedded calcareous sandstone. The limestone is greenish gray to brownish gray, hard and dense, texturally fine to coarse-grained, and sporadically sandy. The shale is gray to dark gray and calcareous. The sandstone is light gray to whitish, thin to thick bedded, quartzose and calcareous. The lower horizon mainly consists of limestone, the middle part composed of thick sandstone and the upper most part of the formation consists of variegated shale.

The formation is 52 m thick and well exposed in the Paniala section and does not continue eastwards (Fig 2.2). It has gradational contacts with the underlying Datta Formation and is unconformably overlain by the Nagri Formation of the Siwalik Group. Ammonites, bivalves, brachiopods and other fossils that indicate an Early Jurassic age have been collected from the lower part of the formation, but the upper part may extend into the Middle Jurassic (Latif, 1970; Fatmi and Cheema, 1972).

The North side of the Khisor Range has well developed Siwalik Group rocks unconformably overlying the Jurassic to Triassic rocks from west towards east. The lithological description of the Siwalik Group rocks is given in the next chapter under the stratigraphic setting of Marwat Range.

CHAPTER 3
Cenozoic Stratigraphy

CHAPTER-3

CENOZOIC STRATIGRAPHY OF THE MARWAT RANGE

3.1 GENERAL DESCRIPTION

The Marwat Range is exclusively composed of Siwalik Group rocks of Pliocene-Pleistocene age exposed instantly south of the Bannu Basin, cropping out in the form of a broad anticline known as the Marwat Anticline in the Marwat Range (Plate 5.4 a, b). The Marwat Range is composed entirely of Siwalik Group rocks that represent the development of a terrestrial foreland basin that controlled generally south-flowing fluvial systems, including the Paleo-Indus River, which was derived from the Himalayas from Pliocene to present. The influence of the advancing orogenic front on the foreland sedimentation becomes more pronounced during the deposition of the Siwalik Group as compared to the Rawalpindi Group because the axis of the Siwalik depocenter shifted southward, resulting in the formation of middle/upper Siwaliks in the Marwat-Khisor ranges (Shah, 1980; Fatmi, 1973; Pilgrim, 1913).

3.2 SIWALIK GROUP

The term "Siwalik" was first used by Meddlicot (1868) for the upper part of the "sub-Himalayan system" of the Siwalik and Simla hills of India. Later on Oldham (1893) and Holland et al. (1913) used the terms "Siwalik Series" and "Siwalik System". The Stratigraphic Committee of Pakistan following Danilchik and Shah (1967) substituted the name Siwalik Group for the "Siwalik Series/System", comprising the following formations, in descending order; the Soan, Dhok Pathan, Nagri and Chinji. The group is mainly composed of alternating beds of sandstone and shale. These rocks were deposited in the riverine belt between the sub-Himalayan hills and the Arabian Sea where

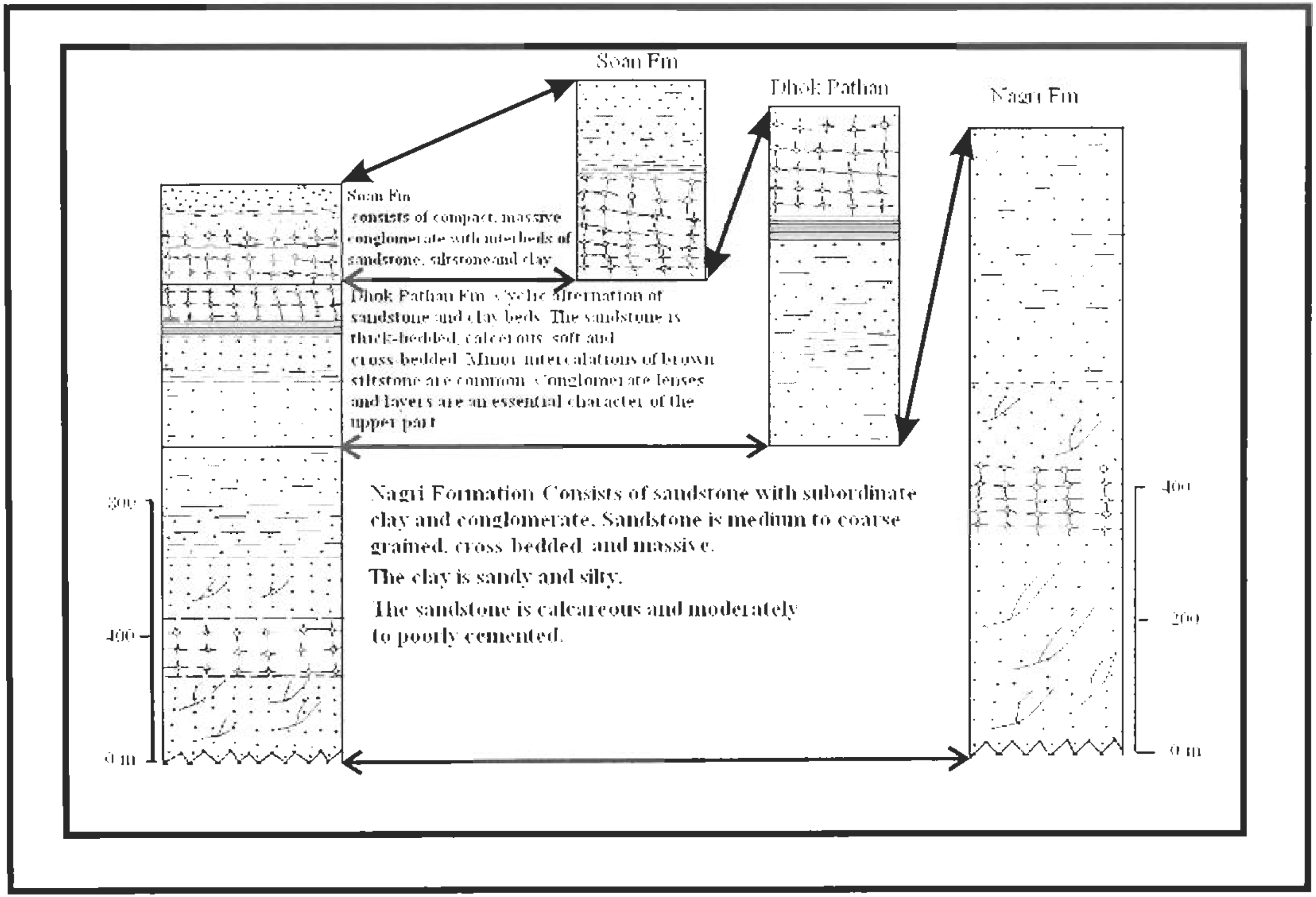


Figure 3.1. General Columnar section of Siwalik Group rocks exposed in the Marwat Range.

a thick pile of fresh-water sediments had been accumulating since the Miocene epoch (Pascoe, 1963). The Shakardarra Formation, which crops out in the southeastern Kohat Plateau is equivalent to the Nagri Formation but contains more conglomerate (Abbasi, 1994). The Shakardarra and Nagri formations were deposited by the south flowing braided fluvial system (Abbasi, 1994). The group, as a whole, consists of sediments of clastic origin of molasse type. The lithology typically consists of red shale with subordinate sandstone (Chinji Formation) at the base that is overlain by thick sandstone with minor shale (i.e., Nagri Formation). This is succeeded by a cyclic alternation of shale and sandstone (Dhok Pathan Formation), followed by a conglomerate, sandstone and shale sequence (Soan Formation) in the upper part.

3.2a Nagri Formation

In the study area, i.e., the northern flank of the Khisor Range and Marwat Range is a whole the Nagri Formation comprised of sandstone with secondary shale and conglomerate beds. The sandstone is grayish to greenish gray, fine to medium-grained, coarse-grained texture observed in the lower part. The sandstone is cross-bedded, thick-bedded to massive. Occasionally the sandstone is bluish to reddish gray, calcareous and fairly to weakly cemented. The shale observed unevenly proportioned from section to section is sandy or silty, dark brown or reddish brown and light orange. The percentage of conglomerate has extremely diverse in thickness and composition in different areas. The conglomerate beds composed of particles of hard rocks and Eocene sedimentary rocks particularly of limestone. The thickness of the Nagri Formation is 950 m in the Marwat Range (Marwat Well-1 and Structural Transects). Transitional contact has been marked with the upper Dhok Pathan Formation. The contact can be easily positioned because it is noticeable by colour alteration from greenish gray to light red or shiny white and also by typical interbedding of shale and sandstone of the overlying Dhok Pathan Formation (Wahid et al., 2004).

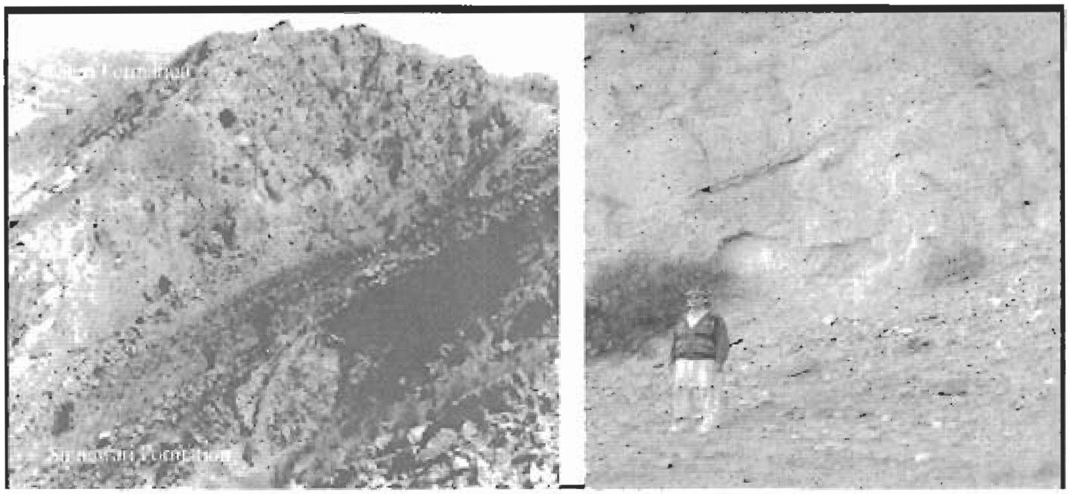


Plate 3.1 Photograph showing the lower unconformable contact of the Nagri Formation with the Mianwali Formation of Triassic age.

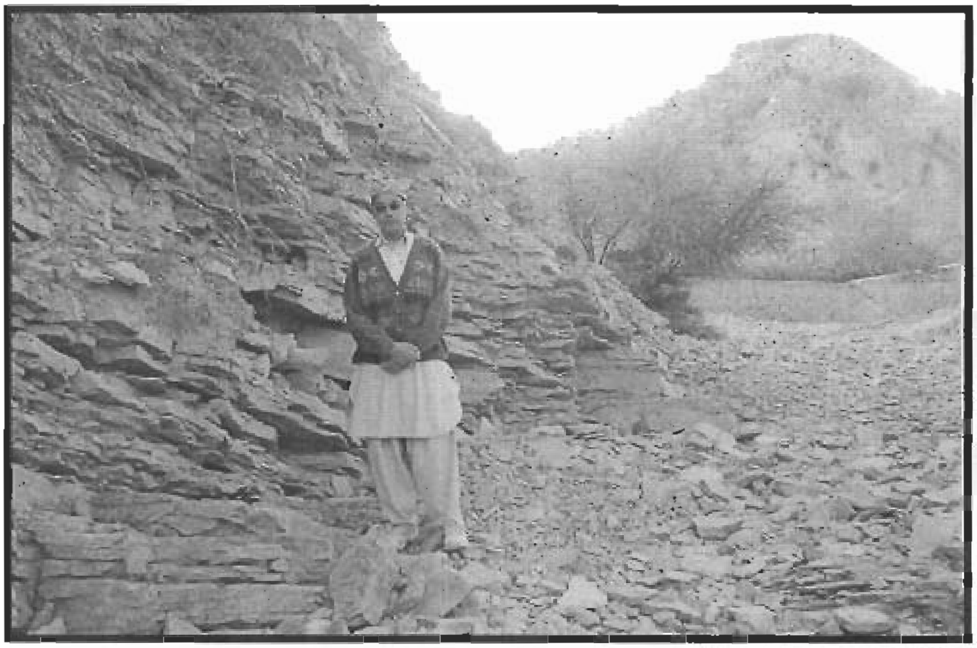


Plate 3.2 Photograph showing the contact of Mianwali Formation with the Nagri Formation, looking towards the south near Badarri Wanda.

The lower unconformable contact of the Nagri Formation is with the Datta and Shinawari formations of Jurassic age in the western Khisor Range that shifts eastwards to Triassic sequence (Plate 3.2 and 3.3). The Hunting Survey Corporation (1961) considered the age of the formation as Pliocene and believed that the lower beds may extend into the late Miocene. The age assigned to the formation in the Kohat-Potwar Province is early Pliocene, on the basis of fossils such as crocodilians, chelonians, perissodactyles, rhinoceratides, carnivors, proboscideans, primates and artiodactyls have been reported by (Pascoe, 1963).

3.2b Dhok Pathan Formation

The name "Dhok Pathan" was introduced by Pilgrim, (1913) in a biostratigraphic sense for the upper subdivision of the "Middle Siwalik" in the northeast Punjab. Cotter (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 Province (1967).

Dhok Pathan Formation is mapped along the northern margin of the Khisor Range and at the both limbs of the Marwat Anticline in the Marwat Range. The formation observed in the appearance like regular reiteration of sandstone and shale beds. The sandstone is generally light gray to gray, shiny white or reddish brown and occasionally brownish gray, greenish gray, thick bedded, calcareous, reasonably cemented, soft and cross beds are the common feature of the out crop . The shale appears is brown to range, reddish brown and occasionally oxidized red, greenish to yellowish brown or coffee brownish. The shale is thin bedded sandy and calcareous at places. Small inclusions of the brownish yellow siltstone are also observed at the lower horizon of the formation. The upper part of the formation frequently comprises on conglomerate. This facies may observe mostly in the form of layers and lenses. The formation is 500 m thick in the study

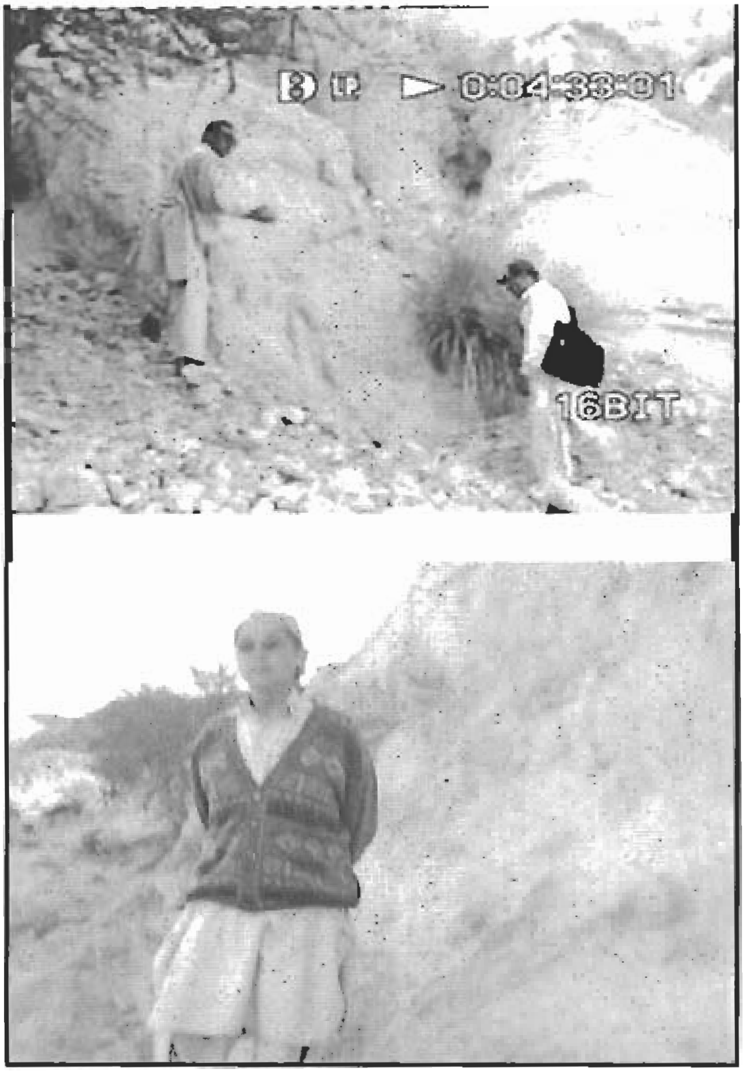


Plate 3.3 a, b North and East looking view of the thick bedded, moderately cemented, soft and cross-bedded sandstone of Dhok Pathan Formation.

area (Marwat Well-1 data and Structural transects across the mapped area). The formation has transitional contact with the underlying Nagri Formation. The upper contact with the Soan Formation is disconformable (Wahid et al., 2004), (Plate 3.4 a, b). The formation is rich in vertebrate fauna, which is remarkable for its rich Hipparion assemblage and numerous artiodactyls. The fauna indicates an early to middle Pliocene age and with exclusive middle Pliocene age in the Kohat-Potwar Province, (Pascoe, 1963).

3.2c Soan Formation

In the study area the Soan Formation consists essentially of compact, massive conglomerate with subordinate interbeds of multicolored sandstone, siltstone and shale (Wahid et al., 2004). The proportion of different rock type varies within short distances. The conglomerate consists of a variety of pebbles and boulders of different sizes (Fig 3.5 a, b, c). The conglomerate is massive and consists mainly of pebbles and boulders of limestone, quartzite, porphyritic rocks, sandstone, gneiss, schist, diabase, etc. The pebbles size ranges from 5 cm to 30 centimeters. Mudstone and sandstone are intercalated. The Mudstone is orange, brown, pale pinkish to red and soft. The sandstone is gray, greenish gray, coarse grained and soft. Thickness of the formation is about 300 m in the study area (Marwat Well-1 data and Structural transects across the mapped area). The formation is underlain by the Dhok Pathan Formation with an apparent disconformity that is marked by sharp coarsening of clastics and by the appearance of massive, densely packed conglomerate. The formation is poorly fossiliferous. The preserved fauna indicates a late Pliocene to early Pleistocene age for the formation, (Pascoe, 1963; and Kravetchenko, 1964)

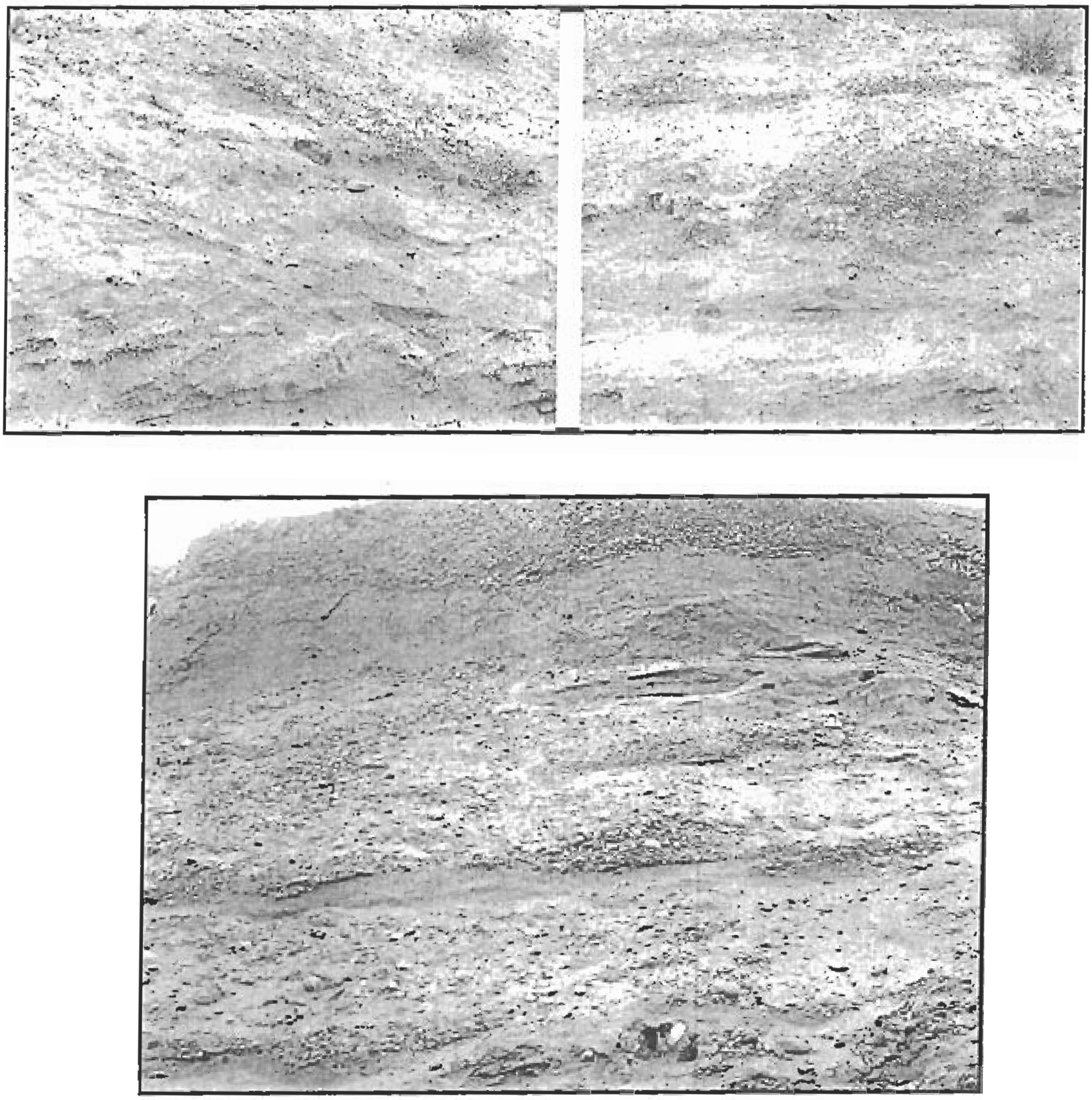


Plate 3.4 a, b, c North looking view of the thick bedded, moderately cemented, soft and cross-bedded sandstone and conglomerate within the Soan Formation.

3.3 WELL DATA AND STRATIGRAPHIC CORRELATION

Deep exploratory wells, including the Dhermund and Dhurnal wells in the western Potwar Plateau, the Kundian well in the Kalabagh reentrant and the Marwat well in the Marwat Range (Fig. 1.8), provide a significant database for regional stratigraphic correlations (Fig. 3.2). The Kundian well penetrates 1478 m thick Siwalik strata and 685 m thick Paleozoic rocks. The Dhermund well, in the west-central Potwar Plateau penetrates a 3059 m thick section of the Siwalik, Kamlial, and Muree formations, a 1291 m thick Lower Tertiary, Mesozoic and Paleozoic Indian shelf sequence and the top of the Eocambrian Salt Range Formation. Compared with the Dhermund well, the Dhurnal well near the Kala Chitta Range encountered about 3742 m thickness of the Siwalik, Kamlial and Murree formations, 427 m thick lower Tertiary sequence, no Mesozoic rocks, 571 m thick Paleozoic sequence and the Salt Range Formation. In the Marwat well 497 m thick Siwalik strata, 712 m thick Mesozoic rocks and 846 m thick Paleozoic rocks have been encountered (Fig. 3.2).

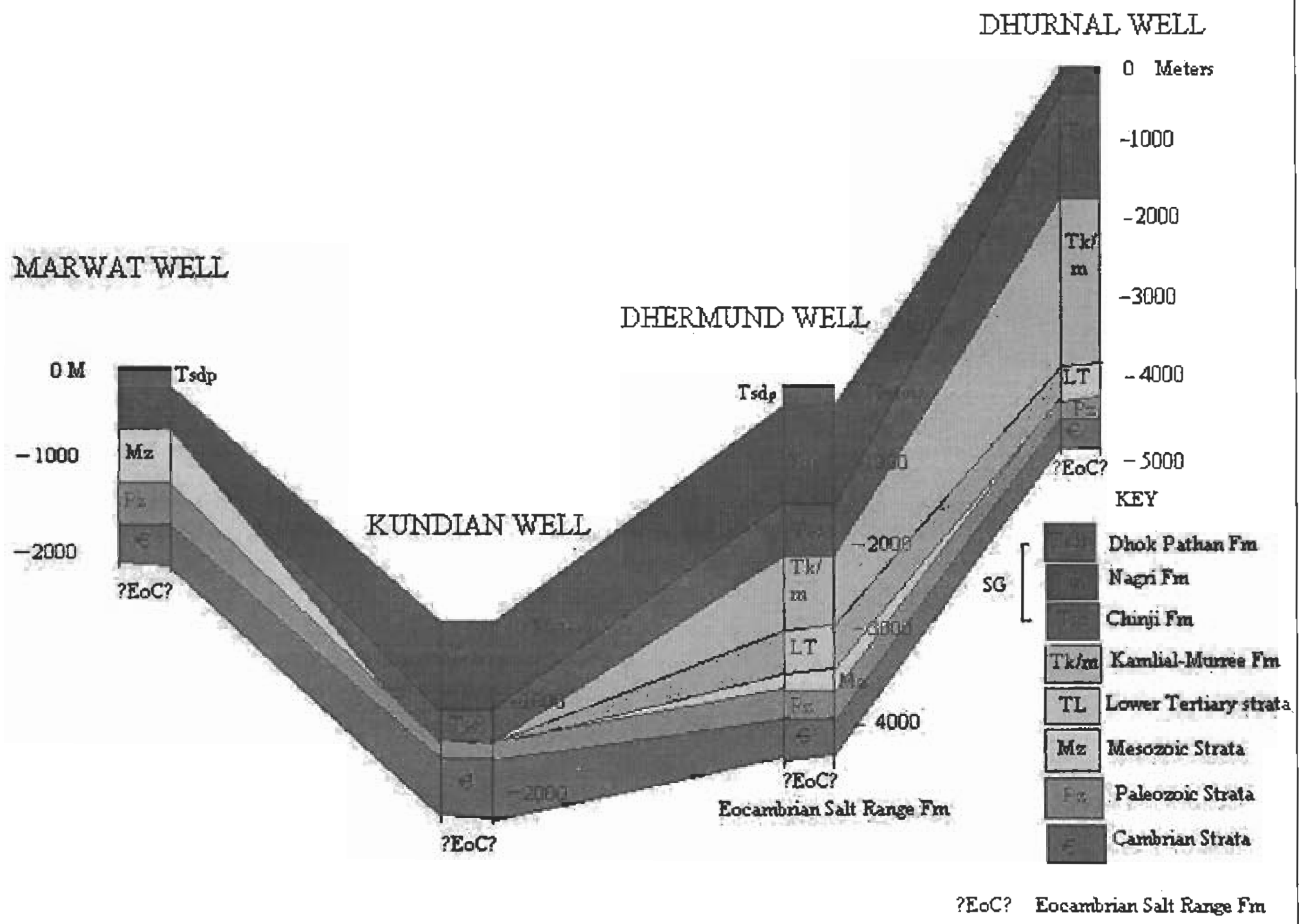


Fig. 3.2 Regional Stratigraphic Correlation through strata encountered in the wells drilled for hydrocarbon development in the region.

CHAPTER 4

Structural Geology of the western Marwat-Khisor ranges

CHAPTER 4

STRUCTURAL GEOLOGY OF THE WESTERN MARWAT-KHISOR RANGES

4.1 OVERVIEW

The Trans-Indus ranges are parts of the Himalayan foreland fold and thrust belt, a product of the collision of the Eurasian and Indian plates that began in the middle to late Eocene (Stöcklin, 1974; Stonely, 1974; Molnar and Tapponnier, 1975). This study focuses on the stratigraphic and structural framework of the Marwat-Khisor ranges that makes up the central part of the Trans-Indus ranges located to the southwest of Kalabagh strike-slip fault system. The Marwat-Khisor ranges define an east to northeast trending fold-thrust belt system where thrusting generally progressed southward with time. Most of the youngest thrusting has occurred along the frontal thrust system in Salt Range in the east and Trans-Indus ranges in the west (Blisniuk et al., 1998) (Fig. 1.1). The Salt Range Thrust that forms the southern margin of the Potwar Plateau apparently continues westward along the southern flank of the Surghar and Marwat-Khisor ranges where it is largely covered by alluvium. However, in the western Salt Range near Kalabagh the thrust is exposed and juxtaposes Paleozoic rocks over late Pleistocene conglomerate (Gee, 1989). According to Allen (1976), there is good evidence for active thrust faulting at the base of Khisor Range, also observed and mapped during this study. Two scenarios, which are south-directed thrusting and normal faulting, are considered to have been responsible for the tectonic evolution of the Khisor Range. The area along the present day thrust front was affected by synorogenic normal faulting within the foreland basin before thrusting began (Blisniuk, 1998). The Khisor Range Frontal Thrust (KRFT) is the youngest and active contractional boundary along which the Khisor Range has been tectonically uplifted and moderately deformed, accommodating shortening in the sedimentary cover sequence above the basal detachment surface. This detachment surface is deeper beneath the Marwat Range as compared to the southern margin of the Khisor Range. The depth to the basal detachment surface is 2 to 4 km and the regional dip of the decollement is 2° to 3°

over the entire study area (Fig. 4.2). This generated open structural features behind the thrust front, especially in the northern fringes of the Khisor Range and in the southern parts of the Marwat Range, and preserved thick sequence of Siwalik Group rocks in the Marwat-Khisor ranges.

Effects of the ongoing collision tectonics is well recorded in the exposed rocks and is represented by a series of large-and small-scale south-verging structures with a common easterly trend in the western parts of Marwat-Khisor ranges to northeasterly in the eastern parts of the study area (Fig. 4.1). The north-south cross sectional views of the study area represent north to southward tectonic transport direction and moderate depth to the decollement surface below the sedimentary cover sequence in both the Marwat and Khisor ranges. The tectonic transport course advanced across the Marwat Range in the north to the most extreme southern fringes of the Khisor Range in the form of a partially buried frontal thrust ramp in the south, related to outward growth of the northwest Himalayan thrust wedge (Fig. 4.3).

The study area is divided into a western and an eastern domain along longitudinal line 71°04′ 00″ E for description (Fig. 4.1). The above division has been made for the better understanding of the structural and stratigraphic framework and interpretation of comparative structural styles and their implications for hydrocarbons and also the assessment of the potential in each domain for the development of underground facilities.

4.2 MAP PATTERN

Key structural elements in this domain are east-east to northeast-trending parallel to en echelon folds and a frontal thrust fault (Fig. 4.1). Folds mapped in the western domain particularly in the Khisor Range are generally asymmetric, overturned and plunging. Most of the folds and faults in this domain are south-vergent.

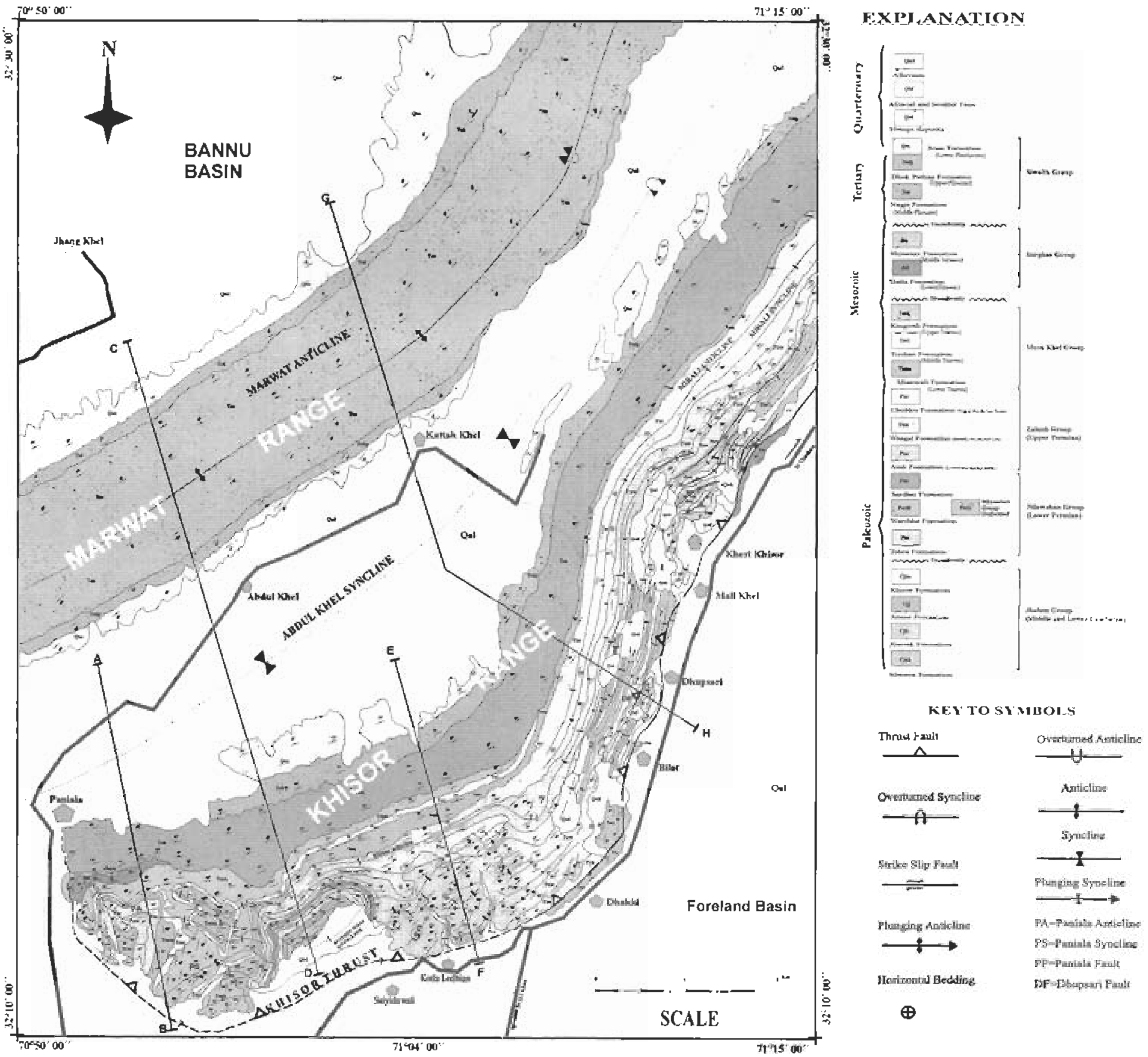


Figure. 4.1. Geological map of the Marwat-Khisor ranges, NWFP., Pakistan by Alam, 2005.

4.2.1 Anticlinal Folds

The major macro scale anticlinal folds mapped in the western Khisor Range and Marwat Range that are the Paniala Anticline, Saiyiduwali Anticline and Marwat Anticline. The Paniala and Saiyiduwali anticlines are located in the hanging wall of the Khisor frontal thrust.

4.2.1.1 Paniala Anticline

The Paniala Anticline is a prominent structural feature of the western domain of Khisor Range and forms the hanging wall of the Khisor Frontal Thrust. Structural data collected along its limbs indicate that its northern limb is comparatively steeper than its southern limb. Its fold axis is shallowly northwest plunging and trends in sub-latitudinal fashion (Fig. 4.2 and Plate 4.1, 4.2). This is a relatively low amplitude structure compared with both the Saiyiduwali and Marwat Anticline. On the basis of attitude data it is interpreted to be slightly asymmetric towards south. Along the west plunging end of this anticline the Jurassic rocks are thrust southwestward over the Siwalik Group rocks of Nagri Formation along a lateral ramp. Southern limb of this anticline is characterized by a couple of low amplitude small-scale east-west trending intervening syncline and anticline. The syncline is northwest plunging, parallel to the Paniala Anticline incorporating the rocks of Triassic age in its core.

The attitude data collected along the northern flank of the anticline has been found in the range of 75° to 90°. The angular unconformity between the Shinawari and Nagri Formation is in the range of 3° to 5°. The dip values persistently decreases further north of this hiatus and become as gentle as 10°~15°.

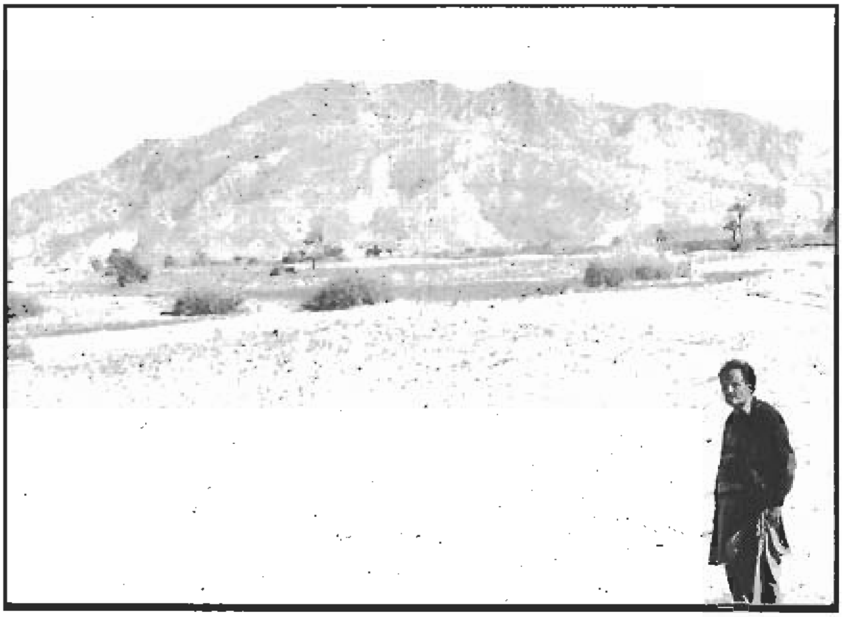


Plate 4.1 East looking view of the outcrop of Paniala Anticline in the western domain.

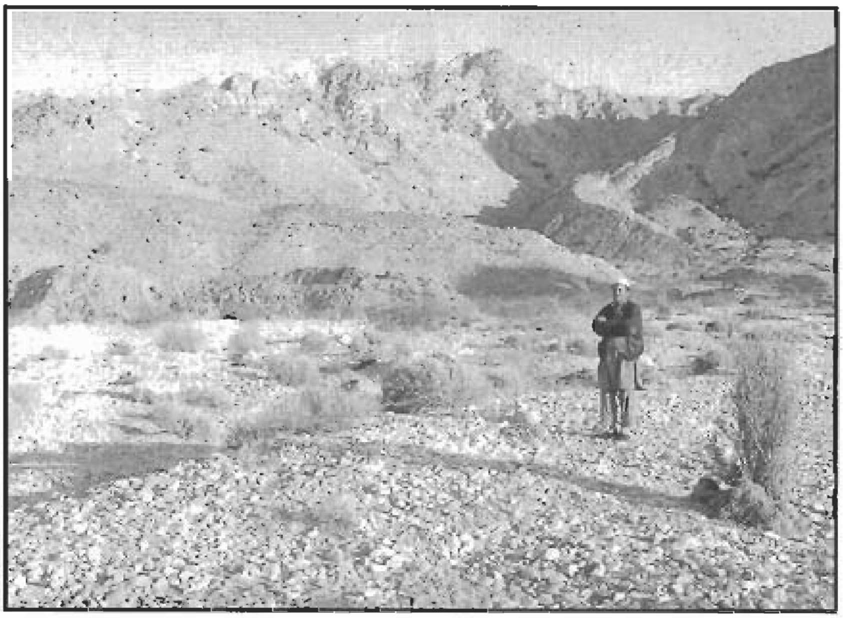


Plate 4.2 Northeast looking view of the outcrop of Chhidru Formation along the southwest limb of the Paniala Plunging Anticline in the western domain.

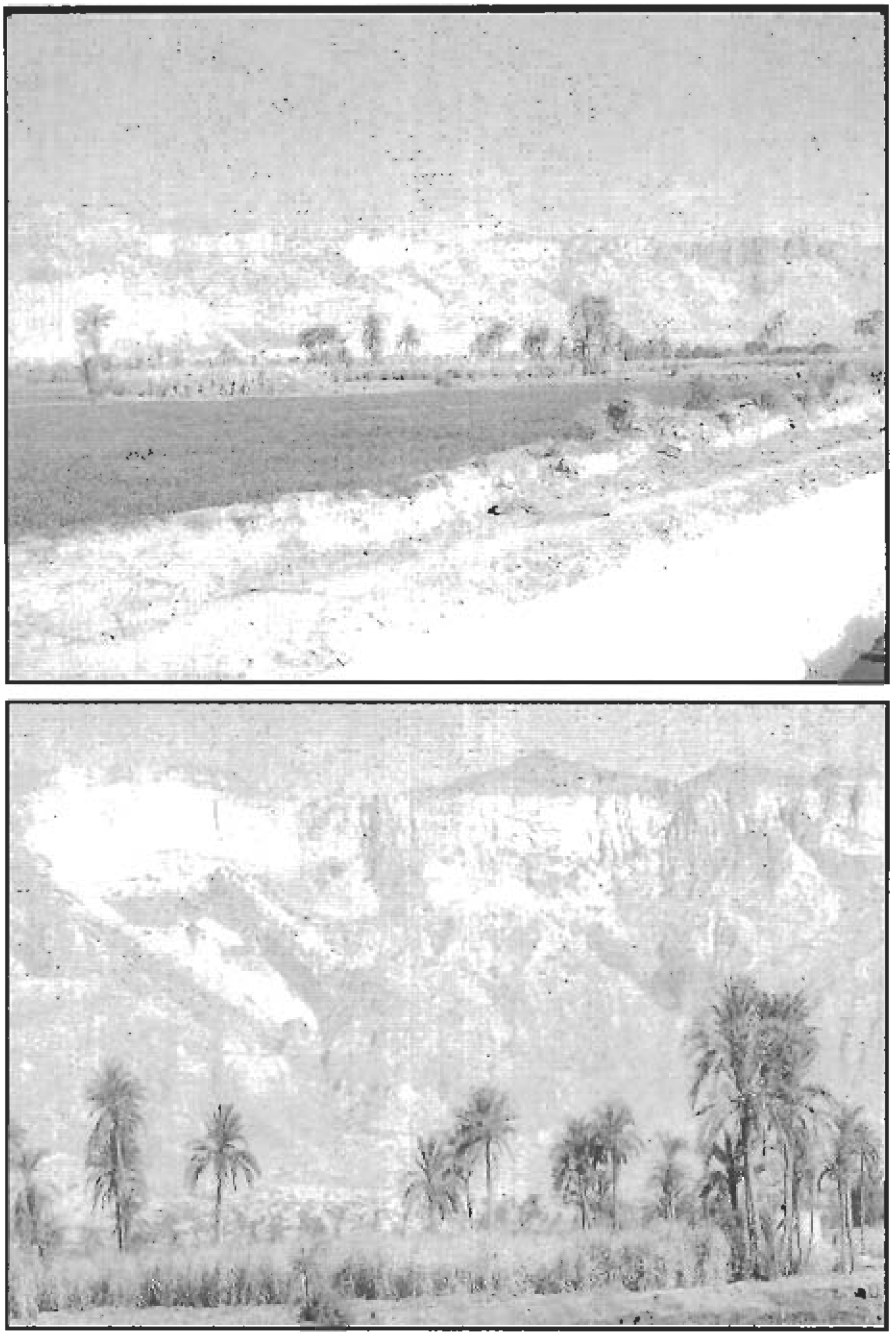


Plate 4.3 a, b North looking view of the outcrop of the Saiyiduwali Anticline in the western Khisor Range.

4.2.1.2 Saiyiduwali Anticline

The Saiyiduwali Anticline is the largest anticlinal fold mapped along the southern foothills of the western domain of Khisor Range where it can be traced for a distance of more than 5 km along its map trace in the east-west direction. The northern flank of the Saiyiduwali Anticline attains greatest structural relief, where Chhidru Formation occupies the summit of the range. The topographic expression of the Saiyiduwali Anticline is mainly attributed to its back limb which consists of rock of Cambrian to Permian age, whereas its forelimb has been eroded and does not crop out with the exception in the east and west, where both of the anticlinal limbs are found intact (Fig. 4.1). The back limb of the Saiyiduwali Anticline is moderately deformed producing shallow folded structures, well developed in the Musa Khel Group rocks of the Triassic age. The oldest rocks entrapped in the core of Saiyiduwali Anticline include Khewra Sandstone, Kussak, Jutana and Khisor Formation of Jhelum Group overlain by the rocks of Tobra Formation, Warchha Sandstone and Sardhai Formation of the Nilawahan Group of lower Permian age. Further upwards the rocks of Zaluch and Musa Khel Group of upper Permian and Triassic age overlie this sequence and are in turn unconformably overlain by the Siwalik Group rocks of Nagri Formation (Fig. 4.3).

4.2.1.3 Khisor Anticline

This fold is located northeast of the Saiyiduwali Anticline, and is characterized by an east trending fold axis. Both the limbs exhibit the same dip angles creating a symmetric geometry. The southern limb consists of rocks of the Chhidru Formation while the northern limb consists of Chhidru Formation overlain by Musa Khel Group rocks of Triassic age which are unconformably overlain by the Siwalik Group rocks (Fig. 4.3). The Khisor Anticline has the highest structural relief compared to other fold structures and exposes the Kingriali dolomite in the apex of fold hinge and forms the Kingriali peak where the Khisor Range attain its highest elevation.

4.2.1.4 Marwat Anticline

The Marwat Anticline is the key structural element of the Marwat Range forming the southern flank of Bannu Basin. Shaikh Budin Hills in the west and Abdul Khel Syncline in the southeast bounds the Marwat Anticline. This orographic feature trends parallel to the Khisor Range that is east northeast. It extends for more than 40 km along its map trace and is mainly composed of Siwalik Group rocks. The Siwalik Group in the Marwat Anticline is divisible into Nagri, Dhok Pathan and Soan Formation. The Southern limb of this anticline is moderately to steeply southeast dipping whereas its northern limb is gently northwest dipping (Fig. 4.1). Attitude data along this anticline shows a pronounced asymmetry to the southeast. Based on its vergence to the southwest Marwat Anticline in this domain is interpreted asymmetrical, with the dominant tectonic transport direction towards the southwest.

4.2.2 Synclinal Folds

Small to large scale synclinal structures have been mapped in the western domain of Marwat-Khisor ranges. The major ones are named after local villages for descriptional purposes and are described below.

4.2.2.1 Paniala Syncline

This structural element is parallel to sub-parallel to the Paniala Anticline and is mapped along the southern margin of the western Khisor Range. It is oriented east-west and is cored by the Triassic rocks of Mianwali and Tredian formations along its outcrop exposures. Paniala Syncline is smaller structural feature as compared to the Paniala Anticline located towards the north northwest. Paniala Syncline is the last exposure of the western Khisor Range towards the southern periphery of the range front.

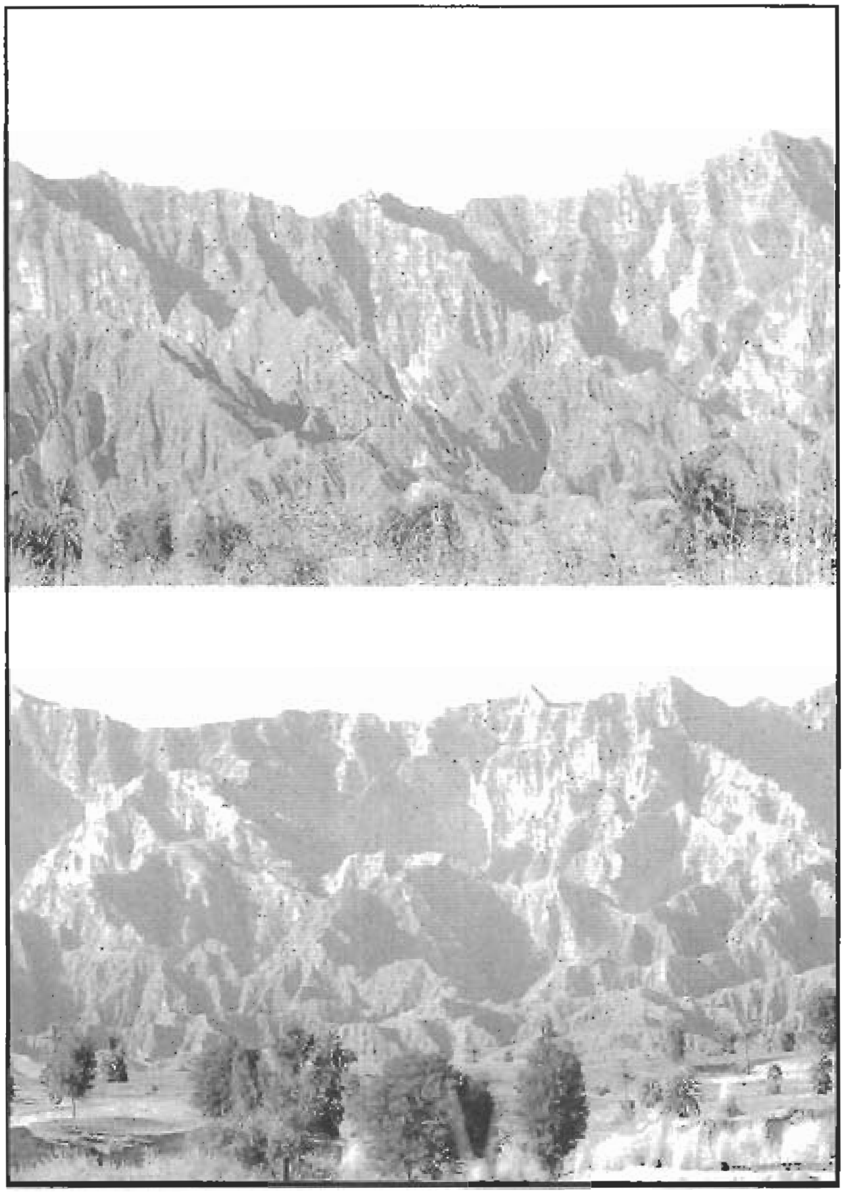


Plate 4.4 a, b Northeast looking view of the outcrop of the Marwat Anticline in the Western Marwat Range.

The outcrop data along the well-developed limbs of this fold has been collected and suggest that it is asymmetrical, northwest-plunging syncline. Its northern limb is steeply dipping towards the southeast whereas the southern limb is dipping moderately towards the northwest. The southern limb of this synclinal feature comprises the hanging wall strata of the Khisor Range frontal thrust system (Fig. 4.1).

4.2.2.2 Khisor Syncline

The Khisor Syncline appears very next to the Saiyiduwali Anticline and is associated with the northern limb of the Saiyiduwali Anticline. The trend of the fold axis of this synclinal structure is east-west. Both limbs dip with the same degree towards each other, creating a symmetrical shape. The southern limb of this syncline comprises the same rock units as that of the northern limb of the Saiyiduwali Anticline whereas its northern limb consists of the rocks of the Chhidru Formation.

4.2.2.3 Abdul Khel Syncline

The Abdul Khel Syncline is a broad, elongated and open synclinal structural feature lying in between the Khisor and Marwat ranges. It is the widest and longest synclinal fold mapped in the study area, and bifurcate both the ranges in sub-latitudinal fashion (Fig. 4.1). This syncline is wide in the vicinity of Abdul Khel village and become narrow towards the northeast of the mapped area. Strata entrapped in the core of this syncline is Soan Formation but most of the core is covered by the disintegrated i n compacted sand derived from the near by molasse deposits.

Attitude data reveals that the southern limb of the Abdul Khel Syncline dips gently towards the northwest whereas the northern limb dips moderately to steep towards the southeast. On the basis of outcrop data the Abdul Khel Syncline appears as an asymmetrical syncline.

4.3 FAULTS

The fault structures are poorly exposed as compared to fold structures in the western sector of the Marwat-Khisor ranges. One mappable strike-slip fault has been observed in the extreme western corner of the Khisor Range and another front bounding thrust fault has been mapped all along the eastern periphery of the Khisor Range.

4.3.1 Paniala Fault

The Paniala Fault is mapped in the western corner of the study area in the Khisor Range along the westerly plunging end of the Paniala Anticline. It trends north-northwest, cross cutting the Mianwali and Tredian formations of the Triassic succession and shows 150 m of lateral displacement. This fault has been described as right-lateral / dextral fault by working out the sense of formational offset (Fig. 4.1).

4.3.2 Khisor Thrust

Khisor Thrust is the latest and one of the prominent and key frontal deformational phases in the Khisor Range. It is part of the youngest and the active deformational episode of the Himalayan foreland and fold thrust belt that skirts the entire Salt and Trans-Indus ranges of north Pakistan (Fig. 1.6). The Khisor frontal thrust is found to be blind or partially emergent in the western Khisor Range except at one locality near Paniala village where the Datta Formation is thrusted westward in a hanging wall against the Nagri Formation in a footwall as a lateral ramp. Based on its known trend the Khisor Thrust from its well-exposed eastern outcrops, its trend has been inferred to be as east west. That switches to north-northwest near Paniala where the Jurassic rocks of the Datta Formation are thrust over the Siwalik Group rocks of Nagri Formation (Fig. 4.3).

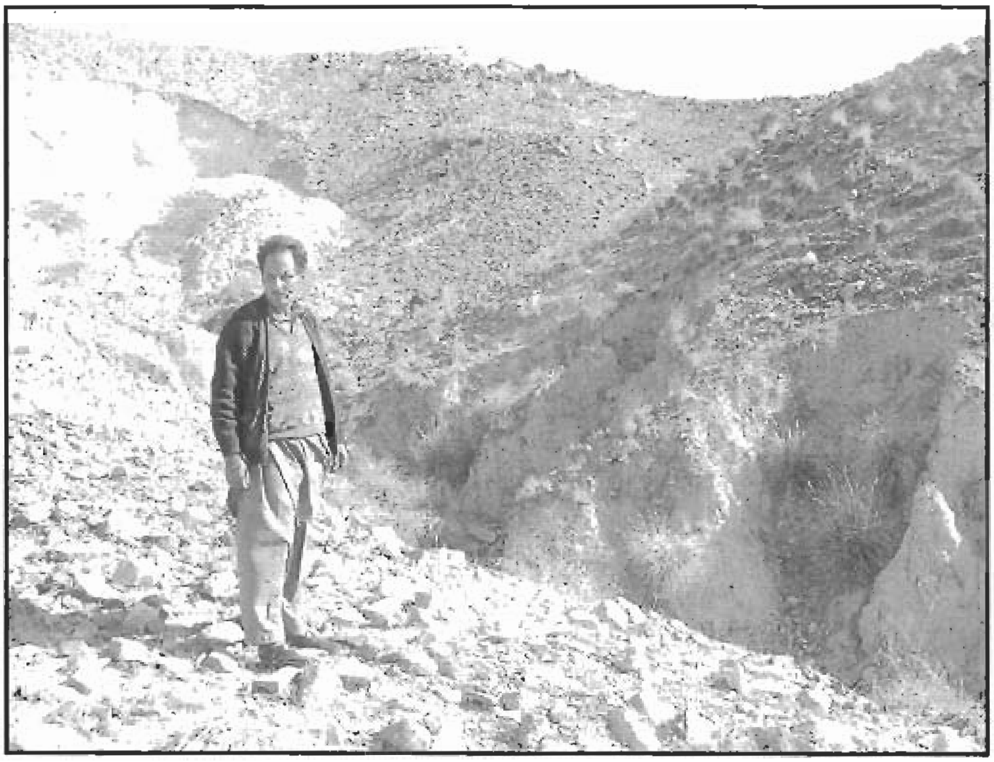


Plate 4.5 South looking view of the outcrop exposure of the Khisor Thrust where Datta Formation of Jurassic is thrusted in a lateral ramp over the Nagri Formation of Siwalik Group.

4.4 SUBSURFACE STRUCTURAL STYLE

Blisniuk and Sonder (1998) studied the development of the southern frontal thrust system by analyzing the studding sedimentological record of the Trans-Indus and Salt ranges. They recognized the presence of north dipping normal faults in the crystalline basement rocks in the foreland basin related to lithospheric flexure as the first phase of deformation. This phase of deformation was followed subsequently by the younger south-directed thrust faulting. These two major phases of deformation regionally control the surface and subsurface structural style and tectonic history in the area of the present day thrust front.

The following factors were considered for the structural interpretation of the Marwat-Khisor ranges: (1) the assessment of major detachment horizons based on the geometric techniques utilizing kink plane bisecting angles; (2) the projection of surface structures to depth in a couple of interpretive cross-sections, using structural styles that are compatible with the surface attitude data; (3) the along-trend variations of the structures.

4.5 LOCATION OF MAJOR DETACHMEMENT

The Trans-Indus and Salt ranges of northwest Pakistan are the mobile perimeter of the Kohat-Potwar fold and thrust belt and display decollement thrust-fold assemblages. Thrusting and associated folding is the means of accommodating shortening within these orogenic belts. The most recent thrusting has occurred along the frontal thrust system in the Salt Range to the east and the Trans-Indus ranges to the west (Blisniuk et al., 1998). Beneath the Potwar Plateau and the frontal Salt ranges, the Precambrian Salt Range Formation forms a laterally extensive basal decollement at the basement-sediment interface. As a result, the structural style is mainly thin-skinned and the basement is convex upward with a gentle dip towards north (Duroy et al., 1989). Similar basement geometry has been interpreted for the basement underneath eastern Kohat Plateau and

Bannu Basin (McDougall and Hussain 1991; Parwez, 1992). Along the Khisor Range foothills the basal detachment is interpreted to be located below the Jhelum Group, as no salt lies beneath the map extension of the Khisor Range.

4.6 STRUCTURAL CROSS SECTIONS

Two widely spaced structural transects in the western Marwat-Khisor ranges along lines AB and CD of Fig. 4.1 were constructed through the Paniala, Saiyiduwali and Marwat Anticline for the better understanding of the surface and subsurface behavior of various formations and to understand the kinematics of and relationship between the various folds and faults and also to recognize the along trend structural variations in the outcropping rocks. The salient structural features are shown on the cross-sections and are discussed in detail below.

4.6.1 Section AB

The structural transect along line AB is north-south oriented, almost perpendicular to the structural trend of the exposed rocks located east of Paniala village (Fig. 4.2). The Paniala Anticline is a north facing, asymmetric anticline that shows its highest structural relief in this section, exposing Permian rocks in the core. It is approximately 4 km width in the north-south direction. The dip of the northern limb (back limb) of the anticline is steep to vertical whereas its southern limb (forelimb) dips gently to moderately, towards the south. The cross-section line is approximately parallel to the north south oriented tectonic transport direction as inferred from the trends of the various structures developed in the area. The southern limb of the Paniala Anticline is marked by an open synclinal structure in the Musa Khel Group rocks and defines the hanging wall strata of the south-vergent Khisor Range Frontal Thrust in the south. Surface structural data along the northern limb of the anticline reveals that its steepning is related to the presence of a blind back

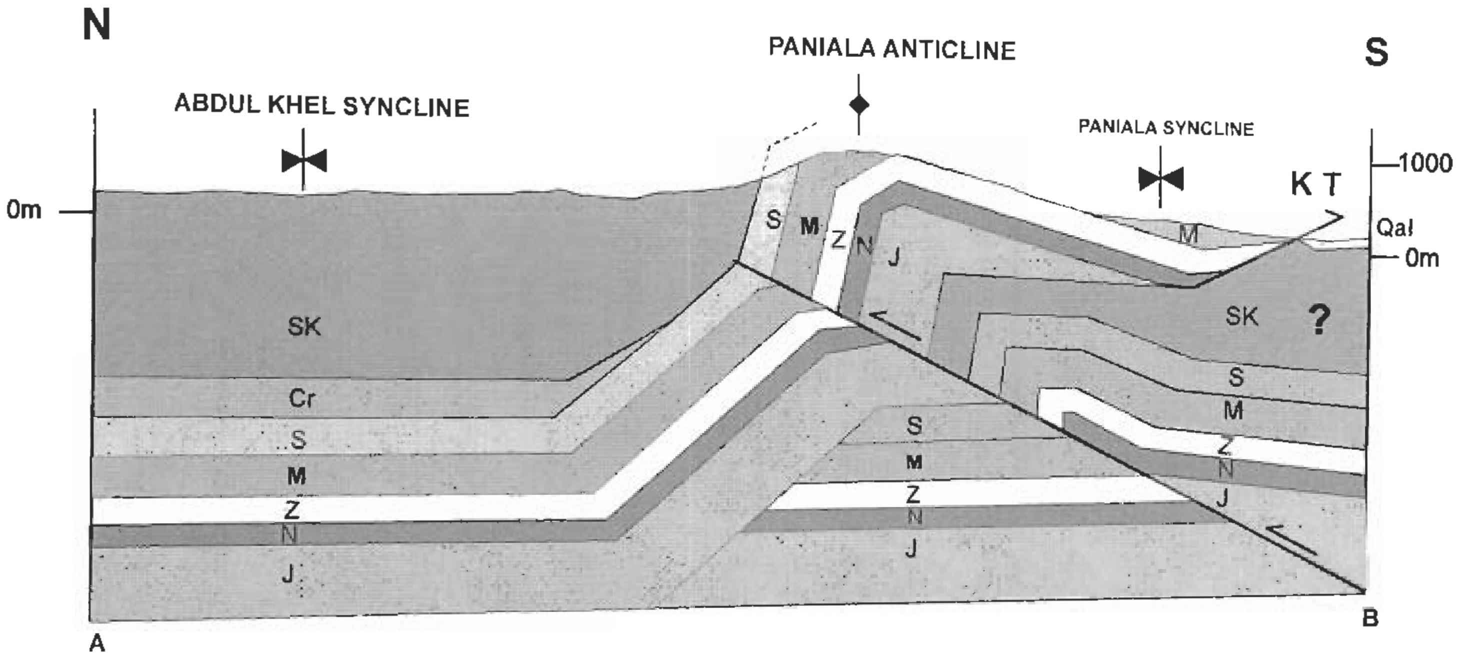
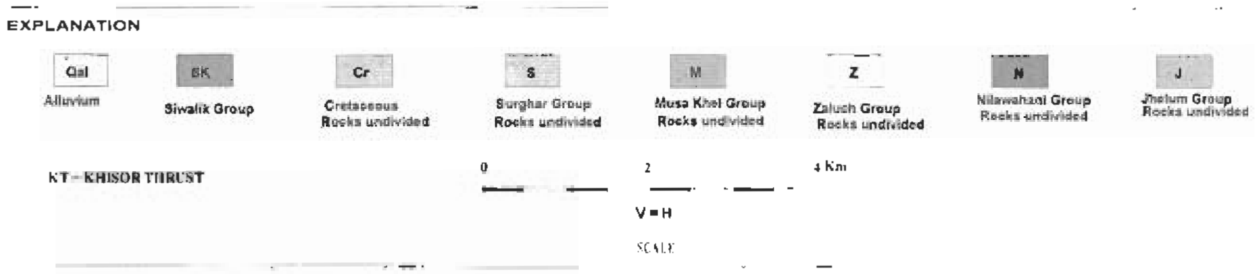


Figure 4.2-Structural Transect along line AB of Figure 4.1, showing subsurface structural style of the Western Khisor Range.



thrust with a tip at a depth of one kilometer. Projection of fold geometries to depth (Fig. 4.2) and well data from the Marwat Well-1 indicates that a regional basal detachment underlies the section at the base of the Jhelum Group rocks at a maximum depth of 3.5 kilometers below sea level. Frontal ramping from decollement thrusting was the initial response to the onset of compressional deformation and the Paniala Anticline formed as a fault-bend-fold above the Khisor Thrust. It was followed by a north verging ramp from the basal decollement that is believed to be responsible for the change of vergence of the Paniala Anticline, offset of the early course of the Khisor Thrust and the formation of a deep-seated anticlinal fold. The geometry of this non-outcropping anticline exhibits fault propagation geometry is in contrast to the Paniala Anticline.

On the northern flank of the Paniala Anticline the Siwalik Group rocks unconformably overlie the Jurassic rocks of the Datta and Shinawari formations suggesting that deformation and uplift of the Paniala Anticline is post Pliocene or Pleistocene.

4.6.2 Section CD

The structural style of the eastern flank of the western domain is summarized by describing a transect along the line CD across the Marwat Range in the north and the Khisor Range in the south in the proximity of Saiyiduwali village. The location of the transect was selected to cross all the significant structures of the region and portray the overall structural geometry (Fig. 4.3). This transect is oriented north-northwest, at nearly right angle to the structural trend of the exposed lithological units. From south to north the back limb of Saiyiduwali Anticline occupies the hanging wall strata of the Khisor thrust, whereas its forelimb has been eroded. The basal strata cropping out in the core of this anticline is the Jhelum Group of Lower Cambrian age, overlain by Permian rocks whereas Chiddru Formation occupies the hinge zone. The forelimb of the anticlinal feature is eroded and may probably cut by the Khisor frontal thrust during its propagation phase. Subsurface projection of the structural geometries indicates that this anticline is underlain by a basal detachment located at the base of Khewra Sandstone of lower Cambrian age. The Salt Range

Formation is not exposed in the study area, so it is therefore promising that the basal regional detachment surface below the Saiyiduwali Anticline may exist directly above the basement crystalline rocks of Precambrian age. The Saiyiduwali Anticline is interpreted as a fault-propagation fold related to frontal ramping from the basal decollement. This transect depicts that this part of the western Khisor Range has been uplifted as a result of a south directed translation. A pair of folds is mapped north of the Saiyiduwali Anticline in the Permian and Triassic strata in the form of Khisor Syncline and Khisor Anticline. Both are symmetrical structural features. North of the Khisor Anticline in the vicinity of Abdul Khel village a broad and open syncline is mapped. This syncline only exposes rocks of the Siwalik Group. The southern limb of the syncline is dipping at a moderate angle toward the north whereas the northern limb of the syncline is dipping steeply to the south. North of the Abdul Khel Syncline is the Marwat Anticline, the main structural element of the Marwat Range. This anticline is interpreted as consequence of a non-emergent ramp from the basal decollement detached at the base of Khewra Sandstone. The ramp underneath this anticline flattens at a shallow depth of 3 km at the northern edge of the Abdul Khel Syncline where it finally tips out. The structural data indicates that the Marwat Anticline is a typical fault-bend fold that is translating southwards over the basal fault.

The structural style depicted along the transect clearly indicates that this part of the Marwat-Khisor ranges has evolved as a south directed fold thrust system, detached from the regional basal decollement. The faults mostly observe in ramp flat trajectory.

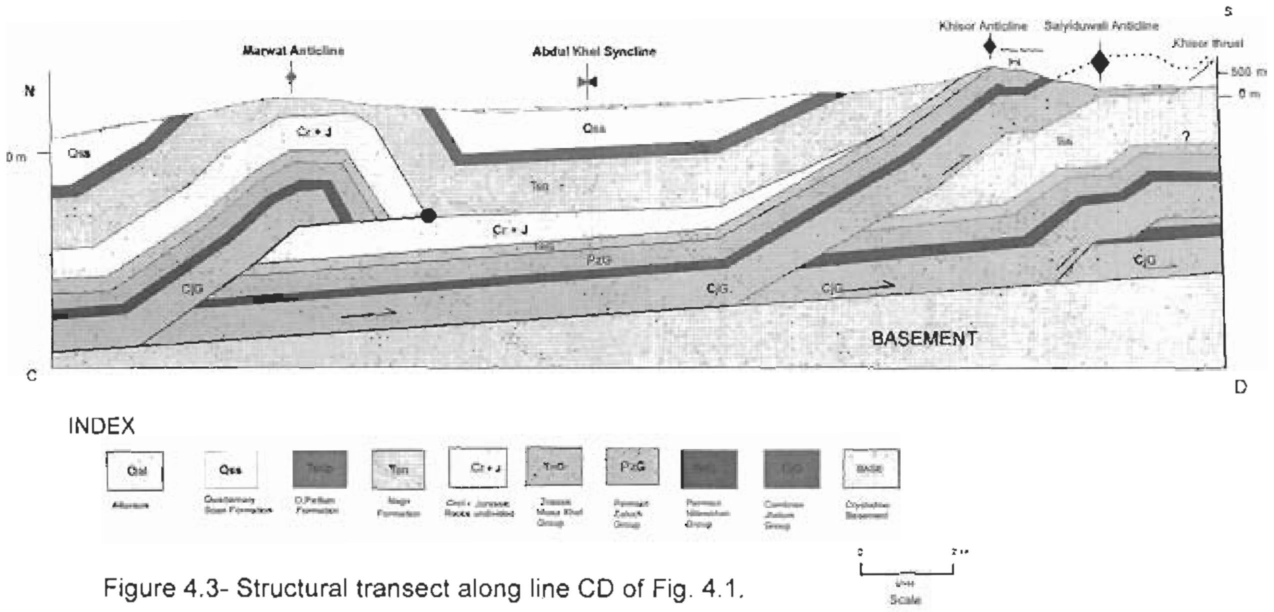


Figure 4.3- Structural transect along line CD of Fig. 4.1.

CHAPTER 5
Structural Geology of the eastern Marwat-Khisor ranges

CHAPTER 5

STRUCTURAL GEOLOGY OF THE EASTERN MARWAT-KHISOR RANGES

5.1 OVERVIEW

Beginning about 40 million year ago, collision of the Indian subcontinent with Eurasian Plate produced the spectacular Himalayan arc, along with a series of mountain belts to the east and west (Molnar and Tapponier, 1975). In northern Pakistan the Himalayan arc changes from a northwest-southeast trend to a nearly east-west orientation, bending southwest at the Hazara-Kashmir syntaxis. From south to north, the three major tectonic elements that define the active foreland deformation belt of North Pakistan are as follows (1) the Jhelum Plain, (2) the Salt and Trans-Indus ranges and (3) the Kohat-Potwar Plateau and the Bannu Basin (Yeats and Lawrence, 1984) (Fig. 1.8). This study concentrates on one of the fringing belts of Himalayas, the Marwat-Khisor ranges that make the central part of the Trans-Indus ranges (Fig. 1.1). Geographically this domain is bounded to the north by Bannu Basin and to the southeast by Indus River. The Punjab forelands demarcate the southern frontier whereas the northwest boundary is marked by the Shaikh Badin Hills (Fig. 1.2). Nine stratigraphic units have been recognized in this part ranging in age from Early Permian to Cenozoic. Top of the sequence in this sector is marked by a break of an angular character with Nagri Formation of the Siwalik Group occupying the apex.

5.2 MAP PATTERN

The eastern domain of the Marwat-Khisor ranges is confined between longitudes 71° 04′ 00″ E to 71° 15′ 00″ E and latitudes 32° 10′ 00″ N to 32° 30′ 00″ N. Regional trend arrangements in the area are found to be northeast except in the western fringes of this domain, where the Permian and Triassic strata reveal longitudinal trend. The oldest rocks exposed in this domain belong to Warchha Sandstone of Permian age, conformably overlain by the Sardhai Formation. In this domain the Quaternary landslide deposits cover significant part of the area. In addition most of the formations are deeply weathered and covered by scree making it difficult to acquire structural data on the outcrop of different formations. These formations are therefore shown on the geological map as an undifferentiated group in the southeastern margins of the eastern domain in the Khisor Range (Fig. 4.1).

There are several stream hacks, which provide excellent approaches for the inclusive traverses in the study area. Equally there are a number of villages located in the facade of these streams to be used as a reference for the sectional lines and traverse courses respectively. Dhupsari village is situated on a road distance of about 4 km from Bilot towards the northeast and utilized as a reference sectional line. The Dhupsari section has been mapped through a comprehensive traverse across the Khisor Range in the south and Marwat Range in the north, where several prominent structural features have been recognized that are described as under:

5.2.1 Thrust Faults

One large and several small-scale thrust faults have been recognized and mapped in the eastern Marwat-Khisor ranges that mostly sole in decollement surface within the Permian strata. In the frontal portion of this sector predominantly Permian rocks are dominantly deformed by gentle to moderate flexural folds, where blind to emergent thrust splay faults occur in cores of these folds.

5.2.1.1 Khisor Thrust

This frontal thrust fault is partially exposed along the frontal slopes of the eastern sector in the Khisor Range. It is well exposed west of Dhakki, Bilot, and Dhupsari villages, and providing good outcrop exposures. All along the map trace of the Khisor thrust, the Permian strata constitutes its hanging wall strata juxtaposed along the Siwalik Group

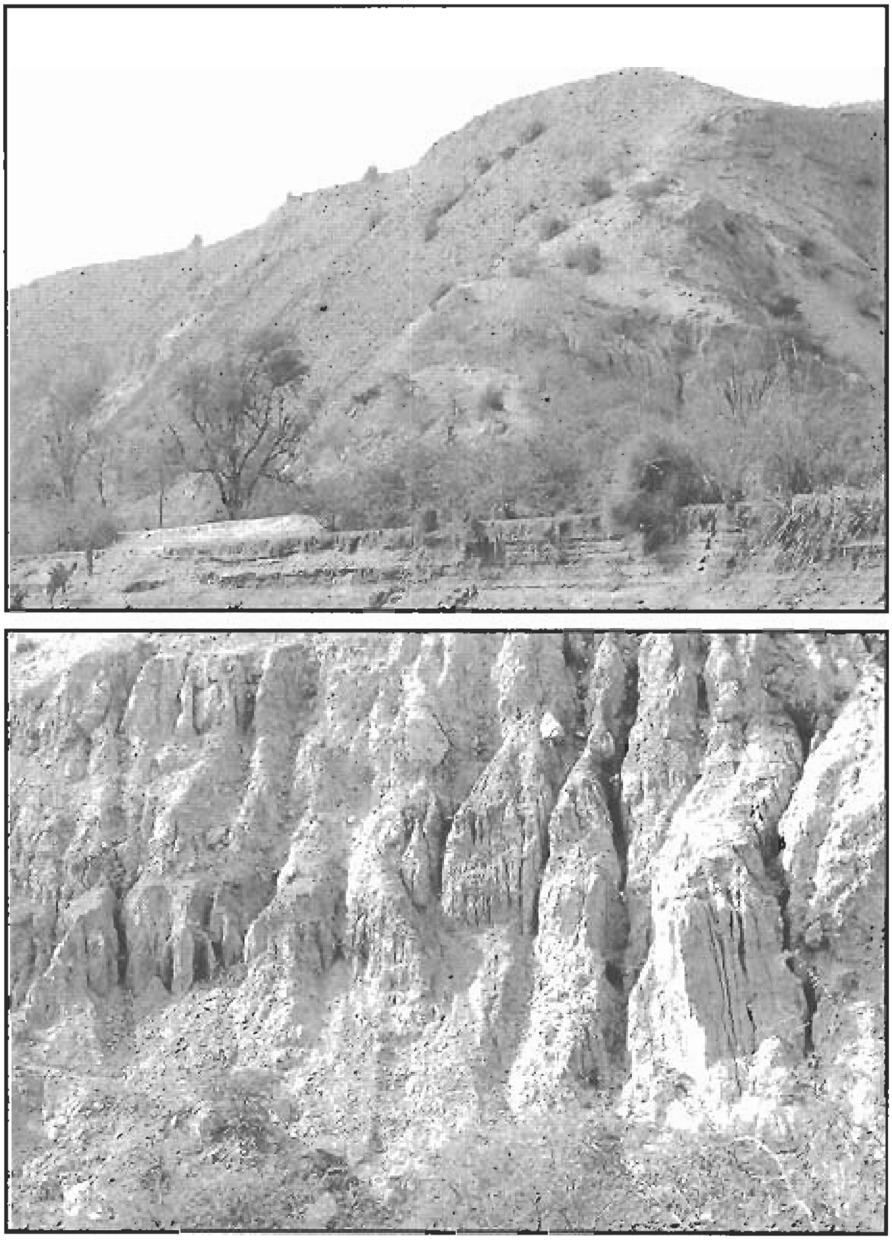


Plate 5.1a, b North looking view of the Khisor Thrust where Amb Fm and Warchha Sandstone is thrusted over the Nagri Formation Northeast of Dhakki Village.

rocks in the footwall. It is dominantly oriented north-northeast and dips moderately toward the northwest (Plate 5.1). The outcrop characteristics of this fault suggest that it is south-vergent fore thrust detached at the base of the Permian rocks.

5.2.1.2 Dhupsari Thrust

The Dhupsari Thrust fault has been mapped 1 km southwest of the Dhupsari village and northwest of the Khisor Thrust. It strikes north-northeast with limited map extension. Along this thrust fault the Amb Formation in the hanging wall strata is thrust over the Nagri Formation in its footwall (Plate 5.2 a, b). On the basis of surface structural data it appears to be an imbricate splay fault associated with the frontal Khisor Thrust and is southeast vergent.

5.2.2 Folds

Folds are the dominant structural elements of the eastern Marwat-Khisor ranges and are represented by open to tight, northeast to north-northeast trending anticlines and synclines. These folds are mostly south vergent indicating southwards direction for the tectonic transport. The macro scale folds have been mapped in both the Marwat-Khisor ranges are summarized below from south to north.

5.2.2.1 Synclinal Structures

Two regional scale synclinal folds are well developed and mapped in this domain. Those are Mir Ali Syncline within the Khisor Range comparatively narrow than the Abdul Khel Syncline. The Abdul Khel Syncline separating Marwat Range in the north from Khisor Range in the south (Fig. 4.1).

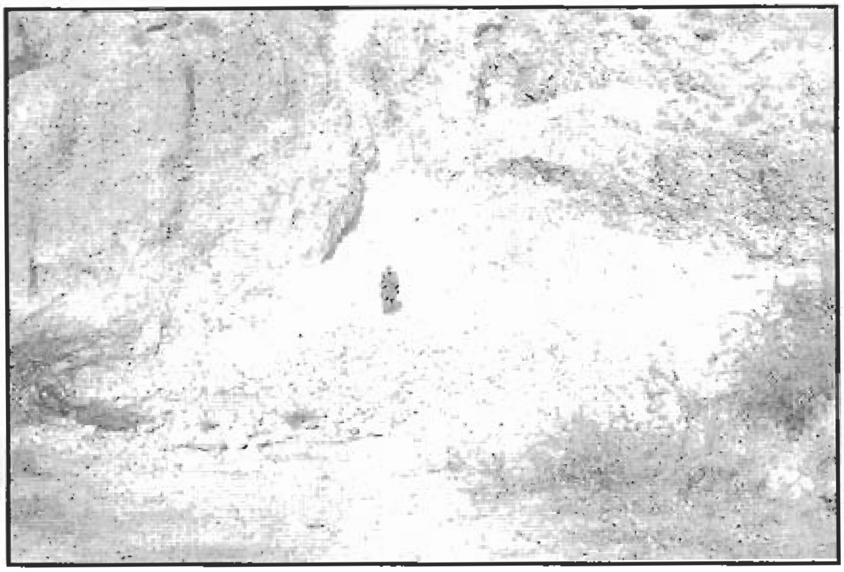


Plate 5.2a, b Northeast looking view of the Dhupsari Thrust where Amb Fm is thrusted over The Nagri Formation of Siwalik Group NW of Dhupsari village.

5.2.2.1.1 Mir Ali Syncline (MAS)

The Mir Ali Syncline is mapped towards the east-northeast of the Kheri Khisor village and developed in the thick-bedded rocks of the Chiddru Formation of Permian age. Its southeastern limb dips gently toward the northwest whereas its northwestern limb dips gently toward the southeast. The axis of the structure trends in the north-northeast. The southern limb of the fold is composed of the rock of the Chhidru Formation and Wargal Limestone. Whereas it's northern limb consists of the rocks of the Chhidru Formation only. It is an open synclinal structure, parallel on the north by the Mir Ali Anticline.

5.2.2.1.2 Abdul Khel Syncline

The Abdul Khel Syncline has been mapped immediately to the northwest of the Mir Ali Anticline. The Mir Ali Anticline and Marwat Anticline bound the Abdul Khel Syncline to the southeast and northwest respectively. It has a long wavelength in the west near Paniala that turn into narrows towards east. The Soan Formation is well developed at the southern limb of Abdul Khel Syncline while the same formation is absent most probably due to erosion associated with deformation. Attitude data collected on the limbs of this syncline indicate that its southeastern limb dips gently to the northwest whereas its northern limb is dips steeply to the southeast and then overturns toward the north-west in the extreme northeast, making the overall sectional geometry of the Abdul Khel Syncline overturned in the eastern sector of the study area.

5.2.2.2 Anticlinal Structures

A pair of macro-scale anticlinal structures has been mapped in the eastern flank of the eastern Marwat-Khisor ranges that are named and described below.

5.2.2.2.1 Mir Ali Anticline

The Mir Ali Anticline is mapped about 4 km north of the Kheri Khisor. The axis of this anticline trends north-northeast and is thus identical to that of the Mir Ali Syncline. Its map extension along the axial trend is more than 25 km, Mir Ali Syncline. Its southeastern limb is comprised of the rock of Chhidru Formation whereas its northwestern limb comprises of the rocks of Chhidru and Mianwali Formation, unconformably overlain by the Siwalik strata. The southeastern and northwestern limbs dip gently to the southeast and northwest with gentle and gentle to moderate angles respectively, attributing south asymmetry to it.

5.2.2.2.2 Marwat Anticline

The Marwat Anticline is bounded to the southeast by the Abdul Khel Syncline and to the northwest by the Bannu Basin to demarcate its northern and southern limits. The northern limb of the Marwat Anticline is composed of rocks of the Dhok Pathan and Soan formations whereas the southern limb constitutes the strata of the Dhok Pathan Formation only. The Nagri Formation of the Siwalik Group is exposed in the core of the anticline. The southeastern limb of the anticline dips to the northwest at a moderate to steep angle (50°~65°) and is overturned in the extreme northeast whereas its northwestern limb dips gently to the northwest (20°~45°). On the basis of attitude data the Marwat Anticline in the eastern domain of the study area is considered to be an overturned anticline with south vergence.

5.3 SUBSURFACE STRUCTURAL STYLE

Two phases of deformation, that are earlier normal faulting followed by south verging thrust faulting, are considered to be regionally expressed and most probably affected the entire present-day NW Himalayan thrust front according to Blisniuk et al., (1998). They suggest that earlier deformation was probably of thick-skinned extensional style related to syn-orogenic flexure of the Indian Plate during the latest Miocene. It was followed by Plio-Pleistocene south-directed thrusting along the present-day thrust front related to outward growth of the NW Himalayan thrust wedge. However, because of the lack of detailed information, the subsurface structural style including the nature of basal decollement, depth to the decollement and fold-thrust styles underneath the Marwat-Khisor ranges is still less understood. Although there are many unanswered questions, only a pair of geological transects of the eastern Marwat-Khisor ranges have been constructed for addressing the same.

5.3.1 Structural Transect EF

The Structural cross-section along the line EF (Fig. 5.1) crosses the western flank of the eastern domain of the Khisor Range and is located northeast of Kotla Lodhian village. Along this cross section the crest of the Khisor Range has undergone great structural uplift forming the highest summit of the Khisor Range namely the Kingriali peak with the Kingriali Formation of Triassic age where the Kingriali Formation is occupying the apex of the range. Along this transect the southernmost part of the range front is occupied by the Permian Wargal Limestone that displays a small scale, continuous fold train structure of synclines and anticlines characterized by short wavelengths of less than 1 km. The Khisor Anticline is the most prominent fold structure of transect and makes the main topographic expression of the Khisor Range. Most of the dip values along the cross sectional line are moderate to gentle especially to north of the Kingriali peak indicating the shallowness of the folds. The subsurface projection of attitude data along the structure reveals that the Khisor Anticline is the result of a ramp emanating from the regional detachment surface. All the small-scale structures in the Wargal Limestone towards the southern margin of the range front are associated with translation above a flat, generated due to the flattening of the major ramp underneath the Khisor Anticline. The ramp from the basal decollement finally ramps out at the site of the Khisor Thrust above the southward-propagating wedge of the cover sequence. Along line EF the major ramp anticline, that is Khisor Anticline, exposes the Zaluch Group rocks of Permian age in its core and its southern limb is comparatively steeper than its northern limb. Projection of the surface data and cut-offs along the frontal thrust suggests that the basal detachment surface exists below the Khewra Sandstone of Jhelum Group rocks at about 2.5 to 3 km depth.

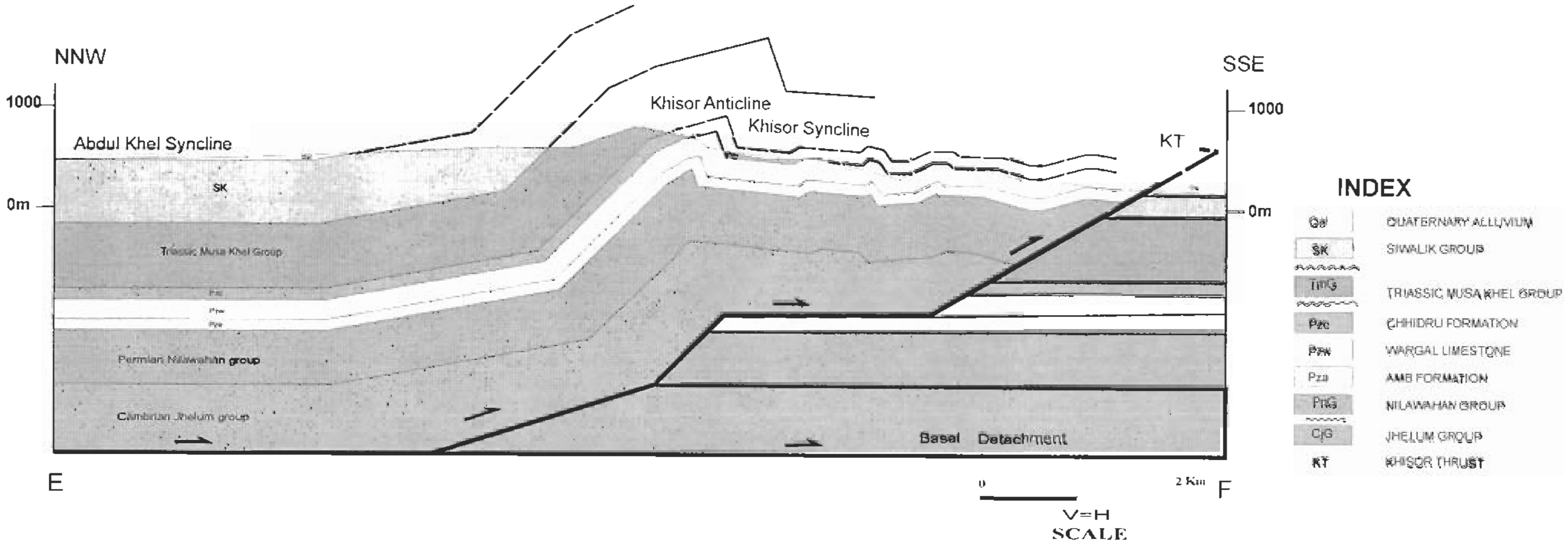


Figure 5.1 Structural transect along line EF of Figure 4.1.

5.3.2 Structural Transect GH

Structural cross section has been drawn along line GH (Fig. 5.2) which crosses both the Marwat-Khisor ranges. The transect line GH is oriented north-northwest in the Marwat Range t the north and bends in the centre of the Abdul Khel Syncline to become northwest across the Khisor Range to the south. From north to s th along the section line the Marwat Anticline depicts high side anticlinal closure relat a major ramp from basal decollement. The dip of the back limb of Marwat Ant lin ows the dip of the underlying ramp, whereas its forelimb is steeply south dipp g and is related to the tip line of the fault where movement on the fault is seized below the forelimb of this anticline. South of the Marwat Anticline lies the Abdul Khel Syncline that is believed to be a flat-syncline between two successive ramp structures. Along this transect the southern most part of the range front is occupied by the N wahan and Zaluch Group rocks of Permian age that exhibit small scale, consistent fo equence of synclines and anticlines, characterized by very short wavelengths of less t n h lf kilometer. Along this transect, deformation is mostly concentrated in the frontal margin of the Khisor Range and makes the hanging wall strata of the Khisor Thrust. This thrust appears as south facing and emplaces Permian rocks of the Zaluch Group over the Siwalik Group strata in the southern frontier of the Khisor Range (Fig. 5.1). North of the frontal Khisor Thrust a small-scale thrust fault has been mapped along the cross sectional line GH. This thrust fault is named as Dhupsari Thrust and juxtaposing Perm n rocks of the Amb Formation in its hanging wall against the Nagri Formation in its footwall. The Dhupsari Thrust is south verging fore thrust and is believed to be a splay fault t emerged from the shallow level flat underneath the Khisor Range in order to acco modate shortening within the hanging wall sequence of Khisor Thrust Sheet. The intervening folds structures between the two successive thrust faults and Abdul Khel Syncline are open to moderately tight and asymmetrical, having short wavelengths.

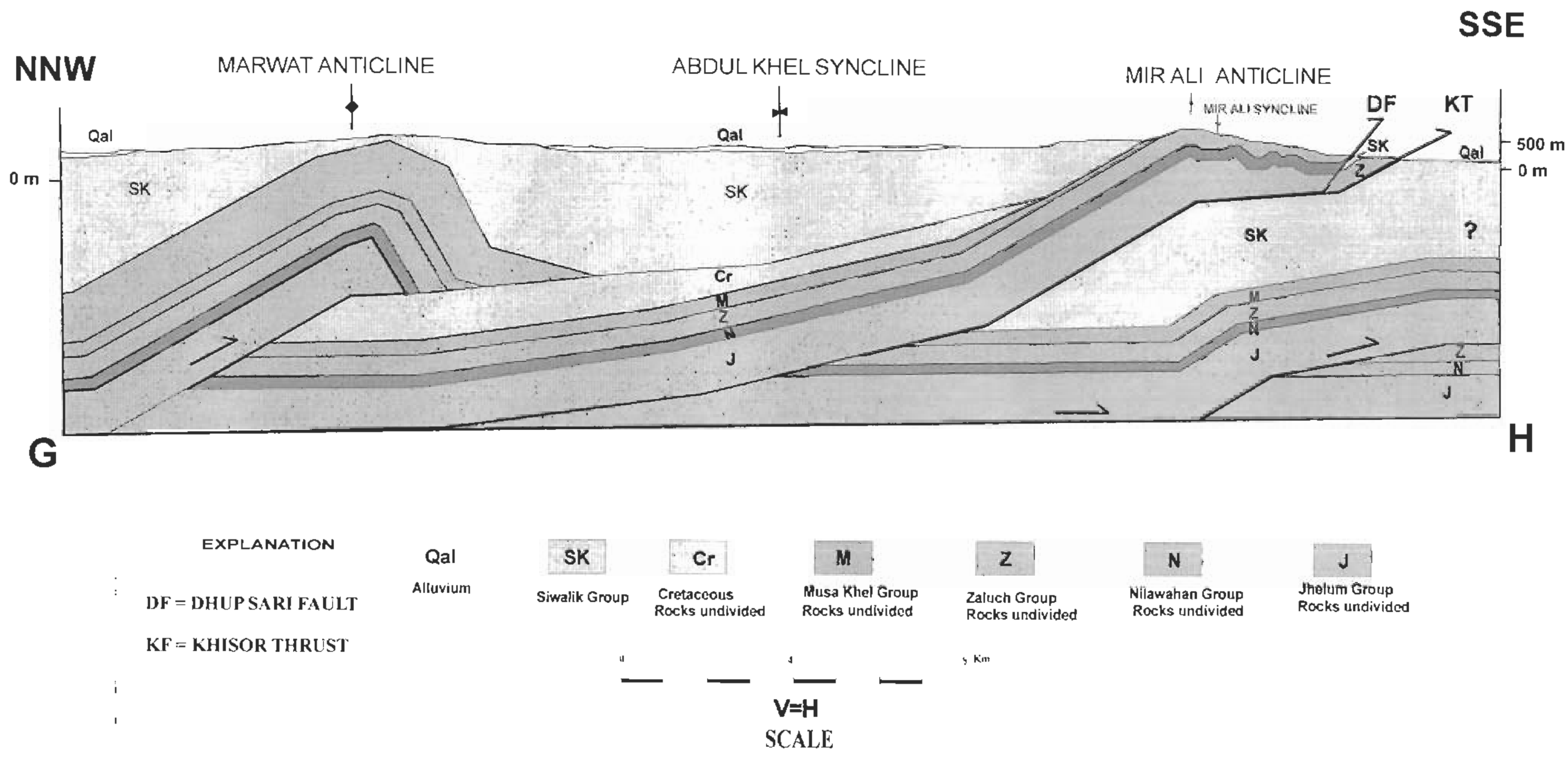


Figure 5.2 Structural Transect along line GH of Figure 4.1.

Structural style depicted along transect clearly indicates that this part of the Marwat-Khisor ranges has developed as a south directed fold-thrust system, detached from the regional basal decollement. The mapped faults along the section line mostly observe ramp-flat trajectory and the deformational style observed along the section is comparable in style in the preceding cross sections.

CHAPTER 6

Structural Analysis

CHAPTER 6

STRUCTURAL ANALYSIS

6.1 REGIONAL PATTERN

The structural province characterized by the Marwat-Khisor ranges constitutes the westernmost part of the Himalayan foreland basin in North Pakistan. It is characterized by the presence of roughly east west to northeast-trending structural features. The fold structures are generally asymmetric, plunging and are mostly associated with sub-cropping thrust faults. The major folds mapped in the area have fold axes that are parallel to sub parallel to the regional structural trend. A major south-vergent thrust fault has been recognized all along the southern periphery of the Khisor Range where Permian strata protrude southward against the Punjab plain. Structural geometries of folds and thrust faults within the study area indicate that a major regional decollement fault underlie the area that have played a major role in its tectonic architecture. The detachment-related southward thrusting has produced north-south structural accommodation in the western domain and approximately northwest in the eastern domain.

6.2 THIN-SKINNED DEFORMATION AND DECOLLEMENT

In order to establish that a fold-thrust belt is thin skinned, it is required to demonstrate that thrust fault surfaces acquire irregular 'staircase' trajectories, with long 'flat' sections, parallel to bedding, divided by short 'ramps' which cut across stratal limitations (Boyer and Elliott, 1982). It is also essential to reveal that movement of hanging-wall rocks shapes the folds over the irregular fault surface. In the Marwat-Khisor ranges the evidence that this part of the foreland fold-thrust belt is thin-skinned comes from the geological mapping, outcrop data and also from limited published well data (Fig. 1.8). The traces of emergent thrust faults have been mapped along the frontal margin of Khisor Range almost parallel to stratal boundaries in both the footwall and the hanging-wall. The exposed thrust surfaces of the Khisor Thrust and Dhupsari thrusts are parallel to bedding in the hanging wall. All major anticlines in the Marwat-Khisor ranges are cored by blind thrust faults being emerged from the basal decollement (structural outcrop data). There is a strong encouraging relationship between topographic and structural relief in this part of the foreland fold-thrust belt. Cross section construction reveals that strata lie close to their regional elevation in the core of Abdul Khel Syncline but elevated above the regional elevation on anticlines (Marwat, Saiyiduwali, Khisor, Paniala and Mir Ali anticlines). These observations are consistent with the philosophy of thin-skinned deformation.

A major sub-horizontal fault surface between the sedimentary cover sequence above and crystalline basement below is called a decollement. The position of decollement is normally at a discontinuity marking major ductility contrast, permitting hanging wall rocks to deform independently of what is underneath. The actual basal decollement itself is commonly a weak horizon, like clay or shale, or salt. At depths of 10 km or less, clay and shale are relatively weak compared to other rocks, and salt is the weakest and soft horizon for gliding view point. Salt will flow when shear stress is 1 MPa or less (Davis and Engelder, 1985). If salt is exist in the subsurface it will provide smooth gliding exterior for the overlying thrust sheet and would responsible for the extended and low elevated foreland orogenic belt. On the other hand if there is no salt situation in the substratum short and elevated orogenic belt will produce with maximum deformation (Fig. 6.1).

Regional stratigraphic and structural data combined with subsurface interpretations indicates that the Marwat-Khisor ranges define a thin-skinned deformed structural province. This thin-skinned deformation is related to a regional structural detachment, located at the contact between the crystalline basement and base Cambrian.

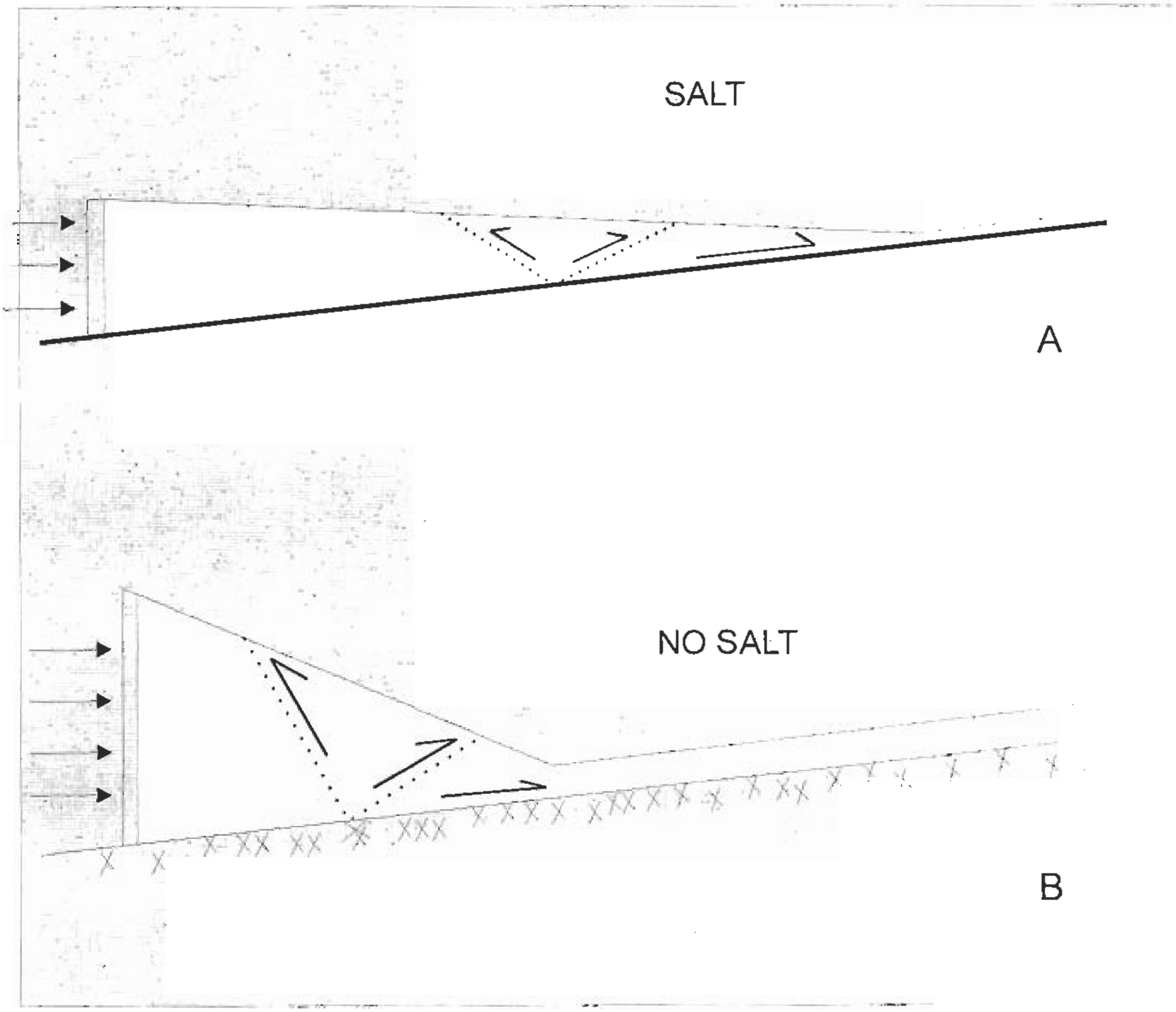


Fig 6.1 A, B- Cartoon illustrating fold-and-thrust belts underlain by salt versus nonsalt substrate. (A) The thrust belt underlain by salt, shown in black, has a narrow cross-sectional taper, a wide deformational belt, and nearly symmetrical strucrures compared to (B) A thrust belt not underlain by salt (after Davis and Engelder, 1985).

6.3 RELATIONSHIP OF STRUCTURE AND STRATIGRAPHY

Throughout the study area thrust faults have dominantly exploited weaker horizons for accommodating horizontal translation. The basal regional decollement is located in the lower part of the Khewra Sandstone. The lower part of the Khewra Sandstone is dominantly comprised of shale; therefore this major decollement exploited the incompetent horizon for determination of its path. Similarly the other thrust faults along the southern periphery of the Khisor Range are also located in the incompetent horizons by exploiting frequently soft shaley units of the Permian strata.

On large scale, abrupt changes in lithology can produce spectacular changes in structural style. The pronounced inequality in competency permits a substantially different response of folding and faulting (Cook, 1967). In the Khisor Range the shaley rocks in the southeast of the map extension produced small scale complex folding whereas, broad and open folds have been observed in the massive competent carbonate rocks in the south-southwestern Khisor Range. The peculiarity in the folding mechanism of the area is controlled by the lithology and the size of a structure depends on the thickness of deformed section. Folds in a thick section are necessary larger than those involving a thin section (Goquel, 1962). From this it follows that deformation of a relatively thick section can produce a large structural culmination. This conclusion can also be derived from the standard assumption that the amount of shortening along an orogenic belt does not change abruptly, so that the ratio of original deposited bed length to final horizontal deformed length is roughly the same for adjacent areas. If shortening is consistent, then any significant longitudinal stratigraphic thickness must be translated into a longitudinal structural thickening; that is into a structural culmination.

Transects along the Marwat-Khisor ranges reveal that the amount of shortening in the upper part of the deformed belt is accommodated by folding where as in the lower part similar amount of shorting is compensated by thrust faulting.

6.4 DISPLACEMENT AND SHORTENING ALONG KHISOR THRUST

Thrust faulting is a phenomenon comparable in many respects to concentric folding, for thickening and shortening a rock package. Individual faults, like individual folds, do not carry on forever. As they disappear, the amount of shortening of the rock package must reduce or their function must be assumed by another structure, either fold or fault. As a common observation, the extent and amount of shortening with in the foothills of an orogenic belt as a whole is more nearly even than that of individual structures. This involves the existence of a fundamental transfer mechanism that facilitates other structures to takeover the shortening role of those that die out (Dahlstrom, 1977). In the Marwat-Khisor ranges the basement is not involved in the structuration and there is a through going sole fault, which separates the basement from the overlying deformed rocks package. The Khisor Thrust joins the underlying decollement, and all the deformation above basement involves sliding upon it towards south. The Khisor Thrust is the youngest thrust ever mapped in the Marwat-Khisor ranges. Throughout the Marwat-Khisor ranges fault-bend folding becomes the dominant mechanism of shortening in the hanging wall sequence of Khisor Thrust.

Shortening basically involves thickening, but in a thrust terrain the thickening may be localized, not pervasive (Dahlstrom, 1977). Since the decollement surface is through going and gently dipping to north, differential structural thickening above this surface have produced structural culmination in both the ranges. Marwat Anticline is produced due to frontal ramp initiated from the basal decollement and accommodates shortening by duplicating strata in the form of culmination. The subsequent Abdul Khel Syncline to the south represents area of less thickening. Further south, broad anticlines of Paniala; Saiyiduwali and Khisor are developed as fault-bend folds mainly responsible for shortening and thickening of the sequence in the Khisor Range. All the shortening and thickening has been accommodated in the hanging-wall sequence above the main detachment surface.

6.5 SEQUENCE AND RELATIONSHIP OF FAULTING AND FOLDING

As far as the sequence of deformation in fold-thrust belts is concerned there are, of course, three potential standpoints: faulting first, folding first or essential contemporaneity. The thrusting-first hypothesis postulates that the original stair-step fault shape is the principal reason of folding. The folding-first hypothesis originates from the fact that concentric folding requires a decollement parallel to bedding, and that the stair-step pattern could result from the concentric folding of a rock package above the detachment horizon. End products of both processes have approximately the same geometry. The third hypothesis, contemporaneity, says that the interval of the early phase of pure faulting or pure folding is as short-lived as to be insignificant, and that both thrusts and folds were formed simultaneously. The younging direction of the structures will be corresponding to the regional tectonic transport trend.

In the Marwat-Khisor ranges fault plates are bounded on their undersides by sole fault with substantial lateral continuity. It is possible to determine the age sequence in faulting by the distribution of stratigraphic throw. However, in the study area only one main frontal thrust is exposed along the foothills of Khisor Range whereas all other faults are non-emergent. Regionally the Khisor Thrust maintains a constant stratigraphic separation along its surface trace, though its footwall stratigraphy is poorly exposed.

Structural transects along the Marwat-Khisor ranges reveal that the Marwat Anticline is the earliest response to shortening related to a simple structural process-fault-bend folding. The steeply south dipping forelimb and the gentle north dipping backlimb of this anticline suggests a southward migrating orogeny as a consequence of south migrating deformation along a basal decollement. The structural evolution of Marwat Anticline is concurrent with the underlying ramp from the basal decollement and the displacement along this ramp seized in the subsurface just ahead of the forelimb of this anticline. It was subsequently followed by gradual south migration of deformation and was followed by another major ramp after the enough critical taper was achieved to initiate the next frontal ramp from the basal decollement. The Khisor Thrust accomplishes most of the shortening in the frontal boundary of the Khisor Range (Fig. 4.2). Fold train in the Khisor Thrust sheet is primarily related to accommodate bending in the underlying thrust ramp; however, the small scale folding observed within the Khisor Thrust is related to accommodate internal shortening within the thrust sheet related to translation along the major frontal ramp. In the study area, faults commenced first from the basal sole detachment, followed by ramp and flat staircase trajectory along with contemporary folding in the hanging wall strata to accommodate bending in the fault.

6.6 STRUCTURAL SYNTHESIS OF THE WESTERN MARWAT-KHISOR RANGES

Structural data collected in the western domain of Marwat-Khisor ranges clearly demonstrates that this part of the Khisor Range has been mainly evolved as a result of contractile deformation and the main expression of the range front owes its evolution to a major anticlinal culmination associated with a major ramp detached at the base of Jhelum Group rocks. The attitude data on the major and minor folds suggest that the dominant structural trend is east west though some exceptions are present. Three prominent anticlinal structures have been mapped such as Paniala, Saiyiduwali and Khisor anticlines in the Khisor Range and Marwat Anticline in the Marwat Range that control the structure of this region. Geometry of the folded Permian strata mapped in the hanging-wall of the Khisor Thrust suggests that these were developed during the emplacement of Khisor Thrust. The folding process is primarily associated with the formation and movement along the ramping from decollement to produce south younging fold-thrust system in the region. Folding and blind thrust faulting in the vicinity of Paniala and Saiyiduwali were contemporaneous, producing fault-bend anticlines and synclines.

Projection of fold geometries for the western flank of the western domain of Khisor Range represents that the decoupling surface lies below the Jhelum Group rocks of Cambrian age and is placed at the base of Khewra Sandstone in the vicinity of

Saiyiduwali village. The sectional geometries of the surficial fold structures along the transect line AB in the western domain (Fig. 4.2), indicates that these folds developed in response to distortion associated with the thrust splays that are blind to partially emergent thrust. The Paniala Anticline is interpreted to be fault bend fold developed in response to the movement along the Khisor Thrust, followed by a blind back thrust generated against the frontal ramp. This blind back thrust imparts a northward asymmetry to the Paniala Anticline that opposite to the generally observed south asymmetry. All the stratified rock units became flatten and remain parallel to the basal detachment behind the backlimb of the Paniala Anticline and extend below the Abdul Khel Syncline towards the Marwat Range and form the giant Marwat Anticline.

Fold and fault geometries across the Saiyiduwali Anticline along the transect CD (Fig. 4.3), indicates that this anticline is underlain by a detachment surface located beneath the Khewra Sandstone of lower Cambrian age. The Salt Range Formation is not exposed throughout the study area, it is therefore promising that this sequence does not extends to this part of the Trans-Indus ranges. Geometric relationships between the Saiyiduwali Anticline and its associated forelimb-cutting thrust fault along the cross-sectional line CD indicates that the Saiyiduwali Anticline developed as fault-bend fold. This phenomenon provides evidence for the southward propagation of deformation system. It is quite clear that the structural system in the western domain is migrating southwards in response to the Himalayan frontal deformation. Shaly beds in the Amb and Sardhai formations are mechanically incompetent therefore these shale beds provide an excellent gliding horizon for the cover sequence to move forward (southward) with response to the tectonic push being observed from north. In this part of the study area the thrust exposed the thrust sheet up to the Wargal Limestone of Permian age while rest of the thrust sheet down to Khewra Sandstone of Cambrian age remains concealed. Age to the deformational activities in the study area is assigned on the basis of the youngest rocks involved in the deformation. Thrust emplacement across the Khisor Range frontal thrust system post-dates the deposition of the Nagri Formation of Siwalik Group, probably in the Pliocene-Pleistocene time.

6.7 STRUCTURAL SYNTHESIS OF THE EASTERN MARWAT-KHISOR RANGES

Geological mapping along with structural analysis and cross-sections construction of the eastern domain of the Marwat-Khisor ranges indicate that this part of the study area is structurally and stratigraphically similar to that of the western domain with some dissimilarity in the regional structural trends. Like the western domain of the Marwat-Khisor ranges it is also underlain by a regional structural detachment surface located beneath the Jhelum Group rocks of Cambrian age at estimated stratigraphic depth of 3 ~ 3.5 km. Orientations of both the large and small scale structural features within the eastern domain demonstrates that this part of the Marwat-Khisor ranges has undergone deformation as a result of north-northwest oriented horizontal compressional stresses. In the this domain, repeated east plunging synclinal and anticlinal folds of medium to very short amplitude less than 1 km have been mapped. The ramp-flat geometry of the major thrust along cross section line EF reveals that the major topographic expression of the Khisor Range is the result of a ramp anticline emanating from a regional basal detachment surface observed below the Jhelum Group rocks. All of the small-scale structures developed in the Wargal Limestone of Permian age towards the southern margin of the range front lies atop the flat related to shortening accommodation within the thrust sheet of Khisor Thrust (Fig. 5.2). Structural transects across these ranges depict that the Marwat Anticline is a high side anticlinal closure related to a major ramp initiated from basal detachment surface. However, in this domain the translation along the underlying ramp is greater then that of the western domain of the study area as the forelimb of the Marwat Anticline is overturned towards south with moderate to steep dips. South of the Marwat Anticline lies the Abdul Khel Syncline that is believed to be a flat-syncline between two consecutive ramps. Age of the deformation in the Marwat-Khisor ranges is assigned post Plio-Pleistocene based on the involvement of Siwalik Group rocks.

6.8 STRUCTURAL MODEL OF THE STUDY AREA

Based on sedimentological studies of molasse deposits exposed along the frontal ranges a model has been proposed for the tectonic evolution of the thrust front along Salt and Trans-Indus ranges that include late Miocene normal faulting followed by Quaternary thrusting, (Burbank & Raynolds, 1988; Burbank & Beck, 1989a, 1989b; Mulder and Burbank, 1993; Davis & Lillie, 1994; Burbank et al., 1996). However, the timing of deformation as worked out from the chronostratigraphy of the Siwaliks is believed to be younger in the Trans-Indus ranges as compared to the Salt Range. It has been interpreted that major thrusting along the Salt Range front started at ~ 2.5 Ma (Burbank & Raynolds, 1988; Burbank & Beck, 1989a) and along the Trans-Indus ranges major convergence started at ~ 1 Ma (Khan et al., 1988; Pivnik & Khan, 1996, Blisniuk and Sonder, 1998), (Fig. 6.2).

Beneath the southern outskirts of the foreland fold-thrust belt of the Salt ranges weak evaporites of the Salt Range Formation constitute a laterally widespread strong decoupling surface in close proximity to the basement cover interface. So consequently the fold thrust belt is thin-skinned and extends far within the foreland basin before ramping out at the thrust front, where the Salt Range Formation below and the entire sedimentary cover sequence above is exposed (Gee, 1980; Lillie et al., 1987; Blisniuk, 1996). So in the Salt ranges the frontal thrust pursued the soft salt cushion for protruding to the south against the Punjab Plain undeformed sediments. Seismic line along the Potwar Plateau and Salt Range area reveals that the upper part of the crystalline basement is convex upward beneath the basal decollement and very gently north dipping. The dip inclination has been observed about 1° below the southern Salt Range to 4° underneath the Northern Potwar Plateau (Lillie et al., 1987; Jaume and Lillie, 1988). Comparable geometry was interpreted for the basement surface below the Bannu Basin (Parwez, 1992); farther south and southwest similar basement geometry is inferred for the Marwat-Khisor ranges.

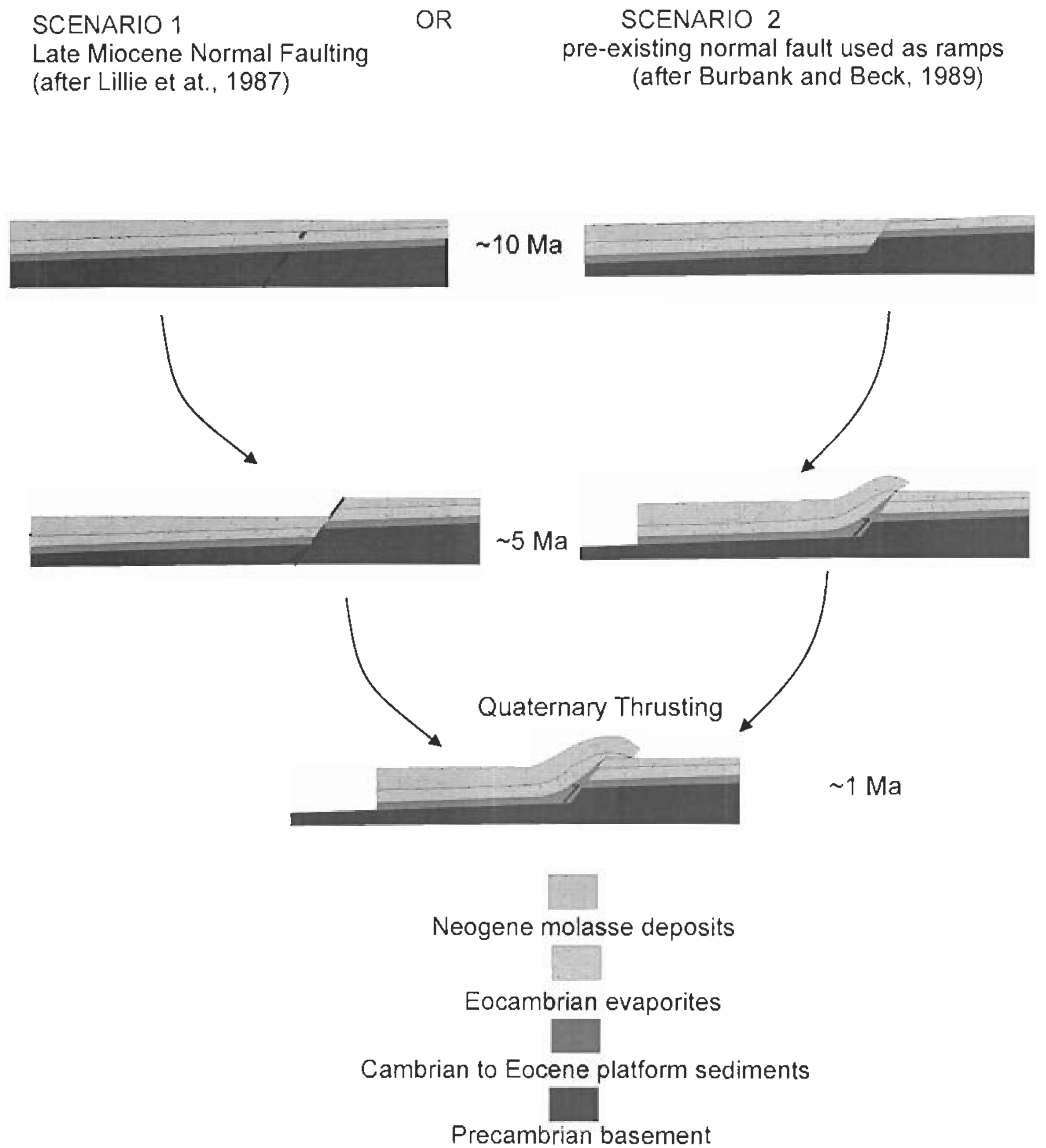


Figure 6.2 Schematic cross-sections of the Salt Range/Potwar Plateau area, illustrating two scenarios for the tectonic evolution of the thrust front (reproduced after Blisniuk et al., 1998).

During the present studies Salt Range Formation has not been found throughout the Khisor Range. Probable cushion exterior is low strength soft shale unit present at the lower horizon of the Khewra Sandstone of Jhelum Group rocks of Cambrian age which is capable for the provision of gliding horizon for the propagation of thrust faulting in the central Khisor Range. This horizon has been observed at the bottom of the Saiyiduwali Anticline and most likely the Khisor Thrust has exploited the same surface for its propagation. In the western and eastern Khisor Range the same frontal ramp oppressed dissimilar Permian stratigraphic horizons for its propagation, but the same ramp is mostly blind in the western periphery of the range front. In the central Khisor Range the thrust sheet above the ramp observed thicken by lifting Cambrian to Neogene sequence. The exposed thrust sheet along the western and eastern flanks comprised of the Permian to Neogene sequence, where the Cambrian horizon is concealed. The entire model for the Khisor Range is a regional scale solitary ramp anticlinal structure emanating promisingly from the basal decoupling surface. As an exposed salt situation has not been observed in the range but may be present in the substrate to tender glide horizon for the southern frontal foothill ramping. As a result the structural model for the Marwat-Khisor ranges is free of complexity while compared to the Kohat-Potwar plateaus and Salt ranges. These models consist of variety of dissimilar structures with pronounced shortening of the cover sequence. The en d products of the contractile deformation in light of the Himalayan orogeny by telescoping the cover sequence in the form of duplication of strata along assemblages of complex and variant structural features

6.9 STRUCTURAL MODEL OF THE SALT RANGE AND POTWAR-PLATEAU

The Salt Range and Potwar Plateau are located south-west of the northwestern syntaxis of the Himalayas and northeast of the Marwat-Khisor ranges. The Salt Range and Potwar Plateau are the division of the active foreland fold and thrust belt of the Himalayan orogenic belt. Salt Range is the southernmost active deformational front of the Potwar Plateau. The southern Potwar which is comparatively flat and less deformed separates the Salt Range from the key Himalayan ranges of northern Pakistan. From base to apex, stratigraphically the Salt Range and Potwar-Plateau can be divided into four units: (1) crystalline basement rocks (2) Eocambrian Salt Range Formation (3) platform sequence and, (4) molasse sequence (Khan et al., 1986). Lithology of the said basement rocks is the same as that of the Kirana Hills (Yeats and Lawrence, 1984). The basement below the Salt Range and Potwar Plateau is not involved in the deformation and Salt Range Formation forms the gliding horizon for the fold and thrust belt which is responsible for the southward deformation front into the foreland due to the presence of weak detachment evaporites surface (Lillie et al., 1987).

Seismic reflection data reveal that a substantial amount of internal shortening has been accommodated in the eastern domain of the Potwar Plateau as compared to the central and western Potwar Plateau, due to differences in the basement dip (Jaume and Lillie, 1988), (Fig. 6.3 a, b). The southern margin of the Salt Range rises immediately on top of the Jhelum River plain, and protrudes southward the exposing a thick sedimentary section including the Eocambrian evaporites (Fig. 6.3 b). The southern parts of the western Potwar Plateau is less deformed and very smaller amount of Internal shortening is recognized, where most of the advance of the thrust wedge appears to have been accommodated along the Salt Range Thrust (Lillie et al., 1987).

Beneath the northern perimeter of the Salt Range and southern Potwar Plateau the most obvious feature is the identification of the large normal faults in the basement which is responsible for the building of ramp structures. Theses normal faults being interpreted as the consequences of the flexure of the Indian plate (Lillie et al., 1987; Duroy, 1986). Significant dissimilarity is the lack of intense deformation in the southern Potwar Plateau and adjoining Soan Syncline. Changes in the basement slope decreases towards the southern limits of the Salt Range which is confirmed by the reflection profiles (Lillie et al., 1987), Steeper Bouguer gravity gradient is recognized for the central region (Fig. 6.4) as compared to the eastern Potwar Plateau (Fig. 6.5). In the western

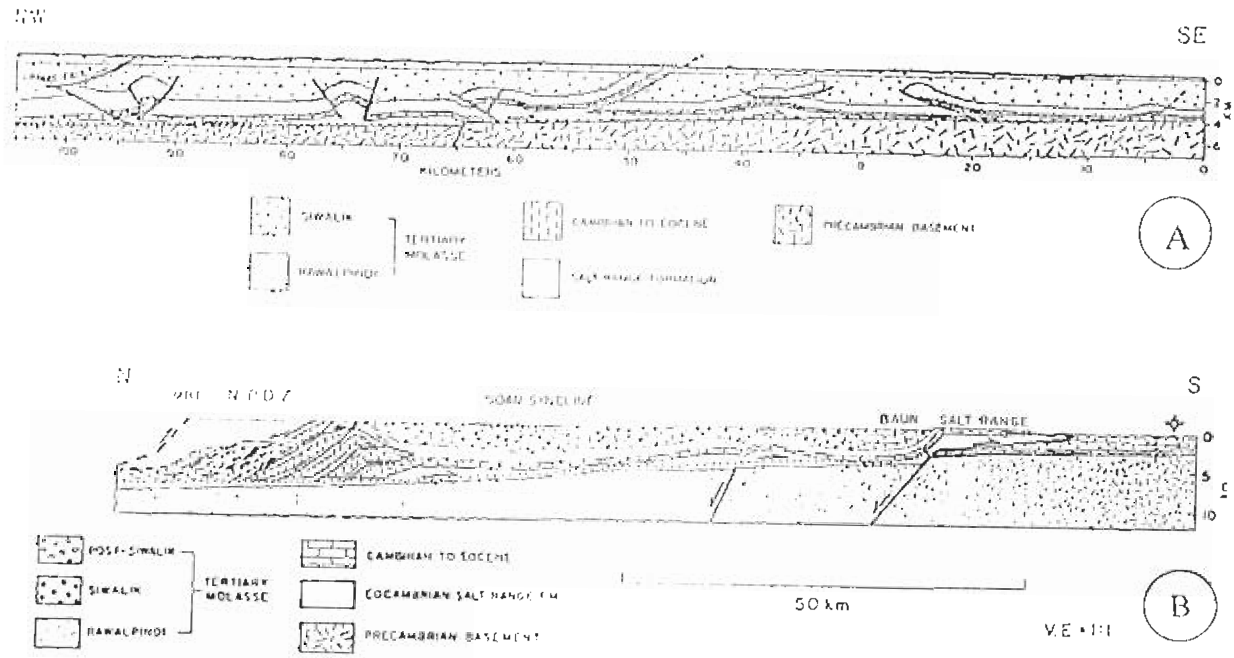


Fig. 6.3 a,b Generalized cross sections of the foreland fold-thrust-belts (a) Eastern Potwar Plateau (after Pennock et al., 1989), (b) Central Salt Range-Potwar Plateau (after baker et al., 1988).

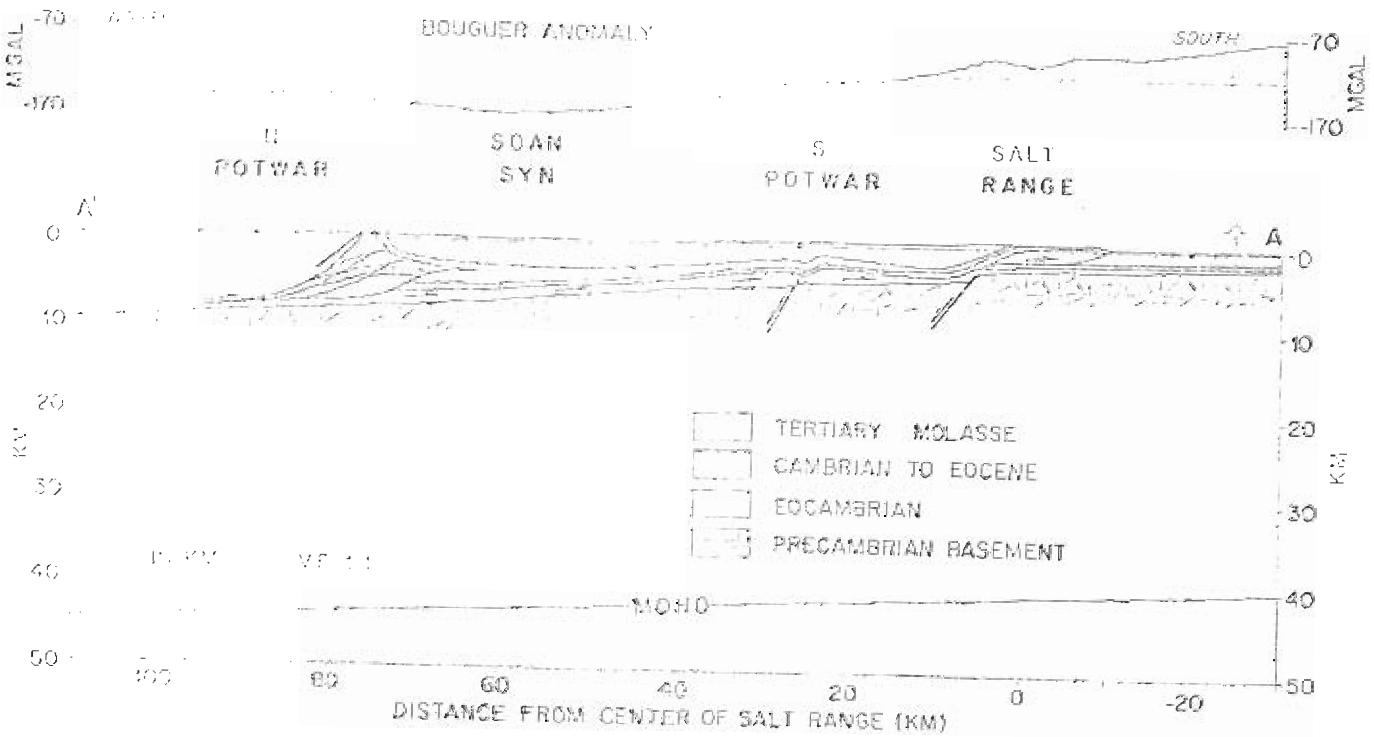


Fig 6.4 Gravity modeling across the central Salt Range–Potwar Plateau by Duroy (1986), suggests that the south to north Bouguer gradient is due to moho and top of the basement dipping at about 1° ~ 4°.

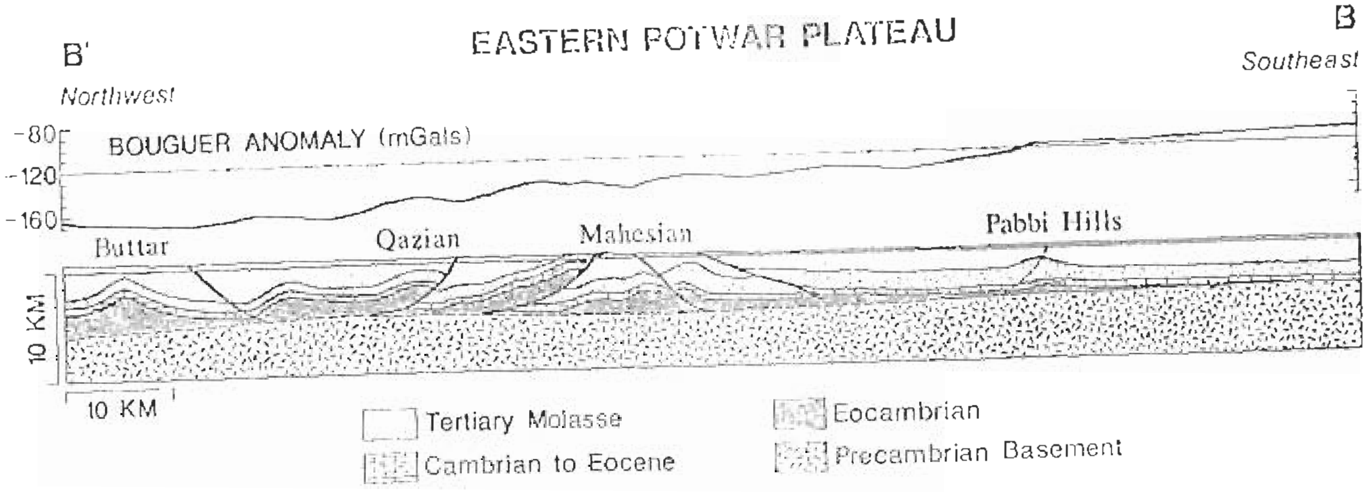


Fig. 6.5 Cross section shows the eastern Potwar Plateau (after Leathers, 1987). Seismic profiles and the gentle Bouguer gravity gradient suggest a basement slope of less than 1°.

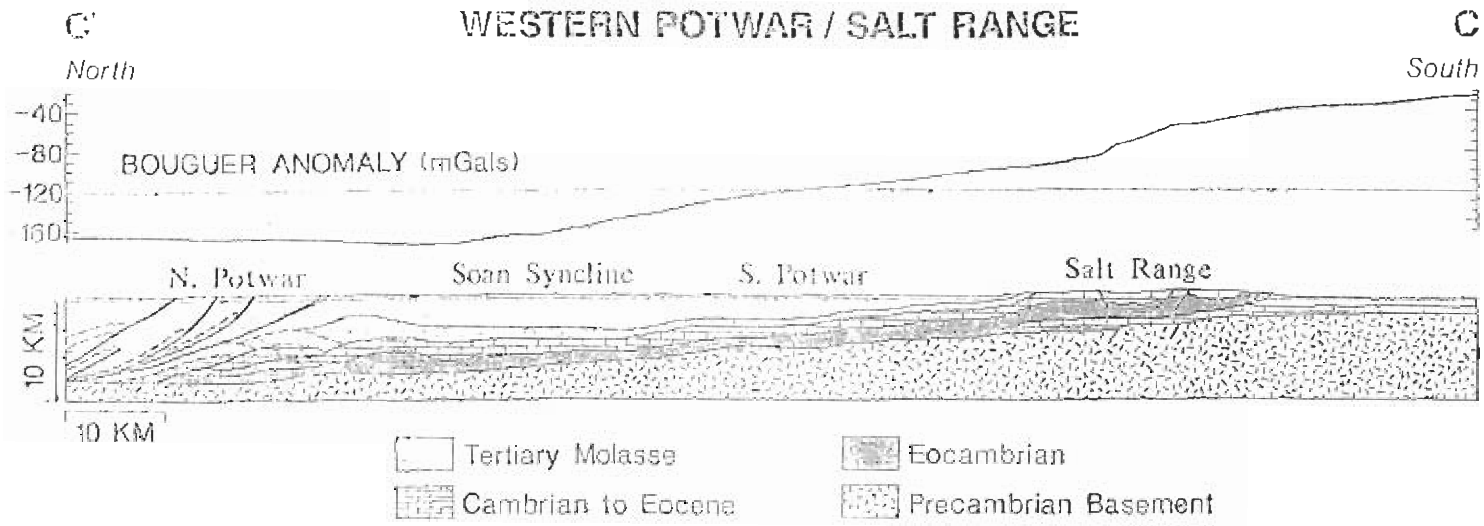


Fig. 6.6 Cross section line across the western Salt Range-Potwar Plateau (after Leathers, 1987), Seismic profiles and a steep Bouguer gravity gradient show northeast flank of the Sargodha basement high under thrusting the Salt Range and the southern Potwar Plateau.

Salt Range and Potwar Plateau some differences are observed that are (1) lack of the large normal faults in the basement to act as ramps for the Salt Range thrust in the west (2) the basement is gently flexed rather than faulted (3) lack of major deformation in Southern Potwar Plateau and the Soan Syncline (4) underneath surface flatness of the central Potwar Plateau (Leathers, 1987), (Fig. 6.6).

Detailed studies and seismic profiles of the structure of the Potwar Plateau (Lillie et al., 1986; Baker et al., 1988; Jaume and Lillie, 1988; Pennock et al., 1989; Gee, 1989) identified that (a) in the north of the area the structure is dominated by an imbricate stack of thrust faults of which some reach the surface and others terminate at depth as blind thrust (b) the Salt Range in the south is interpreted as the surface expression of a structure basement ramp (with 1 km of basement offset, down to the north/0 is generally believed to be the result of extensional tectonics(i.e., loading of the Indo-Pakistani Plate in the north) (c) ramping of the thrust sheet against the basement block started between 2.1~1.6 m.y and was accompanied by considerable thickening of the salt unit of the Salt Range Formation against this subsurface ramp.

Structures in the eastern Potwar Plateau are markedly different which is dominated by broad synclines and narrow, salt-cored anticlines. This change of style is attributed to thinning of the salt deposits and a lesser degree of basement dip which required thickening (by folding and thrusting) of the overall thrust wedge (Lillie et al., 1986).

The Salt Range thrust emerges to translate as a convincingly consistent block, ruptured by various small scale local faults. Contractional deformation in the form folds is mostly associated to the frontal margins of the range (Yeats et al., 1984). Southward push relative to the decollement surface for Southern Potwar Plateau is recognized at least 20 km, so it is suggested that the Northern Potwar Plateau has also been moved about 20 km across the original northern edge of the salt basin 2.1-1.9 m.y before (Baker, 1987).

6.10 STRUCTURAL MODEL OF THE NPDZ

southern limits of the Potwar Plateau. Most of the NPDZ is covered by the molasse deposits but competent Eocene lithologies crop out above the ground level in the form of ridges and their structural trend is right angle to the regional tectonic transport direction. The northern perimeter of the NPDZ is marked by the MBT and its faults zone, where Eocene and older lithological sequence of the MBT thrust sheet is thrusted southward against the molasse deposits of the Potwar Plateau. Structural model of the NPDZ reveal that all the thrust related faults are commenced from the basal decollement zone being observed in the incompetent Salt Range Formation in the hanging wall against the platform sequences in the footwall. As a result, a roof thrust is observed at the top of the Murree Formation along the frontal limits of the NPDZ (Jaswal, et al., 1997). Cross section line across the Northern Potwar Deformed Zone (NPDZ) reveal the existence of a basal decollement surface where the imbricate thrust faults terminate at the decollement, as a basic characteristic feature of the foreland fold-thrust belt (Jones, 1987) (Fig. 6.7). Thin-skinned deformation during the telescoping of sedimentary cover sequence above the basal detachment and southward propagation of thrust faults has been recognized. Triangle zone, passive roof thrusting, piggy back blind thrusting and pop-up structures developed at the southern margin of the Northern Potwar Deformed Zone (Jaswal, et al., 1997). Flat topography and gentle basement dip and presence of the Eocambrian evaporites beds beneath the platform sequence in the NPDZ have been recognized by (Jaume and Lillie, 1988). The severe deformation in this zone must have produced an extensive taper i.e., basement dip with topographic slope, which involves high fraction at the basal decollement (Davis et al., 1983), as a consequence intense folding and various imbrications have been developed.

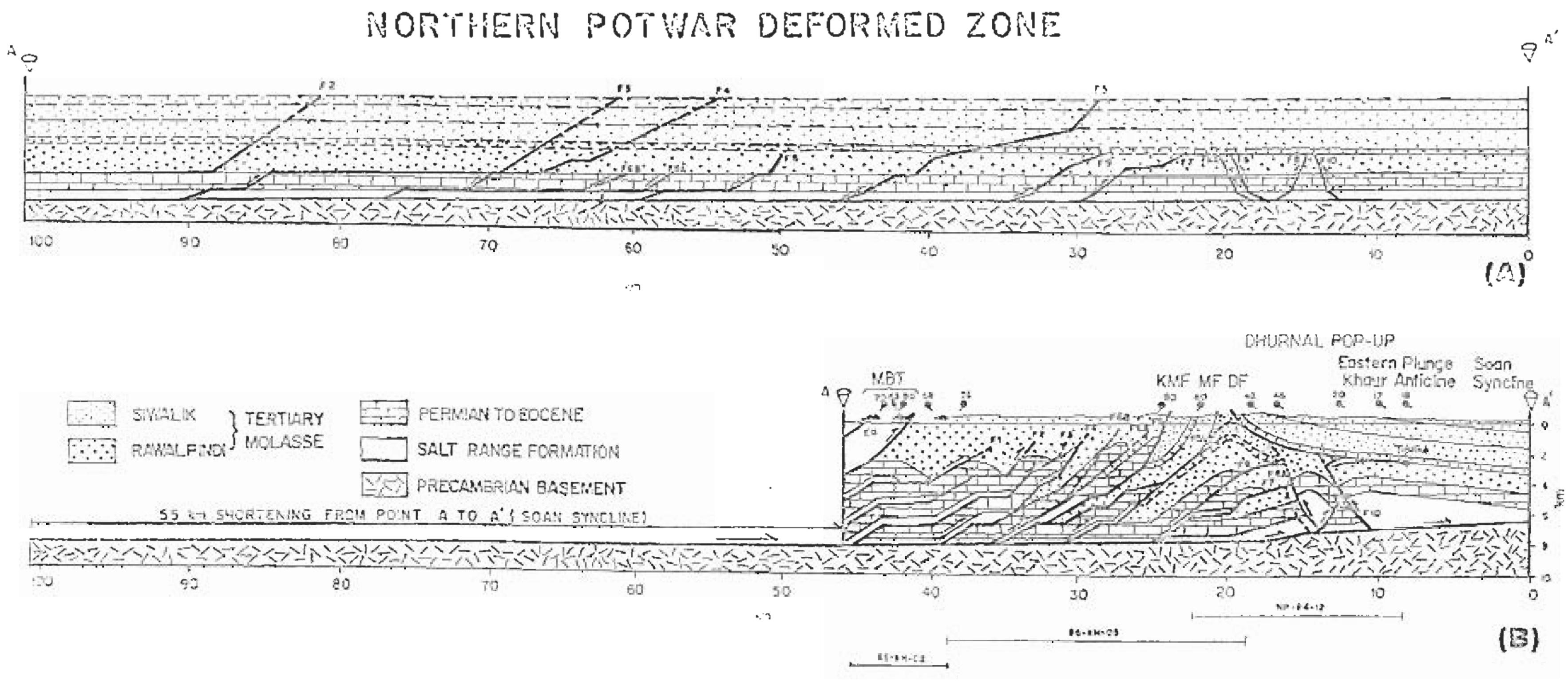


Fig. 6.7 - Balanced cross section across the NPDZ. The labels F1 to F10 represent the chronological development of major Faults. from oldest to youngest. (A) Post Siwalik restoration. (B) Cross section showing present structural geometry of the NPDZ.

6.11 COMPARATIVE REVIEW

Characteristic features of the tectonically active thin-skinned contractional wedge of the Southern Kohat Plateau, Surghar Range, Potwar Plateau and Salt Range have been summarized and compared to the present studies in the Marwat-Khisor ranges as under:

Southern Kohat Plateau is dominantly deformed by south directed contractile deformation with a later phase of strike-slip faulting towards its leading edge. This distinctive structural province is named as the Kohat plateau Boundary Zone (KPBZ) (Ahmad, 2003). The strike-slip faulting in the KPBZ is related to the west directed underthrusting of the Southern Kohat Plateau rocks beneath the Sulaiman and Samana ranges in the west along the transpressional boundary called the Kuram Fault (Pivnik and Sercombe, 1993 and Ahmad, 2003).

South to southeast, Surghar Range forms the frontal deformational boundary of the Kohat Plateau and provides opportunity to understand the structural style of deformation within the Paleozoic-Mesozoic strata which is not exposed in the internal Kohat Plateau. The Surghar Range suggests that this part of the Himalayan orogenic belt is dominantly a south verging thrust front which is detached at the base of Triassic sequence. The Surghar Rage frontal thrust fault protrudes southward against the Punjab Foreland comparable in style with the Khisor frontal thrust. Structural model of both the ranges reveals that this structural province is thin-skinned and developed in response of southward migration of deformation above a regional basal decollement at the contact of Paleozoic-Mesozoic sediments and basement interface (Ahmad, 2003).

Potwar Plateau is the eastward geographic extension of the Kohat Plateau (Fig. 1.1). Potwar Plateau is a well documented thin-skinned structural province underlain by a regional decollement at the contact between the Eocambrian Salt Range Formation above crystalline basement (Jaume and Lillie, 1988). In the Potwar Plateau south directed deformational transferal system along the regional basal decollement is immensely facilitated by the existence of the soft salt horizon. Subsequently the same gliding horizon is exposed at the surface along the Kalabagh hills (Ahmad et al., 2005). Stratigraphy of the Salt Range is similar to the Khisor and Surghar ranges except the Rawalpindi Group rocks which is absent in the Khisor and Surghar ranges. Additionally the Salt Range Formation is also found absent throughout the Khisor and Surghar ranges. The Salt Range front is comparable in fashion and in outcrop geometry to the Khisor Thrust and probably Khisor Thrust is the western continuation of the SRT. Thin-skinned deformation towards the northern and southern margins and latest Miocene basement involved north dipping normal faults in the central Salt Range have controlled the gross structural features and tectonic habitat of the Salt Range. These normal faults were used as ramps by the southward translated sedimentary wedge and are mostly responsible for the growth of ramped anticlines in the central Salt Range.

Gross structural model and topography of the Surghar Range, Potwar Plateau Salt Range and adjoining ranges are most probably comparable due to the presence of both aspects such as weaker layer of evaporite and changes in gradient of the basement surface. Consequently ramp flat geometry is consistent for the entire Salt and its tangential equivalent ranges and comparable in propagation and structural style to the Marwat-Khisor ranges.

CHAPTER 7

Economic Importance of the Marwat-Khisor ranges

CHAPTER 7

ECONOMIC IMPORTANCE OF THE MARWAT-KHISOR RANGES

7.1 OVERVIEW

The Marwat-Khisor ranges fraction of the Trans-Indus ranges is important due to its diverse economic potential. The Marwat-Khisor ranges are prosperous in varieties of industrial raw materials, construction materials and economic industrial minerals. As the Permian succession of the area comprised a thick sequence of carbonates and mixed carbonate-siliciclastic rocks representing a wide variety of shallow marine to non-marine environments of deposition. The exposed stratigraphic sequence suggests an important petroleum system comprised of potential source, seal and reservoir rocks for oil and gas generation and accumulation. These ranges are also capable of providing suitable structures for the development of underground facilities.

7.2 ECONOMIC INDUSTRIAL RAW MATERIALS AND MINERALS

This group includes rocks and minerals, which can be utilized as such or after some processing in various industries. Bountiful reserves of the industrial raw materials exist throughout the Marwat-Khisor ranges. Deposits of several industrial raw materials of great importance have been observed that include limestone, dolomite, sandstone, gypsum, silica sand, laterite, bentonite, shale and minor coal deposits.

7.2.1 *LIMESTONE AND DOLOMITE*

Limestone and dolomite is of great interest because of their economic worth. Huge deposits of limestone and dolomite have been mapped throughout the map extension. Limestone is by far the most abundant mineral commodity of the area. Major limestone deposits are associated with the Permian Zaluch Group rocks while dolomite reserves are found in the Kussak and Jutana formations of Cambrian and Kingriali Formation of Triassic age.

7.2.2 *GYPSUM*

Economically viable gypsum deposits are mapped in the core of Saiyiduwali Anticline belonging to the Khisor and Jutana formations of Cambrian age. The thickness of these deposits is greater than 200 m in both the formations (Plates 2.3 and 2.4).

7.2.3 *SILICASAND*

The basal part of Jurassic Datta Formation southwest of Paniala village dominantly consists of silica sand (Plate 8.1). The bed of silica sand is about 20 m thick and is exposed for a length of 16 km from Paniala to Pezu (Siddiqi, 1973). Sieve analyses have shown that the sand size is medium to fine grained, suitable for glass making. Silica content varies between 76% to 97% and ferric oxide range from 0.67% to 4.5%. The sand is friable, thus easy to mine. Total reserves as estimated by Siddiqi (1973) are 20 million tones up to a workable dip depth of 30 m.

7.2.4 *LATERITE*

Mine able laterite beds are commonly associated with the Datta Formation southwest of Paniala village. Laterite is a red, residual soil containing large amount of aluminum and ferric hydroxides, formed by the decomposition of several kinds of rocks. Laterite is being mined as Portland cement raw materials.

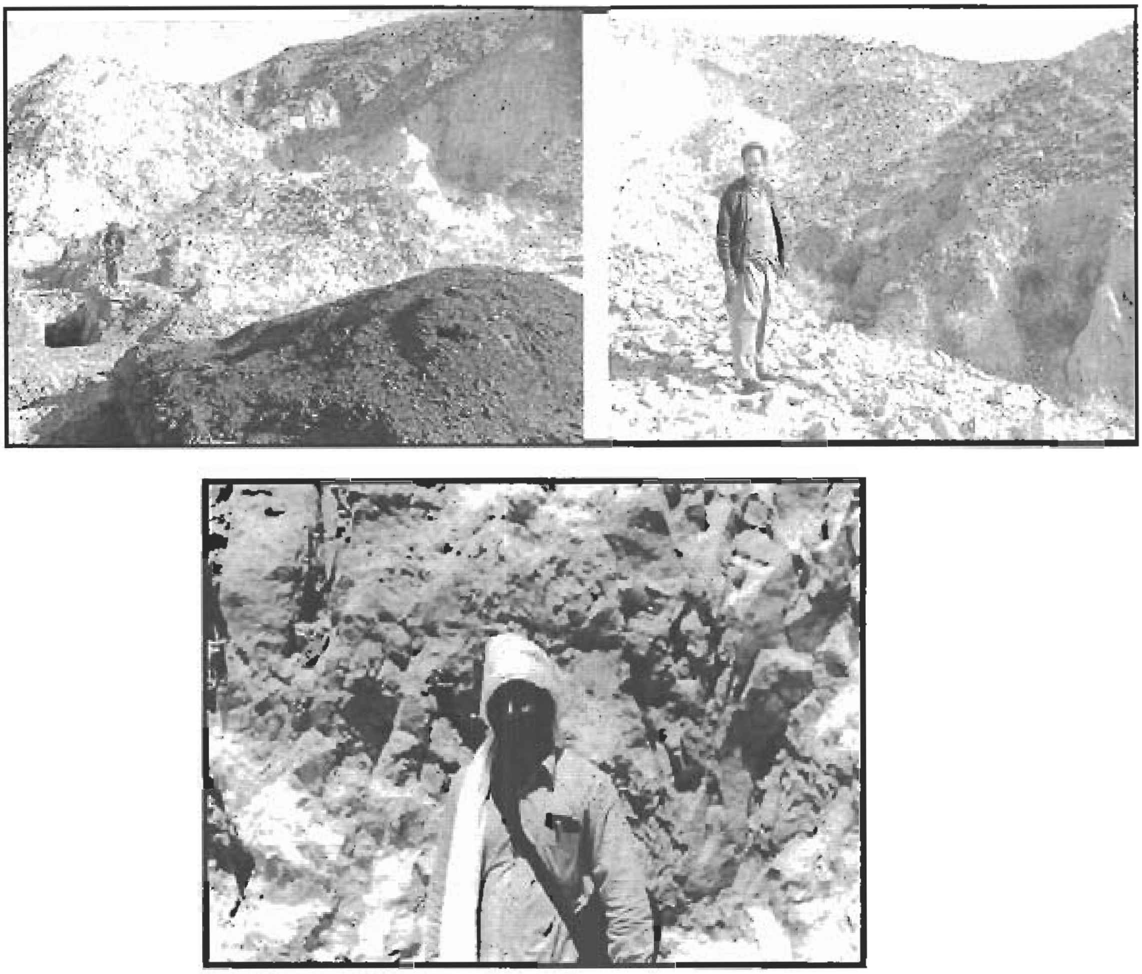


Plate 7.1a, b, c Silica sand and coal deposits of Datta Fm in the western domain of the study area southwest of Paniala village.

7.2.5 *BENTONITE*

Bentonite beds have been found in the lower part of the Nagri Formation through out the study area. Huge deposits are located east of the Paniala village along the back limb of the Paniala Anticline and south of Katta Khel village along the southern limb of Abdul Khel Syncline. Bentonite can be used in manufacturing of ghee, used in the drilling industry as drilling fluid/mud. Bentonite has the property of swelling into a gelatinous mass or disintegrating into a granular to fluffy aggregate. Bentonite, unlike ordinary shales and clay, commonly has a waxy translucence in thin chips.

8.2.6 *FIRECLAY*

Fireclay is a kind of clay capable of resisting intense heat, used for making firebricks, furnace linings etc. It is commonly associated with the upper part of the Nagri Formation and in the lower parts of the Dhok Pathan Formation both in the Marwat-Khisor ranges.

7.2.7 *MINOR COAL DEPOSITS*

In the study area towards the northwestern terminus of the western Khisor Range minor coal deposits are present southeast of Paniala Village in the Datta Formation of Jurassic age. The outcrop of Datta Formation is confined to the northern limb of Paniala Anticline in the Gori Tang Nala. At this locality the coal beds is about 01 m thick (Plate 7.1).

7.3 DEVELOPMENT OF UNDERGROUND FACILITIES

There is great potential for the construction of underground caverns and special chambers in the western and central parts of the Khisor Range for our national security purposes. These caverns may be exploited as public underground air raid shelters for the purpose of civil defense in any eventual war and in peacetime crises; as state emergency storages; distribution and bulk storage for oil and consumption storage for power plants and industry as situated in surrounding of the study area. The Khisor Range is composed of several kinds of solid lithological units, these units can be utilized for the construction of fortifications which will give many advantages on surface construction, because these rock units are difficult to penetrate and the construction of subsurface chambers are difficult to discover and easy to guard. The front of the Saiyiduwali Anticline is suitable for the construction of repository to store the waste of nuclear fuel. Field applications of the western and central part of the study area are huge, may be excavated for the protection of guns, ammunition, and soldiers, for the storage of missile and mobile launching pad/vehicle, and for the storage of nuclear residue.

7.3.1 *CAVERNS*

Large underground caverns can be developed especially for storage purposes in the Khisor Range. These caverns will be designed and excavated in the form of chambers of small to large dimensions according to the requirements of the end users. Suitable locations for the construction of caverns subsist in the back and fore limbs of the Paniala Anticline along the Gori Tang stream section. Thick bedded to massive dolomite of Kingriali Formation exists at the ground level that offers good location for the said facility.

The Gori Tang stream section provides excellent portal locations and immediate overburden for several caverns construction. Similar activities can be performed in the Saiyiduwali, Khisor and Mir Ali Anticlines of Khisor Range. The entire range has the capability to provide several suitable and feasible localities for the desired excavation. Exact location will not be exposed due to security reasons. These caverns will be exploited for different storage purposes may be for the use of civilians or for armed defense viewpoint.

7.3.2 *STORAGE TUNNELS*

Straight to curved storage tunnel can be constructed in the western, central and eastern Khisor Range. The essential parameters for the desires storage tunnels such as hard to self-supported rocks, more than 100 m rock cover (overburden), and easy entrance and free population locations are available in the mentioned parts of the Khisor Range. Rocks of the Wargal limestone and Chhidru Formation will provide good potential for self to partial supported rocks in the vicinity of Paniala. Saiyiduwali Anticline can be utilized for the construction of circular storage tunnel. In this area hard rocks of the Khewra Sandstone, Kussak and Jutana formations have the potential to sustain for long time under the load of huge overburden of the Saiyiduwali Anticline. Besides tunnel, storage adits can also be constructed in the western and central part of the range.

7.3.3 *UNDERGROUND DISPOSAL OF WASTES*

The use of nuclear energy implies the generation of radioactive wastes that have to be controlled adequately to protect man and his environment from the potential radiological hazard they pose at present and in future (Richter, 1981). There are few reactors in the power production, research and health care domains in the country, which generates these wastes that need safe handling. Marwat-Khisor ranges have the capability to provide the desire locations for such purposes.

7.3.4 *CONSTRUCTION OF REPOSITORY*

Underground disposal of the radioactive waste is considered to be the best method of safe disposal of radioactive wastes. For these purposes suitable geological formations consist of thick shales and salts. For the deposition of low and intermediate-levels waste, shallow ground and rock cavities are essential geological sites; whereas for the disposal of high-level waste deeply buried geological formation is recommended. The formation where the waste is disposed off is called the host formation. The host formation plays a threefold ròle in the disposal system. First, the migration of radionuclide towards man and his environment must be prevented or delayed. Second, it must form a physical barrier to minimize the likelihood of the waste becoming accessible to humans. Third, the geological host formation creates geochemically and mechanically stable environments within which the engineered barrier can operate as designed. There are few host formations, which fulfill the desired parameters for the construction of underground disposal system. Khisor Formation is dominantly an evaporates-shale lithofacies with excellent potential for the construction of repository for all kinds of nuclear waste. Sardhai Formation, dominantly shale is the other horizon for the construction of repository located in the western and eastern domains of the Khisor Range.

CHAPTER 8

Conclusions

CHAPTER 8

CONCLUSIONS

- Geological mapping in the study area indicates that thin-skinned deformed fold-thrust assemblages dominate the structural style of the Marwat-Khisor ranges. The key structural elements of these ranges are defined by eastwest to northeast trending anticline-syncline pairs that are generally asymmetric and dominantly southeast vergent. Paniala, Saiyiduwali, Mir Ali and Khisor Anticline constitute the main topographic expression of Khisor Range whereas Marwat Anticline is the key structural element of the Marwat Range.

- Structural analysis of the surface geometries and the construction of balanced structural transects indicate that the study area is underlain by a regional basal detachment located at the base of Jhelum Group rocks of Cambrian age. The basal decollement is dipping northwards by 2-3°.

- Using the projection of surface structures to depth using kink plane bisecting angles, it is found that in Marwat-Khisor ranges basement is not involved in structration and there is a through-going sole fault at the base of Jhelum Group rocks. Shortening above this basal decollement is the consequence of sequential up-section frontal ramping.

- Structural geometries of the fold assemblages suggest that most of the prominent anticlines have been evolved as fault-bend or fault-propagation folds, being the consequences of the compressional deformation related to south progression of Himalayan deformation.

- The deformation event in the region post-dates the deposition of late Miocene to Pleistocene Siwaliks indicating that the age of compressional deformation is post Pleistocene.

- In the study area, faults commenced first from the basal sole detachment, followed by ramp and flat staircase trajectory along with contemporary folding in the hanging wall strata to accommodate bending in the fault.

- The essential elements of a petroleum system such as reservoir, source, seal and fault related anticlinal culminations are present throughout the study area that proves the hydrocarbon potential of the surrounding region.

References

REFERENCES

Abbasi, I. A., 1994. Fluvial architecture and depositional system of the Miocene molasse sediments, Shakardara Formation, southwestern Kohat, Pakistan. Geological Bulletin University Peshawar, v. 27, pp. 81-98.

Abdul Gawad, M., 1971. Wrench movements in the Balochistan arc and relation to the Himalayan-Indian Ocean tectonics. Bull. Geological Society of America, v. 82, pp. 1235-1250.

Ahmad, S., Ahmad, I. & Irfan, M. 2005. Imprints of transtensional deformation along the Kalabagh Fault in the vicinity of Kalabagh Hills, Pakistan. Pakistan Journal of Hydrocarbon Research. Vol.15

Ahmad, S., 2003. Comparative Structural Analysis of the Kohat Plateau, NWFP, Pakistan: Unpublished Ph.D Thesis submitted to NCEG, Univ., of Peshawar, p-1~119.

Ahmad, Z., 1969. Directory of mineral deposits of Pakistan; Pakistan Geological Survey Resources, v. 15, pt. 3, p. 220.

Alam, I., Ahmad, S., Ali, A., and Irfan, M., 2005. Fold-Thrust Style in the Marwat-Khisor ranges, Trans-Indus Range, Pakistan. Annual Technical Conference, Nov. 2005, p. 80-93, Islamabad.

Alam, J., and Aziz. A, 2003. Geology of the Western Khisor Range, East of Paniala village, D.I.Khan District, NWFP., Pakistan. Unpublished M.Sc Thesis submitted to the Deptt., of Geology, University of Peshawar.

Allen, C. R., 1976. Report to the Pakistan Atomic Energy Commission on the geologic and seismic aspects of the proposed nuclear power plant at Chashma.

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

Bannert, D. and Raza, H. A., 1992. The segmentation of the Indo-Pakistan Plate, Pakistan Journal of Hydrocarbon Resources., v. 4(2), pp. 5-18.

Bard, J. P., Maluski, H., Matte, P. and Proust, F., 1980. The Kohistan sequence; Crust and mantle of an obducted island arc. Geological Bulletin University of Peshawar, v. 13, pp. 87-93.

Beck, R. A., Burbank, D. W., Sercombe, W. J., Riley, G. W., Brandt, J. R., Afzal, J., Khan, A. M., Jurgen, H., Metje, J., Cheema, A., Shafique, A., Lawrence, R. D. and Khan, M. A., 1995. Stratigraphic evidence for an early collision between northwest India and Asia. Nature, v. 373, pp. 55-58.

Blisniuk, M. P., 1996. Structure and tectonics of the northwest Himalayan frontal thrust system, Trans-Indus ranges, Northern Pakistan. Unpublished Ph.D thesis, Dartmouth College, Hanover, New Hampshire, U.S.A.

Blisniuk, M. P., Sonder, L. J., Lillie, R. J., 1998. Frontal normal fault control on northwest Himalayan thrust front, Tectonics, v. 17, No.5, pp.766-779.

Boyer. S. E., Elliot, D., 1982. Thrust systems. American Association of Petroleum Geologists Bulletin v. 66, pp. 1196-1230.

Burbank, D., Raynold, R., and Johnson, G., 1986. Late Cenozoic tectonics and sedimentation in the northwestern Himalayan foredeep: II. Eastern limb of the Northwest Syntaxis and regional synthesis. In: Foreland Basins (Ed. By P. Allen and Homewood), International Association of sedimentalogists special publication v. 8, pp. 222-240.

Burbank, D. W., and R. A., Beak. 1989b. Comment on “Development of the Himalayan frontal thrust zone: Salt Range, Pakistan.” Geology, v. 17, pp. 378-380.

Burbank, D. W., and T. J., Mulder. 1996. The Himalayan foreland basin, in The Tectonic Evalution of Asia, edited by A. Yin and T. M., Harrison, pp. 149-188. Cambridge University Press, New Yark.

Burret, C. F., 1974. Plate tectonics and fusion of Asia. Earth Planet. Scientific Lett., 21. pp. 181-189.

Chapple, W. M., 1978. Mechanics of thin-skinned fold-and-thrust belt, Geological Society of America, Bulletin, v. 89, pp. 1189-1198.

Chester, J. S., 1992. Role of mechanical anisotropy in the internal evolution of a thrust sheet. Ph.D thesis. Texas A and M University.

Cook, D. G., 1967. Structural style influenced by a Cambrian regional facies change in the Mount Stephen- Mount Dennis, British Columbia: Ph.D. Thesis, (unpub.), Queen's University.

Cotter, G. de P., 1933. The geology of the part of the District Attock, west of Longitude 72° 45' E: India Geological Survey, Mem., v. 55, pp. 63-161.

Coward, M. P., Windly, B. F., Broughton, R. D., Luff, I. W., Petterson , M. G., Pudsey, C. J., Rex, D. C. and Khan, M. A., 1986. Collision tectonics in the NW Himalayas. In: Coward, M. P., and Ries, A. C., (eds). Collision Tectonics, Geological Society London, Special Publication, 19: pp. 203-219.

Coulson, A. L., 1938.The water supply of te Issakhel and Mianwali, Tehsils of the Mianwali District, Punjab. Geological Survey of India Resources, v. 72, pt 4, pp. 440-446.

Dahlstrom, D. A., 1977. Structural geology in the eastern margin of the Canadian rocky mountain. Wyoming Geological Association 29th Annual Field Conference, pp. 407-439. Originally published in the Bulletin of Canadian Petroleum Geology, v.18, no.3 (1970), pp. 332-406.

Danilchik, W., and Shah, S. M., 1967. Stratigraphy nomenclature of formations in the Trans-Indus Mountains, Mianwali district, West Pakistan. United States Geological Survey, Prof. Report (IR) PK-33: 45p.

Danilchik, W., 1987. Stratigraphy and coal resources of the Makarwal Area, Trans-Indus Mountains, Mianwali district, Pakistan. United States Geological Survey, Prof. Paper 131: 38 p.

Davis, D. M., Engelder, T., 1985. The role of salt in fold-and-thrust belts. Tectonophysics, v. 119, pp. 67-88.

Davis, D. M., J. Suppe, and F. A. Dahhlen, 1983, Mechanics of fold and thrust belts and accretionary wedges: Journal of Geophysical Research, v. 88, pp. 1153-1172.

Davis, D. M., and R. J., Lillie, 1994. Changing mechanical response during continental collision: active examples from the foreland thrust belts of Pakistan: Journal of Structure Geology, v. 16, pp. 21-34.

DeCelles, P. G., Mitra, G., 1995. History of the Sevier orogenic wedge in term of critical taper models, northeast Utah and southwest Wyoming. Geological Society of America Bulletin, v. 107, pp. 454-462.

Dietrich, V. J., Frank, W. and Honegger, K., 1983. A Jurassic-Cretaceous island arc in the Ladakh-Himalayas. J. Vole. Geothermal Resources, 18, pp. 405-433.

Dipietro, J. A., Pogue, K. R., Hussain, A. and Ahmad, I., 1996. Geology and tectonics of the Indus syntaxis, northwest Himalaya, Pakistan.

Dunbar, C. O., 1933. Stratigraphic significance of the Fusulinids of the Lower Productus limestone of the Salt Range. Geological Survey of India, Rec. 66, pp. 405-413.

Duroy, Y. A., Farah, and R. J. Lillie, 1989. Subsurface densities and lithospheric flexure of the Himalayan foreland in Pakistan, Special paper Geological Society of America, no. 232, pp. 217-236.

Du Toit, A. L., 1937, see Toit, A. L., 1937.

Farah, A., Mirza, M.A., Ahmad, M. A. and Butt, M. H., 1977. Gravity field of the buried shield in the Punjab plain, Pakistan. Bulletin of Geological Society of America, v. 88, pp. 1147-1155.

Fatmi, A. N., and Cheema, M. R., 1972. Early Jurassic Cephalopds from Khisor-Marwar ranges (Shaikh Budin Hills), D. I. Khan District, N.W.F.P., Pakistan: Ibid., Recs., v. 21, pt. 2, 9 p.

Fatmi, A. N., 1973. Lithostratigrahic units of the Kohat-Potwar Province, Indus Basin, Pakistan. Geological Survey of Pakistan, Memoir 10: 80p.

Fatmi, A. N., Hyreri, I.H., Anwar, M., and Waliullah, 1999. Stratigraphy of the Khisor Range and Shaikh Badin Hills (Marwat Range) D.I.Khan, NWFP, Pakistan. Geological Survey of Pakistan, Memoir 1~14 p.

Fleming, A., 1853. On the Salt Range in the Punjab. Quart. J. Geological Society London., v. 9, pp. 189-200.

Gansser, A., 1964. Geology of the Himalayas. Wiley, New York, 289p.

Gansser, A., 1981. The geodynamic history of the Himalaya. In: Gupta, H. K. and Delany, F. M., (eds.) Zagros-Hindukish-Himalaya: geodynamic evolution. Am. Geophys. Union, Geodyn. Ser. 3, pp. 111-121.

Gee, E. R., 1945. The age of the saline series of the Punjab and Kohat. India. Natl. Acad. Sci., See. B. Proc., 14 (6), pp. 269-310.

Gee, E. R., 1980. Pakistan geological Salt Range Series: (6 sheets, scale 1:50,000) Directorate of Overseas surveys, U.K. for the Govt. of Pakistan and Geological Survey of Pakistan.

Gee, E. R., 1989. Overview of the geology and structure of the Salt Range, with observations on related areas of northern Pakistan. In: Malinconico, L. L. and Lillie, R. J. (eds.) Tectonics of the Western Himalayas. Geological Society of America, Special Paper. No. 232, pp. 95-112.

Goquel, J., 1962. Tectonics (trans. 1952 edn.): San Francisco, Freeman and Company, p. 384.

Hamidullah, S. and Onstot, T.C., 1992. Ar_{40}/Ar_{39} evidence for Late Cretaceous Formation of the Kohistan Island Arc,NW, Pakistan. Kashmir Journal of Geology, v. 10. pp. 105-122.

Hemphill, W. R. and Kidwai, A. H., 1973. Stratigraphy of the Bannu and Dera Ismail Khan area, Pakistan. United States Geological Survey, Professional Paper 716-B: 36p.

Holland, T. H. and Tipper, G. H., 1913. Indian geological terminology. Geological Survey of India, Mem. 43, 1: pp. 1-27.

Hunting Survey Corporation (H. S. C.), 1961. Reconnaissance geology of part of West Pakistan (Colombo Plan Cooperative Project): Canada Govt., Toronto, pp. 1-550.

Hussain, B. R., 1967. Saiyiduwali member, anew name for the lower part for the Permian Amb Formation, West Pakistan: Univ. Studies (Karachi), Sci. and Tehnol., v. 4, no. 3, pp. 88-95.

Irving, E., 1979. Pole position and continental drift since the Devonian. In: McElhinny, M. (Eds), the Earth: its Origin, Structure and Evolution. Acad, Press, London, pp. 567-593.

Jaswal, T. M., Lillie, R. J. and Lawrence R. D. 1997, Structure and Evolution of the Northern Potwar Deformed Zone, Pakistan. AAPG Bulletin, v. 81, no.2, pp. 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 evaporates; Tectonics, v. 7, pp. 57-71.

Johnson, G. D., Johnson, N. M., Opdyke, N. D. and Tahirkheli, R. A. K. 1979. Magnetic reversal stratigraphy and sedimentary tectonic history of the upper Siwalik Group, eastern Salt Range and south-western Kashmir. In. geodynamic of Pakistan, Geological Survey of Pakistan, Quetta, pp. 149-165.

Johnson, G. D., Raynolds, R. and Burbank, D., 1988. Late Cenozoic tectonics and sedimentation in the northwestern Himalayan foredeep. Thrust ramping and associated deformation in the Potwar region, in foreland Basins, edited by Allen, P., and Homewood, P., Spec. Publ. Int. Assoc. Sedimentol., 8, pp. 273-291.

Johnson, N. M., Stix, J., Cerven, P. F. and Tahirkheli, R. A. K., 1985. Paleomagnetic chronology, fluvial processes, and tectonic implications of the Siwalik deposits near Chinji village, Pakistan. Journal of Geology. V. 93, pp. 27-40.

Jones, P. B., 1987, Quantitative geometry of the thrust and fold belt structures: AAPG Methods in Explorationn Series 6, pp. 26.

Khan, M.J., N.D. Opdyke, and R.A. K. Tahirkheli, 1988. Magnetic stratigraphy of the Siwalik Group, Bhittani, Marwat and Khisor ranges, northwestern Pakistan and the timing of Neogene tectonics of the Trans-Indus, J. Geophy. Res., 93, pp. 11773-11790.

Klootwijk, C. T., Gee, J. S., Pierce, J. W., Smith, G. W., and Mc Fadden, P. L., 1992. An early India-Eurasia contact; Palaeomagnetic constraints from the Ninet-yeast Ridge, ODP Leg. 121. Geology, v. 20, pp. 395-398.

Kravtchenko, K. N., 1964. Soan Formation-upper unit of Siwalik Group in Potwar: Science and Industry, v. 2, no. 3, pp. 230-233.

Kummel, B., 1966. The lower Triassic formations of the Salt Range and Trans-Indus ranges, West Pakistan: Mus, Comp. Zoology, Bull., v. 134, no. 19, pp. 361-429.

Kummel, B. and Teichert, C., 1970. Stratigraphy and paleontology of the Permian-Triassic boundary beds. Salt Range and Trans-Indus Ranges, West Pakistan. In: Stratigraphic Boundary Problems, Permian and Triassic of West Pakistan. Geology Department University of Kansas, Special Paper, 4, pp. 1-110.

Lawrence, R. D., and Yeats, R. S., Khan, S. H., Subhani, A. M., and Bonelli, D., 1981. Crystalline rocks of the Spinatizha are, Pakistan. Journal of Structural Geology, v. 3, pp. 449-457.

Leathers, M. R., 1987. Balanced cross-section of the western Salt Range and Potwar Plateau, Pakistan: deformation near the strike-slip terminus of an over thrust sheet. Unpublished M.S. dissertation, Oregon State University.

Le Fort, P., 1975. Himalaya: the collided range; Present knowledge of the continental arc. Amer. J. Sci., 275A, pp. 1-44.

Lillie, R. J., Johnson, G. D., Yousaf, M., Zaman, A. S. H., and Yeats, R. S., 1987. Structural development within the Himalayan foreland fold-and-thrust belt of Pakistan. In: Beaumont and Tankard (eds.) Sedimentary Basins and Basin-forming Mechanisms. Canadian Society of Petroleum Geologists, Memoir 12; pp. 379-392.

Lewis, G. E., 1938. A new Siwalik correlation (India), American Journal of Science, 5, 195, 33; pp. 191-204.

Madin, I. P., 1986. Geology and neotectonics of the north-western Nanga Parbat-Haramosh Massif. Unpublish M.S Thesis, Oregon State Univ., Corvallis, 160 pages.

Malinconico, L. L., Jr., 1986. The structure of the Kohistan arc terrane in northern Pakistan as inferred from gravity data. Tectonophysics, 124; pp. 297-307.

McDougall, J. W., and Hussain, A., 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, pp. 463-478.

Medlicott, H. B., 1868. Note on the analysis of three specimens of coal from the "hills about Murree". Geological Survey of India, Rec. 64: pp. 117-118.

Meissner, C. R., Master, J. M., Rashid, M. A. and Hussain, M., 1974. Stratigraphy of the Kohat quadrangle, Pakistan. United States Geological Survey, Professional Paper 716-D, 30p.

McKenzie, D. P., and J. G. Sclater, 1971. The evolution of the Indian ocean once the late Cretaceous: Geophysical Journal, v. 25, pp. 437-528.

Mitra, S., 1986. Duplex structures and imbricate thrust systems: geometry, structural position, and hydrocarbon potential. American Association of Petroleum Geologists Bulletin v. 70, pp. 1087-1112.

Mitra, G., Sussman. A. J., 1997. Structural evolution of connecting splay duplexes and their implications for critical taper: an example based on geometry and kinematics of the Canyon Range culmination. Sevier belt. Central Utah. Journal of Structural Geology, v.19, pp. 503-522.

Molnar, P. and Tapponnier, P., 1975. Cenozoic tectonics of Asia: effects of a continental collision. Science, 189; pp. 419-426.

Morris, T. O., 1938. The Basin Boulder-Bed; a glacial episode in the Siwalik Series of the Marwat Kundi Range and Shaikh Budin, North West Frontier Province. India. Quart. Journal of Geological Society of London, 94; pp. 385-421.

Noelting, F., 1894. On the Cambrian formation of the eastern Salt Range. Geological Survey of India, Rec. 27. 4; pp. 71-86.

Noelting, F., 1901.Beitrage zur Geologic der Salt Range, insbesondere der Permichen unde Triasuchea. Ablagerungen. Venues Jahrb. Mineral. Beilage, 14; pp. 369-471.

Oldham, R. D., 1893. A Manual of the Geology of India. Govt. India Press, 2nd Ed.

Parwez , M. K., 1992. Petroleum geology of Kohat Plateau and Bannu Basin, N.W.F.P., Pakistan. Ph.D. Thesis, University of South Carolina, Columbia.

Pascoe, E. H., 1963. A Manual of Geology of India and Burma, v. III; Ibid, Calcutta, pp. 13442130.

Patriat, P. and Achche, J., 1984. India-Eurasia collision chronology and its implications for crustal shortening and driving mechanisms of plates. Nature, 311; pp. 615-621.

Petterson, M. G. and Windley, B. F., 1985. Rb-Sr dating of the Kohistan arc batholith in the Trans-Himalaya of North Pakistan and tectonic implications. Earth Planet. Sci. Lett., 74; pp. 54-75.

Pilgrim, G. E., 1913. The correlation of the Siwaliks with mammal horizons of Europe. Geological Survey of India, Rec. 43 (4); pp. 264-326.

Pilgrim, G. E., 1926. Tertiary formations of India and interrelation of the marine and terrestrial deposits. Pan Pacific Sci. Cong. 1923, Proc. 806-931.

Pivnik, D. A., and Wells, N. A., 1996.The translation from Tethys to the Himalaya as recorded in northwest Pakistan. Geological Society of America Bulletin, v. 108, pp. 1295-1313.

Powell, C. M. A., 1979. A speculative tectonic history of Pakistan and surroundings: some constraints from the Indian Ocean. In: Farah, A. and DeJong, K. A., (eds) Geodynamics of Pakistan. Geological Survey of Pakistan Quetta, 5-24.

Pudsey, D. J., 1986. The northern suture, Pakistan: margin of a Cretaceous island arc, Geological Magazine, 123; pp. 405-423.

Richter, D. K., 1981. The Agency activities in radioactive waste management International Atomic Energy Authority Bulletin, v. 23, No. 2; pp 41-45.

Riaz, A., 1998. Hydrocarbon resources base of Pakistan. Pakistan Journal of Hydrocarbon Research v.10, pp. 1-10.

Sarwar, G. and De Jong, K. A., 1979. Arcs, oroclines, syntaxes-the curvatures of Mountain Belts in Pakistan. In: Farah, A. and De Jong, K. A., (eds.) Geo-dynamics of Pakistan. Geological Survey of Pakistan, Quetta, pp. 341-350.

Schindewolf, O. H., and Seilacher, A., 1955. Beitrage zur Kennits des Kambriums in der Salt Range (Pakistan): Abh, Akad. Wiss. Lit. Mainz., Abh., Math-Not Kl., no. 10 p. 446.

Searle, M. P., 1991. Geology and Tectonics of the Karakuram Mountains. J. Wiley and Sons, New York, 358p.

Seeber, L., and Armbruster, J., 1979. Seismicity of the Hazara arc in northern Pakistan: decollement versus basement faulting. In: Farah, A., and DeJong, K. A., (eds). Geodynamics of Pakistan. Geological Survey of Pakistan, Quetta, 131-142.

Sengor, A. M. C., 1984. The Cimmeride orogenic system and the tectonics of Eurasia. Geological Society of America, Special Paper, 195, 74p.

Sengor, A. M. C., Altiner, D., Cin, A., Ustaomer, T. and Hsu, K. J., 1988. Origin and assembly of the Tethy side orogenic collage at the expense of Gondwanaland. In: Audley-Charles, M. G. and Hallam, A. (eds.) Gondwana and Tethys. Geological Society of London, Special Publication, 37, pp. 81-119.

Shah, S, M. I., Precambrian. In: Shah, S. M. I. (ed.) 1977. Stratigraphy of Pakistan. Geological Survey of Pakistan, Memoirs, 12, pp. 1-5.

Siddiqi, R. A., 1973. A note on silica sand deposit of Khisor and Marwat ranges D.I. Khan Division N.W.F.P., Pakistan. Geological Survey of Pakistan, no. 57, 81p.

Smith, A. G. and Hallam, A., 1970. The fit of the southern continents. Nature 225: 139p.

Smith, A. G., Hurley, A. and., Bridon, J. C., 1981. Phanerozoic Paleocontinental world maps. Cambridge University Press, 102p.

Smith, H. A., Chamberlain, C. P. and Zeitler, P. K., 1994. Timing and duration of Himalaya metamorphism within the Indian plate, northwest Himalaya, Pakistan. Journal of Geology, v. 102, pp., 493-503.

Stocklin, J. and Nabavi, M. 1973. Tectonic map of Iran at 1:2,500,000. Geol. Surv. Iran, Tehran.

Stoneley, R., 1974. Evolution of the continental margins bounding a former southern Tethys. In: Burk, C. A. and Drake, C. L., (eds.) The Geology of continental Margins. Springer-Verlag, New York, pp. 889-903.

Strayer, L. M., Hudleston, P. J., 1997. Numerical modeling of fold initiation at thrust ramps. Journal of Structural Geology. v. 19, pp. 551-556.

Sues, E., 1893. Are great ocean depths permanent? Nat. sci. Lond., 2; pp. 180-187.

Tahirkheli, R. A. K., 1979. Geology of Kohistan and adjoining Eurasian and Indo-Pakistan continents, Pakistan. Geological Bulletin University of Peshawar, v. 11, pp. 1-30.

Tahirkheli, R. A. K., 1982. Geology of the Himalaya, karakoram and Hindukush in Pakistan. Geological Bulletin University of Peshawar, v. 15, pp. 1-51.

Teichert, C., 1964. Recent German work on the Cambrian and Saline Series of the Salt Range, West Pakistan. Geological Survey of Pakistan, Rec. 11, 1; 20p.

Teichert, C., and Blame. 1966-67. Stratigraphic nomenclature and correlation of the Permian "Productus limestone" of the Salt Range, West Pakistan. Geological Survey of India, Rec. 15, 1; 19p.

Treloar, P. J., 1989. Imbrications and unroofing of the Himalayan thrust stack of the north Indian plate, north Pakistan. Geological Bulletin University of Peshawar, v. 22, pp. 25-44.

Treloar, P. J., and Izatt, C. N., 1993. Tectonics of the Himalayan collision between the Indian Plate and the Afghan Block: A synthesis. In: Treloar, P. J., and Searle, M. P., (eds) Himalayan tectonics, Geological Society (London) Special Publication, v. 74, pp. 69-89.

Ustritsky, V. I., 1962. Principal stages in the Permian evolution of Asian marine basins and brachiopod fauna: intern. Geol. Rev., v. 4, pp. 415-426.

Waagen, W., 1879-81. Salt Range fossile, Productus limestone group. Geological Survey of India, Mem. Palaeont. India, Ser. 13, 1; pp. 4-6.

Waagen, W., 1889-1891. Salt Range fossils; geological results: Ibid., Mm., Palaeont. Indica, ser. 13, v. 4, pt. 1 and 2; 242 p.

Wadia, D. N., 1961. Geology of India Macmillan, London, 536p.

Wahid, S., Rehman. S and Babar, S. 2004. Structural analysis of the central Khisor Range, NW of Dhakki, D. I.Khan , NWFP, Pakistan, unpublished M.Sc Thesis submitted to the Deptt. of Geology Univ. of Peshawar.

Wegener, A. L., 1924. The origin of Continents and Oceans. Dutton and Co., New York, 212p.

Wells, J. T. and Coleman, J. M., 1984. Delta morphology and sedimentology, with special reference to Indus River Delta. In: Haq. B. U. and Milliman, J. D. (eds.) Marine Geology and oceanography of Arabian sea and Coastal Pakistan. Van Nostrand Reinhold Co., New York, 85-100.

Windley, B. F., 1983. Metamorphism and tectonics of the Himalaya. Geological Society of London, 140, pp. 849-865.

Wynne, A. B., 1878. On the geology of the Salt Range in the Punjab. Geological Survey of India, Memoirs. 5 (14); pp. 1-305.

Yeats, R. S. and Hussain, A., 1987. Timing of structural events in the Himalayan foothills of north-western Pakistan. Bulletin Geological Society of America, 99; pp. 161-175.

Yeats, R. S. and Lawrence, R. D., 1984. Tectonics of the Himalayan thrust belt in northern Pakistan. In: Haq, B. U. and Milliman, J. D., (eds.) Marine Geology and oceanography of Arabian sea and coastal Pakistan. Van Nostrand Reinhold Co., New York, 177-200.

Yoshida, M., 1996. Paleomagnetic synthesis of three phases collision in the himalay-Karakoram belt and surrounding terranes. In: extended Abs. international seminor on Paleomagnetic atudies in Himalaya-Karakoram collision Belt and surrounding countries. Geoscience Laboratory, Geological Survey of Pakistan, Islamabad, 23-26.

Zeitler, P. K., 1985. Cooling history of the NW Himalaya, Pakistan. Tectonics, v. 4, pp. 127-151.