A COMPARATIVE STUDY OF THE STRUCTURAL STYLES IN THE EASTERN KALACHITTA RANGE (FATEH JHANG-HASSANABDAL TRANSECT), POTWAR PLATEAU, N. PAKISTAN

By

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NATIONAL CENTRE OF EXCELLENCE IN GEOLOGY
UNIVERSITY OF PESHAWAR

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Abstract

The Eastern Kalachitta Ranges (EKR) and Northern Potwar Deformed Zone (NPDZ) is the part of the active foreland fold and thrust belt in northern Pakistan. The EKR is separated from the Northern Potwar Deformed Zone by a regional thrust fault; the Main Boundary Thrust (MBT). EKR lies in the hangingwall of MBT while NPDZ is in its footwall. Structural analysis of this area is carried out with the help of TM image, field mapping and published seismic data. The data is processed with the help of 2DMove, a structural modelling program that allows line length and area balancing of cross sections. ILWIS (GIS software) is used to geo-reference and overly different map types. From the surface and subsurface data detailed balanced sections are constructed across the study area using the application of the 2DMove software.

The EKR occupies the southern periphery of the hill ranges and the stratigraphy ranges in age from Mesozoic to Cenozoic. The area is characterized by minor brittle shortening. The structure studies of EKR show a "passive roof duplex structure" with lower and upper detachments. Thrusting controls the deformation between the upper and lower detachment levels. In this area of deformational front, the oldest stratigraphy involved with the emergent thrust faults is Samana Suk Formation. This indicates that the basal detachment lies at the base of Samana Suk Formation and the upper detachment lies within the Patala Formation as the overlying Eocene formations are not affected by the thrusting but the upper detachment has caused them to fold and lift above. The folding controls the structures above the upper detachment level. The area shows progradation of thrusting towards the foreland and this deformation produces interesting and complex geometry of stacked fold. A similar type of fold structure is observed near Katha Colony, which can be called as Katha Colony stacked anticline structure. The folds within EKR are detachment folds and their detachment lies within the Patala Formation, which has flowed in the core of these folds.

The rocks of Rawalpindi and Siwalik Group dominate the surface outcrop of NPDZ, while the subsurface data shows Precambrian-Eocene stratigraphy. The area is intensely folded and faulted. The unusual thickness of the Murree Formation within the area is due to imbricate thrust sheets and fault propagation folds. The structure of NPDZ is also a passive roof duplex like the EKR but varies in upper and lower detachments. In NPDZ, the floor thrust lies within the Eo-Cambrian evaporates and a roof thrust in the Rawalpindi Group. The stacking of folded blind thrust under the passive roof thrust give rise to the development of a triangle zone and foreland syncline. The triangle zone defined by the inter-relationship of N-dipping Khairi-Murat Fault and S-dipping Dhurnal Fault in the North and South respectively. The foreland dipping Soan Syncline separates the highly deformed strata in the north from moderately deformed strata to the south. A pop-up structure developed below the northern limb of Soan Syncline is the result of flowage of Salt Range Formation in its core, which has lifted it up.
About 62-km of horizontal shortening has been calculated from EKR to the Soan River making use of the application of the 2DMove program.

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Dedicated

To

My Parents & Apa

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CHAPTER 1

INTRODUCTION

The name "Kalachitta" means black and white hills, "the black" refers to the dark weathering hills of the Murree Formation in the south and "the White" refers to the Mesozoic-Tertiary limestones of the Kalachitta Ranges. The Kalachitta Range occupies a very significant position in Lesser Himalayas in Pakistan forming the northern edge of the hydrocarbon bearing Potwar Basin (Fig 1.1). It is a narrow strip of mountainous belt extending in E-W direction merging laterally into the Hazara Mountain in the east and extends westward into the Kohat and Samana Range (Fig. 1.1 & Fig. 1.2). The Kalachitta Range is one of the epicontinental troughs developed as a result of continent – continent collision between Indo-Pakistan Plate and the Eurasian Plate. The Indus River borders the Kalachitta Range towards west and northwest, whereas towards its south lies a large intensely dissected Plateau – the Kohat-Potwar Plateau (Fig. 1.1).

The Potwar Plateau is located to the south of the northern mountains and lies between the Indus River on the west and Jhelum River on the East (Fig. 1.1). Its northern boundary is marked by Kalachitta Range and Margalla Hills while the famous scalloped Salt Range forms the southern margin of Kohat-Potwar Plateau (Fig 1.1). Northern Potwar Deformed Zone (NPDZ) falls in the Punjab province located in the northern part of the Upper Indus Basin – the Potwar Plateau, which is the active foreland fold and thrust belt in Pakistan. Northern Potwar Deformed Zone – NPDZ, is the name given to the region of poorly exposed tightly folded Murree Formation; sediments that are found lying between Kalachitta and the Hazara Hill Ranges to the north and Khair-i-Murat Thrust Fault in the south (Leathers, 1987).

The Main Boundary Thrust (MBT) is a regional thrust fault that extends westward from the front of the Himalayan Ranges around the Hazara – Kashmir syntaxial bend, and thrusts the hill ranges over the Potwar – Kohat Plateaus (McDougall and Hussain, 1991). The Kalachitta Range lies in the hanging wall of MBT and Potwar – Kohat Plateaus in the footwall (Fig. 1.1).

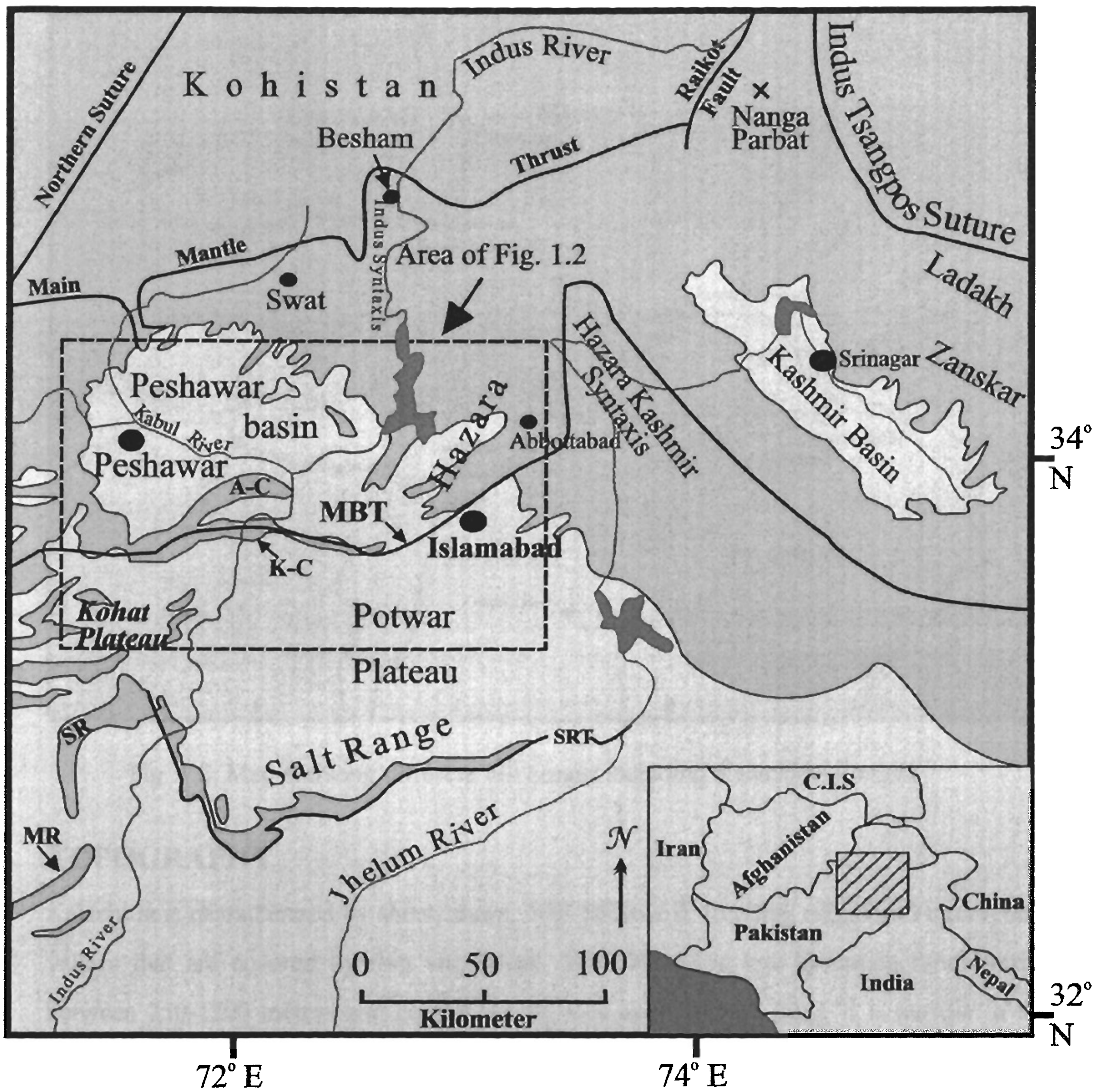

Fig. 1.1. Location map of the Himalaya of northern Pakistan and northwestern India showing selected major faults and ranges. A-C Attock-Cherat Range; K-C Kalachitta Range; SR Surghar Range; MR Marwat Range MBT Main Boundary Thrust; SRT is the Salt Range Thrust. Location of the faults are from Gansser (1981), Yeats and Lawrence (1984), Baker et al., (1988), Lawrence et al., (1989), and Baig (1990).

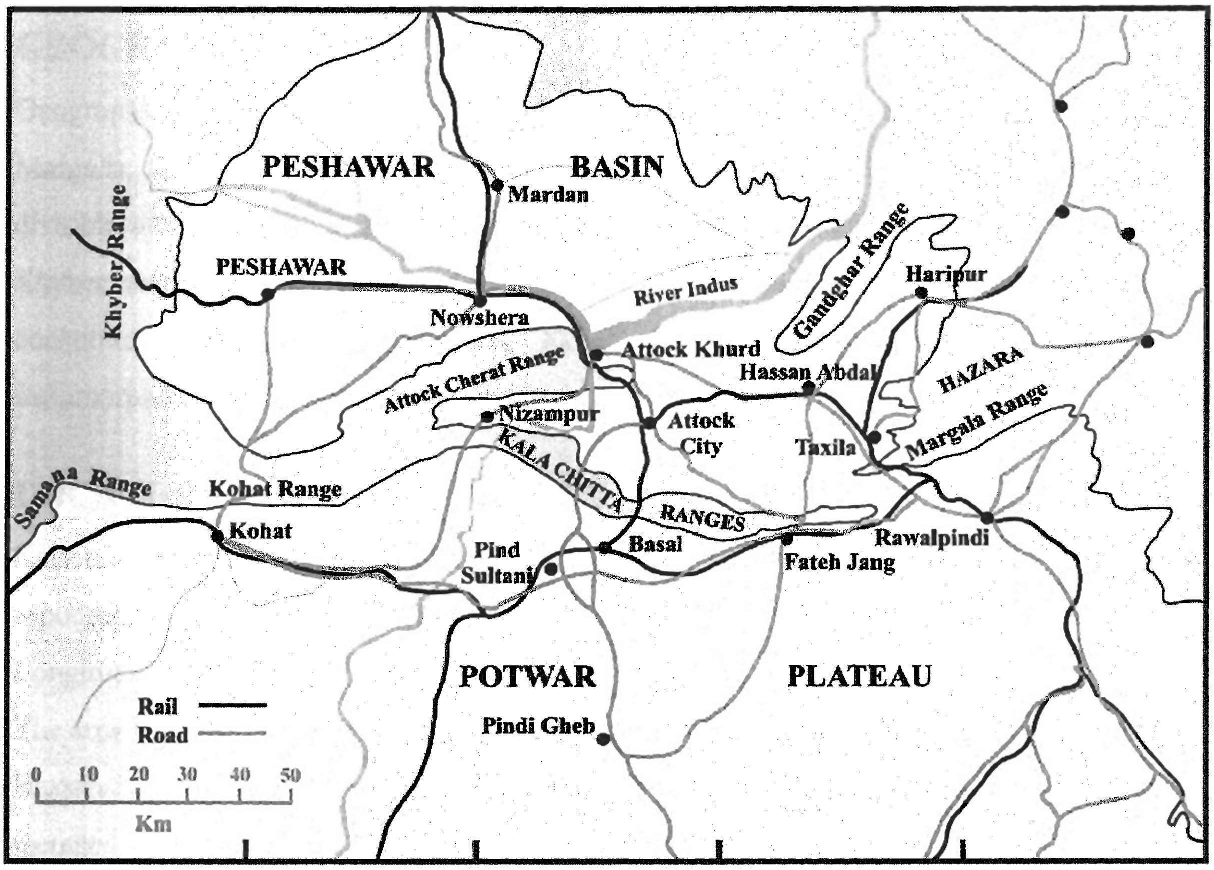

Fig. 1.2. Map showing different hill ranges including Kalachitta Ranges.

1.1 TOPOGRAPHY

Kalachitta is characterized by short, sharp, NW-SE to EW trending ridges and intervening valleys that are covered by thin vegetation. The altitude in this mountain range varies between 250-1200 meters and on the whole, it is about 80-km long. It is narrow in the east, broadens near Fateh Jhang and is about 13-km wide in the extreme west near Indus River. The range attains its greatest heights in the west near the Indus River. In the close vicinity of Kalachitta Range, isolated range such as Khairi Murat rises to about 950 meters. An important topographic feature of Kalachitta Range is its general slope, which is from northeast to southwest. It marks the southern boundary of the Campbelpur basin, an intermountain basin formed due to uplift of the range. This basin is filled with sediments derived from the range and also by the sediments deposited by Indus and Haro rivers, making the basin suitable for agriculture.

1.2 GEOGRAPHY

Geographically the Kalachitta Range falls in the hill ranges, which in addition include Margalla, Gandghar, Attock-Cherat and Samana Ranges (Fig. 1.2). The hill ranges are divisible into two blocks. The northern block comprises Gandghar, Attock-Cherat and Khyber ranges predominantly consist of Precambrian slates (Fig 1.2). The southern block constitute the Kalachitta, Margalla, Kohat and Samana ranges; consist of un-metamorphosed sedimentary rocks (limestones, sandstone etc).

1.3 LOCATION AND ACCESSIBILITY

Kalachitta range and NPDZ are located in Punjab, covered by the survey of Pakistan topographic sheets No. 43C/10 and 43C/11. The study area is restricted between the Longitude 72° 35' 00"– 72° 45' 00" E and Latitude 33° 15' 00" – 33° 45' 00" N.

The area is accessible by metalled roads linking Pindi Ghaib - Fateh Jhang with Attock and Hassanabdal (Fig 1.3). Eastern Kalachitta Range is accessible by partly metalled and un-metalled road from Fateh Jhang. Bahatar – Gakhar metalled road offers a good access to the exposures near the Kath Colony in the north while the central part is of the range is accessible by an un-metalled jeepable fair weather road; linking Dhok Baloch - Gakhar from the west and Dhok Baloch – Jhang in the east (Fig. 1.3). While the southern part of the study area is accessible by a metalled road from Fateh Jhang to Talagang. The road between Attock and Pindi Gheb also provide a good and easy access to this area.

1.4 CLIMATE

The climate of the area is extreme with hot summers and cold winter. The summer is comparatively short and the cold weather is long and severe. The annual average rainfall is 330 millimeters. The rainfall months are June to September in summer and January to March in winter. The mean maximum and minimum temperatures for the summer are 40°C and 26°C while the mean maximum and minimum temperatures for the winter months are 21°C and 2°C respectively.

1.5 DRAINAGE

There is a major stream Bahandra Kas running almost parallel to the range from west to east. Nandna Kas a tributary of Bahandra Kas flows south into the Shahpur Dam. Numerous fresh water streams can be observed in the Murree Formation north of Fateh Jhang running from southwest to northeast. NPDZ is characterized by seasonal streams-River Soan flows from east to the west and after crossing the region; falls in the Indus River (Fig. 1.3).

1.6 ECONOMIC GEOLOGY

The rocks and minerals of economic value occurring in the area include fireclay, laterite, dolomite, gypsum, limestone, building material and some prospects of coal. Oil and Gas Development Corporation Limited drilled two holes in the Kalachitta area. Both the holes were dry and abandoned.

The History of oil exploration in Potwar is as old as the oil industry itself. The first oil discovery in this region was made as far back as 1916 in Khaur, south west of Islamabad. The drilling in Potwar region took place in 1866, exactly three years after the first well was drilled in the United States. Oil was discovered by OGDC in Potwar at Sadkal near Fateh Jhang, located at a distance of 45 km in the southwest of Islamabad.

1.7 PREVIOUS WORK

Being a part of the settled area with an easy accessibility, the Kalachitta Range has been the focus of attention since long time. Because of the stratigraphic significance of Kalachitta and NPDZ (having potential for the hydrocarbon) has made it, the major focus of attention for the structural geologists. The Geological Survey of India carried out much of the earlier work in the Potwar Plateau. Pinfold (1918 and 1954); studied the stratigraphy and structure of the area, Pascoe (1920), Sokolov and Shah (1960), Gardezi (1974); presented isoclinal or fan-fold concept of the Kalachitta Range.

Cotter (1933) gave a comprehensive account of the stratigraphy of the Kalachitta Range and reproduced a cross-section to reveal the difference in structural style of the Kalachitta Range with those of the adjacent areas (Fig 1.4). According to him the Jurassic sediments

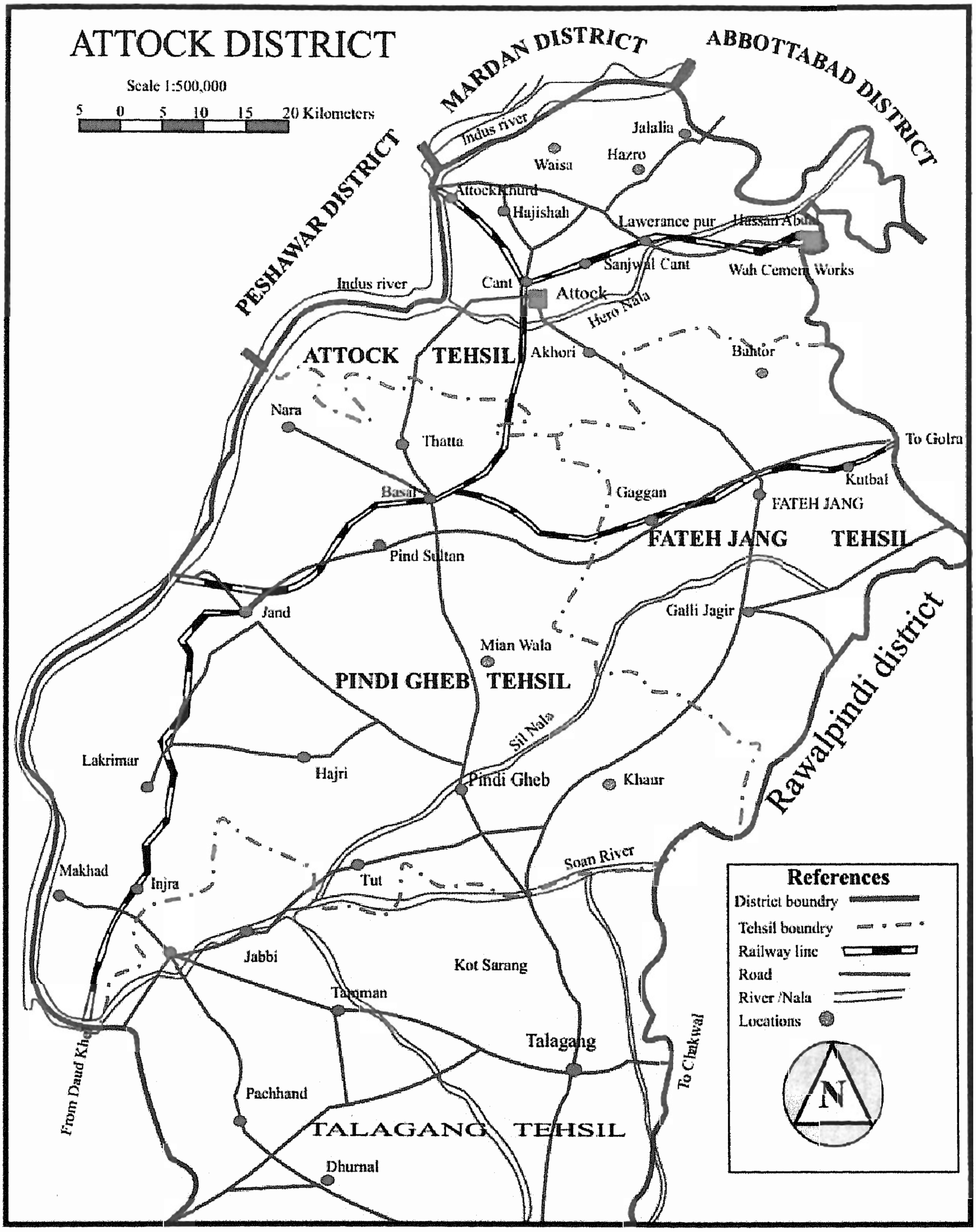

Fig. 1.3 Map showing the location and accessibility of the study area.

occupy the base of the stratigraphy succession of the region. The ammonite fauna studied by Fatmi (1973) has shown the presence of Triassic rocks. The stratigraphy of the area is summarized by Fatmi (1973) and Hussain et al., (1980). Gill (1952b) has given a complete note on the Siwalik series of the area. Martin (1965) has described in more detail the structure of the Paleocene-Eocene limestones. Butt (1987) has reviewed the Paleogene stratigraphy of the Kalachitta Range in the context of basin analysis framework. Baker et al., (1988), Lillie et al., (1987) and Pennock et al., (1989), present cross-sections from central to eastern Potwar Plateau based on subsurface seismic reflection data, shows the effect of the Salt Range evaporites on the regional tectonics.

Recently Jadoon et al., (1997) have described the thrust geometries and kinematics of the foreland basin in more detail. Jaswal et al., (1997) have integrated seismic reflection profile with surface geological and drilling data to examine the deformation style and structure of NPDZ. Akhtar and Butt (1999) have recorded age-diagnostic benthonic larger foraminifera from the Tertiary formations of the Kalachitta Range. Raza (2001) has given the implications of Eocene (Kuldana Formation) of the Kalachitta Range on the Himalayan foredeep basin.

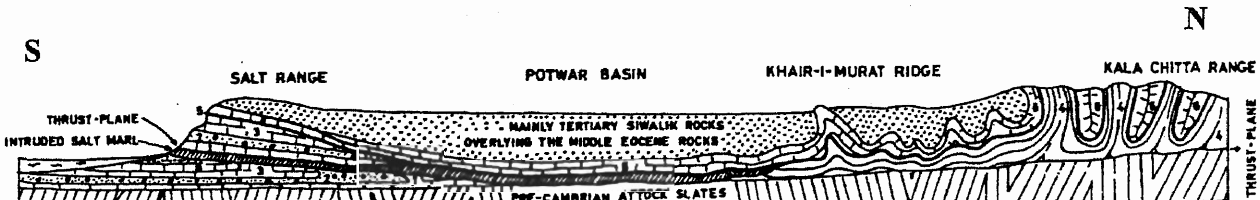

Fig. 1.4. Cross-section from the Kalachitta Range to Salt Range, showing the decollement of the Kalachitta rocks (after Cotter, 1933).

1. Cambrian 2. Carboniferous 3. Permian and Triassic 4. Mesozoic

5. Ferruginous pisolite marking the Cretaceous Tertiary contact 6. Paleocene – Eocene

1.8 AIMS AND OBJECTIVES

The main objective of this thesis is to constrain thrust geometries of the area and provide framework from which amount and rate of shortening can be estimated. During this research the following studies are conducted:

- Extensive field investigations to prepare a detailed geological/structural map of the region at a scale of 1:50,000 scale.
- To understand the deformation style of the eastern Kalachitta Range and to compare it with NPDZ.
- To compare the stratigraphy of Eastern Kalachitta Range and NPDZ.
- Geometric analyses of different structural entities and their relation to the regional structures.
- Estimates and calculate the amount of shortening accommodated by structures using computer modeling software – 2DMove.

1.9 METHODOLOGY

- Landsat image (1:65000) of the plateau is acquired for mapping of lithological units and construction of structural map using GIS software ILWIS.
- Fieldwork conducted in order to put the actual field data on the base map (toposheets).
- Balanced cross-section is constructed along NS orientation in order to understand the structural styles.
- Published seismic data is acquired to relate the surface structures with those in the subsurface.
- Important stratigraphic and structural features were photographed in the field.
- Computer software i.e. coral draw was used for the graphics, photographs and drafting of maps.
- The map of the study area is geo-referenced in GIS software ILWIS. From which x –y – z (dimensions) database for topographic, structural and stratigraphic features was created and import in 2DMove in ASCII format for the construction of balanced sections.
- 2DMove a structural analysis and modeling program that allows line length and area balancing is used to construct cross – sections.

1.8 AIMS AND OBJECTIVES

The main objective of this thesis is to constrain thrust geometries of the area and provide framework from which amount and rate of shortening can be estimated. During this research the following studies are conducted:

- Extensive field investigations to prepare a detailed geological/structural map of the region at a scale of 1:50,000 scale.
- To understand the deformation style of the eastern Kalachitta Range and to compare it with NPDZ.
- To compare the stratigraphy of Eastern Kalachitta Range and NPDZ.
- Geometric analyses of different structural entities and their relation to the regional structures.
- Estimates and calculate the amount of shortening accommodated by structures using computer modeling software – 2DMove.

1.9 METHODOLOGY

- Landsat image (1:65000) of the plateau is acquired for mapping of lithological units and construction of structural map using GIS software ILWIS.
- Fieldwork conducted in order to put the actual field data on the base map (toposheets).
- Balanced cross-section is constructed along NS orientation in order to understand the structural styles.
- Published seismic data is acquired to relate the surface structures with those in the subsurface.
- Important stratigraphic and structural features were photographed in the field.
- Computer software i.e. coral draw was used for the graphics, photographs and drafting of maps.
- The map of the study area is geo-referenced in GIS software ILWIS. From which x –y – z (dimensions) database for topographic, structural and stratigraphic features was created and import in 2DMove in ASCII format for the construction of balanced sections.
- 2DMove a structural analysis and modeling program that allows line length and area balancing is used to construct cross – sections.

1.10 COMPUTER MODELLING

Structure analysis, interpretation, and modelling rely heavily on the graphical representation of structure horizon and fault surface geometry. Using structure workstation software, the end product of this graphical representation results in the construction of cross sections. Graphical methods of structure analysis can be applied to geologic data to determine the viability of cross sections. In early 90's, structural modelling relied heavily on manual drafting to create cross sections. Due to revolution in computer technology has provided a powerful tool for 2D and 3D structure evaluation. Two-dimensional and three-dimensional structure workstation software significantly expands the interpretive capacity and accuracy. The workstation facilitates the visualization and modeling of structural data and allows interpreters to attack more complicated problems (Fig. 1.5). The technical and economic benefits of computer-aided structure analysis are important in the petroleum exploration. Utilizing computer modelling I used 2D Move program of Midland Valley Ltd. for the construction of cross sections for this study area (Fig 4.3, 4.6, 4.7 and 5.5-Annexure 2). 2DMove is a structural analysis and modelling program that allows line-length and area balancing of cross-sections. Both structural restorations and forward modelling can be carried out within 2DMove.

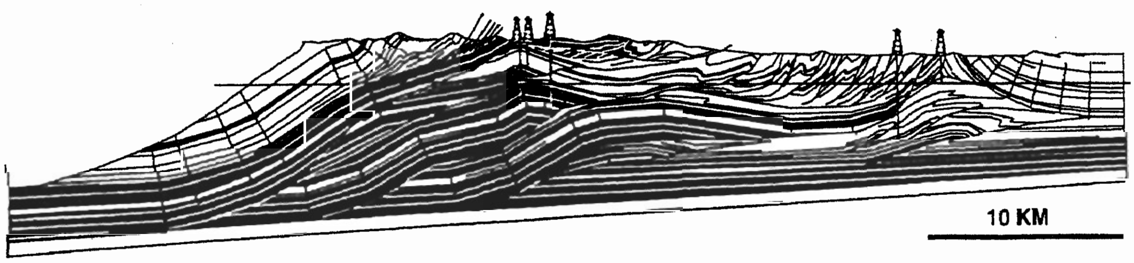

Fig. 1.5 Structural cross section across Savanna Creek Duplex and Canadian Rockies (Davis et al., 1983).

2D sections can be imported, digitized or loaded into 2DMove. 2DMove uses the "DXF" file format to allow easy transfer of data with other software. This allows sections to be held within in 3D space and a World Co-ordinate system to be attached. The length of the section on the screen is referred as X direction and the depth referred to as the Z direction

(Fig. 1.6). As a result of this, data may be imported from 3D seismic interpretations, from 3D well files and from 3D dip data. Data that is out of the plane of the 2D section is automatically projected orthogonally onto the section. First of all data base is created using any text editor for dip and stratigraphic contacts etc. and this data is imported as ASCII file from various third party software (Table 1.1).

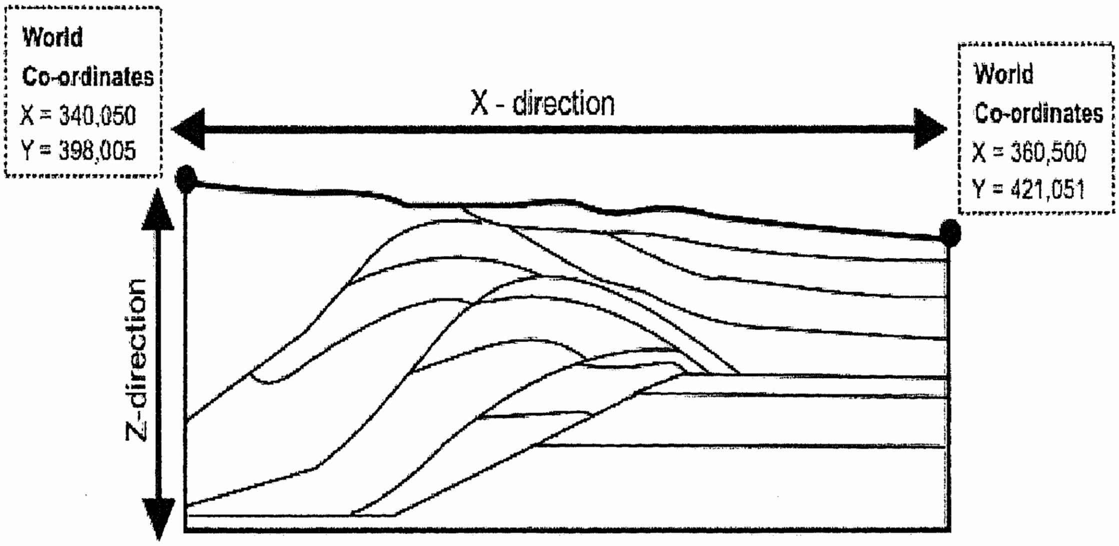

Fig. 1.6 Diagram showing the position of X-axis and Z-axis in 2DMove.

1.11 BALANCED CROSS-SECTIONS

2DMove computer aided structural balancing and restoration program is used for the construction of balanced sections. Based on surface and published subsurface data Following cross sections are constructed making use of 2DMove.

- Section along line A-B (Eastern Kalachitta Range, Fig. 4.3).
- Section along line B-C (south of Fateh Jhang, Fig. 4.6).
- Section along line C-D (Soan area, Fig. 4.7).
- Section along line A-D (from Eastern Kalachitta Range – Soan River, Fig. 5.5-Annexure 2).

As 2DMove allows line-length and area balancing, the mechanically competent layers of the study area (Permian-Eocene) and Murree Formation are balanced by using line-length balancing technique of 2DMove while the Salt Range Formation is balanced with the help of area balancing technique.

X	Y	Z	Dip	Azimuth
3173299	1053551	620	60	180
3173504	1053077	612	42	174
3173891	1052792	625	34	175
3173971	1052173	632	72	178
3172937	1052023	641	86	359
3172789	1051653	645	67	000
3173215	1051239	623	40	003
3173590	1049688	627	50	354
3174357	1049220	635	23	347
3172873	1048843	621	34	144
3173843	1048713	603	32	181
3174145	1048363	610	29	002
3172178	1047990	611	35	189
3172824	1047664	645	80	180
3174336	1047222	656	64]	339
3171899	1046250	676	75	178
3176690	1046603	634	75	337
3174721	1044528	607	60	352
3175917	1042688	601	50	338
3173913	1028617	530	70	98
3173987	1027274	523	58	282
3175016	1027314	515	70	284
3175596	1027118	543	70	276
3177958	1026424	540	70	075
3178786	1025666	556	70	101
3177913	1024321	531	65	107
3177992	1023603	540	52	093
3178395	1023341	550	85	109
3178474	1022768	532	80	113
3179004	1022085	569	70	117
3179055	1021642	613	65	117
3178730	1019646	603	15	120
3179400	1018572	632	13	127
3179657	1015939	563	13	143
3181627	1013116	534	6	177
3180786	1010649	523	5	172
3182653	1008332	540	3	258
3178727	1016769	537	10	159
3181898	101289	523	7	169

Table 1.1 Showing database for X, Y, Z, Dip and Azimuth used for the construction of balance section in 2DMove Software, along the line A-D.

CHAPTER 2
STRATIGRAPHY

The Kalachitta falls in the hill ranges; carbonates with shale and sandstone make the dominant lithology of the range. The Kalachitta Range can be divided into two blocks, Western and Eastern (Fig. 2.1). The stratigraphy sequence of the western block varies from Triassic to Paleocene, with Murree Formation lying unconformably over the Paleocene Patala Formation (Hussain et al., 1990). The absence of the Eocene stratigraphy may be the result of the ongoing tectonic activity at that time (Fig 2.1). While, in the eastern block Cretaceous Chichali and Kawagarh formations, and Paleocene Hangu Formation is missing, which can be related to the Mesozoic rift tectonic in the Indain Plate (Jadoon and Baig, 1991).

As the eastern block was more exposed as compared to the other parts, resulted in the erosion of whole Chichali Formation and part of the Samana Suk Formation, while partial trangression of the sea resulted in the deposition of the Lumshiwal Formation. The Late Cretaceous tectonic event may be the cause of the missing of the Kawagarh and Hangu Formations in the area (Tahirkhelli, 1982), which in turn resulted in the uplift and erosion of the eastern part of the Kalachitta Range.

First major unconformity occurs between the Upper Cretaceous Kawagarh Formation and the Upper Lockhart Liemstone. It is marked by a ferruginous pisolite. The second major unconformity occurs between the Middle Eocene Kohat Formation and the Miocene Murree Formation and is marked by the pebbly deposit – the Fateh Jhang Member.

The Potwar Plateau is 150-km wide, translated along the Eo-Cambrian evaporates, resulted in the broader, more open and less internally deformed style of the foreland belt (Khan et al., 1986). The Himalayan foreland basin is one of the largest and most dynamic terrestrial basin on the earth's surface. Since the time that first sediments entered the Himalayan foreland, before 50 Ma, the Indian subcontinent has experienced more than 3000-Km of convergence with Asia (Le Pichon et al., 1992).

The stratigraphic successions in the Potwar Plateau can be broken into four major unconformity-bounded sequences (Table 2.1).

1. Late Precambrian through Early Cambrian platform strata, including a basal evaporite layer
2. An early to late Permian platform sequence
3. Paleocene to early Eocene marine carbonates and shales
4. A time-transgressive, Neogene molasses sequence

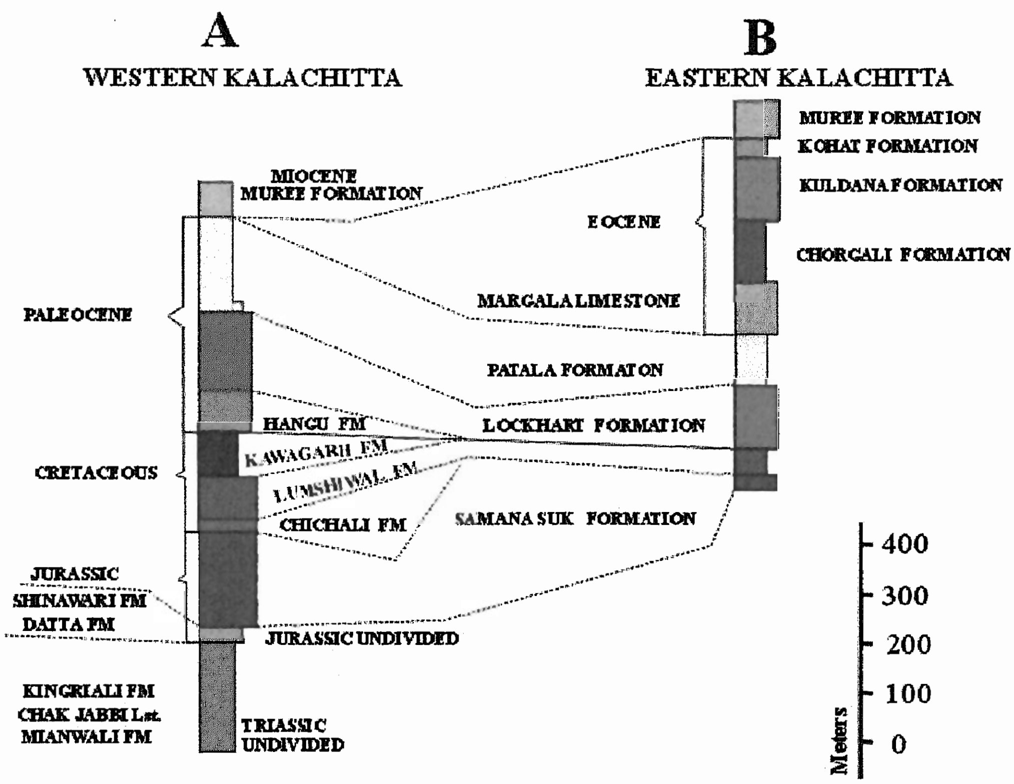

Fig.2.1. Comparison of Western and Eastern Kalachitta Range (After Hussain et al., 1990).

The Eocambrian evaporite beds of the Salt Range Formation were deposited unconformably on a Precambrian basement in a restricted, hypersaline basin of the Gondwana interior. The overlying Cambrian rocks of the Jhelum Group are composed of sandstones, shale, dolomite and anhydrite. These rocks were deposited in shallow-marine environments. The Baghanwala Formation, which contains salt pseudomorphs, represents a regressive cycle of deposition in the Late Cambrian (Khan et al., 1986). The overlying unconformity extends from the Ordovician to Upper Carboniferous. Erosion during this time resulted in the maximum preserved thickness of Cambrian rocks in the eastern Salt Range/Potwar Plateau (SR/PP), thinning gradually towards the west. Deposition started again in the Early Permian as glacial deposits of the Tobra Formation. In the Dhurnal area, Permian rocks directly overlie the Eocambrian Salt Range Formation, and the whole Cambrian section is missing (Table 2.1). The rocks of Triassic, Jurassic and Cretaceous age were deposited on a west-northwest-facing passive margin after the breakup of Gondwana, such that the maximum development of Mesozoic is in the western SR/PP, overlapped by Paleocene strata toward the east (Yeats and Hussain, 1987). In the Dhurnal area the whole Mesozoic section is missing due to a combination of a thin original section and later erosion (Table 1). During the Paleogene, shallow-marine to lagoonal sediments were deposited on the earlier, eroded surface. Thick sequences of carbonate and shale beds were deposited in the western and central SR/PP, thinning toward the east. The third period of uplift and erosion corresponds to major collision between the Indian and Eurasin plates in the late Eocene and continues today in the Himalayan foredeep, represented by Pleistocene conglomerates that rest on the older rocks with an angular relationship (Seeber et al., 1981; Gee, 1983; Ni and Barazangi, 1984 and Yeats and Hussain, 1987). The collision resulted in deposition of the fluvial, time-trangressive deposits of the Rawalpindi and Siwalik groups during uplift of the Himalayas (Johnson et al., 1979). Miocene Rawalpindi Group ~2106 m thick, consists of Murree and Kamlial Formations of dominantly arenaceous strata with a pelitic sequence at the interface (Table 1). Top of the Murree Formation is dated at 17 Ma. These strata are non-marine time transgression molassic facies that represents the erosional products of southward advancing Himalayan thrust front. The fluvial and fluvio- deltaic Rawalpindi Group strata indicate the initiation of the significant Himalayan uplift (Johnson et al., 1979). The Siwalik have been deposited between 0-13 Ma (Johnson et al., 1979 and 1982). The Siwalik Group record continued uplift of the Himalayas. However, where Lower Siwalik strata are derived from the crystalline and metamorphic terrains of the higher Himalaya; Upper Siwalik strata is consist of recycled Lower and Middle Siwalik debris due to continuous southward migration of the deformation front (Keller et al., 1977 and Abid et al., 1983). Magnetostratigraphy combined with sedimentation and tectonics provides

AGE			GROUP	FORMATION	DESCRIPTION	ENVIRON.OF DEPOSTION	TECTONIC SETTING	THICKNESS (M)	INVTERVAL VELOCITY	HYDROCAR-BONS
CENOZOIC	TERTIARY	PLIOCENE	SIWALIK	DHOKPATHAN	Claystone, sandstone contains heavy mineral kyanite in abundance	Fluvial	Foreland basin molasse	600	3950 m/s	
				NAGRI	Sandstone with subordinate siltstone & clay + intraformational conglomerates + kyanite.			518		
				CHINJI	Interbedded red brown clay with sandstone and siltstone + kyanite			1312		
		MIOCENE	RAWA-LPINDI	KAMLIAL	Interbedded grayish sandstone and claystone with minor siltstone			393		
				MURREE	Alternative light gay sandstone with dark green heavy minerals, claystone and siltstone			1713		
		OLIGO-CENE								
		EOCENE	CHHARAT	MAMIKHEL	Brick red claystone/shale with subordinate siltstone and micritic limestone	Red bed coastal plain	Platform	70	4700 m/s	
				CHORGALI	Gray shale with buff limestone	Marine		77		●
				SAKESAR	Light brown limestone with thin streaks of dark gray shale	Marine		87		●
		PALEOCENE		PATALA	Light gray limestone with thin streaks of gray shale	Shallow marine-lagoonal	Platform	168		●
				LOCKHART	Interbedded light gray limestone and gray shale	Shallow marine		11		●
				HANGU	Light gray sandstone and dark gray shale	Marine-continental		13		
MESOZOIC	CRETACEOUS									
	JURASSIC									
	TRIASSIC									
PALEOZOIC	PERMIAN	LATE	ZALUCH	WARGAL	Buff limestone with thin streaks of creamy dolomite and grayish shale	Shallow marine	Passive margin platform	100	4700 m/s	●
				AMB	Light gray sandstone interbedded with creamy limestone and greenish shale	Shallow marine		83		○
		EARLY	NILAWAHAN	SARDHAI	Predominantly bluish gray, purple, brown shale with minor white sandstone and brown claystone	Lacustrine to shallow marine		116		
				WARCHA	Mainly whitish sandstone with reddish claystone and greenish shale	Fluvial to lagoonal		110		○
				DANDOT	Interbedded chocolate brown claystone grayish siltstone and shale	Shallow marine		33		
				TOBRA	Interbedded quartzose sandstone grading to conglomerate with siltstone and shale	Glacial to fluvial		183		
	CABONIFEROUS									
	DEVONIAN									
	SILURIAN									
	ORDOVICIAN									
	CAMBRIAN									
PRECAMBRIAN			SALT RANGE		Upper part is reddish claystone, olive green dolomite and gray shale, lover part is evaporite	Restricted marine hypersaline	Intrac-ratonic	+87	4600 m/s	
			BASEMENT INDIAN SHIELD		Biotite schist, quartzite, rhyolite	Metamorphic complex	Continent al shield	Not drilled	6000 m/s	

Table 2.1 Generalized stratigraphy section based on horizons encountered in the Dhurnal 3 well. Dark circle hydrocarbon production & light circle hydrocarbon shows (Jaswal et al., 1997)

useful details of dynamic processes in the Himalayan foreland of Pakistan (Raynolds and Johnson, 1985; Johnson et al., 1986 and Burbank and Raynolds, 1988).

The stratigraphy of the study area mainly consists of sedimentary rocks of various formations ranging in age from Jurassic to recent. On the basis of previous investigation and present work, the following formations have been recognized in the study area.

2.1 JURASSIC:

At the close of Triassic system, the sea regressed and the break in deposition is marked by pisolitic laterite and bauxite disconformably overlying the uneven top surface of Kingriali Formation. The marine conditions prevailed throughout Jurassic period except for a short time at the close of Middle Jurassic and this break is represented by a laterite encrustation on top surface of Samana Suk Formation (Plate 2.1). The overlying Chichali Formation was deposited during the Jurassic to Early Cretaceous period; as such, there is no lithological discontinuity at the Jurassic Cretaceous boundary.

2.1.1 SAMANA SUK FORMATION:

Davis (1930) introduced the name "Samana Suk" which later on applied to similar limestone sequences by Gee (1945), Cotter (1933), Middlemiss (1896), Latif (1970), exposed in Salt Range, Trans Indus Ranges, Kalachitta Range and Hazara.

Type section is located in the western part of Samana Range north east of Shinwari village.

The Formation consists of various lithologies units. The major unit is limestone, having light pinkish gray, and yellow to yellowish brown colour (Plate 2.2), others are marls, sandstone and clays. The limestone is medium to thick bedded, having variety of microfacies from low energy micritic limestone to high-energy intrasparite and oosparite facies. Dolomitic limestone and rare calcareous dolomites are present. Bioturbated surface are common e.g. burrow mottling (Plate 2.2).

The thickness of the Formation varies from 120-225 m, while in the study area its thickness is 37m.

The lower contact is not exposed and its upper contact with the Lumshiwal Formation is disconformable. A rich fauna has been reported which includes ammonite, corals and gastropode (Akhtar et al., 1985). On the basis of fauna Early to middle Jurassic age has been assigned to it.

The Samana Suk Formation is correlated to Chilton Limestone and Mazar Drick Formation of lower Indus Basin and axial belt by stratigraphic committee of Pakistan.

2.2 CRETACEOUS:

The Cretaceous system is composed of part of Chichali Formation, the Lumshiwal Formation, and Kawagarh Formation. The regression of sea occurred twice during the Cretaceosus period. The first at the close of Early Cretaceous and the second after the deposition of Kawagarh Formation. In southern Kalachitta, the Kawagarh Formation has not been deposited thus indicating non deposition/erosion from Early Cretaceous to Early Paleocene.

2.2.1 LUMSHIWAL FORMATION:

Stratigraphic committee of Pakistan revised the name as "Lumshiwal Formation" to "Lumshiwal sandstone" of Gee (1945) in Salt Range, "Giumal sandstone" of Middlemiss (1896), Cotter (1933) in Hazara and Kalachitta.

Type locality is one kilometer north of Lumshiwal Nala Salt Range. Due to varying lithofacies and thicknesses three reference sections have been designated.

1) Fort Lockhart section in Samana Range.
2) Wach Khawar section in Nizampur area, Kalachitta Range.
3) Jamiri village on Haripur Jabrian road in Hazara.

Lumshiwal Formation is well exposed in the northern part of the mapped area. The Formation is comprised of alternation of sandstone, siltstone, shale and limestone (Plate 2.3). The sandstone is glauconitic which is greenish grey in colour, the weathering colour is brownish green, fine to coarse grained, medium to thick bedded, feldspethic silty, calcareous and at places ferrogenious. Limestone inter-beds are also present in the upper part, which is dark gray, brownish gray and greenish orange to pink, medium to thick bedded shelly and contains broken shells of bivalves and oysters.

It forms steep slopes alternating with escarpments of harder rocks. Thickness in the eastern Kalachitta Range is not more than 50 meters The lower contact with the Samana

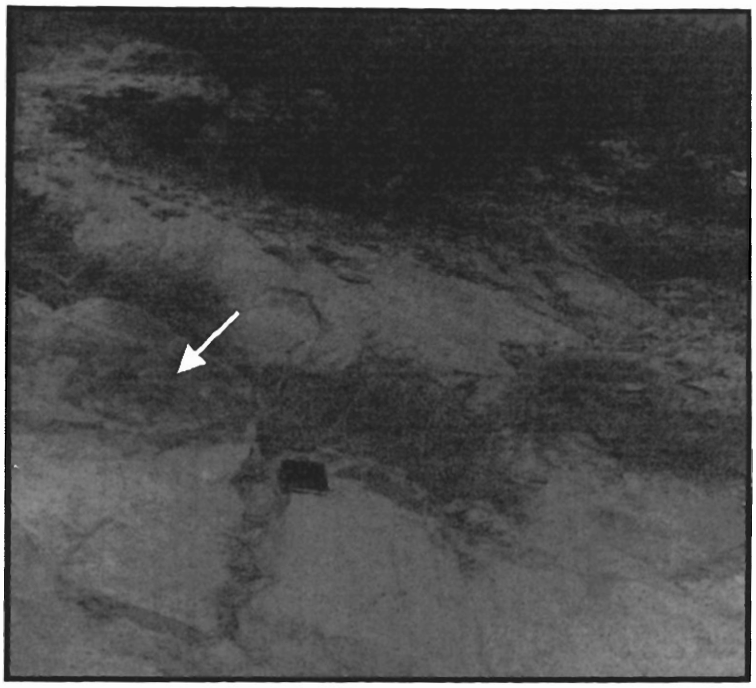

Plate 2.1. Yellowish limestone of Samana Suk Formation having encrustation of laterite on its surface.

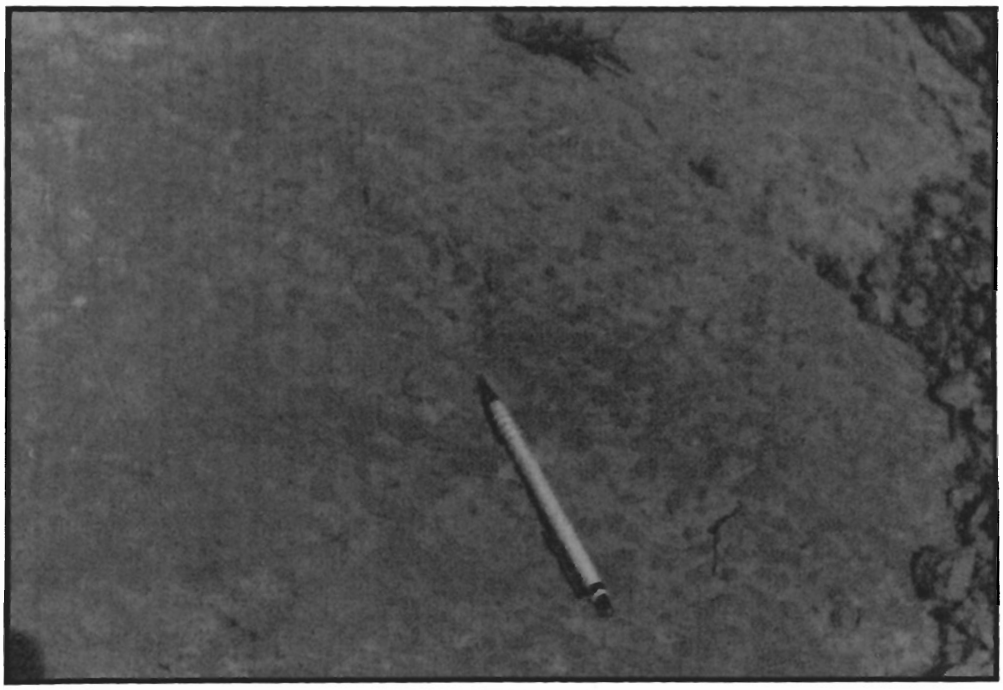

Plate 2.2. Burrow mottling on the bedding surface of Samana Suk Formation.

Suk Formation is disconformable as shown by glacunitic sandstone while the upper contact with Lockhart Limestone is unconformable as suggested by the presence of ferrogenious sandstone. The Formation is fossiliferous and contains brachiopodes, ammonides and gastropodes (Akhtar et al., 1985).

On the basis of fauna Early Cretaceous age (Neocomian) to late early Cretaceous (Albanian) age has been assigned to this Formation. The Formation is correlated with the Goru Formation of the axial belt and the lower Indus basin by stratigraphic committee of Pakistan.

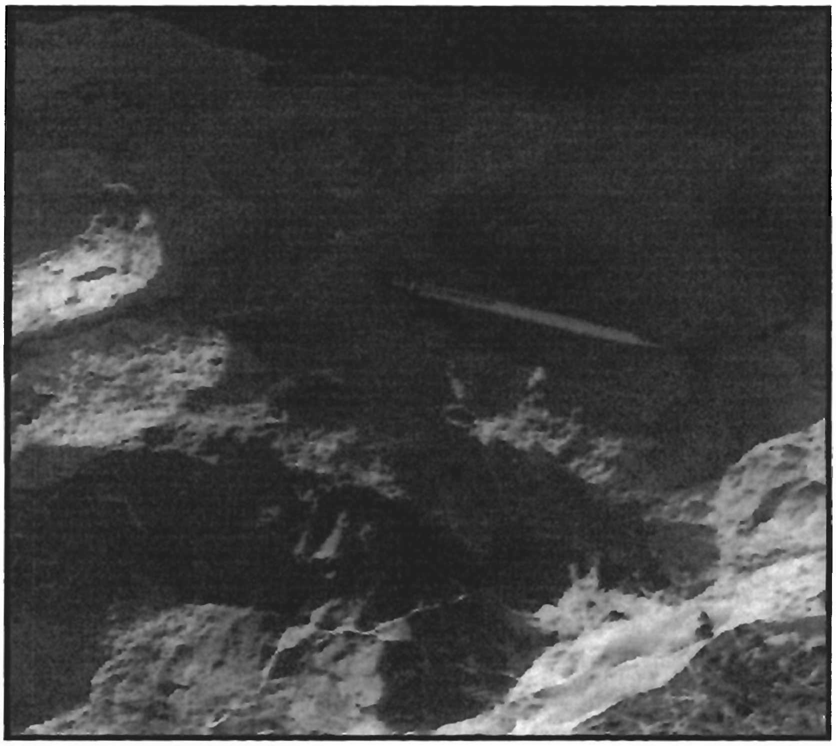

Plate 2.3. Lumshiwal Formation exposed south of Katha Colony along Gakhar road.

2.3 TERTIARY:

At the close of Cretaceous period, the area once again emerged from sea into dry land. The sea transgressed again during Early Paleocene time and deposition of Hangu Formation took place with laterite at its base overlying Kawagarh Formation in Northern Kalachitta, and Lumshiwal Formation in southern Kalachitta. This indicates that the southern part of the Kalachitta area remained emerged after the deposition of Lumshiwal Formation and deposition of Kawagarh Formation did not take place in this part.

After the Middle Eocene, the sea regressed and no deposition took place during Late Eocene-Oligocene time. This break is represented by 50 cm to over 1 meter thick boulder bed named as Fateh Jhang member, which contains pebbles and boulders of Tertiary limestone, embedded in a sandy matrix (Plate 2.4). During Miocene time Rawalpindi Group of continental origin was deposited.

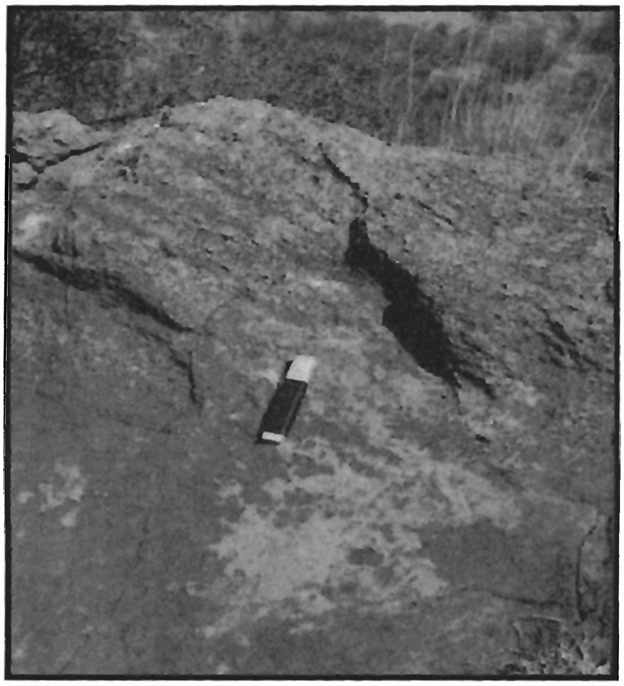

Plate 2.4. Fateh Jhang Member containing pebbles and boulders of Tertiary limestone, north of Fateh Jhang city.

2.3.1 LOCKHART LIMESTONE

Davies (1930) introduced the name "Lockhart limestone" to the Paleocene limestone unit in Kohat area. Stratigraphic committee of Pakistan generalized the term for "Nummulitic series" of Middldemiss (1896), lower part of "Hill limestone" of Wynne (1873) and Cotter (1933), the "Tarkhobi limestone" of Eames (1952) and "Main limestone"of Latif (1970). Type locality is near Fort Lockhart in the Samana Range. The Formation consists of limestone, marl and rare shale. The limestone is dark grey, weathers whitish to dark grey and brownish grey. It is nodular and massive, micritic to biomicritic in nature, shelly and fossiliferous. The nodules are 3 to 20 mm in diameter (Plate 2.5). Freshly broken limestone gives feted smell. Marl is intercalated along the nodules interspaces. Shale and marl are creamish grey in colour. It forms ridges and cliffs (Plate 2.6).

Plate 2.5. Nodular beds of Lockhart Formation, east of Katha Colony.

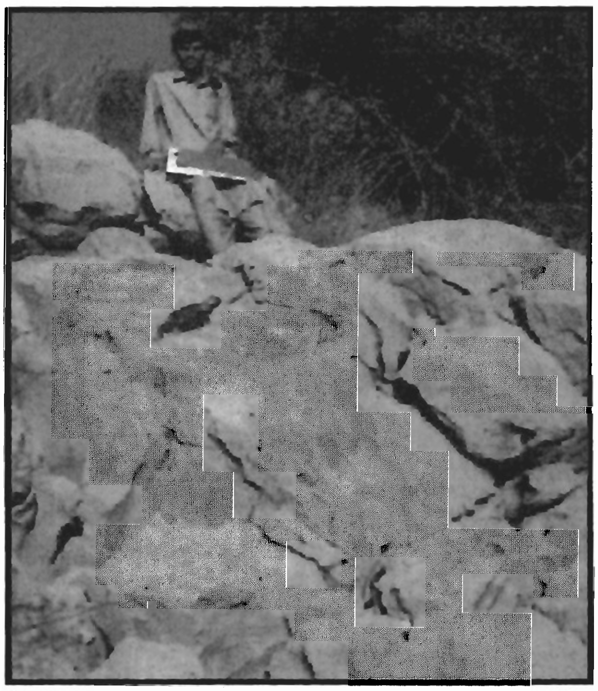

Plate 2.6. Lockhart Limestone forming ridges (North of Gadwali village).

Maximum thickness of the Formation in the Kalachitta Range is 165 meters. In the study area it is about 140 meters thick.

Lockhart limestone overlies the Lunishiwal Formation with an unconformable contact, whereas upper contact with the Patala Formation is transitional. The Formation is richly fossiliferous preserving foraminifers, molluscus and echinoids. On the basis of fauna Paleocene age is assigned to the Formation (Akhtar and Khan, 1983).

Stratigraphic committee of Pakistan has correlated Lockhart Limestone with the Bara Formation, the lower part of the Dungan and Rakhshai formations of lower Indus basin, Axial Belt and Baluchistan basin respectively.

2.3.2 PATALA FORMATION:

Davies and Pinfold (1937) introduced the name "Patala shale" for the shale of Patala Nalah. Stratigraphic committee of Pakistan amended it as "Patala Formation" and generalized it to "Tarkhobi shale" of Eames (1952), Part of "Hill limestone" of Wynne (1873) and Cotter (1933), part of "Nummulitic Formation" of Waagan and Wynne (1872), part of "Nummulitic series" of Middlemiss (1896) and the "Kuzagah shale" of Latif (1970). Type section is in Patala Nala.

In the mapped area Patala Formation is exposed in the Northern and southern parts. The Formation is composed of light grey to greenish brown marl with interbeds of pale grey limestone and calcareous shale (Plate 2.7). The interbedded limestone is nodular, medium bedded, medium grained, fossiliferous, and increases thickness laterally towards east (Plate 2.8). The shale is light brownish gray and lusty yellowish green, laminated to thin bedded, fissile and splintery. The marl is light gray, thin bedded and richly fossiliferous. It has transitional contacts with the overlying Margala Hill limestone and underlying Lockhart limestone. Maximum reported thickness is 225 meters. In the studied area it is about 113 meters thick. The Formation contains Foraminifers, Molluscs and Ostrocods as a fossil record (Plate 2.9). In Kalachitta Range it has been assigned late Paleocene age on faunal basis (Akhtar and Khan, 1983). It is correlated with the Lakhra Formation, the upper part of Dunghan and Rakshani formations, lower part of Ghazij and Lahi formations of lower Indus basin, Axial belt and Baluchistan basin by stratigraphic committee of Pakistan.

Plate 2.7. Interbedded thin limestone and shale of Patala Formation at Katha Colony.

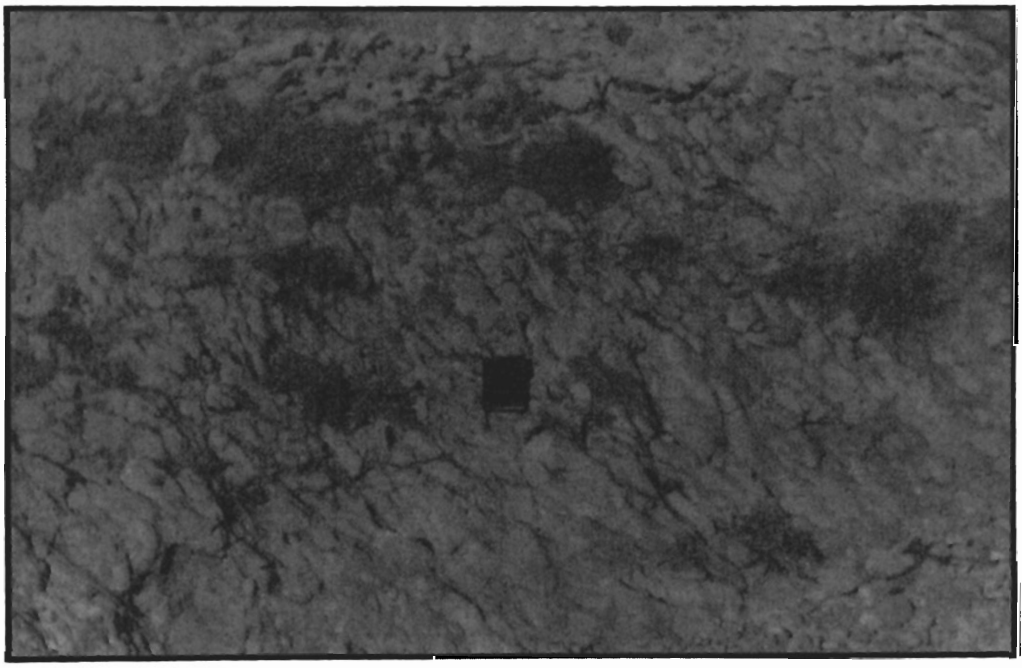

Plate 2.8. Nodular bedding surface of Patala Limestone at Katha Colony.

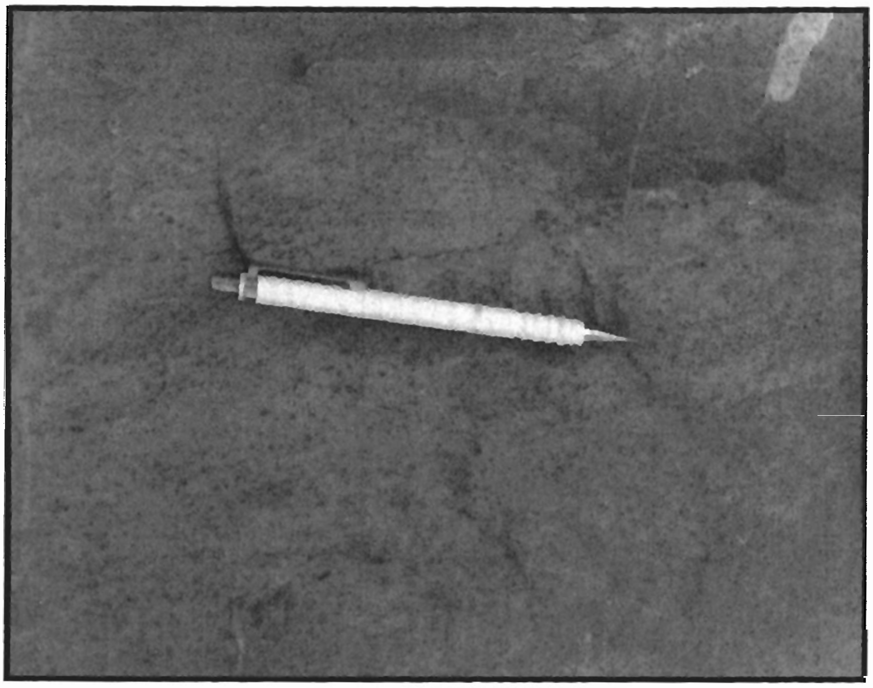

Plate 2.9. Richly fossiliferous bed of Patala Limestone at Katha Colony.

2.4 EOCENE:

Chharat Group:

The Chharat Group comprises of the following formations in ascending order;

Margala Hill Limestone

Chorgali Formation

Kuldana Formation

Kohat Formation

2.4.1 MARGALA HILL LIMESTONE:

Latif (1970) introduced the name "Margala Hill limestone" which later on formalized to "Nummulitic Formation" of Waagan and Wynne (1872), upper part of the "Hill limestone" of Wynne and Cotter (1933) and part of "Nummulitic series" of Middlemiss (1896), by stratigraphic committee of Pakistan.

Type section is Shahdara in south - eastern Hazara. It is well exposed in the study area.

The Formation consists of limestone with subordinate marl and shale. The limestone is grey to dark grey in colour and weathers pale grey. It is fine to medium grained, nodular, massive and jointed (Plate 2.10). The marl is pale grey to brownish grey in colour, while shale is greenish brown in colour. The Formation forms high cliffs and steep slopes (Plate 2.11). In the mapped area it is about 110 meters thick and is fossiliferous (Plate 2.12). The contacts with overlying Chorgali Formation and underlying Patala Formation are conformable. Preserved fossil record includes Foraminifera, Molluscus and Echinoids (Akhtar and Khan, 1983). Early Eocene age has been assigned to Margala Hill limestone.

2.4.2 CHORGALI FORMATION:

The term "Chorgali Formation" was introduced to "Chorgali beds" of Passcoe (1920) by stratigraphic committee of Pakistan and formalized for "Passage beds" of Pinfold (1918), "Badhrar beds" of Gee and Evan (in Davis and Pinfold, 1937) and "Lora Formation" of Latif (1970).

The Chorgali Formation is well developed in Kalachitta Range. In the study area the Formation is exposed in the central and southern parts. The Formation consists of limestone and shale. The limestone is brownish grey in colour, weathers cream and whitish grey. It is nodular, jointed and fossiliferous. The shale is greenish grey in colour, weather brownish grey, splintery and is more prominent in lower part. The Formation generally forms hills with gentle slopes.

Type section is Chorgali pass in Khair-i-Murat Range. In the study area it has conformable lower and upper contacts with the Margala Hill limestone and the Kuldana formations respectively. It is about 125 meters thick in the study area. The fauna record shows Foraminifers, Molluscs, Ostrocods, suggesting it Early Eocene age. (Akhtar et al., 1985)

It is correlated with the Jatta Gypsum of Kohat Province "Baska shale" and Alabaster member of Ghazij Formation of lower Indus basin and Axial belt by stratigraphic committee of Pakistan.

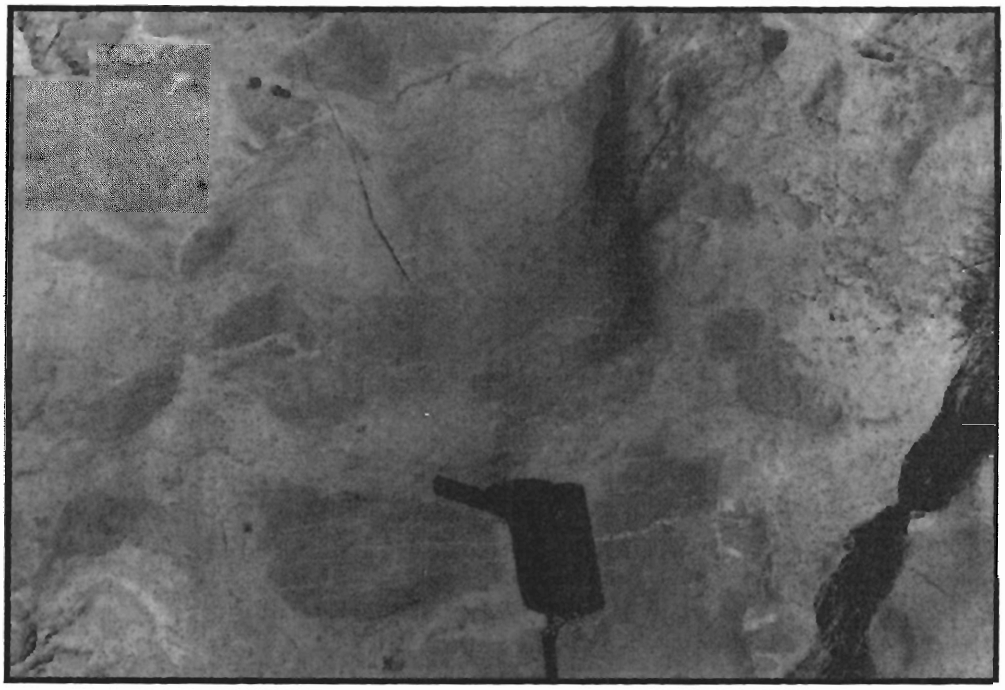

Plate 2.10. Nodular beds of Margalla Hill Limestone (south of Piro Shahi village).

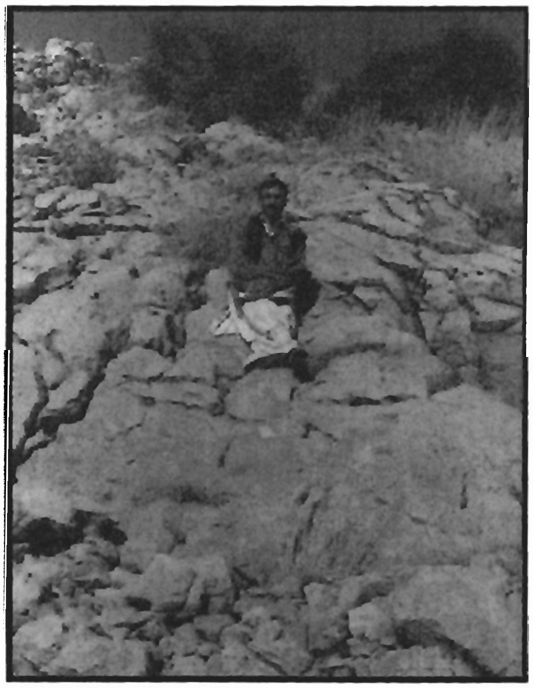

Plate 2.11. Highly jointed Margala Hill Limestone forming cliff and steep slope (east of Kath Colony).

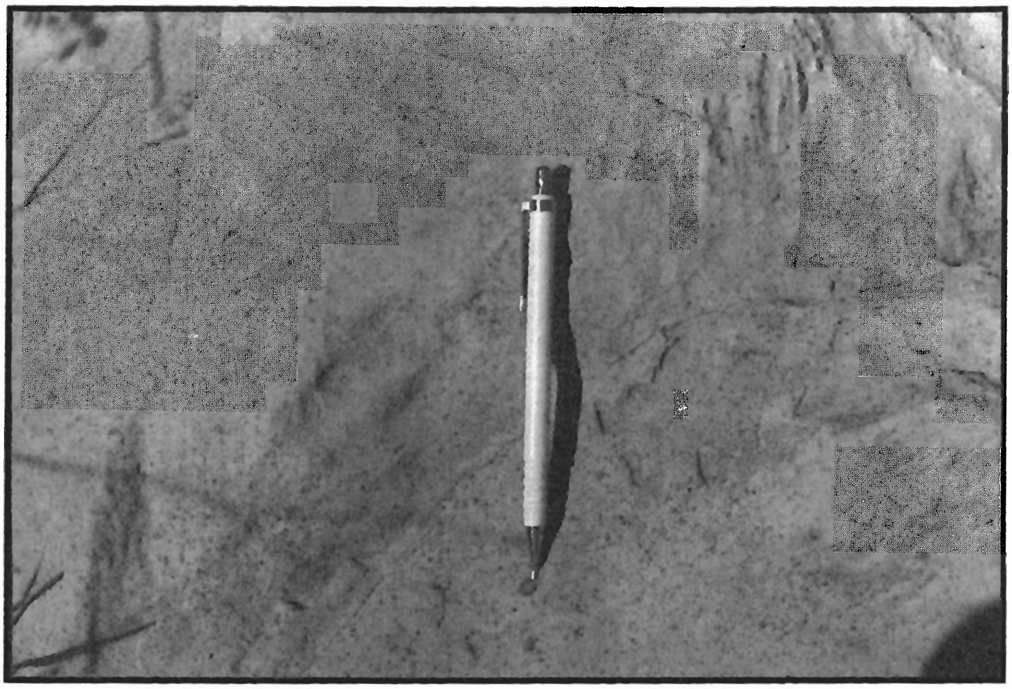

Plate 2.12. Fossiliferous bed (foraminifera) of Margala Hill Limestone (South of Piro Shahi).

2.4.3 KULDANA FORMATION:

Latif (1970) introduced the name "Kuldana Formation" for "Kuldana beds" of Wynne (1874), "Kuldana series" of Middlemiss (1896), "variegated shale" of Pinfold (1918), "Lower Cherat series" of Eames (1952), and "Mami khel clay" of Meissner et al., 1968.

Type section is located near "Kuldana village" north of Murree hill station. The Formation is well developed in southern Hazara, Kalachitta, northern Potwar and Kohat areas. The Formation is exposed in the southern part of the study area, composed of vari-coloured shale, marl and argillaceous limestone. The shale is maroon, brown to chocolate brown with some red gypsiferous horizons (Plate 2.13). The marl is grayish green and is associated with fibrous gypsum. Gritsone beds embedded in siliceous matrix are also present. The Formation forms gentle slopes and valleys. The Formation has conformable lower and upper contacts with the Chorgali and the Kohat formations respectively (Plate 2.14). It is about 124 meters thick in the study area. Bivalves, Foraminifers and Gastropodes have been reported by Akhtar et al (1985), assigning it Early to Middle Eocene age.

Plate 2.13. Gypsiferous horizons within Kuldana Formation (North of Gakhar village).

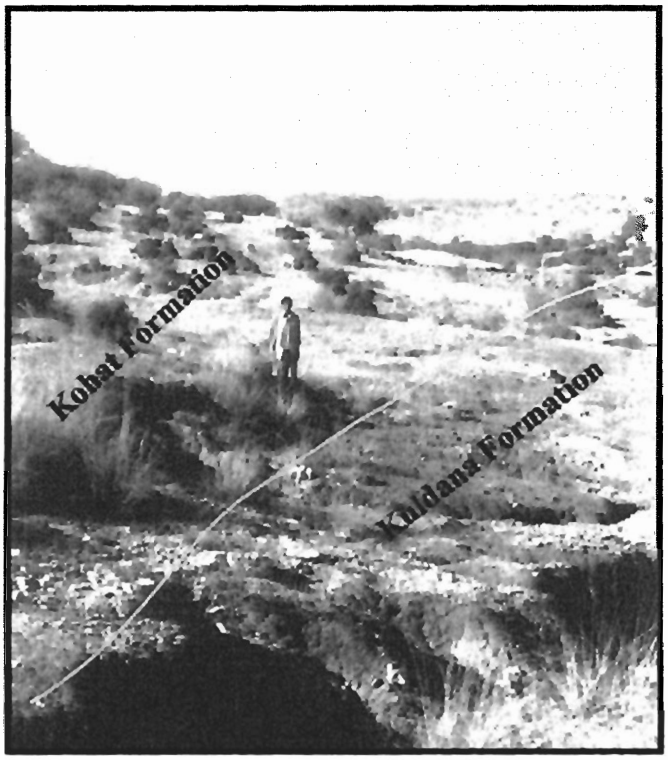

Plate 2.14. Looking westward, conformable contact between Kohat Formation (South) and Kuldana Formation (North).

2.4.4 KOHAT FORMATION:

"Nummulitic shale" of Pinfold (1918) and "Kohat shale" of Davis (1926) was subdivided into three subdivisions i.e., "Nummulitic shale", "Kohat limestone" and "Sirki shales" by Eames (1952), and Meissner et al., (1968), naming it as "Kohat Formation.

The Kohat Formation is confined to Kohat, Northern Potwar, and Kalachitta Range. Type section is exposed on Kohat-Khusahlgarh road.

It is exposed to the south - eastern side of the study area. It comprises mainly of limestone and shale. The limestone is grey to olive gray, medium bedded, constituted by foraminiferal shells and fossils, flooded with nummulites (Plate 2.15). The interbedded shale is greenish gray thin bedded, rice crispy and fossiliferous (Plate 2.16). It is about 33 meters thick in the study area.

The upper contact with the Murree Formation is disconformable, whereas, the lower contact with Kuldana Formation is conformable. Foraminifers and bivalves have been reported by earlier workers. Middle Eocene age has been assigned to it in the study area by Akhtar et al., (1985).

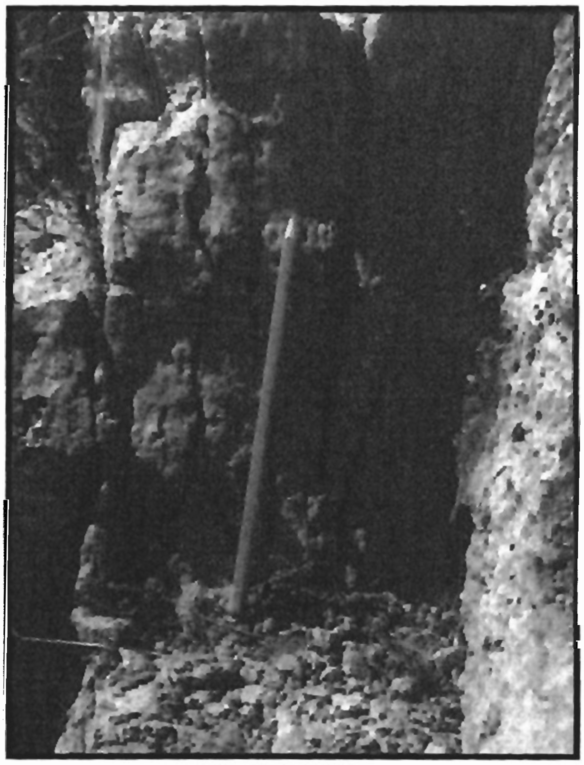

Plate 2.15. Nummulitic flooded beds of Kohat Formation (near Gadwali village).

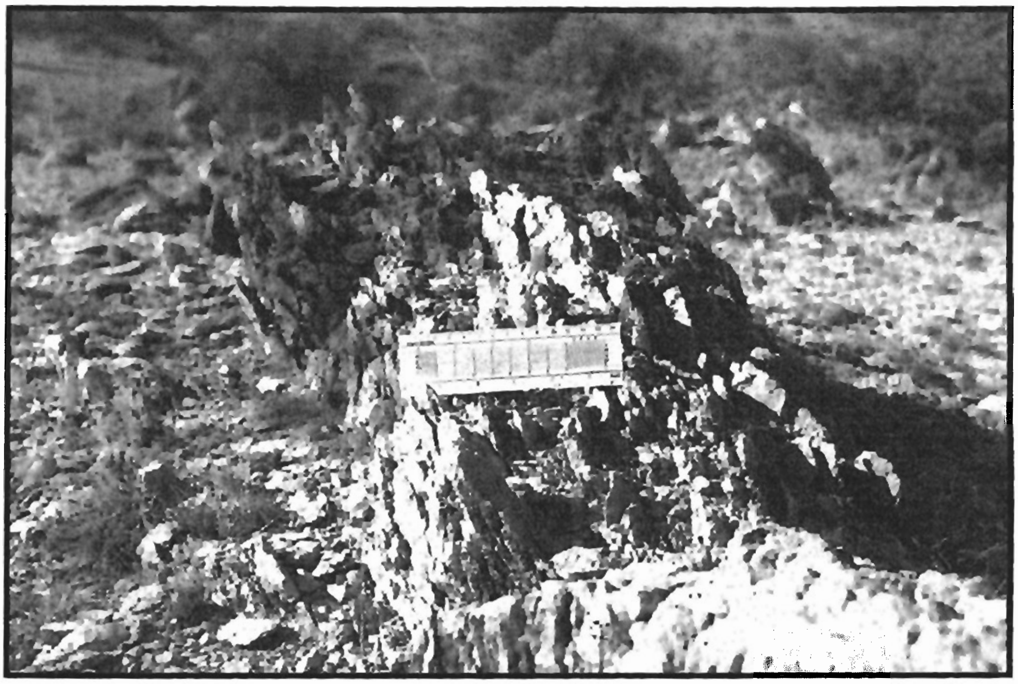

Plate 2.16. Rice crispy shale of Kohat Formation (Near Gadwali village).

2.5 Rawalpindi Group:

The group as a whole is a body of fresh water clastics and consists of sandstone and shale. The sandstone is dark, purple and grey in colour, alternating with purple and red shale. There are two members of this group

Murree Formation

Kamlial Formation.

2.5.1 MURREE FORMATION:

Stratigraphic committee of Pakistan introduced the term "Murree Formation" to the "Mari group" of Wynne (1874), "Murree beds" of Lydekker (1876) and "Murree series" of Pilgrim (1910).

Type section is referred to the north of Dhok Maiki in the Attock district. The Formation is widely distributed in Kohat-Potwar province and is also reported from Kashmir.

In the mapped area, it is exposed to the south of main boundary front. The Formation is composed of 1-meter thick zone having pebbles and boulders of Eocene limestone embedded in sandy matrix and is named as Fateh Jhang member. The Formation is divisible into lower and upper part.

The *upper part* is composed of alternate beds of sandstone and shale. The sandstone is brown buff, coarse grained whereas the shale is red to purple (Plate 2.17). The *lower part* is distinguished by purple and red sandstone; generally flaggy, pseudo-conglomerate beds occur at places (Plate 2.18). The shale is splintery purple and red with abundant calcite veins. Clay is purple and pink (Plate 2.19). Weathering of sandstone into lose material due to solution activity have been observed (Plate 2.20). Gray calcareous sandstone and conglomerate with abundant derived fossils are present as basal bed. Maximum reported thickness in the adjacent areas is 600 meters (Akhtar et al., 1985). The upper contact with Kamlial Formation is sharp; Hussain et al., (1979) have marked a para-confirmity at the contact. The lower contact with Kohat Formation is disconformable. Vertebrate fauna has been reported Early Miocene age has been assigned to the Formation. Wells (1984) has correlated it with the Subathu Formation near Simla, India.

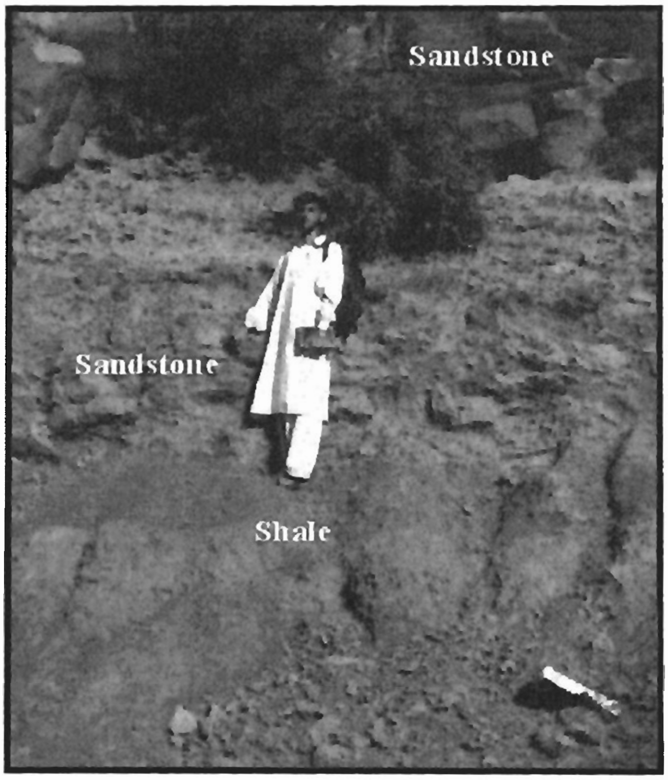

Plate 2.17. Interbeds of shale and sandstone of the Murree Formation (near Sadkal well).

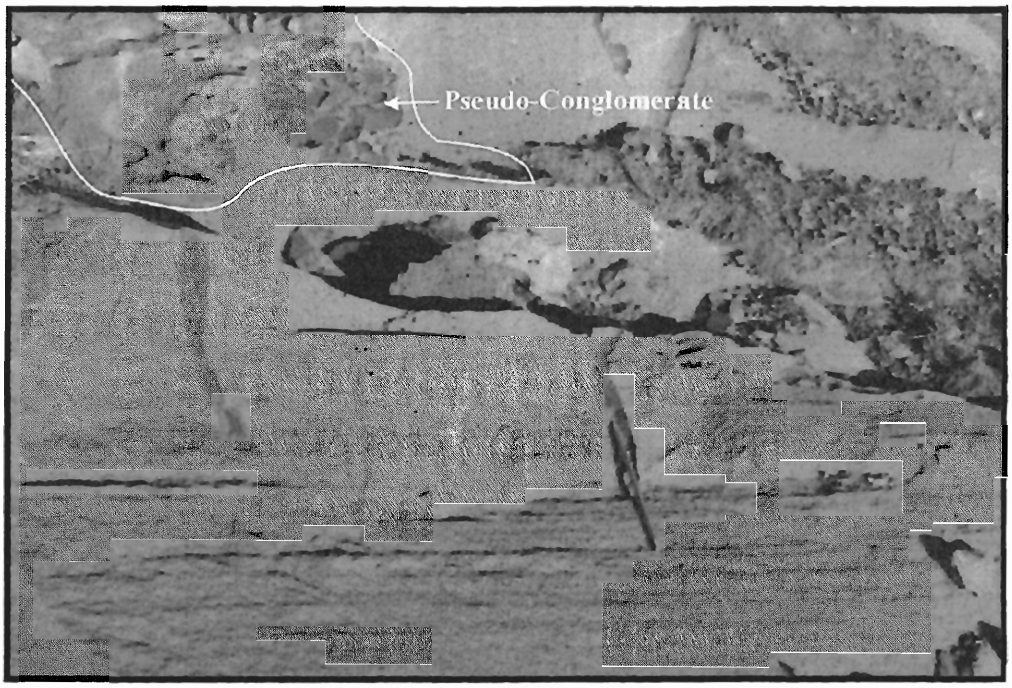

Plate 2.18. Coarse-grained sandstone of Murree Formation with pseudo-conglomerate.

Plate 2.19. Purple and Pinkish clay alternating with gray sandstone beds of Murree Formation.

Plate 2.20. Weathering of the Murree Formation into loose material, due to solution activity.

2.5.2 KAMLIAL FORMATION:

The Formation comprises sandstone of purple grey and dark brick red colour, hard coarse grained. Interbeds of shale and pseudo-conglomerate of yellow and purple colour are present at different intervals. The Formation is distinguished from underlying the Murree Formation by its spheriodal weathering (Plate 2.21). Another character, which distinguishes it from the Murree Formation, is that Murree Formation contains the accessory mineral epidote, the Kamlial Formation contains tourmaline (Shah, 1977). The Formation forms low strike ridges traceable for many km and is 100-150 meters thick. It is conformably overlain by Chinji Formation of Siwalik Group. Abundant verteberate fauns are reported to occur in this Formation. Middle to Late Miocene age has been assigned to the Formation, on the faunal basis.

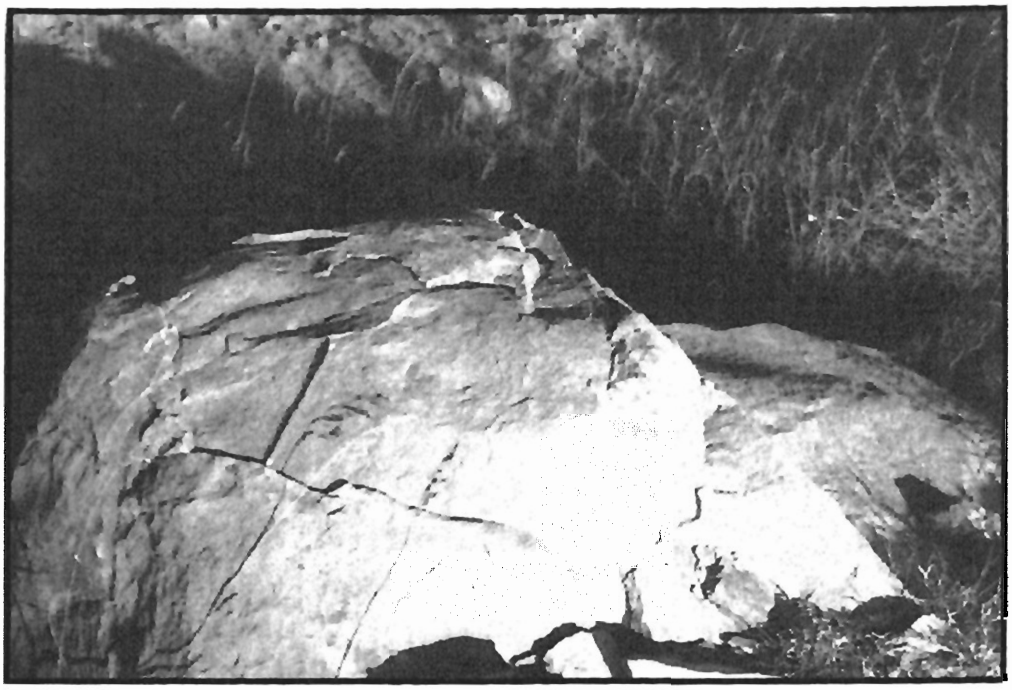

Plate 2.21. Spheriodal weathering in the Kamlial Sandstone.

2.6 SIWALIK GROUP:

The name Siwalik was first used by Meddlicott 1964, from the Siwalik Hills of India. The Siwalik deposits are one of the most comprehensively studied fluvial sequences in the world. They comprise mudstones, sandstones and coarsely bedded conglomerates laid down when the region was a vast basin during Middle Miocene to Upper Pleistocene times. The sediments were deposited by rivers flowing southwards from the Greater Himalayas, resulting in extensive multi-ordered drainage systems. Following this deposition, the sediments were uplifted through intense tectonic regimes (commencing in Upper Miocene times), subsequently resulting in a unique topographical entity – the Siwalik Hills. Establishing the timing, duration and frequency of this upliftment history has great implications for our understanding of hominid land-use patterns, relative site chronologies, and natural site-formation processes. The Siwalik Hills is located within in the political boundaries of Pakistan, India, Nepal and Bhutan and range between 6 to 90-Km in width (Acharyya, 1994 and Fig. 2.2).

Pilgrim (1913), proposed a three-fold division of the Siwalik System, which included the Lower Siwalik (Kamlial and Chinji Zone), Middle Siwalik (Nagri and Dhok Pathan

Zone) and Upper Siwalik (Tatrot, Pinjor and Boulder Conglomerate Zone). Cotter (1913), suggested that Kamlial Stage should be grouped with Murree Formation as the boundary between the two units is quite arbitrary, which was accepted by the Stratigraphy Committee of Pakistan. Ultimately, the Stratigraphy Committee of Pakistan substituted the "Siwalik System" comprising of the following formations.

4 Soan Formation

3 Dhok Pathan Formation

2 Nagri Formation

1 Chinji Formation

The Siwalik group represents a coarsening upward mollase sequence in the Indo-Pakistan sub-continent and has a thickness thounsands of meters. The group has yielded rich fauna (Pilgrim, 1913 and Pascoe, 1963), which indicates Middle Miocene to Early Pleistocene age.

In the study area, however, only the Chinji, Nagri and Dhok Pathan formations are exposed.

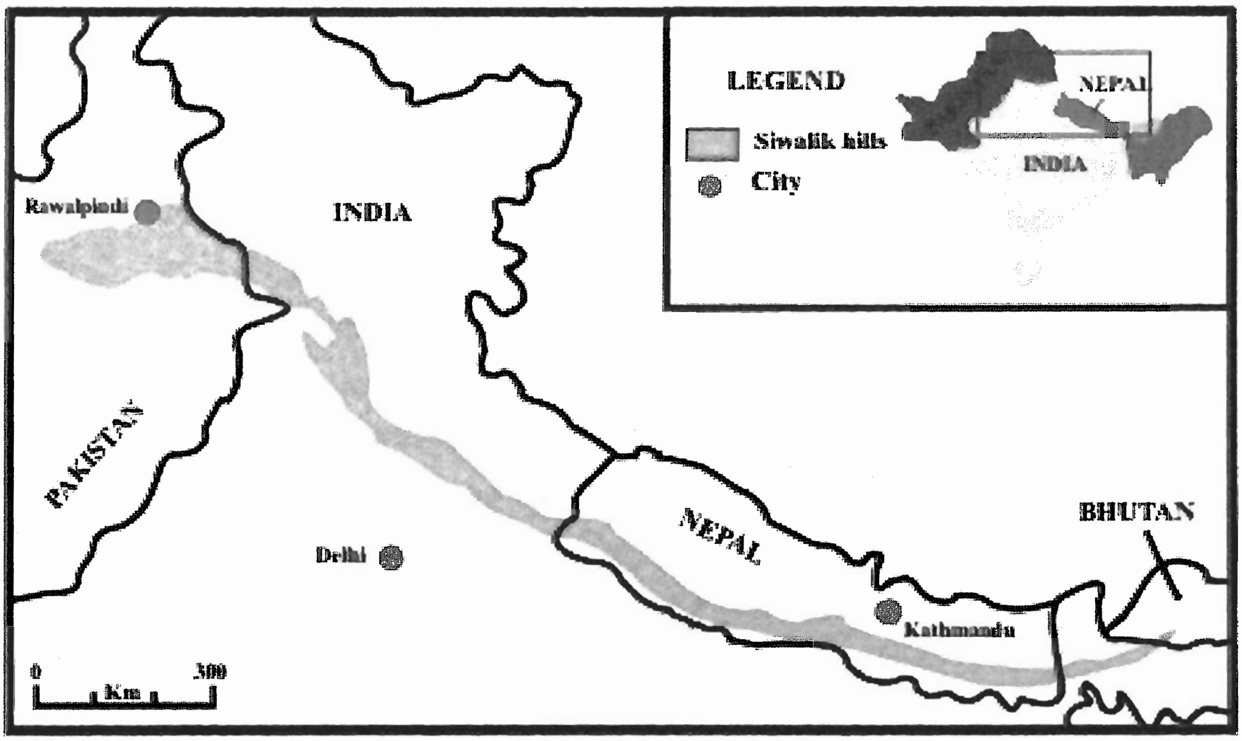

Fig. 2.2 Map showing distribution of Siwalik sediments in Pakistan, Nepal, India and Bhutan.

2.6.1 CHINJI FORMATION:

Lewis (1937) used the name "Chinji Formation' for the "Chinji stage of Pilgrim (1913), which was accepted by the Stratigraphy Committee of Pakistan (Shah, 1977). Chinji Formation is present throughout the Potwar Plateau. The Formation is mainly composed of claystone, mudstone and siltstone of distinctive brick red colour with subordinate grey sandstone.

The sandstone is fine to medium grained and at places gritty. It is thin to medium bedded and shows cross bedding. At the base of each sandstone bed, pebbly layers of siltstone and claystone are present. The sandstone extend as sheets which laterally mege into siltstone and claystone over long distances.

The sandstone unites grade upward into the much thicker siltstone and claystone beds. The claystone is indistinctly bedded and poorly sorted.

The Formation is about 1030 meters thick in the study. It has a conformable contact with the overlying Nagri Formation. The Chinji Formation is rich in vertebrate fossils (Pascoe, 1963), indicating a Middle Miocene age.

2.6.2 NAGRI FORMATION:

Lewis (1937), renamed the Nagri stage of Pilgrim (1913), as Nagri Formation, which was approved by the stratigraphy Committee of Pakistan (Shah, 1977). Composed largely of sandstone with subordinate clay and conglomerate. The sandstone is light grey to greenish grey and buff in colour, medium to coarse grained, medium to thick bedded, cross-bedded, and are moderately to poorly cemented.

Conglomerates contain igneous and Eocene limestone clasts derived from the Hill Ranges (Shah, 1977). The Formation is about 822 meters thick in the study area.

The Formation lies conformably over Chinji Formation and is overlain transitionally by Dhok Pathan Formation. The Formation has yielded fairly rich assemblage of vertebrate remains as recorded by Pilgrim (1913) and Lewis (1937). The fauna indicates Early Pliocene age of the Formation.

2.6.3 DHOK PATHAN FORMATION:

Typically represented by monotonous alternating cycles of sandstones and clay beds, the sandstone are commonly light grey-white in colour, soft, and cross-bedded. The clay is orange, scarlet to dull red. Conglomerates occur in the upper part. The upper contact of the Formation is not exposed in the map area. It is 900 meters thick. Vertebrate fauna is reported from this Formation. Late to Early Pleistocene age has been assigned to the Formation. It has a maximum thickness of 1830 m in the Potwar Plateau southeast of Khair-i-Murat Fault (Shah, 1977).

CHAPTER 3
REGIONAL TECTONIC SETTING

3.1 INDIAN PLATE (THE HIMALAYA)

The Himalayas, from geological and plate-tectonic point of view represent the deformed northern part of the Indian plate involved in continent-continent collision (Khan et al., 2004). Pakistan constitutes the northwestern boundary of the Indian lithospheric plate (Fig 3.1). Thus the region to the south of the MMT is included in the Himalayas (Khan et al., 2004). The most northerly part of the Himalayas, in northern Pakistan is represented by the Nanga Parbat-Haramosh Syntaxis. The mountain ranges of Kashmir, Upper Kaghan (south of Babusar), Upper Hazara (Allai Kohistan and to the south), Besham and Indus Syntaxis, lower Swat (south of Mingora), Chakdara, and Bajaur-Mohmand define the northern part of the Himalayas. The Salt Ranges and the Trans-Indus Ranges are the southern limits of the Himalaya in north Pakistan.

3.1.1 Tectonic Subdivision

The Himalayas are regionally divisible into internal (or hinterland) and external (or foreland) zones (Coward et al., 1988). The internal zone occurs immediately to the south of the MMT and comprises crystalline rocks of Naran, Hazara, Besham and Swat (Figs. 3.1 & 3.2). The external zone, which in essence, is a typical foreland thrust-fold belt, comprises successions of stratified sedimentary rocks of Hill Ranges (e.g., Margala, Kalachitta, and Kohat), Potwar-Kohat plateau, and Salt Ranges-Trans-Indus Ranges (Fig. 3.2). The tectonic boundary between the internal and external zones is marked by the Nathiagalli-Khairabad Thrust (Fig. 3.2). Another classification, adopted for the central and eastern Himalayas (Gansser, 1964), divides the Himalayas into Tethyan, higher, lesser and sub Himalayas (Fig. 3.3). The Tethyan Himalayas, comprising Precambrian – Eocene unmetamorphosed stratified rocks, are best developed in eastern and central Himalayas but are absent from the western Himalayas of north Pakistan. The Higher Himalayas comprising crystalline rocks of Protorozoic age with imprints of Himalayan metamorphism are abundantly exposed just to the south of the MMT in Kaghan, Hazara, and Swat areas.

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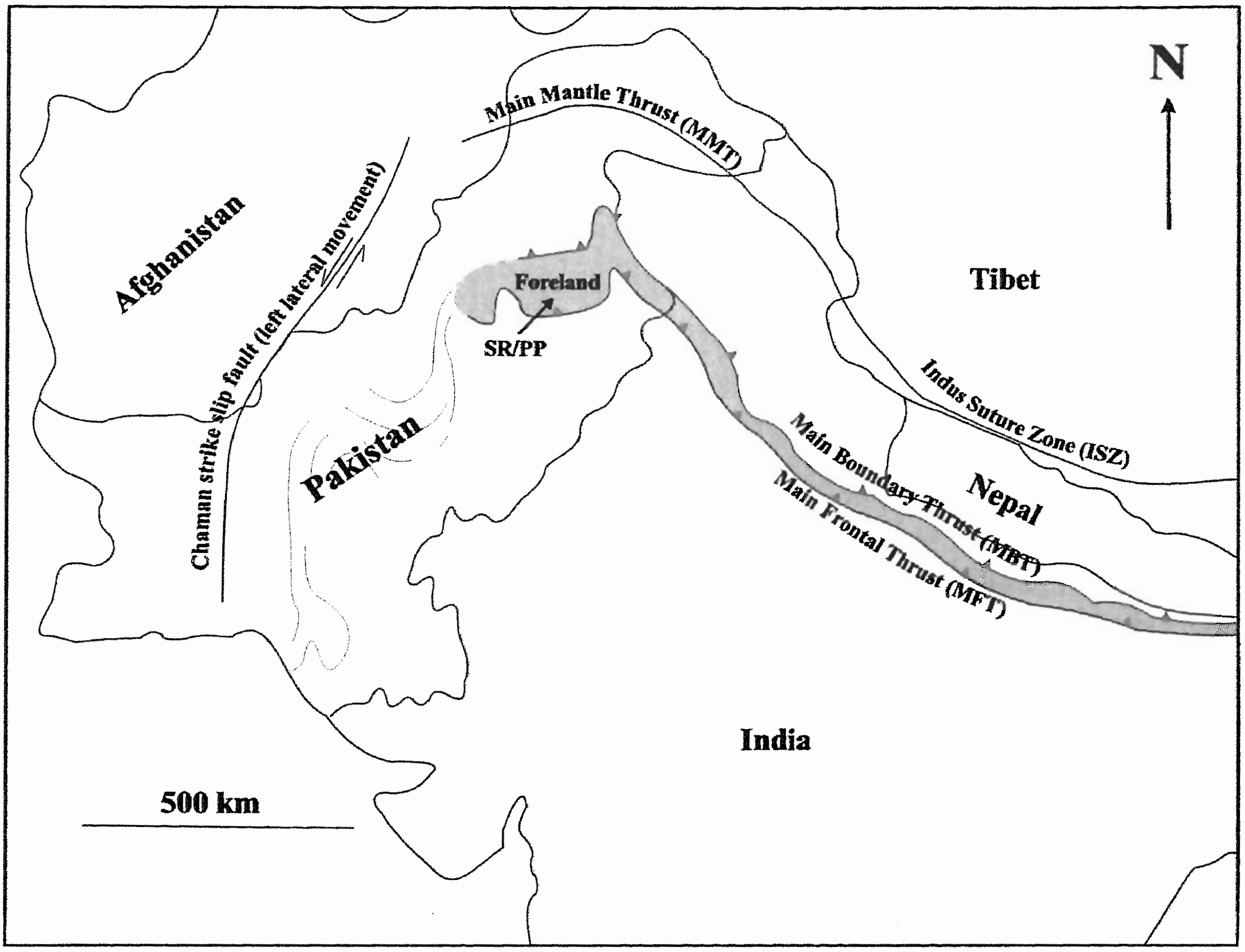

Fig. 3.1 Tectonic map of the Himalayas. Showing the Himalayan foreland (SR/PP) in North Pakistan. Chaman Fault, Indus suture zone, Main Boundary Thrust; Main Frontal thrust; Main Mantle thrust, SR/PP Salt Range/Potwar Plateau. Modified after Jadoon et al. (1997).

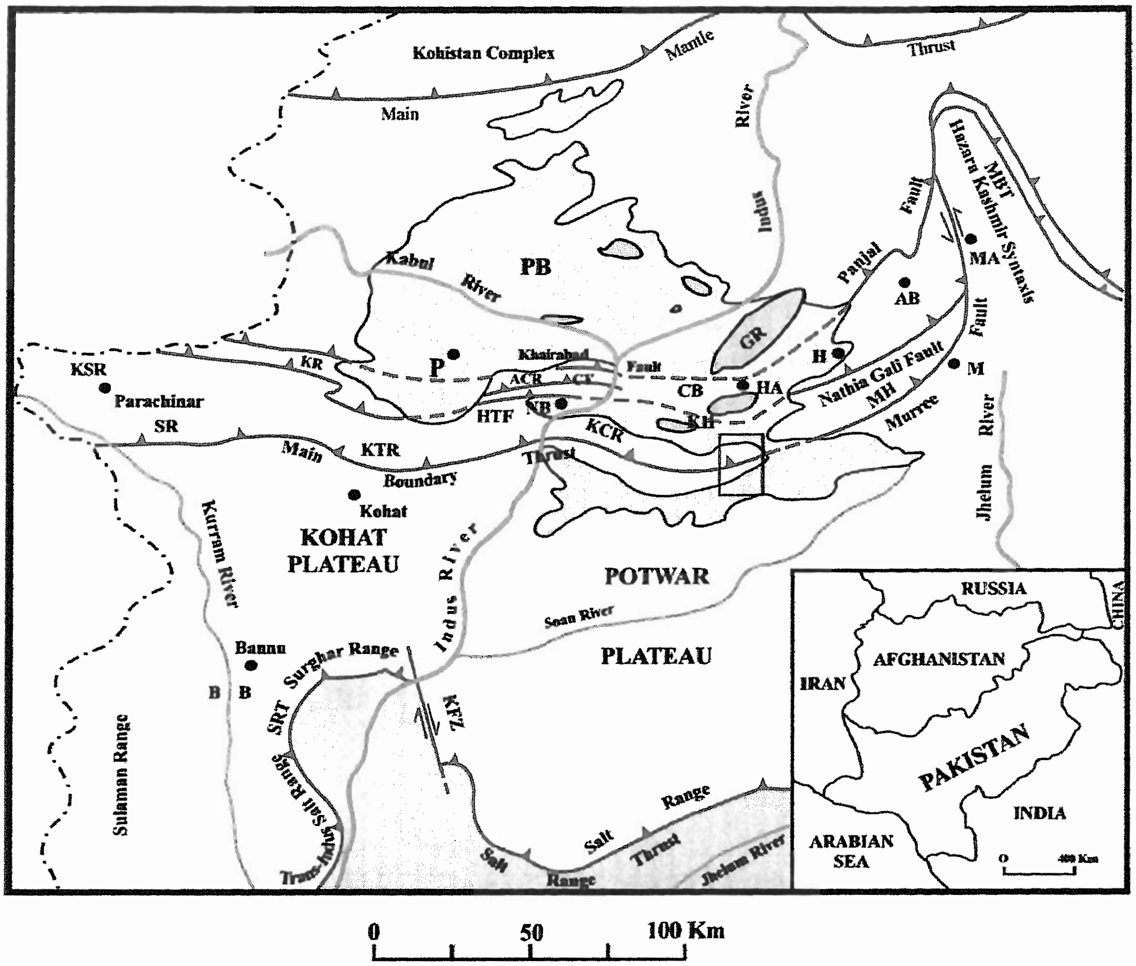

Fig. 3.2 Tectonic map of Northern Pakistan, showing major structural boundaries. GR Ganghar Range, KH Kherimar Hills, ACR Attock-Cherat Range, KR Khyber Range, MH Margalla Hill Range, KCR Kalachitta Range, KTR Kohat Range, SR Samana Range, KSR Koh-e-Sofaid Range, MBT Main Boundary Thrust, CF Cherat Fault, HTF Hisartang Fault, KFZ Kalabagh Fault Zone, SRT Surghar Range Thrust, PB Peshawar Basin, CB Campbellpore Basin, NB Nizampur Basin, BB Bannu Basin, MA Muzaffarabad, AB Abbottabad, M Murree, H Hassanabdal, P Peshawar (Modified after Hylland et al. 1988). The box shows the location of the study area.

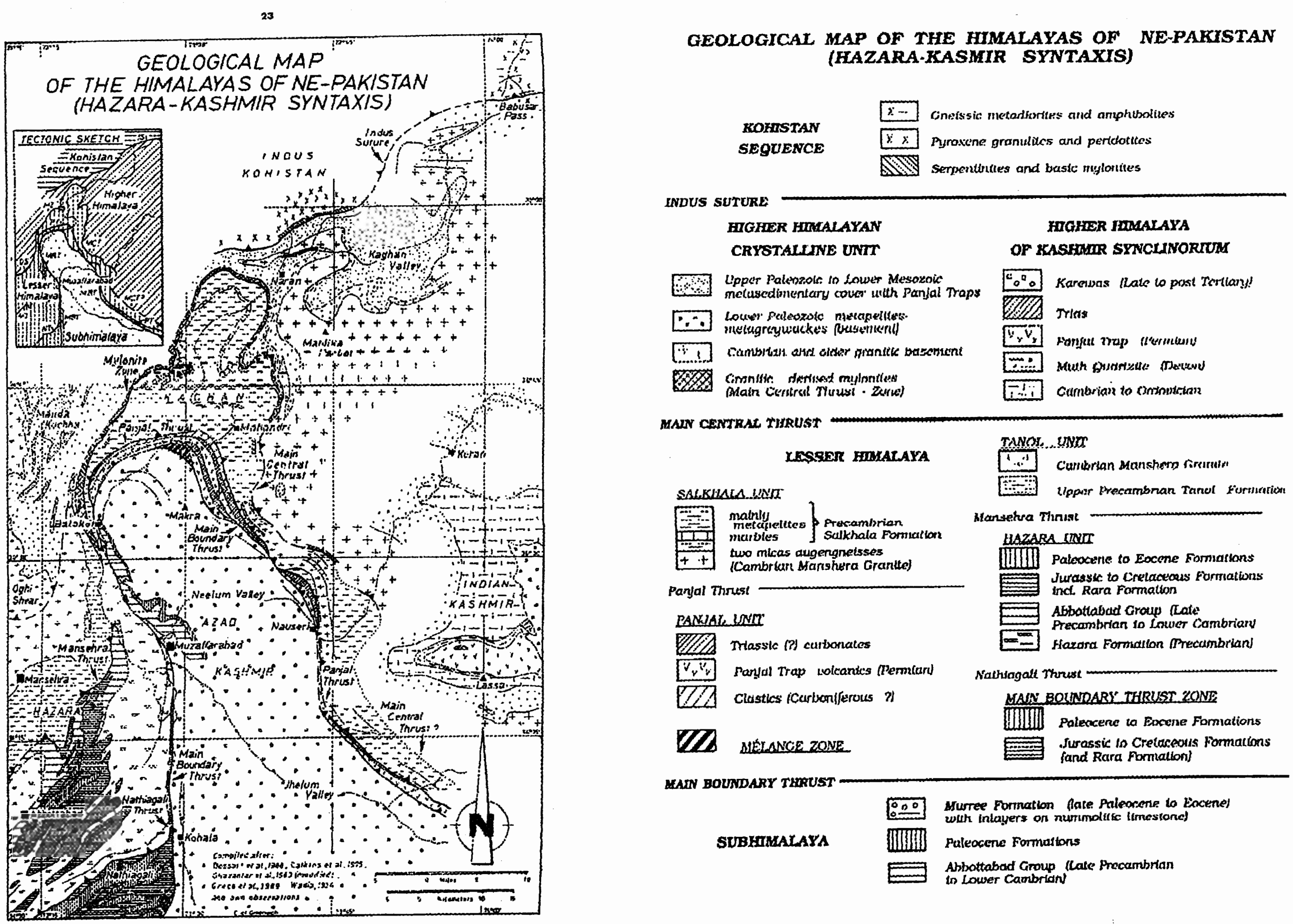

Fig. 3.3 Geological map of NW Himalayas of N. Pakistan (Hazara, Kaghan, Kashmir). Note the series of boundary faults including Main Mantle Thrust (MMT), Main Central Thrust (MCT), Panjal Thrust (PT) and the Main Boundary Thrust (MBT). The north-vergent Hazara Kashmir Syntaxis refolds all the major thrusts except MMT, which is folded by the Nanga Parbat Syntaxis. After Greco (1989).

The Main Central Thrust (MCT) demarcates the Higher Himalayas from the Lesser Himalayas (Fig. 3.4). The MCT is well developed in eastern and central Himalayas but its extension beyond Kaghan is controversial in north Pakistan, rendering the distinction of the Higher from Lesser Himalayas little problematic (Fig. 3.4). The equivalents of the Lesser Himalayas in northern Pakistan have been tentatively divided into an inner or Abbottabad zone and an outer or Kalachitta zone. The latter comprises unmetamorphosed sedimentary rocks ranging in age from Triassic to Eocene, and includes Kohat, Kalachitta, and Margala Hill Ranges (Fig. 3.2).

The Abbottabad zone comprises unmetamorphosed fossiliferrous rocks of early Palaeozoic age (e.g., Abbottabad Group), which overlies a sequence of variable metamorphosed rocks of imprecisely defined Late Proterozoic age (including Salkhala Formation, Tanawal Formation, Hazara, Manki (Attock), Landikotal and Dakhner Slate Formations). The Lesser Himalayas are demarcated from the Sub-Himalayas by the Main Boundary Thrust, which is a mountain front defined by a blind thrust, except for the west of the Indus river, where it becomes emergent.

The Sub Himalayas of north Pakistan are defined by the Potwar-Kohat Plateau comprising thick succession of Miocene-Recent molasse sediments (Rawalpindi and Siwalik Groups). The Salt Range lies at the southern edge of the Potwar plateau (Fig 3.2). The gently dipping detachment essentially running through the Salt Range Formation ramps along a basement normal fault and exposes the entire sequence from Precambrian to Recent in the Salt Range area.

3.1.2. Major Structures

The Himalayas of north Pakistan are the structural manifestation of the Himalayan orogeny and thus comprise numerous major structures. According to Treloar et al., (1989), the internal zone of north Pakistan comprises five major thrust sheets, which include, from east to west, Upper Kaghan, lower Kaghan, Hazara, Besham and Swat.

All the major thrusts in the Internal Zone of the Himalaya are affected by a later phase of N-S oriented fold structures such as the Nanga Parbat Syntaxis, Hazara Kashmir Syntaxis, Besham-Darband Syntaxis.

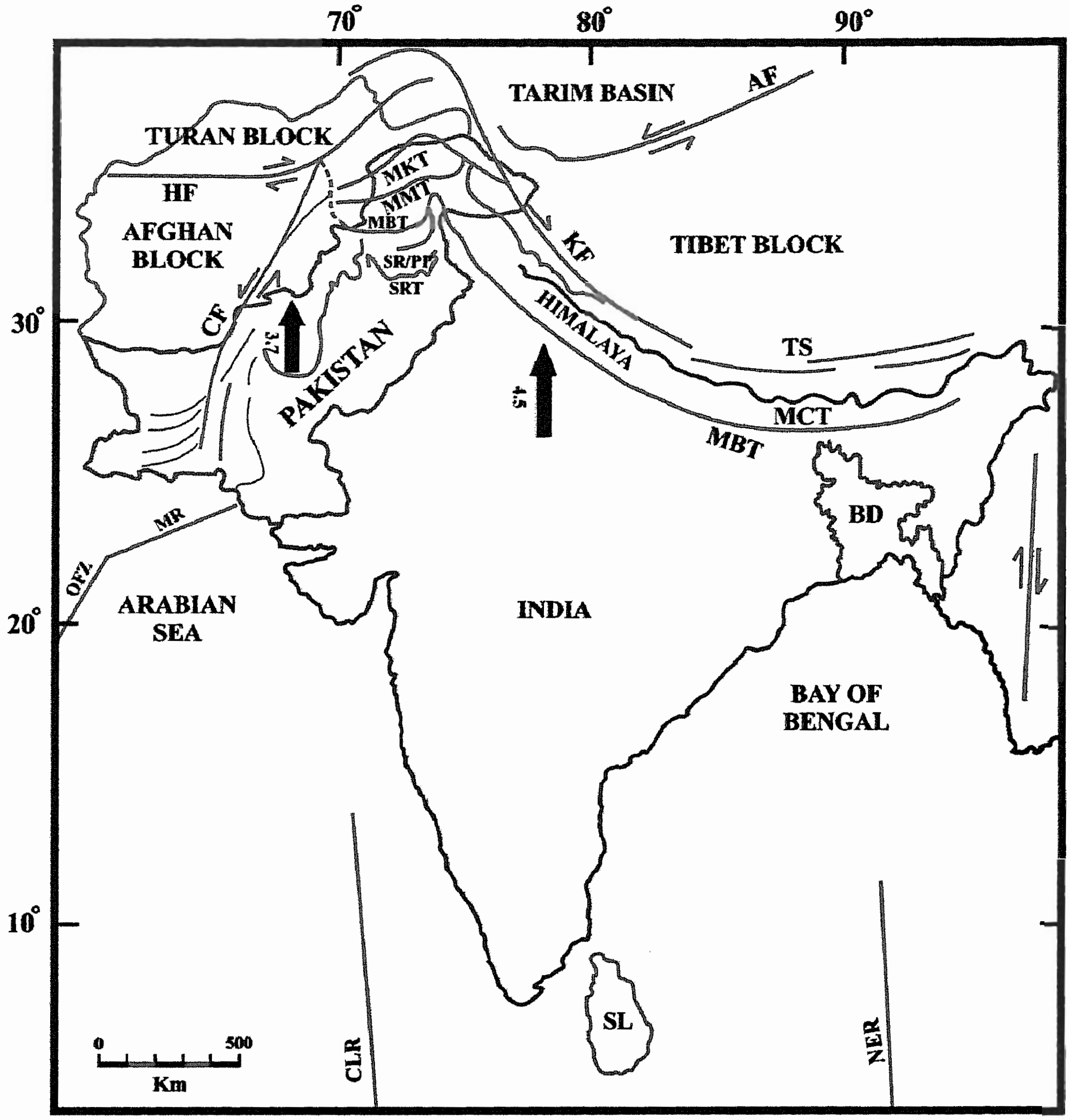

Fig. 3.4. Tectonic sketch map showing Himalayan collison zone and motion of India relative to Asia (in cm year^{-1}, after Jacob and Quittmeyer 1979). AF Alltyn Tagh Fault, BD Bangladesh, CF Chaman Fault, CLR Chagos-Laccadive Ridge (Reunion Hotspot), HF Herat Fault, KF Karakoram Fault, MBT Main Boundary Thrust, MCT Main Central Thrust, MKT Main Karakoram Thrust, MMT Main Mantle Thrust, MR Murray Ridge (Kerguelen hotspot), OFZ Owen fracture zone, SL Sri Lanka, SR/PP Salt Rang/Potwar Plateau, SRT Salt Range Thrust, TS Tsangpo suture. Modified after Davis and Lillie (1994).

To the south of the Main Boundary thrust, the Kohat-Potwar Plateau and the Salt ranges are bounded at their southern margin by a major boundary fault termed the Main Frontal Thrust, which is youngest of the boundary faults in the Himalayas (Fig 3.1).

Higher Himalaya Thrust Sheet	Paleozoic-Mesozoic Metasedimentary Cover Sequence Cambrian and older orth- and Para-gneisses
Main Central Thrust	
Inner Lesser Himalaya Thrust Sheet	Precambrian Salkhala Formation (metapelites, marbles, two-mica augen gneisses)
Panjal thrust	
Intermediate Lesser Himalaya Thrust Sheet	Carboniferous-Triassic Panjal Group (pelites, marbles, metavolcanics)
Thrust Fault	
Outer Lesser Himalaya Thrust Sheet	Jurassic-Eocene Carbonate Platform
Main Boundary Thrust	
Sub-Himalaya Thrust Sheet	Eocene-Miocene Balakaot (Murree) Formation

3.2 SYNTHESIS OF REGIONAL TECTONIC EVOLUTION

The Himalayas, the world's youngest and highest orogenic belt, resulted due to the process of active continent-continent collision. The collison between the Indian and Eurasian plates began during the middle to late Eocene (Stöckline 1974; Stonely 1974; Molnar and Tapponnier 1975; Beck et al., 1995 and Yoshida et al., 1997) in association with Late Cretaceous-Cenozoic spreading along the Carlsberg-southeast Indian Ocean Ridge (McKenzie and Sclater, 1971). Since the collision began, sea-floor reconstruction indicate about 2000 km of convergence has occurred between India and Eurasia (Patriat and Achache, 1984 and Fig 3.4).

The initial phase of the Himalayan orogeny is believed to have started by Middle Cretaceous (~90 Ma ago), when the Kohistan Island Arc terrane collided with the southern margin of the Karakoram Plate (Hodges, 2000). This phase of the Himalayan orogeny, termed the Proto-Himalayan phase is believed to continue until Early Eocene, just before the India-Eurasia collision. The orogenic phase marking the main India-Eurasia collision is termed the Eo-Himalayan phase that started around 55 Ma and continued to

Oligocene. The latest part of the Himalayan orogeny covers the Early Miocene-Present time span and is termed the Neo-Himalyan orogeny. This phase includes the neotectonic activity such as that of the Nanga Parbat Syntaxis (Khan et al., 2004).

In northern Pakistan, the Himalayan ranges are divided into four major subdivision (Farah et al., 1984 and Yeats and Lawrence, 1984 and Fig 3.4). North of the Main Karakoram thrust lie the Karakoram Range and Hindu Kush, terranes of Gondwana affinity sutured to Eurasia (Turan block) in the Late Triassic-Middle Jurassic (Sengor, 1979). South of the Main Karakoram thrust and north of the Main Mantle thrust lies the Kohistan block, a terrane believed to have been formed as an island arc (Jan and Asif, 1981; Tahirkheli, 1982 and Farah et al., 1984), which docked with Eurasia in the Late Cretaceous (Windley, 1983) to early Eocene (Kennett, 1982).

Zeitler et al. (1982) suggest that the Main Mantle Thrust locked approximately 15 Ma, subsequent to rapid uplift north of the fault 30-15 Ma (Zeitler et al., 1980). During the early Miocene, deformation propagated southward near the Main Boundary thrust (Bird, 1978), where unmetamorphosed lower Tertiary rocks are thrust over Neogene molasse. In the latest phase in Pakistan, thrusting transferred to Salt Range thrust, where deformation as young as 0.4 Ma has been documented (Yeats et al., 1984).

This collision is producing a remarkable variety of active fold-and-thrust wedges (Salt Range and Kohat-Potwar plateaus) within Pakistan, which is still continuing at a rate of 5mm/year (Patriat and Achache, 1984). These zones extend from the Kashmir fold-and-thrust belt southwestward to the Salt Range-Potwar Plateau fold-belt, the Sulaiman fold-belt and the Makran accretionary wedge (Fig. 3.5).

The lesser Himalaya of northern Pakistan (Hill Ranges) detachments at upper crustal levels occur along a series of south-verging thrust (Yeats and Lawrence, 1984). On the basis of microseismicity, the Salt Range, Potwar Plateau and Hill Ranges are interpreted as thin skinned, underlain by a low-angle decollement, which surfaces out at the Salt Range front (Seeber and Armbruster, 1979).

3.3 HILL RANGES

The Hill Ranges include Attock-Cherat, Kalachitta, Samana, Kohat and Margala hills (Figs. 1.2 and 3.2). Stratigraphically these ranges are comprised of shelf platform rocks of

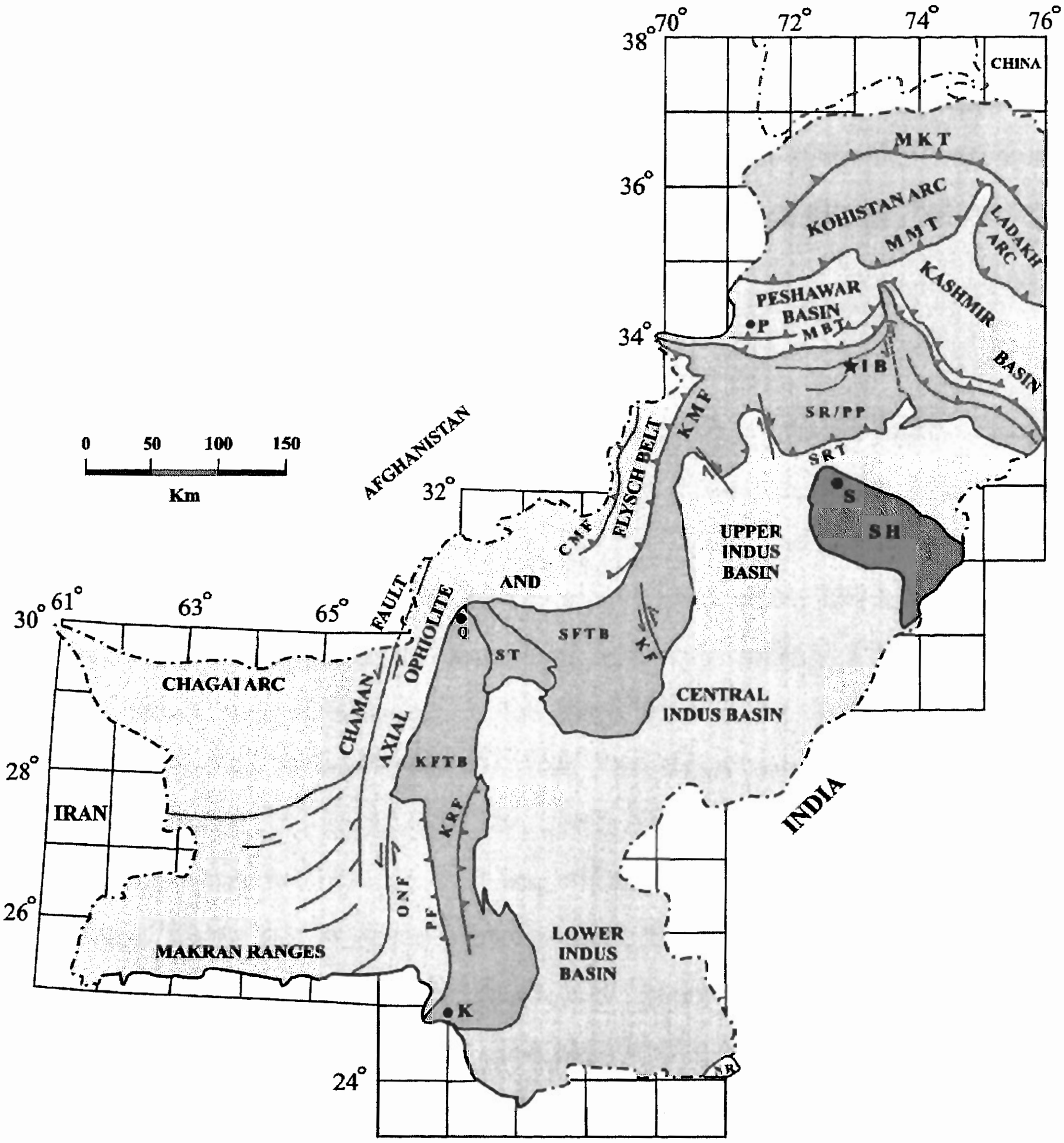

Fig. 3.5 Generalized tectonic map of Pakistan emphasizing dative foreland thrust belt and the location of the Makran accretionary wedge. CMF Chukhan Manda Fault, IB Islamabad, K Karachi, KF Kingri Fault, KFTB Kirthar foreland-and-thrust belt, KMF Kurram Fault, KRF Kirthar Fault, NR Nagarparkar ridge, ONF Ornach Nal Fault, P Peshawar, PF Pab Fault, Q Quetta, S Sargodha, SFTB Sulaiman foreland fold-and-thrust belt, SH Sargodhar basement high, SR/PP Salt Range/Potwar Plateau, SRT Salt Range Thrust, ST Sibi Trough. Modified from Davis and Lillie (1994).

the Mesozoic-Cenozoic age. The hill ranges exposed in the hanging wall of the Main Boundary Thrust are deformed by the uplift along this major lineament and are characterized by a complex pattern of folds and faults. Most of the faults are south vergent while few are north vergent. The Main Boundary Thrust separates hill ranges from the Kohat-Potwar Plateau (Fig. 3.2)

3.3.1 Kurram-Cherat-Margalla Fold-and-Thrust Belt

This arcuate and narrow (20 to 39 km wide) thrust belt lies to the north of Kohat-Potwar fold belt (Figs. 1.2 and 3.2). From near Balakot (Hazara-Kashmir Syntaxis), it extends southwestward through Margalla Hills, Attock-Cherat and Kalachitta Ranges to the Sufaid Koh Range on Afghanistan border; a distance of about 350 km (Figs. 1.1 and 3.2). It is an intensely deformed and tectonized belt with isoclinal folds and several south-verging thrust sheets. Eastward it has been cut by the Jhelum Fault and thrusted southward over the Kohat-Potwar fold belt. This thrust zone is now being referred to as the Main Boundary Thrust (Lillie et al., 1987; Yeats and Hussain, 1987; Burbank et al., 1988; McDoughall and Hussain, 1991 and Abbasi and McElroy, 1991).

The Panjal Thrust and its western continuation, the Khairabad Fault, define the northern limits of Kurram-Cherat-Margalla thrust belt. Across the Panjal-Khairabad Thrust the metamorphic grade and stratigraphy differ significantly (Kazmi and Jan, 1997).

The stratigraphic sequence in various thrust blocks ranges from Proterozoic to Neogene, though the Ordovicain to Permain sequence is largely missing. The unfossiliferous Proterozoic rocks (Hazara Formation) are mainly comprised of a flysch type sequence of dark grey slate, phyllite, quartzite and subordinate limestone. The Mesozoic and Cenozoic rocks consist of platform-type shallow marine to non-marine sequence characterized by many unconformities, but devoid of basic dykes and sills. The Tertiary sequence (Lockhart, Patala and Murree formations) probably represents a sediment pile derived from the northern highlands and thrust sheets (Yeats and Hussain, 1987).

3.3.1.1 Attock-Cherat Ranges

The Attock-Cherat Range lies in the south of the Peshawar Basin (Figs. 1.2 and 3.2). The general trend of the range is east-west and in extreme west it swings to south-west and finally merges into Nizampur-Kohat ranges near Darra Adam Khel village south of Peshawar. This range covers an area of 576 km^2 in Peshawar and Nowshera districts and 80 km^2 in the Attock district of Punjab Province. The relief is low on eastern side of the Indus River, while in the west it gradually rises and near Cherat varies from 310 m to 1000 m and 1820 m to 1933 at Jala Sar from the sea level. Topographically, the Attock-Cherat Range forms high peaks and steep southward slopes. In the Attock plains, the thick argillite sequence (Dakhner Formation) disappears beneath alluvium near Kamra town about eight kilometers east of Attock Khurd. These argillites reappear in Hazara and Khyber mountains in the east and west (Dag Ismail Khel village) respectively (Tahirkheli, 1970). The stratigraphic sequence is composed of Pre-Cambrian and Paleozoic rocks (Stauffer, 1968b and Tahirkheli, 1970). The rocks are composed of argillite, slate, phyllite, subordinate quartizite and limestone intruded by dolorite sills and dykes. The Attock-Cherat Range is structurally more complicated then the other ranges. The three main structural features of the Attock-Cherat Range are the EW striking thrusts; Khairabad Thrust, Cherat Fault and Hissartang Fault run almost parallel to one another (Fig. 3.2). The Khairabad fault is folded roof thrust for the duplex of thrust slices in the basement underlain by the Cherat Fault (McDougall et al., 1991). The duplex was emplaced between the N dipping Cherat and Khairabad thrusts during Paleozoic time (Yeats and Hussain, 1987), and these thrusts, that plucked Precambrian rocks from the top of the basement, project downdip toward the subsurface projection of the MBT floor thrust (McDougall et al., 1991). Both the Cherat and Hissartange faults project eastward to the southern Kherimar hills and farther east merge along the Nathia Gali fault in the northern Margalla hills (Hylland, 1990). The Hissartang thrust marks the southern boundary of the Attock-Cherat Range, where the Pre-Cambrian rocks are thrust over the Mesozoic-Cenozoic rocks of the Kalachitta Range (Yeats and Hussain, 1987). The Attock-Cherat Range lies in the hanging wall of Hissartang thrust and the Kalachitta Range in its footwall (Fig. 3.2).

3.3.1.2 Kalachitta Ranges

The Kalachitta Range occupies a very significant position in Lesser Himalayas in Pakistan. It is characterized by short, sharp, NW-SE to SW trending ridges and intervening valleys that are covered by thin vegetation. The alttitude in this mountain range varies between 250-1200 m and on the whole, it is about 80 km long in east west direction. The eastern limit of the Kalachitta Range ends approximately six kilometer south of Sangjani village. It lies south and southwest of the Attock-Cherat Range and the Margalla Hills respectively (Fig. 3.2). The Indus River borders the Kalachitta Range towards west and southwest, whereas towards south lies a large dissected Plateau – the Kohat-Potwar Plateau. The Kalachitta Range is separated from Attock-Cherat Range by well-defined Hissartang Fault (Yeats and Hussain, 1984, Fig. 3.2).

Stratigraphically Kalachitta Range can be divided into two blocks Western block and Eastern block (Fig. 2.1). The stratigraphy of the Western block varies from Triassic to Paleocene, while the stratigraphy of the Eastern side comprised of Jurassic to Eocene formations (Fig. 2.1). There are two major unconformities in the Kalachitta Ranges. The first major unconformity occurs between the Cretaceous Kawagarh Formation and Upper Lockhart Formation marked by ferruginous pisolites, while the second between the major break is between Middle Eocene Kohat Formation and the Miocene Murree Formation, marked by the pebbly deposits of Fateh Jhang Member (Butt, 1987).

The Kalachitta Range is intensely deformed and tectonized belt, which along with the Attock-Cherat Range and the Margalla Hills, represents the uplift margins of the Peshawar-Campbellpur Basins. It is part of the active Himalayan foreland-fold and thrust belt. The deformation is progressively transferred southward in a series of south verging thrust to a weak zone represented by Main Boundary Thrust, which is the frontal thrust of Kalachitta Range and Margalla Hills (Yeats and Hussain, 1984). Kalachitta Ranges lies in the hangingwall of Main Boundary Thrust (Fig. 3.2).

The typical cross-section is not in conformity with the isoclinal or fan fold concept of Kalachitta Range (Pasco, 1920; Pinfold, 1918 and Sokolove and Shah, 1966). The range represents pile of thrust sheets with most of the faults exposed on the surface (Gardezi, 1974). The tectonic style of the Kalachitta Range shows that during its tectonic history the Kalachitta Range fold-and-thrust belt is being affected by a number of deformational phases. The first phase of deformation is responsible for the formation of the large thrust sheet, which is displaced southward along the Main Boundary Thrust and have resulted in horizontal shortening and vertical thickening. The second phase of deformation is the folding, which deforms the earlier southward verging structures related to the displacement on the Main Boundary Thrust. The source of deformation is thought to be above a regional roof thrust to a large duplex (Izatt, 1990, Fig. 3.6).

3.4 KOHAT-POTWAR AND SALT RANGE FOLD BELT

The western deformed portion of the Himalayan foreland basin is known as the Kohat-Potwar fold thrust-belt. It has east west trend and is comprised of low altitude hills and valleys of the uplifted Kohat-Potwar Plateau, the Salt Range and Tran-Indus mountain ranges (Figs. 1.1 and 3.2). This sedimentary fold belt is bounded in the north by the main Boundary Thrust (Sarwar and DeJong, 1979; Yeats et al., 1984 and Coward et al., 1986). While southward Salt Range and Surghar Range and Surghar thrusts form its southern boundary (Gee, 1989 and Yeats and Lawrence, 1984). West and eastward it is bounded by the N-S oriented Kurram thrust (Fig. 3.5) and Jhelum Fault respectively (Kazmi and Rana, 1982). This belt can be divided into two structural provinces; the Potwar Plateau to the east and the Kohat Plateau to the west of the River Indus (Figs. 3.2 and 3.7).

3.4.1 Kohat Plateau

The Kohat Plateau, which constitutes the western most part of Himalayan fold thrust belt is about 70 Km wide in north-south direction (Figs. 3.2 and 3.7). The Kohat Plateau is bounded by Main Boundary Thrust to the north and by the Surghar Range Thrust to the south (Kazmi and Rana, 1982), which is separated from the Salt Range Thrust by the Kalabagh strike-slip fault and in the southwest it merges in Bannu Basin (Figs. 1.1 and 3.2). The Indus River marks its eastern limit, which separates it from the Potwar Plateau (Fig. 3.2), whereas towards west it is truncated by the Kurram Fault (Fig. 3.5). North of the Kohat Plateau the Main Boundary Thrust brings Mesozoic and younger strata over the molasse sediments (McDougall et al., 1991). The structural trend of the Kohat Plateau is generally E-W, but in the southeastern part changes to N-S along the Kalabagh Fault zone (Fig. 3.2). Kohat Plateau is comprised of east-west trending, gentle to steeply dipping, doubly plunging, overturned folds tens of kilometer long (McDougall et al., 1991). It is

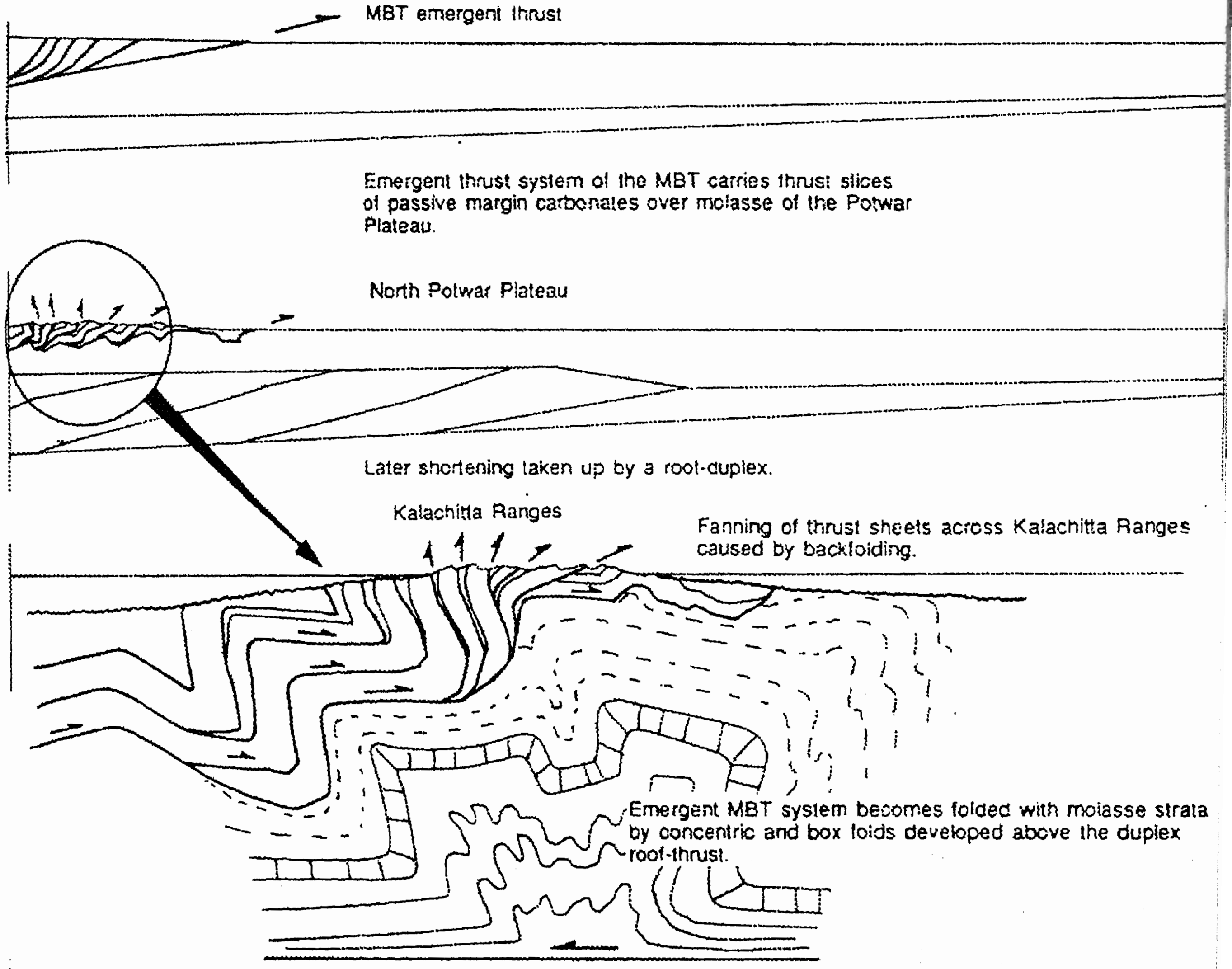

Fig. 3.6 Structural model to explain the deformation style of the Kalachitta Range after Cotter, 1933 and Izatt, 1991.

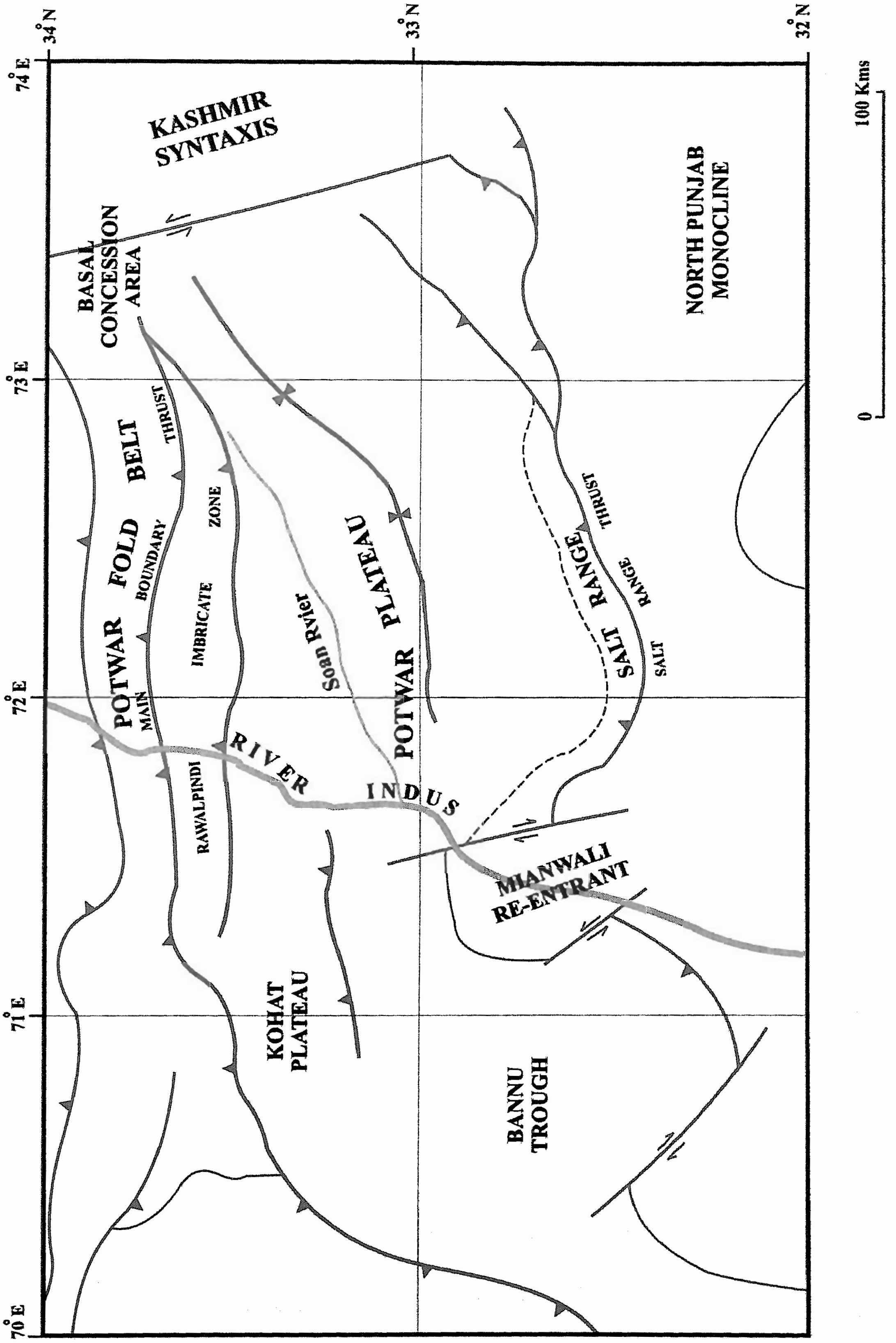

Fig. 3.7. Generalized tectonic setup of Kohat-Potwar Plateau, Salt Range & Bannu Trough.

divided into two parts northern and southern. Tight, commonly overturned folds, out-of-syncline faults and several thrust faults; characterize the northern region (McDougall and Hussain, 1991).

In the southern part of the Kohat Plateau east-west trending folds and north-and-south-dipping reverse faults and fault propagation folds are common in the southern part.

The Kohat Plateau shows greater internal deformation because of lower basal dip and higher relief as compared to the western Potwar (Abbasi and McElroy, 1991). According to them shortening in the Kohat Plateau (between the MBT and the Surghar Thrust) is estimated about 55 ± 5 km and two detachment levels exist beneath the Kohat Plateau. The upper detachment level lies within the Kohat Formation and the lower detachment is located at the base of the Mesozoic-Palaeozoic section (Abbasi and McElroy, 1991 and Fig. 3.8).

According to Pivnik and Sercombe (1993), it is compression related thin-skinned thrust belt. The Bahadur Khel Salt is exposed in anticlinal cores, where Jatta Gypsum is commonly imbricated and folded with slives of Panoba Shale. In this region, the lower Eocene rocks have been thrusted over the Miocene molasses at several places (Pivnik and Sercombe, 1993). Based on field surveys and seismic profiles across the Kohat Plateau, Pivnik and Sercombe (1993), demonstrated the absence of duplexes, passive roof thrusts, antiformal stacks in this region. They invoked that the Kohat basement is traversed by high angle conjugate reverse faults and this shows a significant degree of wrench faulting and positive flower structure. Thus the geometries of structures in Kohat Plateau are the product of both compressional and transpressional tectoncis (Pivnik and Sercombe, 1993).

3.4.2 Potwar Plateau

Potwar Plateau is bounded by Hazara-Kalachitta Range to the North and by Salt Range Thrust to the South, Indus River to the west and Jhelum River to the east (Fig. 3.2), having approximately 150 Km N-S width (Kazmi and Rana 1982). It is an elevated area of little relief, called the Potwar trough (Voskresenkiy, 1978) or Potwar depression (Khan, et al., 1986), due to its thick sedimentary fill. The Potwar Plateau can be divided into Northern Potwar Deformed Zone (NPDZ) and a southern area; called the Soan trough because of its alignment with the Soan River. Most of the deformation is concentrated in the northern part of the Plateau NPDZ while the southern part is of little deformation (Leather 1987, Baker, 1988 and Baker et al., 1988 and Fig. 3.9). It is characterized by east-west tight folds, overturned to the south and sheared by steep-angle faults, pop-up and triangle zones (Kazmi and Rana, 1982 and Bannert, 1986). Beneath NPDZ the Phanerozoic sedimentary wedge thickness to 9 km and forms a north dipping stack of thrust faults, some of which reach to the surface while other terminate at depth as blind thrust (Lillie et al., 1987).

The NPDZ is uplifted slightly above the southern Potwar Plateau and is analogous to the Kohat Plateau. NPDZ is followed to the south by a wide and broad asymmetrical Soan Syncline, with gentle northward dipping southern flank along the Salt Range and a steeply dipping northern limb along the NPDZ (Khan et al., 1986 and Bannert, 1986). In its eastern part the strike abruptly changes to the northeast and the structures comprise tightly folded anticlines and broad synclines (Khan, et al., 1986). Faulting of the anticlines is rare (Pennock et al., 1989). In the western part this basin is comprised of several east-west, broad and gentle folds. This east to west difference in the structure style has been attributed to the reduced thickness of evaporates and lesser basement slope in the eastern part of the Potwar and Salt Range.

Subsurface data and surface geology of the area shows that the Salt Range and Potwar Plateau are underline by a gentle northward-dipping basement, with an upward convexity and traversed by north-dipping normal faults (Lillie et al., 1987). Above the basement there is a decollement zone in Pre-Cambrian evaporates, which has been an effective zone of decoupling allowing thrusting without involving the basement (Lillie et al., 1987). The Salt Range-Potwar fold-and-thrust belt of the northern Pakistan (Fig. 3.5) is currently active foldbelt. In general the range represents a foreland bend fold (Baker et al., 1988).

Both the plateaus (Kohat and Potwar) are separated from each other by the Indus River flowing between them (Figs. 3.2 and 3.7). The uplift region of the Kohat and Northern Potwar Plateau is thought to be above a "passive roof" duplex (Bank and Warburton, 1986) similar to the structure of the Kirthar Range to the south. The duplex ends at a "triangle-zone" to the south of the Kohat and northern Potwar Plateau.

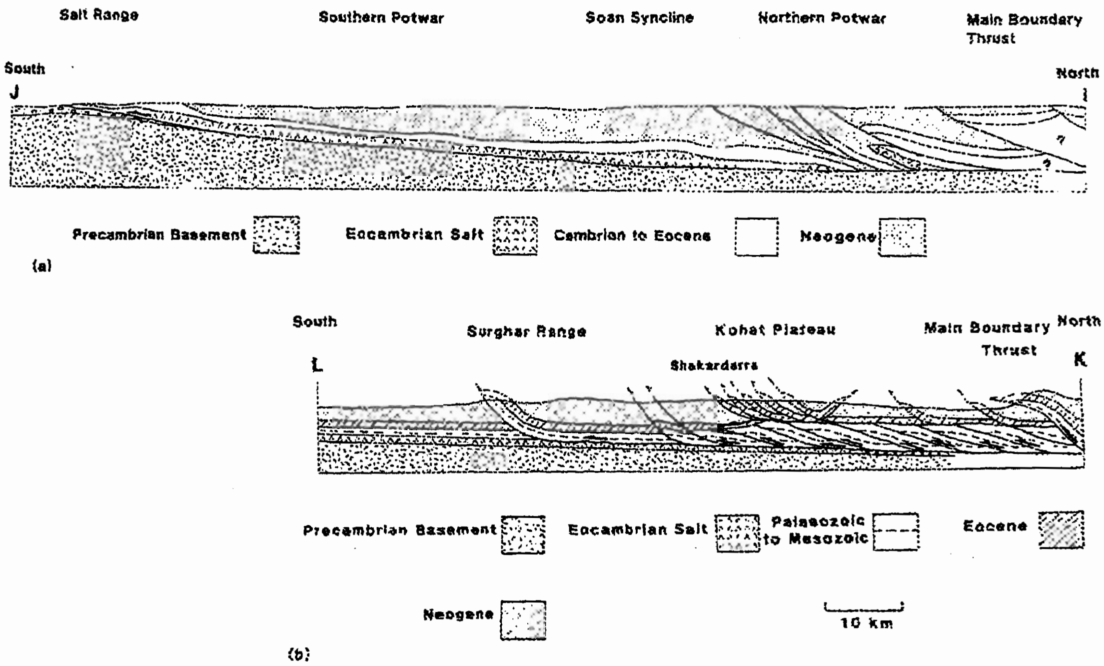

Fig. 3.8 (a) Cross-section I-J; from Attock-Cherat Ranges in north through western Potwar to western Salt Range (After Leathers, 1987) (b) Cross-section L-K; from MBT through Kohat Plateau to Surghar Range, exhibiting style of deformation in the Kohat Plateau (After Abbasi and McElroy, 1991).

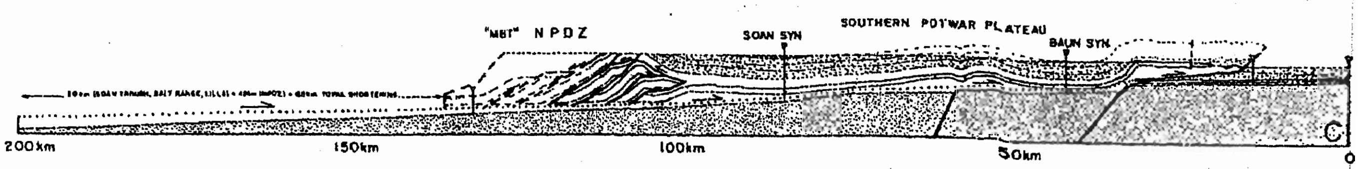

Fig. 3.9 Balanced cross-section depicting present day structure of the Potwar and Salt Range area (After Baker, 1988)

3.4.3 Salt Range

The Salt Range is an east-northeast trending highland, bent northward at both ends. The thrust front at the Salt Range is strongly emergent (Morley, 1986, Figs. 1.1, 3.2 and 3.7). To the west the range is truncated from the Surghar Range by Kalabagh Fault zone (McDougal and Khan 1990). The Kalabagh Fault zone is a prominent N-S structural feature formed after the uplift of Surghar Range along the emergent thrust (McDougall and Hussain, 1991).

It is a complex anticlinorium structure with a series of salt anticlines (Gee, 1945 and 1989). The structure along its northern slop is comprised of broad, simple and shallow folds followed by a gentle monocline (Gee, 1945 and 1989). Along the southern scarp the structures are more complicated and comprise east-west trending faults and tight overfolds (Gee, 1945 and 89). The Precambrian Salt Formation is exposed along these overfolded and faulted anticlines. The general trend of the folds is east-west in the Central Salt Range, a few north-north-east and north-north-west trending and northward plunging anticlines forming "nose" type structures (Kazmi and Jan, 1997). Eastward the Salt Range bifurcates in two narrow northeast trending ridges, the Diljabba and the Chambal-Jogi Tilla, both are folded and thrusted (Gee, 1989).

The structural style in the west and in the central Salt Range is dominated by south verging thrust, whereas the eastern portion is dominated by folding (Pennock, 1989). This difference in style and frequency structure between eastern and central Salt Range is due to change in basement dip and change in salt thickness (Davis and Engelder, 1985).

The advance of deformation far into the foreland in this area has been attributed by many workers to the presence of the Salt Range Formation evaporites as weak detachment horizon (Sarwar and DeJong 1979; Seeber et al., 1981; Lillie et al., 1987 and Butler et al., 1987).

3.4.3.1 Salt Range Thrust

The Salt Range thrust forming the southern margin of the Salt Range, apparently continues westward along the southeastern margins of the Surghar-Shinghar and Khisor-Marwat ranges (Gee, 1989). The thrust is largely covered by recent conglomerates (Gee, 1989). However, near Jalapur and Kalabagh, the thrust is exposed and shows the Pleozoic rocks overlying the Neogene or Quarternary deposits of Jhelum plain (Gee, 1945 and 1989 and Yeats and Lawrence, 1984). Along the Salt Range Thrust, effective decoupling of sediments from the basement along the Salt layer has led to southward transport of the Salt Range and Potwar Plateau in the form of a large slab over the Jhelum plain (Lillie et al., 1987).

A few teleseismic events are located along the southern margin of the central and eastern Salt Range (Kazmi, 1979). According to Allen (1976), there is a good evidence for ongoing thrust faulting at the base of the Khisor Range. The teleseismic data from Tarbela-Chashma network shows that the Salt Range, particularly the Trans-Indus Ranges is an active structure (Seeber et al., 1980).

South of small anticlines in front of the Salt Range thrust, sediments overlying the Punjab Plain are undeformed; the current foredeep to the Pakistan Himalayas lies in this area (Fig. 3.7) Approximately 80 Km south of the Salt Range thrust lie the Kirana Hills, composed of east- southeast-trending Precambrian basement rocks of the Indian shield (Farah et al 1977 and Yeats and Lawrence 1984). These exposures lie along the east-southeast-trending Sargodha High (Fig 3.5), a topographic ridge. Trend of this ridge is compatible to the overall Himalayan trend. This is perhaps an "outer swell" related to the down-flexing of the under-thrusting Indian Plate (Seeber et al., 1981 and Duroy, 1986).

3.5 TRANS-INDUS RANGES

Trans-Indus Mountain includes the Surghar-Shinghar, Marwat and Khisor ranges flanking the northeastern and southeastern margins of the Bannu Basin (Fig. 3.2), respectively (Danilchik and Shah, 1987), whereas, Pezu, Manzai and Bhittani ranges form the sourthern margin of the Bannu Basin (Gee, 1989). These ranges are the part of the Himalayan Frontal Fold and Thrust belt of Pakistan lying west of the Indus River (Gee, 1989 and Danilchik and Shah, 1987). These ranges are apparently the western extension of the Salt Range displaced by an active Kalabagh Fault (Yeats and Lawrence, 1984 and Kazmi, 1979). Hemphill and Kidwai (1973), mentioned two parallel NE trending faults, west of Bhittani Range, parallel to the Bhittani Syncline, the Mandanna Kach and Sora Rogha Faults.

3.6 THE MAKRAN ACCRETIONARY WEDGE

The Makran margin of southwestern Pakistan and southeastern Iran (Fig. 3.5) is a zone in which northward subduction of neo-Tethyan crust has been taking place since the Early Cretaceous (Sengör et al., 1988). Located to the west of the Chaman Fault zone, the Makran is not strictly part of the same India-Asia collison rather; it currently constitutes the boundary between the Eurasian and Arabian plates (Fig. 3.4). The Makran is bounded on the west by the Oman line, a zone of major strike-slip motion to the west of which is the salt-dominated Zagros Mountain belt. Of the total 300 Km width of the accretionary wedge, 200 Km is exposed subaerially.

3.7 SULAIMAN FOLD-BELT

The Sulaiman foldbelt is a part of the obliquely convergent margin at the western edge of the Indian plate (Fig. 3.4 & 3.5), which is moving northward with respect to Asia at about 4 cm year^{-1} (Minster and Jordan, 1978). One remarkable aspect of the festoon-shaped Sulaiman lobe is that it includes both E-W striking thrust at its southern boundary and N-S striking thrust at its eastern edge (Fig. 3.5), although convergence at the eastern front must have a very large oblique component. The rocks exposed at the front of the Sulaiman Range, facing east, and the Sulaiman lobe front, facing south, are all Tertiary in age. The sedimentary section in those areas is extremely thick; seismic reflection lines show that Precambrian basement is at least 10 km deep at the deformation front (Banks & Warburton 1986, Humayon et al., 1991, Jadoon et al., 1992). Behind the deformation front, the section is expected to be considerably thicker than that, based on cross-section balancing (Banks and Warburton 1986 and Jadoon et al., 1992) and gravity modeling (Khurshid 1991). A likely explanation for this thick sedimentary pile is that it represents northern continuation of the Mesozoic rifted margin sequence on the western edge of the Indian subcontinent (Humayon et al., 1991).

CHAPTER 4

STRUCTURE OF THE AREA

The study area is part of the active foreland fold-and-thrust belt of northern Pakistan. The frontal thrust of the Kalachitta and Margalla Hill Ranges is the Main Boundary Thrust (MBT), running in ENE-WSW direction and displays a very complex geometry. The Neogene synorogenic series and the underlying passive margin sequence of Northern Potwar Deformed Zone (NPDZ) are widely underthrust beneath the MBT. This major structure of the Himalayan orogeny also accounts for the recent tectonic uplift and the unroofing of the Mesozoic and Paleocene platform sequence in its hanging wall, which thus constitutes the core of the Margalla Hills, a major topographic feature at the northern extremity of the NPDZ.

For the comparative structure studies of Eastern Kalachitta Range (EKR) with Northern Potwar Deformed Zone (NPDZ), the study area is divided into two structural domains on the basis of their tectonic position in relation to Main Boundary Thrust (MBT):

1. Eastern Kalachitta Range (EKR).
2. Northern Potwar Deformed Zone (NPDZ).

The Kalachitta Range lies in the hanging wall of the Main Boundary Thrust and the Northern Potwar Deformed Zone in its footwall (Fig. 4.1). Only the Eastern part of the Kalachitta Ranges and the NPDZ is the focus of this study.

4.1 STRUCTURES OF EASTERN KALACHITTA RANGE

Eastern Kalachitta Range occupies the southern periphery of the hill ranges. The stratigraphy of this part varies from Jurassic to Eocene in age. Limestones along with few shale horizons characterize the stratigraphy of the area. Due to variation in litholgies and different decollement levels, different style of deformation is observed in the area where most of the folds are chevron folds with much layer parallel slip.

The surface outcrops south of village Bahatar show a doubly plunging anticline having 1/2 wavelength of about 4-km (Akhtar et al., 1985) called the Katha Colony Anticline,

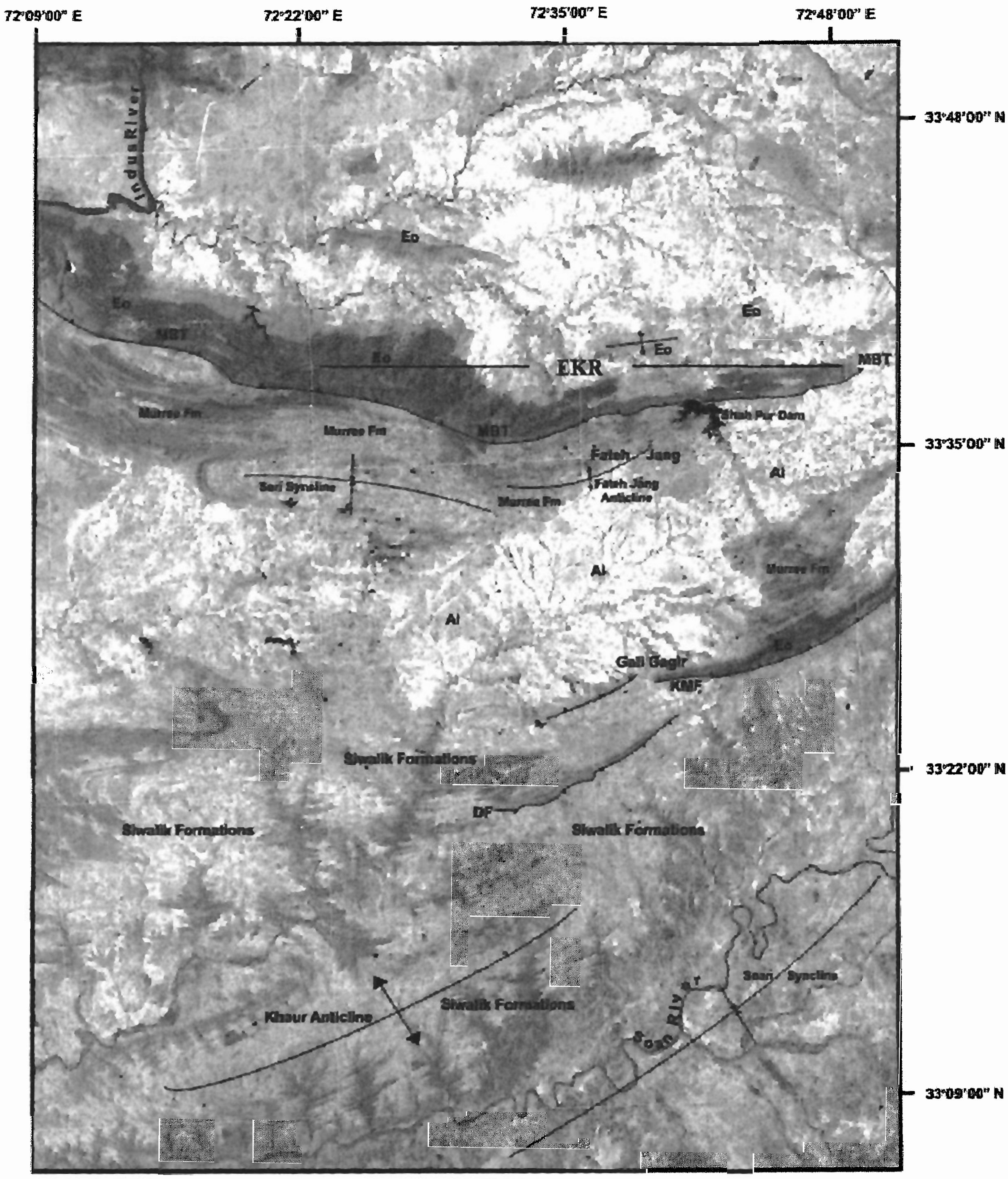

Fig. 4.1 Satellite image showing the stratigraphy and structure of the study area and adjacent locations.

EKR = Eastern Kalachitta Range, Eo = Eocene Formations, Al = Aluvium, MBT = Main Boundary Thrust, KMF = Khair-i-Murat Fault and DF = Dhurnal Fault.

(Fig. 4.2-Annexure 1). The eastern closure of this anticline is observed south of village Jhang (Fig. 4.2-annexure 1), where Margalla Hill Limestone is observed in the outer limb Conformably overlying the Paleocene Patala Formation (Plate 4.1). The western closure of the anticline can be observed south of village Langar (Fig. 4.2-Annexure 1). Near Katha Colony Patala, Lockhart Limestone and Margalla Hill Limestone outcrops are exposed making the northern limb of the anticline (Plate 4.2). These outcrops are highly deformed and some beds are even overturned. These folds are flanked by Margalla Hill limestone and cored by Patala Formation (Figs. 4.2-Annexure 1 and 4.3). The synclines are cored by Margalla Hill Limestone with Patala Shale occupying their limbs.

The core of the Katha Colony anticline is well exposed along the metal road from Gakhar-Bahatar, where Samana Suk and Lumshiwal Formations repeated three-four times (Plate 4.3) over a distance of 900-1000m area across the core of the anticline (Figs. 4.2-annexure 1 and 4.3). The main characteristic features of these thrust sheets are:

- The trend of these thrust sheets is in East-West direction along the strike of the rocks (Plate 4.4).
- Each thrust sheet is defined by stratigraphy from Mesozoic to Paleocene (Fig. 4.3).
- The Eocene succession is not found to be involved with the thrust sheets (Figs. 4.2-Annexure 1 and 4.3).
- They are laterally extensive 200-300 meters (Plate 4.3).
- Their steepness increases from south to north.
- At some points (at higher relief) these faults are overturned locally (Plate 4.5.).
- The dip of the rocks in the hanging wall of the thrust sheets is towards the north, (along the Gakhar-Bahatar road Plate 4.6).
- These rocks in the hanging wall of the thrust sheets dip steeply (e.g. 87^{o}-67^{o}).
- These thrust sheets run in east-west direction but don't meet each other at any point (Fig. 4.2-annexure 1).

The southern limb of the anticline can be observed north of Dhok Baloch (Fig. 4.2-Annexure 1) where Patala Formation is exposed (Plate 4.3).

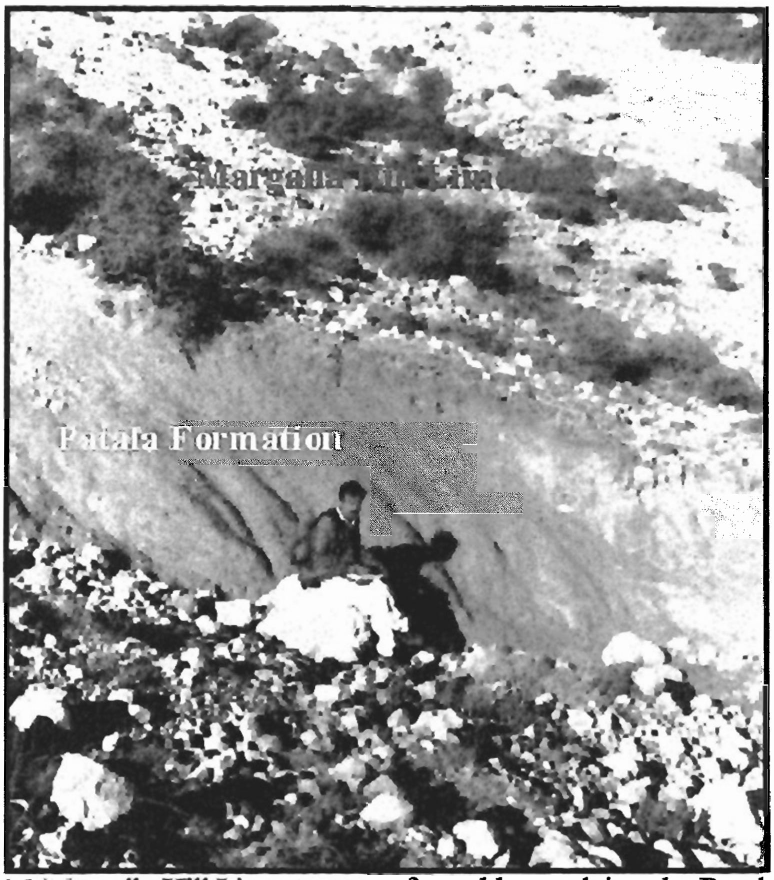

Plate 4.1 Margalla Hill Limestone conformably overlying the Patala Formation East of Katha Colony.

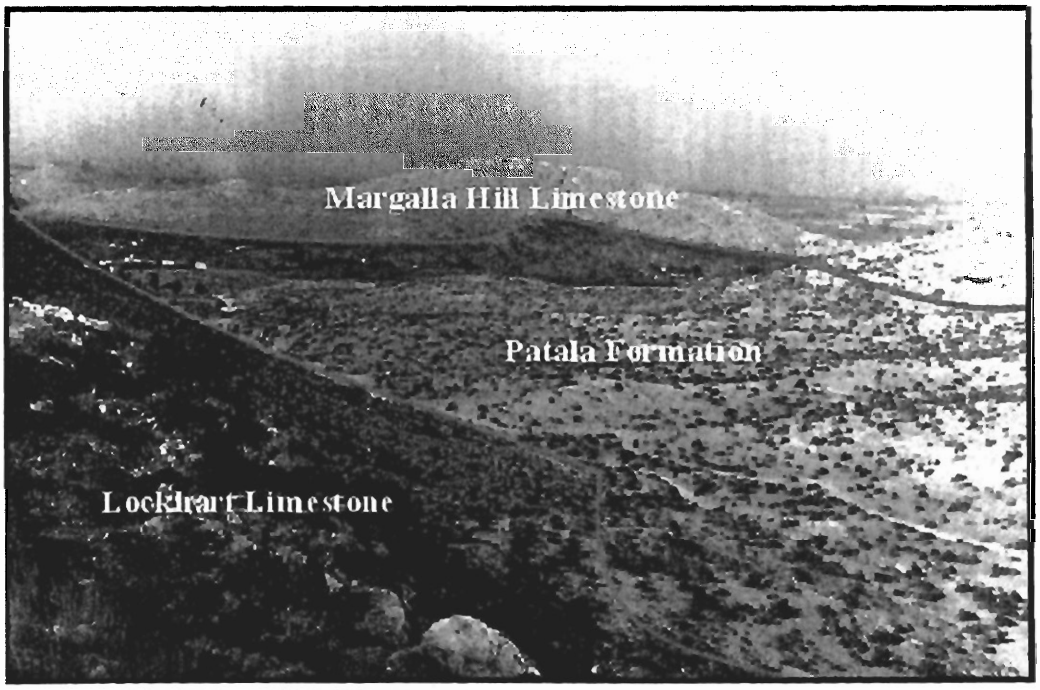

Plate 4.2 Looking westward Katha Colony Anticline northern limb.

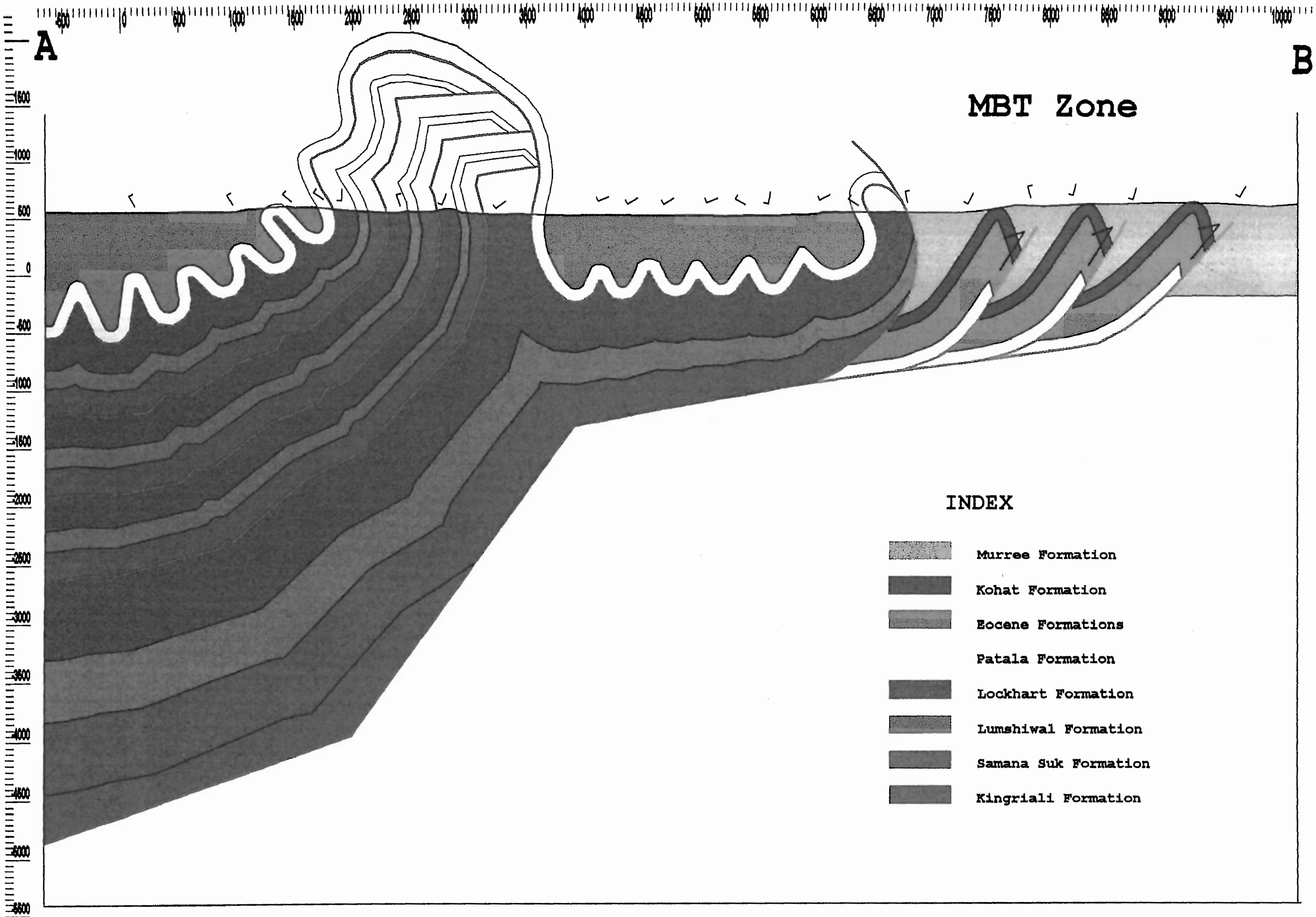

Fig. 4.3 Cross-Section along line A-B, of the Eastern Kalachitta Range.

x axis = 1:46802, y axis = 1:46802

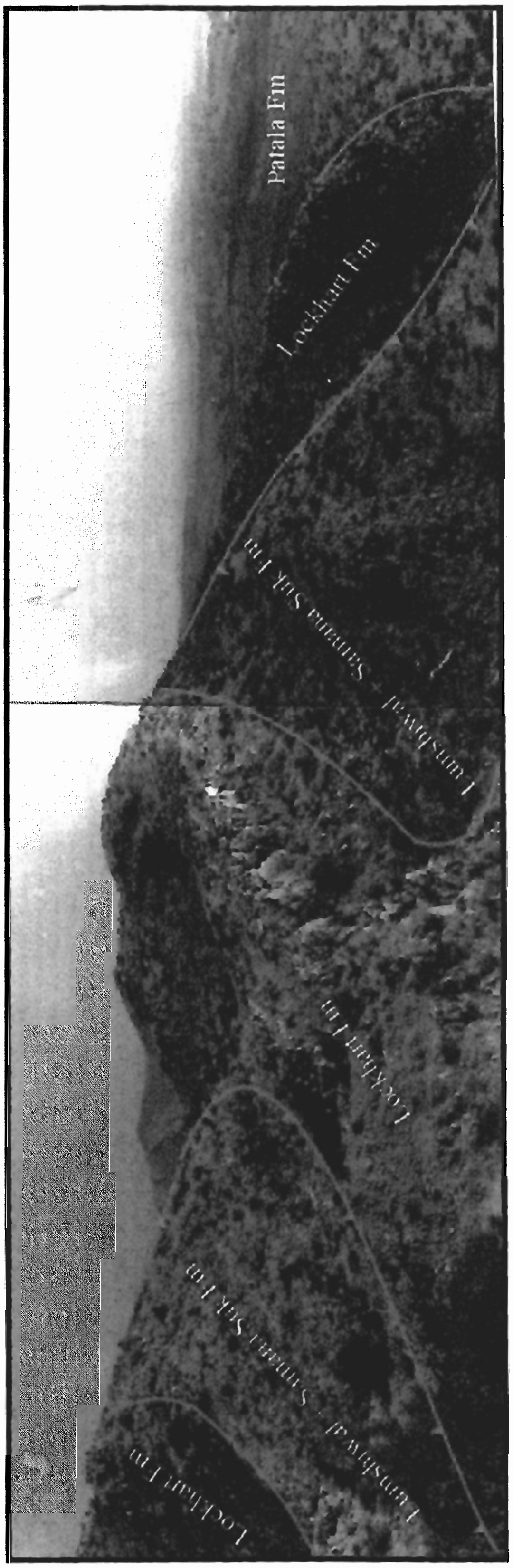

Plate 4.3. Repetition of Mesozoic and Paleocene formations, trending in E-W direction

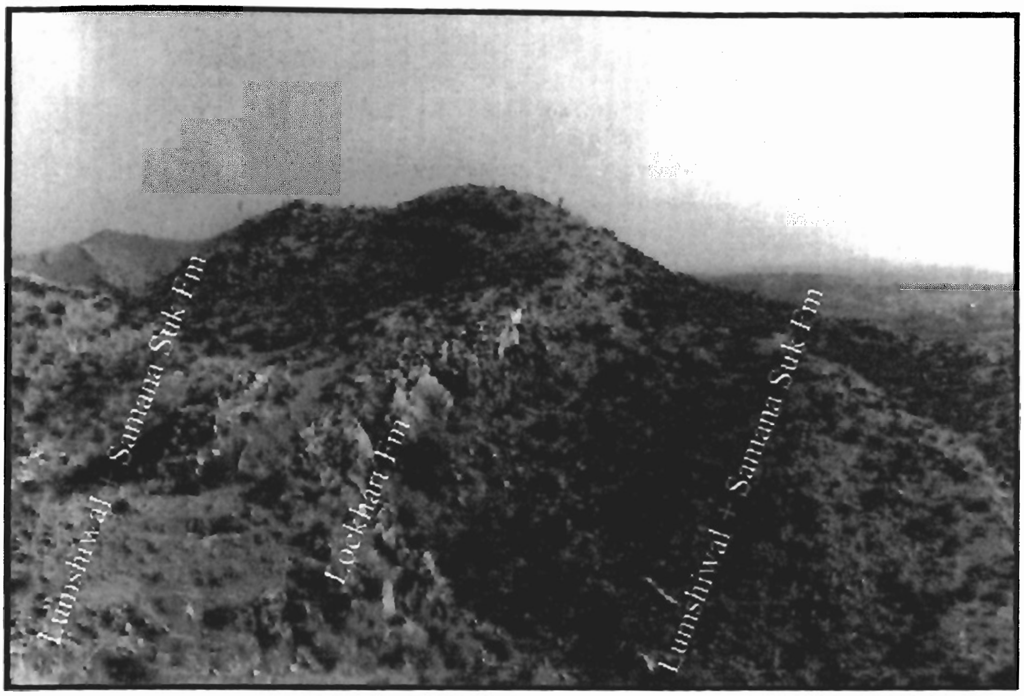

Plate 4.4 Looking eastward, east-west trend of the Mesozoic slices.

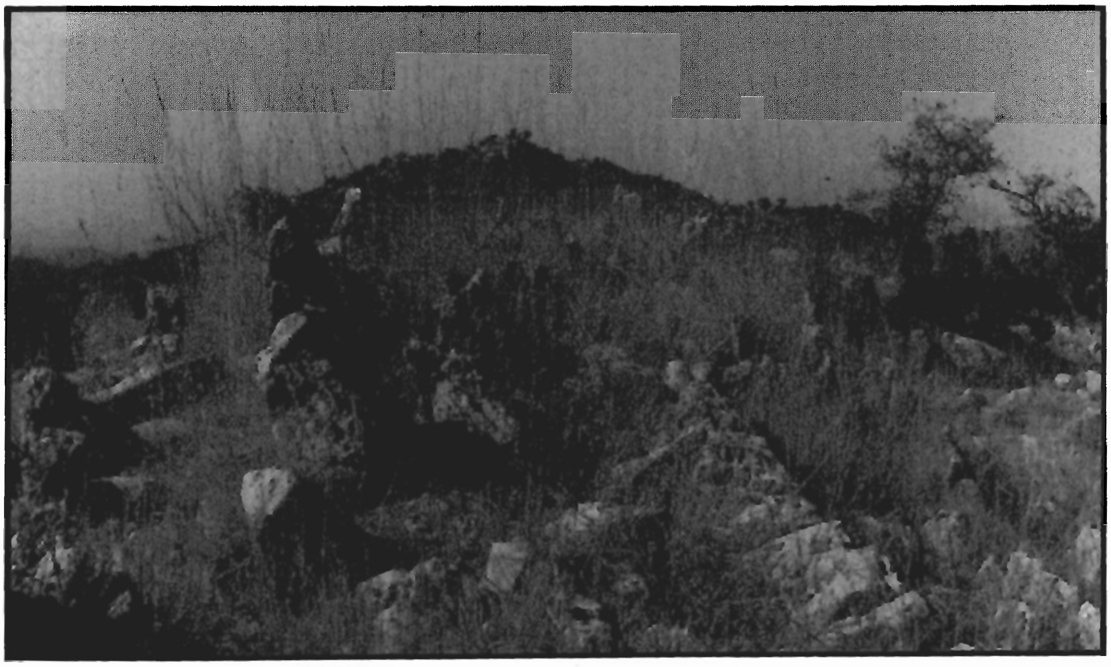

Plate 4.5 At high relief the beds of Samana Suk Formation are overturned.

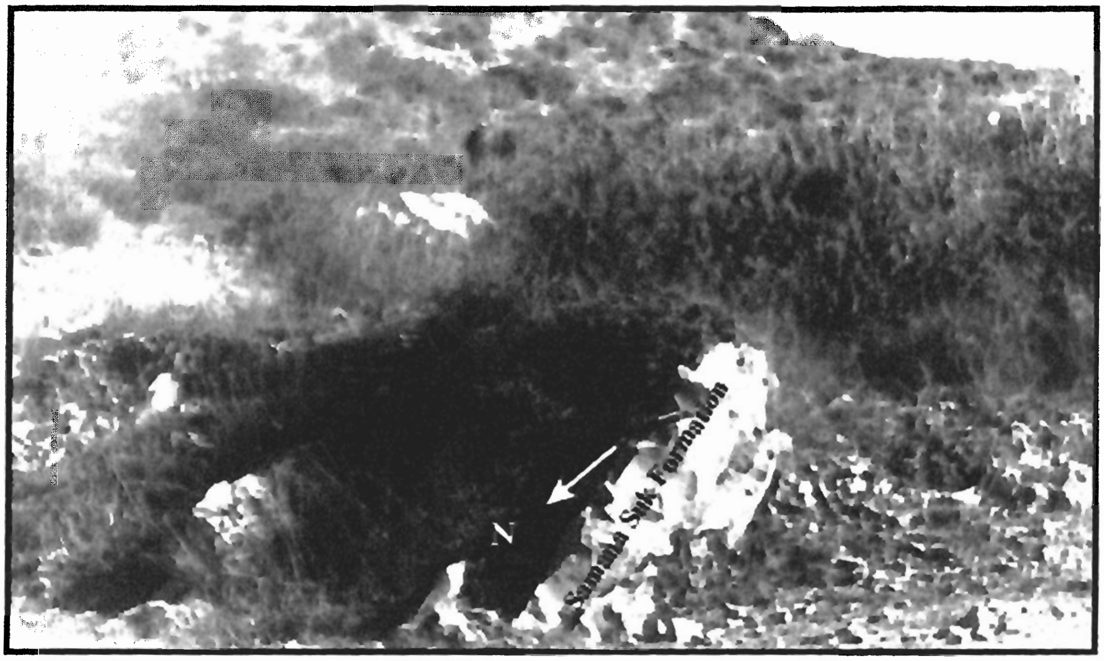

Plate 4.6. Looking east, Samana Suk Formation exposed south of Katha Colony.

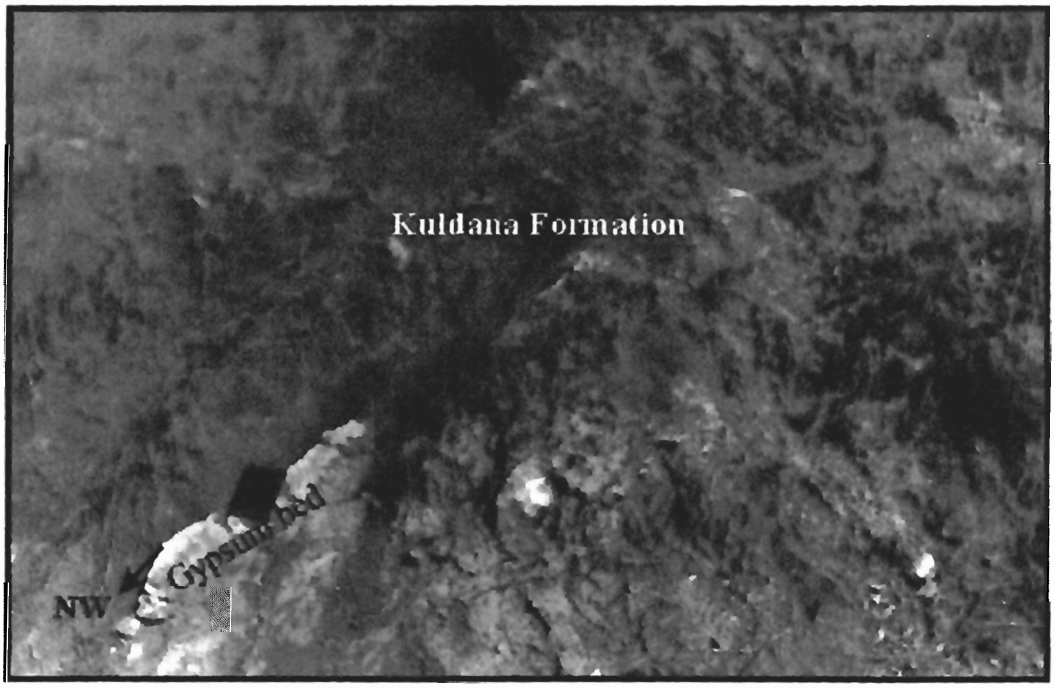

Plate 4.7 Kuldana Formation exposed at the southern limb of Katha Colony anticline with gypsum bed dipping in NW direction.

The Eocene formations (Margalla Hill Limestone, Chorgali and Kuldana formations) are not the part of the thrust sheets but they are deformed independently. Also these outcrops are folded differently as compared to the Mesozoic-Paleocene formations (Plate 4.7).

South of Dhok Baloch lies the main Eastern Kalachitta Range. It lies in the hanging wall of the Main Boundary Thrust (MBT) and is highly deformed. The Paleocene Lockhart, Patala formations and the Eocene Margalla Hill Limestone, Chorgali and Kuldana formations are involved in the folding (Fig. 4.2-Annexure 1). North and northwest of Shahpur village the area is deformed due to alternative anticlines and synclines in the outcrops of Patala, Margalla and Chorgali formations. South of village Shahpur a major syncline is observed (Fig. 4.2-Annexure 1). This syncline is cored by Eocene Kuldana Formation with Chorgali Formation making the limbs of the syncline (Fig. 4.2-Annexure 1). The trend of this syncline is in the east-west direction.

Most of the fold structures are truncated laterally by Main Boundary Thrust (Fig. 4.2-Annexure 1), such as the one to the southwest of Shahpur village. Both limbs of this truncated anticline are overturned with Main Boundary Thrust (MBT) cutting its southern limb (Fig. 4.3). To the south of Karima village another overturned anticline can be observed (Fig. 4.2-Annexure 1). This anticline is south dipping with the forelimb being overturned. Beside some major folds the area is characterized by local asymmetric folds of small wavelength (Fig. 4.2-Annexure 1). Most of these folds are trending in east-west direction following the trend of the Main Boundary Thrust. On the surface it appears that the area is deformed mainly by folding. Most of these folds are interpreted to be cored by blind thrust. These blind thrust most probably lie within or at the base of the Patala Formation. It is suggested that most of the folds are originated during the southward progradation of the Main Boundary Thrust (MBT). The most frontal anticline was formed along the fault tipline and was dissected as the fault breached the surface.

4.1.1 Structure Analysis of Eastern Kalachitta Range

The core of Katha Colony anticline shows that the stratigraphic sequence bounded between these thrust sheets is from Jurassic to Paleocene Lockhart Formation, except the southern most having Patala Formation in its hanging wall (Fig. 4.2-Annexure 1). Margalla Hill Limestone is exposed only in the outer limbs of the Katha Colony anticline and is not found to be bounding between these thrust sheets. The Eocene Kuldana Formation exposed north of Gakhar village is also not found to be involved in the thrusting (Fig. 4.2-Annexure 1). While the gypsum beds within this formation dip in NW direction as compared to steeply dipping bed in the hanging wall of the thrust slices (Plate 4.7). The folds within the Eocene formations dip gently as compared to the steeply dipping thrust sheets within the core of the Katha Colony anticline (e.g. 86^{o}-67^{o}). It clearly suggests that none of these Eocene formations are involved in the thrusting but are deformed independently. This gives an idea of an existence of detachment level below the Eocene strata possibly at the base of Patala Formation. All the thrust sheets merges along this detachment level (roof thrust).

Evaporite is missing under the Kalachitta Range and different researchers have reported different basal detachment levels within this area. But the oldest stratigraphy repeatedly exposed in the Eastern Kalachitta Range by the thrust sheet is Samana Suk Formation (Figs. 4.2-Annexure 1 and 4.3). This shows that basal detachment (sole thrust) lies at the base of Samana Suk Formation and the upper detachment (roof thrust) at the base of Patala Formation. The sole thrust joins the roof thrust forming a structure called "duplex" as shown by Boyer and Elliot (1982) and Geiser (1988). The Eocene successions above the roof detachment behaves passively (not involved in thrust) and therefore the structure of the area is called as "passive roof duplex" (Figs. 4.4a and 4.4b). The progressive steeping and overturning of the thrust sheet from foreland to hinterland suggest a piggyback style of thrusting and foreland propagation (Dahlstrom, 1970; Eillot and Jhonson, 1980; Butler, 1984; Izatt, 1990; Davies and Lillie, 1994 and Jadoon et al., 1997). The thrust sheets tracing eastward at higher relief are overturned dipping to the south (Plate 4.5). This is due to progressive development of thrust sheets in the foreland and the earlier formed thrust faults in the hinterland are overturned.

The deformed area south of Dhok Baloch shows that these folds within this area are the detachment folds. Their detachment lies at the base of Patala Formation forming a duplex structure (Figs. 4.4a and 4.4b), the lower detachment of which lies at the base of Samana Suk Formation. The Eocene strata above the roof duplex thrust is folded passively (Figs. 4.4a and 4.4b) due to the stacking in the blind duplex (Mitra, 1986) or drape over reactivated horsts (Vann et al., 1986). The steep dipping foreland limb of the anticline

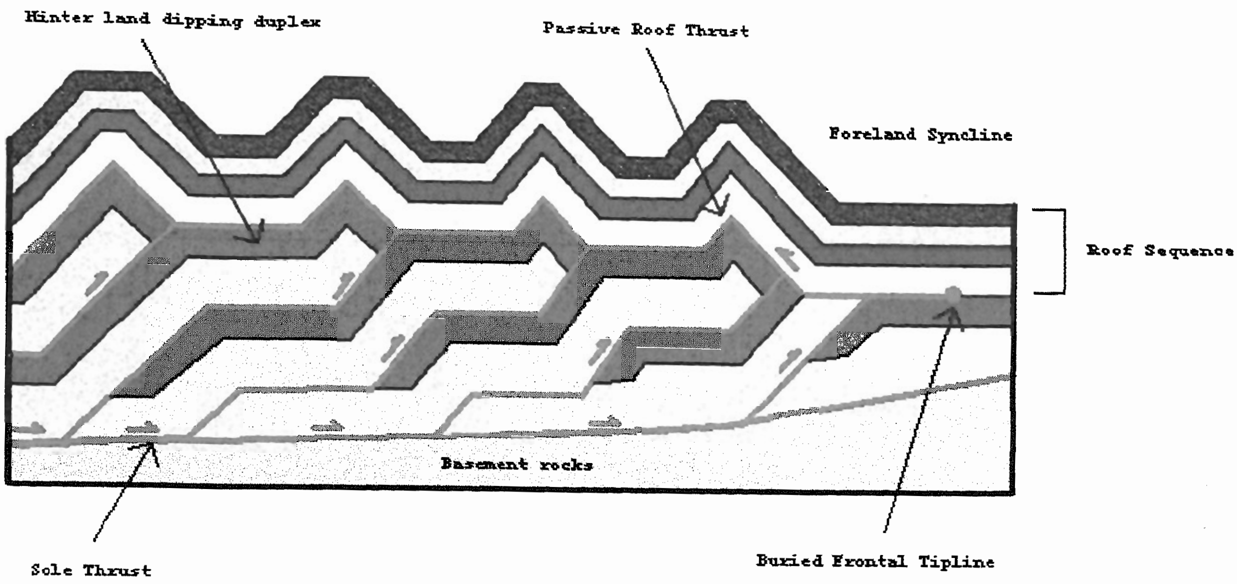

Fig. 4.4a. Passive roof duplex model of the study area, foreland fold and thrust belt before erosion, showing hinterland dipping duplex and foreland dipping syncline (monocline) with upper and lower detachment levels.

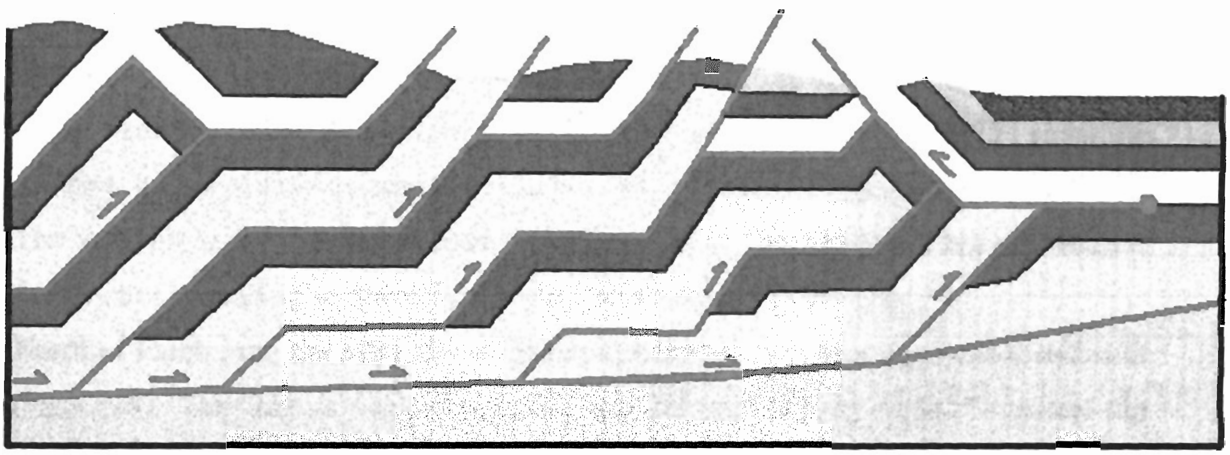

Fig. 4.4b. After the erosion of the area, shows narrow faulted anticlines with broad syncline and also the roof and sole detachments are exposed.

south of Karima village is due to the sticking up of the sole thrust making a steep culmination wall to the southern side (Butler, 1982 and Banks and Warburton, 1986). The surface expressions and geometry of the folds show that the structures were first developed and later on due to the sticking of sole thrust reactivated the roof thrust, which resulted in the north vergence of the folds. Thrusting controls the deformation between the upper and lower detachment levels and the litho-tectonic units above the roof thrust have observed layer parallel shortening in the form of upright folds (Figs. 4.4a and 4.4b). These upright folds are formed due to foreland propagation of strata bounded between the roof and sole thrusts in the form of duplex structure (Ferril and Dunn, 1989). The high elevation of the range and relatively undeformed strata towards the foreland side, show a blind back thrust on the foreland side. To compensate shortening in the foreland, there must be a hinterward dipping blind thrust (Butler and Warburton, 1986). The north verging anticline south of Shahpur village suggest a back thrust (Fig. 4.3). Banks and Warburton (1986) have shown that a foreland dipping monocline is the important structure of a back thrust (Figs. 4.4a and 4.4b).

4.2 STRUCTURES OF NORTHERN POTWAR DEFORMED ZONE

The Potwar Plateau can be divided into Northern Potwar Deformed Zone (NPDZ) and a southern area; called the Soan trough because of its alignment with the Soan River. Most of the deformation is concentrated in the northern part of the Plateau NPDZ while the southern part is of little deformation (Leather, 1987; Baker, 1988 and Baker et al., 1988). This area lies in the footwall of Main Boundary Thrust. The NPDZ is a belt of Neogene deformation extending southward from MBT to the Soan Syncline (Fig. 3.2).

North of Fateh Jang the MBT thrust Eocene-Paleocene rocks over the molasse sediment (Plate 4.8). This area is complexly folded and deformed having moderate-vertical dip involving the rocks of nummulite-bearing Kohat limestone, Kuldana and Murree formations. The rocks of these formations in some places are even overturned (Plate 4.9). Most of the folds are fault propagation folds (Fig. 4.3). These blind thrust are the imbrication of MBT and dies out in the overlying Murree Formation (Fig. 4.3). The folds within this area open folds as compared to the Eastern Kalachitta Range but some local tight folds can be observed in the area (Plate 4.10). Because of the ductile nature of the

Patala shale, it has flowed in the cores of these anticlinal structures (Fig. 4.3). The northern limb of these folds are gentle dipping as compared to the southern limb (Fig. 4.3). One of these steeply dipping anticline is the Fateh Jhang Anticline, in the footwall of MBT (Figs. 4.1 and 4.2-Annexure 1). Fateh Jhang is a northward verging fold with steep to overturned northern limb and gently dipping southern limb. The rocks of Kohat and Murree formations are involved in this folding. The trend of most of these folds in this area is in east-west direction and has upright axial planes. The unusual thickness of Murree Formation in the wells (Table 2.1) in this area and to the south is due to the out-of-sequence deformation due to which the strata of Rawalpindi Group is overturned. This area marks the MBT Zone:

- The unconformity between Murree Formation and Kohat Formation is marked by the Fateh Jhang Member (Plate 4.11).
- The trend of thrust fault is east-northeast approximately perpendicular to the tectonic transport direction (Fig. 4. 3 and Plate 4.12).
- Fault breccia in the area showing the presence of thrust fault (Plate 4.13).
- Fresh water spring can be observed in the area, which is another indicator of the presence of thrust fault i.e. MBT (Plate 4.14).
- Slickenside showing the sense of movement of the blocks, the other block has moved upward (Plate 4.15).
- MBT has caused the steps in the topography of the area (Plates 4.9 and 4.12).
- The area is characterized by horizontal shortening with imbricate thrust faults (Fig. 4.3).
- The folds within this area are fault propagation folds (Fig. 4.3).

South of Fateh Jhang the area is mostly covered by alluvium, with few scattered exposures of Murree Formation in the eastern side (Fig. 4.2-annexure 1). The outcrops of Murree Formation in this area have moderate to high dips and are severely faulted. Seismic profile reveals that these thrust faults are blind thrust and dies in the Murree Formation (Fig. 4.5). The blind thrusts are responsible for the deformation of the area and the folds

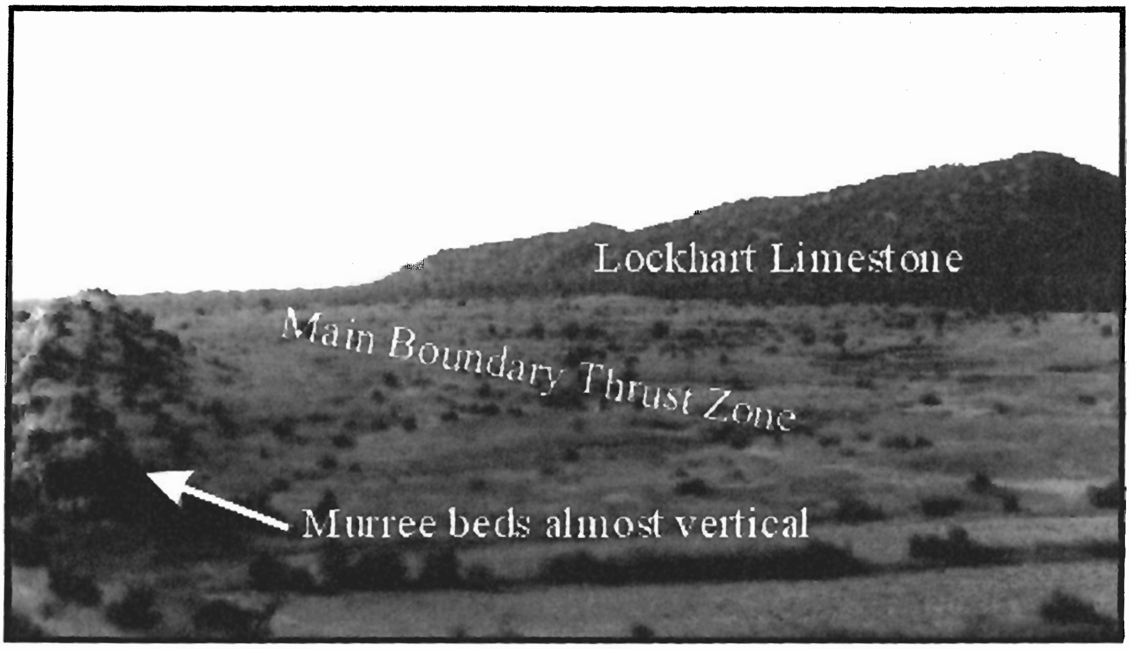

Plate 4.8. MBT thrust Paleocene (Lockhart Limestone) over the Murree Formation.

Plate 4.9. Intensely folded and faulted beds of Murree Formation North of Fateh Jhang.

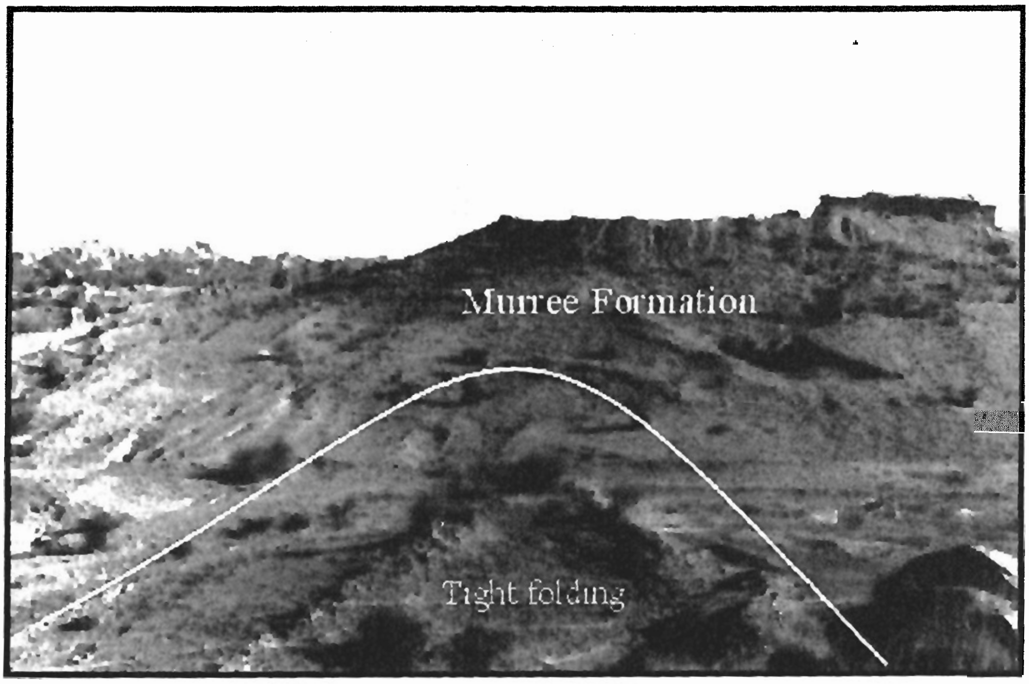

Plate 4.10. Tight folding (fold closure) in Murree Formation North of Fateh Jhang.

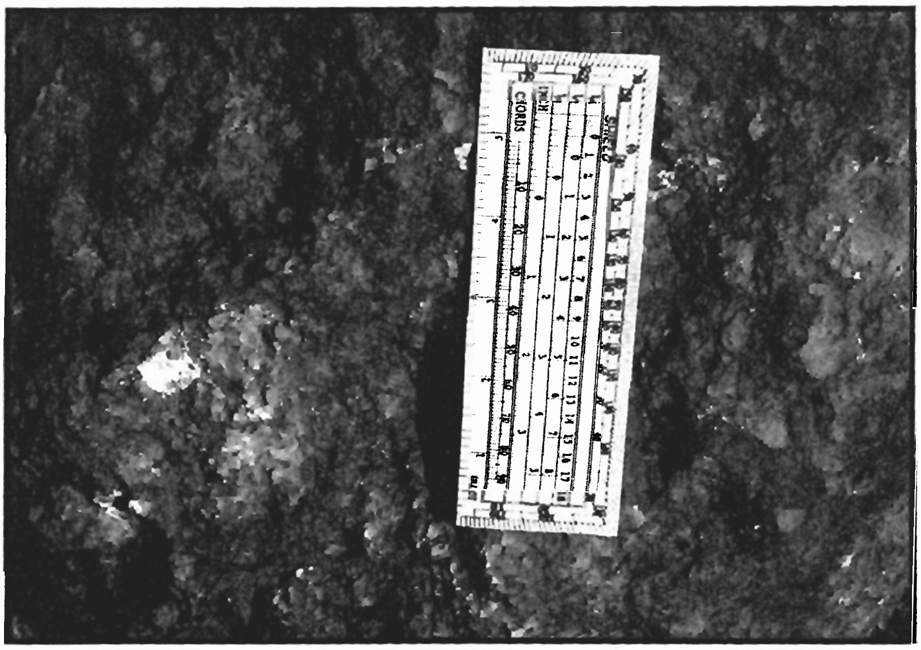

Plate 4.11. Fateh Jhang Member marked by unconformity between Murree and Kohat formations, north of Fateh Jhang.

Plate 4.12. Trend of fault (MBT Zone) within Murree Formation is in E-W direction.

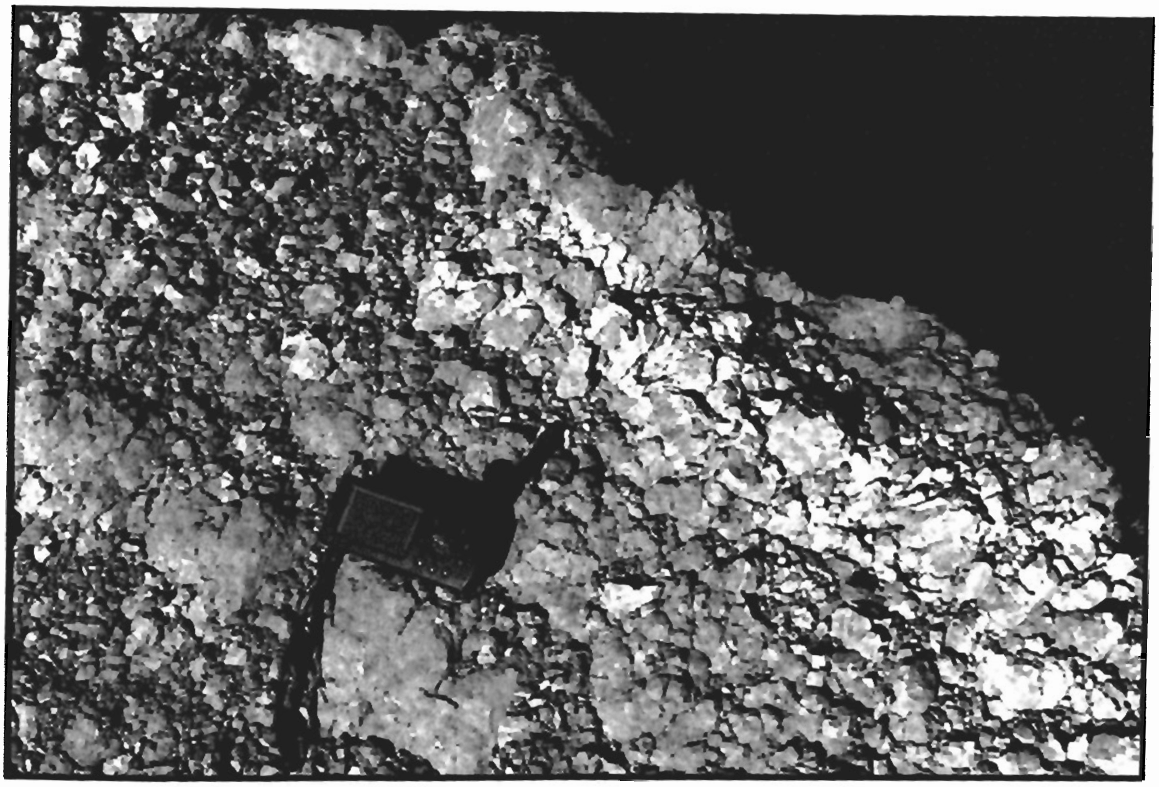

Plate 4.13. Fault breccia associated with thrust faults within the Murree Formation.

Plate 4.14. Fresh water spring near Gadwali village, North of Fateh Jhang.

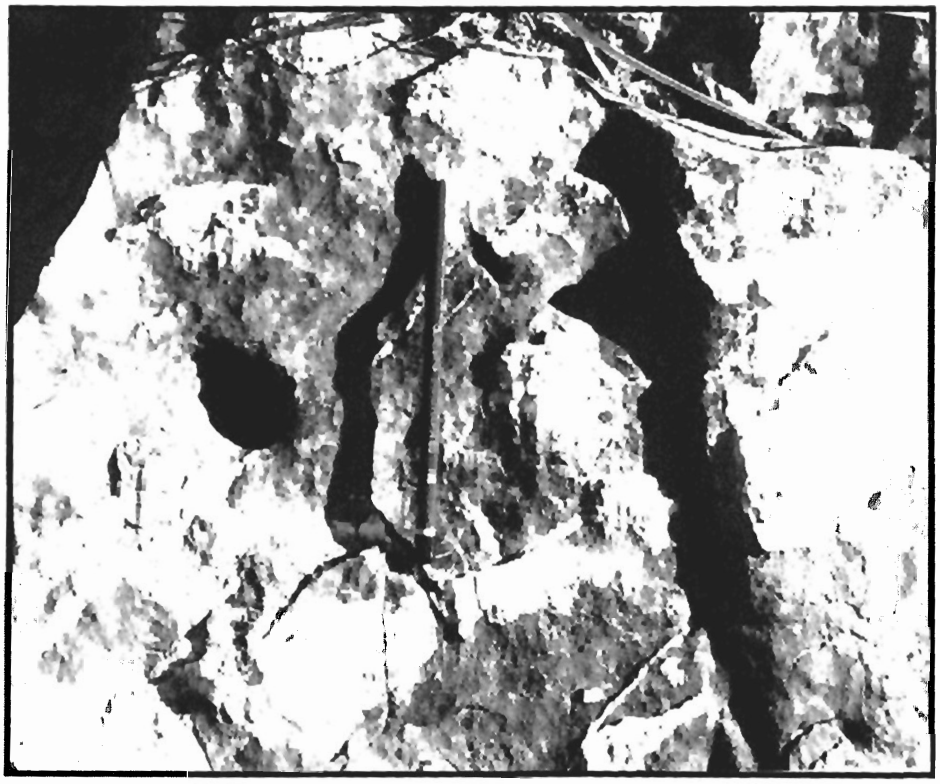

Plate 4.15. Slickenside within Murree Formation, showing the blocks movement.

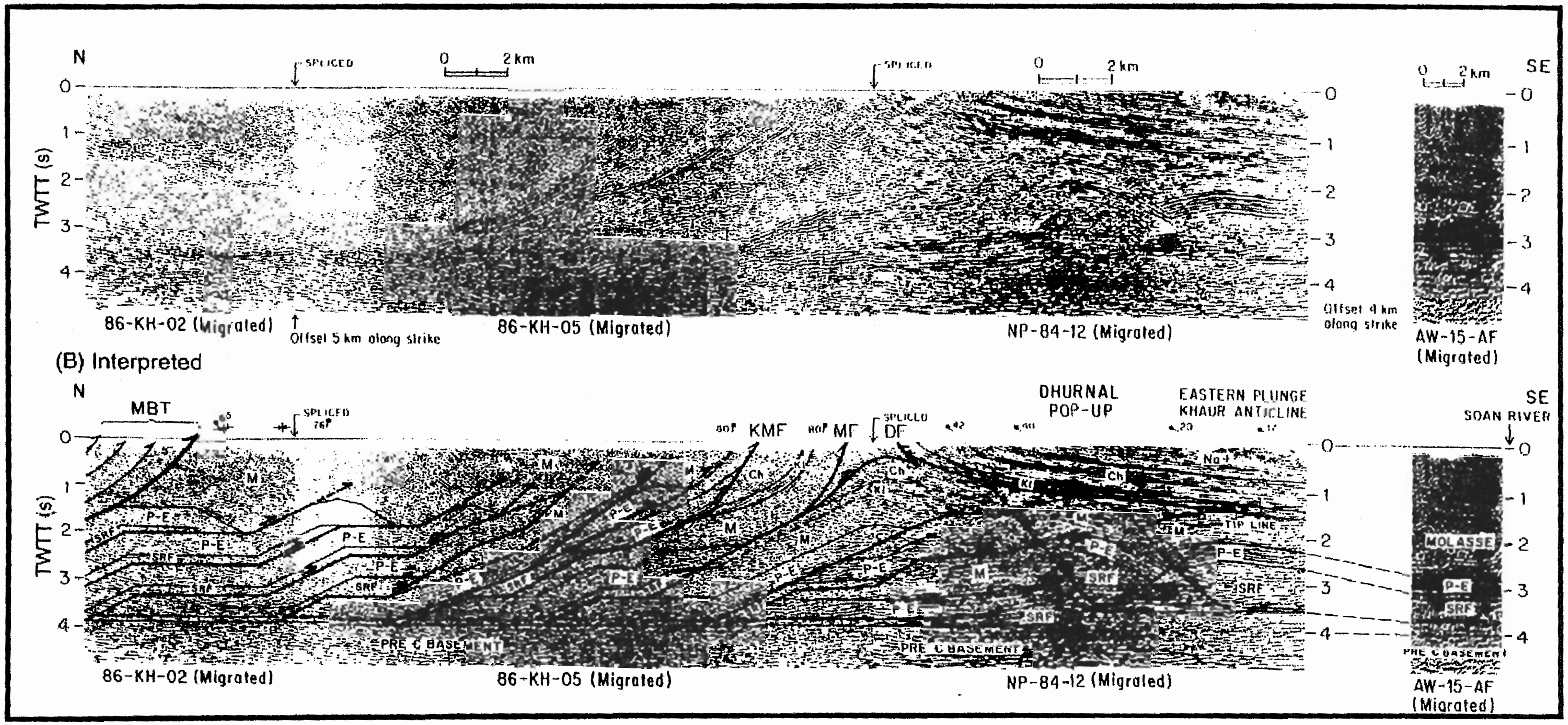

Fig. 4.5. Published composite seismic line (time section) across Northern Potwar Deformed Zone (After Jaswal et al., 1997).

KMF = Khairi Murat Fault, DF = Dhurnal Fault, MF = Mianwala Fault, P-E=Permian – Eocene Formations, M= Murree Formation, SRF = Salt Range Formation Ch = Chinji Formation, Na = Nagri Formaiton and Kl = Kamlial Formation.

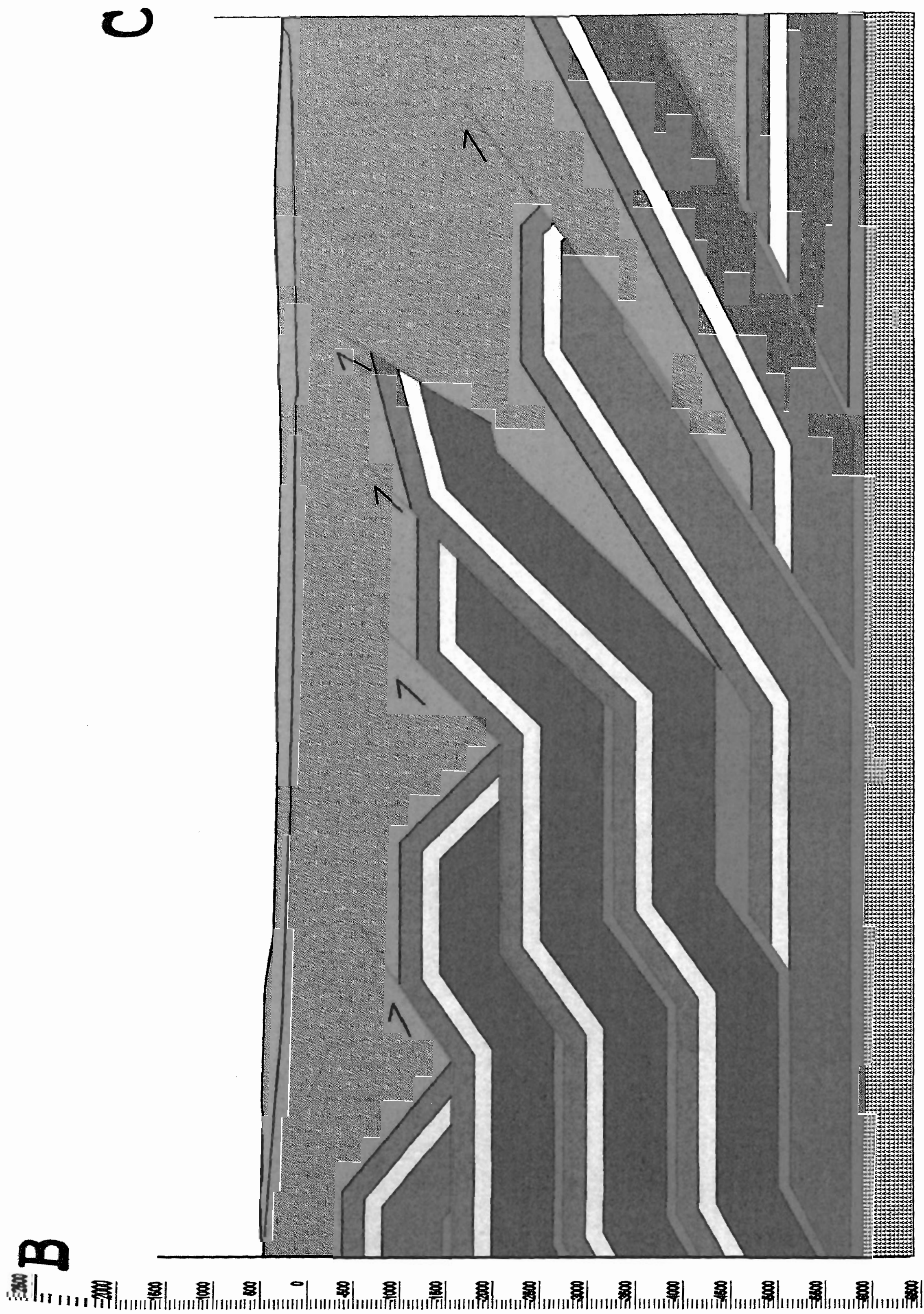

Fig. 4.6 Cross section south of Fatehjang along the line B-C

Scale 1: 65000

INDEX

Alluvium

MURREE FORMATION

EOCENE FORMATIONS

PALEOCENE FORMATIONS

PERMIAN FORMATIONS

SALT RANGE FORMATION

BASEMENT

are fault propagation folds (Fig. 4.6). The faults initiated from a basal detachment level in the incompetent Salt Range Formation and ramp against the competent platform sequence (Permian-Eocene, limestone), and the roof thrust is located at top of the Murree Formation (Figs. 4.5 and 4.6).

4.2a Khair-i-Murat Fault

In Gali Jagir area rocks of Eocene carbonates thrust over the molasse sediments of the Murree Formation (Fig. 4.2-annexure 1) along the Khair-i-Murat Fault (KMF). It is the only major topographic feature between the Main Boundary Thrust and Salt Range and is named as Khair-i-Murat Fault after the Khair-i-Murat Range. KMF is the major emergent thrust fault of the NPDZ, along which high-velocity Eocene limestone is thrust over the low-velocity Siwaliks. It continues westward before dying out in the Indus River and its eastern extension is not known. The rocks associated with it have steeps dips and represent the northern most exposure of Siwalik rocks. The steep dips of KMF on the surface is due to its back rotation. The Eocene to Miocene formations in the hanging wall of KMF are highly deformed as compared to the Siwaliks in its footwall. KMF soles out from the main decollement lying within the Salt Range Formation at a depth of approximately 7500-8000 m (Fig. 4.7). According to Jaswal, et al. (1997) the KMF is an out of sequence thrust fault developed later then the emplacement of Mianwala Fault (Fig. 4.5).

Near Gali Jagir at the surface an anticline with steeply dipping lithologies is observed in the hanging wall of KMF (Figs. 4.2-annexure 1, 4.5 and 4.7). The rocks of Eocene and Miocene formations are deformed along this fold. These formations are steeply dipping towards the north. The anticline is overturned and is truncated laterally by KMF. Both the limbs of this anticline are steep dipping with the southern limb being cut by KMF. The general trend of this anticline is in east west direction.

4.2b Khair-i-Murat Triangle Zone

In the footwall of the Khair-i-Murat Fault (Figs. 4.5 and 4.7), a major triangle zone is developed, involving the basal infra-Cambrian decollement and the molasse backthrust,

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NAGRI FORMATION

CHINJI FORMATION

KAMLIAL FORMATION

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BASEMENT

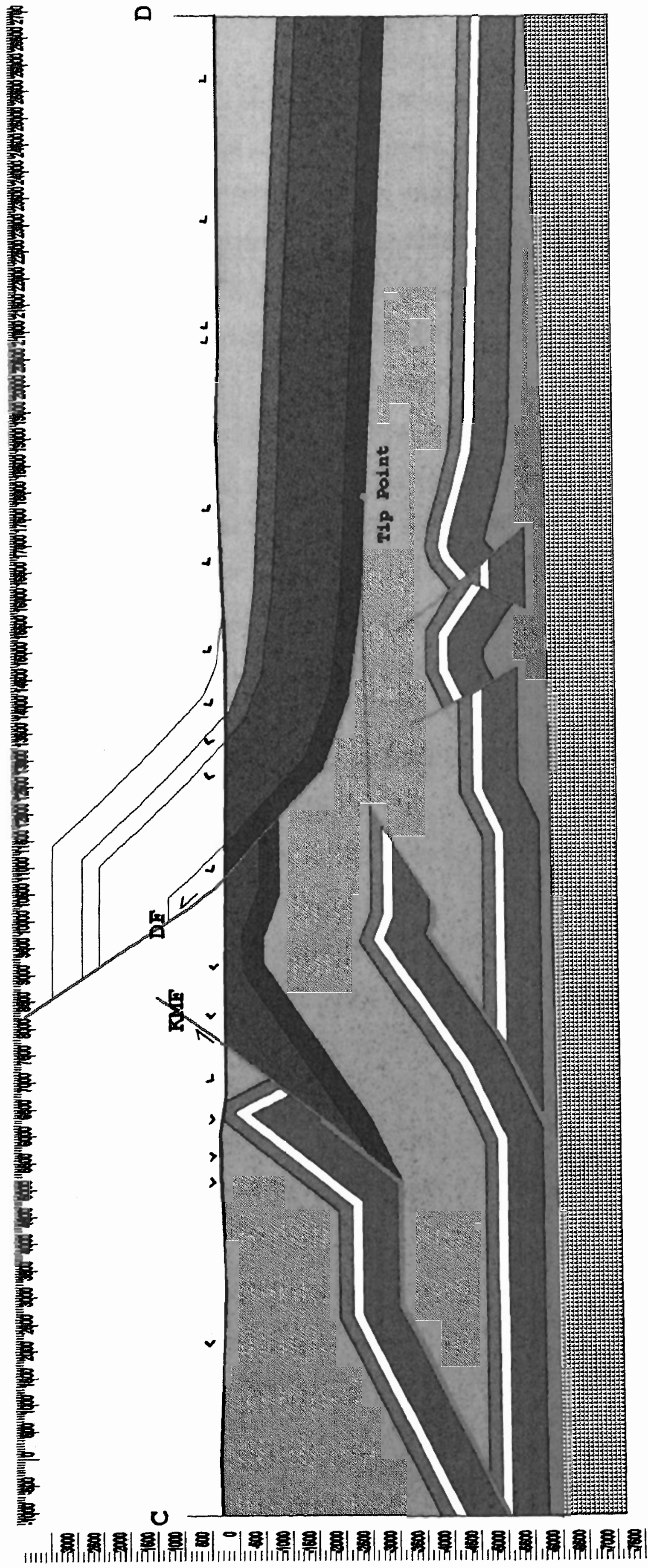

Fig. 4.7 Cross-Section along line C-D, of the Soan area.

KMF = Khair-i-Murat Fault DF = Dhurani Fault

x axis = 1:120377, y axis = 1:120377

called the Khair-i-Murat triangle zone. This triangle zone is bounded between the Khair-i-Murat hinterland dipping thrust fault and foreland dipping backthrust (Dhurnal Fault) at the northern limb of Saon Suncline. During orogenic process, the deformation advances towards the foreland and the deformation terminates where the roof thrust meet the sole thrust, creating a half-syncline and seismic data also reveals a similar feature (Fig. 4.5). Earlier researches have considered this triangle zone as an anticline and that was why seven wells were drilled around 1930's and were unsuccessful (Lillie, et al., 1987).

This triangle zone is a complex structure that has both lower and upper detachments (in Salt Range Formation and at the base of Kamlial Formation respectively). The imbricate slices developed into a hinterland dipping duplex was emplaced under a passive roof thrust resulting in a "triangle zone" geometry (Figs. 45 and 4.7). The presence of an upper detachment shows that each thrust fault beneath it generated a ramp anticline where it flattens along the upper detachment surface (Jones, 1987).

Gordy and Frye, 1975 and Gordy et al., 1977; initially used the concept of triangle zone to explain the complex relationships associated with an anticlinorium located at the front of the Canadian Rockies. Jones (1982) refined the concept and showed that the structure contained a duplex and that it was responsible for the termination of the eastern-directed thrusting along the Rockies Mountain.

Seismic data reveals that at the southern edge of NPDZ in the passive roof duplex a pop-up structure is developed at the northern limb of Soan Syncline (Fig. 4.5). This structure lying at the depth of approximately 6500-7000 m is bounded by hinterland dipping thrusts. Salt Range Formation has flowed in its core due to which the overlying strata are elevated at the northern limb of Soan Syncline (Figs. 4.7 and 4.8). At the same depth the seismic data also suggest graben structure (Figs. 4.5 and 4.7).

4.2c Soan Syncline

South of KMF, the Siwalik group dip southward in a monocline structure called the Soan Syncline. The Soan River marks the axis of the Soan Syncline. It is a molasse basin containing thick Siwalik sediments. This structure separates the highly deformed strata to the north from moderately deformed strata in the south (Figs. 4.2-annexure 1and 4.7). The general shape of the syncline is a broad asymmetric synclinorium with steep dipping

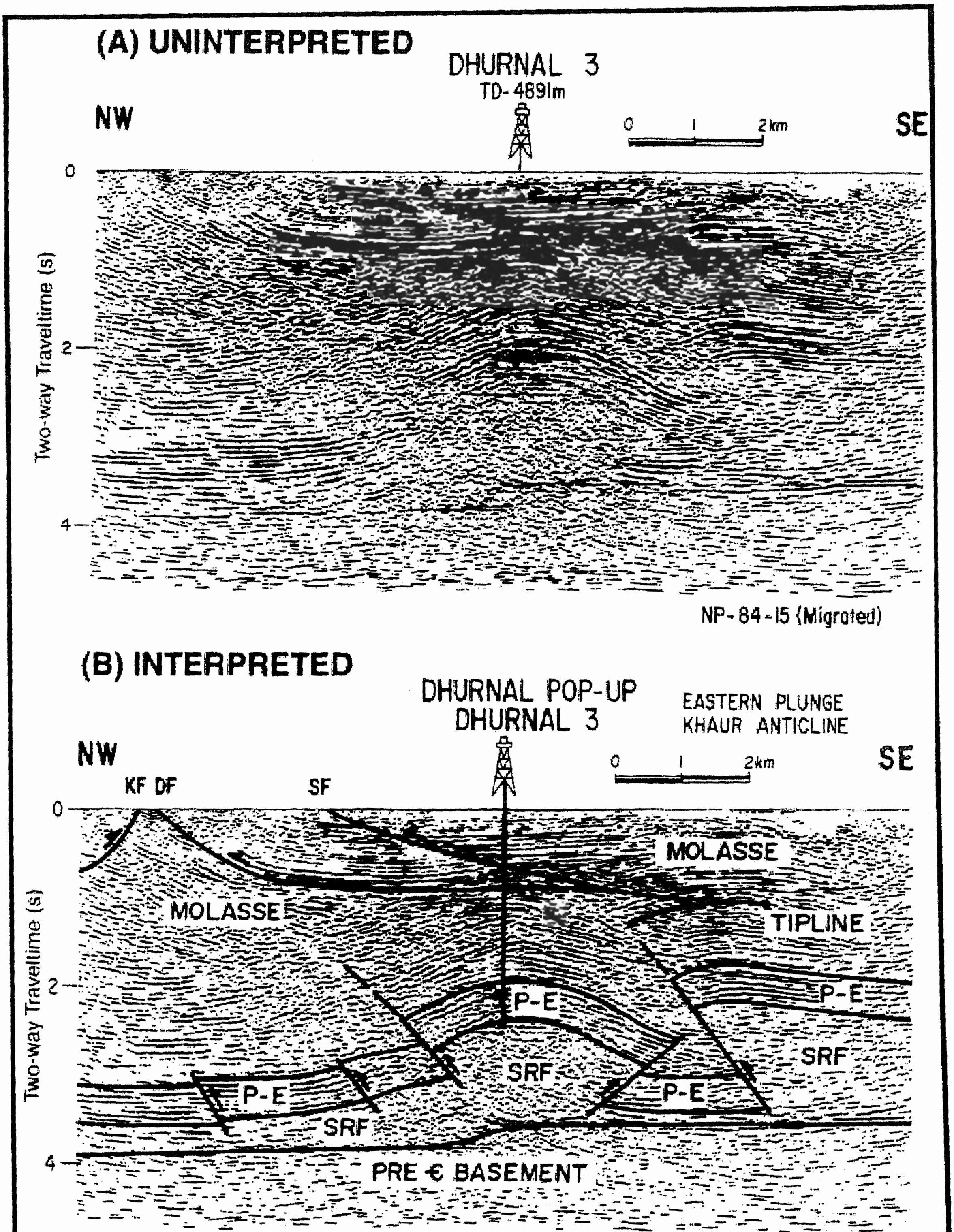

Fig. 4.8. Published Seismic line of Dhurnal popup and the graben structures (After Jaswal et al., 1997).

DF = Dhurnal Fault, KF = Kanet Fault, P-E = Permian to Eocene Formations, SF = Sakhwal Fault, SRF = Salt Range Formation northern limb and gentle dipping southern limb. Surface and subsurface data indicate that this structure consist of broad folding with wavelength of approximately 20-30 km (Lillie et al., 1987 and Figs. 4.5 and 4.7). The Soan Syncline constitutes the trailing portion of the Salt Range thrust sheet, which has been translated southward with very little internal deformation (Lillie et al., 1987). It appears to be analogous to the Molasse Basin in the foreland of Alps, 50 km wide zone of undeformed clastic deposits that have been translated 23 km over the Triassic evaporite (Mugnier and Vialon, 1986).

Towards the northern lime of Soan Syncline Kamlial Formation is thrust over the Chinji Formation by a back thrust. Seismic data shows that this thrust fault is a south-dipping back thrust initiated from a tipline at the base of Kamlial Formation (Figs. 4.5 and 4.7), which is the continuation of Dhurnal Fault in this area. The Kamlial sandstone beds tilted upward along this fault, forming the northern limb of the Soan Syncline (Figs. 4.5 and 4.7).

4.2.1 Structure Analysis of Northern Potwar Deformed Zone (NPDZ)

The structure in the northern part of NPDZ is due to the fault propagation fold. These faults are blind thrust and are the imbrications of MBT (Fig. 4.3).

Like the Eastern Kalachitta Range the structure style of the Northern Potwar Deformed Zone is same (passive-roof duplex) but with variable upper and lower decollement levels. The passive roof structure of NPDZ have basal detachment lying within the Salt Range Formation and the roof detachment lying at the top of Rawalpindi Group (Fig. 4.5 and Fig. 4.7). The passive roof duplex geometry in the NPDZ developed as the sole thrust ramped upward against the competent platform sequence from the Eocambrian Salt Rang Formation and flattened slowly along the bedding at the base of Kamlial Formation (Figs. 4.4a and 4.4b). The molasse bed above the roof detachment developed a foreland dipping Soan Syncline due to its upward tilting (Figs. 4.4a and 4.4b). As a result of continued convergence from hinterland progressively stacked thrust sheets under the passive roof thrust, resulting in the steeply dipping of the northern limb of the Soan Syncline. The popup structure disturbs the duplex structure and due to which the upper detachment is elevated. Because of the ductile nature of the Salt Range Formation resulted in disharmonic structures. Salt can have both active and passive role in the development of folds. An active role implies that deformation results from the buoyancy of salt (Martinez, 1974). The salt can behave passively, when compressive forces are applied, shows ductile nature (Martinez, 1974). The KMF is out of sequence thrust as it developed after Mianwala Fault (Fig. 4.5).

This passive duplex structure under the continued compression from the hinterland, the frontal thrust started to cut the roof sequence above the passive roof thrust to form a fault propagation fold (Suppe, 1983).

CHAPTER 5

DISCUSSIONS

5.1 STRUCTURE MODEL OF THE EASTERN KALACHITTA RANGE

The structure of the Kalachitta Ranges is dominated by south verging thrust faults, which is later, folded by a north verging deformational event. The Kalachitta Range represents the deformational front of the Hill Ranges.

In the core of Katha Colony anticline repeatedly exposed stratigraphy along the emergent thrust sheets is Jurassic (Samana Suk Formation) and Paleocene (Lockhart Formation), except the southern most thrust sheet, which bring Patala Formation (Paleocene) in contact with the Samana Suk Formation (Fig. 4.2-Annexure 1). Samana Suk Formation is the oldest stratigraphy involved in these thrusting, give an idea that a lower detachment lies at the base of this Formation (Fig. 4.3). The Eocene formations are not found to be bounding between these thrust faults sheets. The folds within these formations are detachment folds, which is lying at the base of Patala Formation. This suggesting a second level of detachment below the Eocene Formation within the Patala Formation. This shows a duplex structure as described by Boyer and Elliot (1982). In a duplex structure the lower thrust is called sole thrust and the upper thrust is called roof thrust (Figs. 4.4a and 4.4b). The sole thrust doesn't cut the litho-tectonic unit above it but joins the roof detachment and the geometry is termed as duplex (Fig. 5.1). The major displacement takes place along the sole thrust and the roof thrust observe layer parallel shortening in the form of upright folds (Figs. 4.4a and 4.4b). In the Eastern Kalachitta Range this seems to be the case, Samana Suk Formation represents the sole thrust while Patala Formation is the roof thrust (Fig. 4.3). The surface expressions of the thrust faults show that their dip gets steeper towards the south (Fig. 4.3), which suggest a piggy back style of thrusting (Jones, 1982and Figs. 3.6 and 5.2). The area also shows progradation of thrusting towards the foreland (Butler, 1982).

The structures within the Eocene formations are not compatible with the structure within the Jurassic and Paleocene formations. As the deformation progress, motion along the

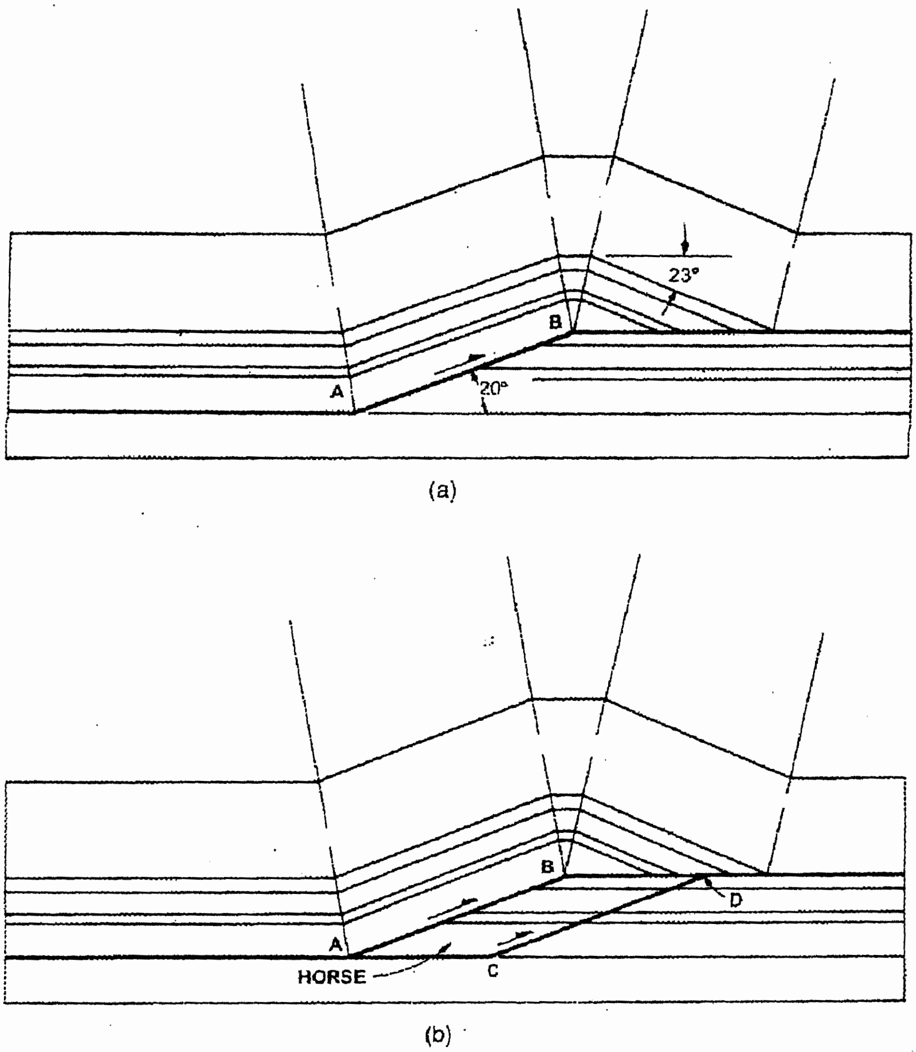

Fig. 5.1. Duplex model with ramp and flat geometry

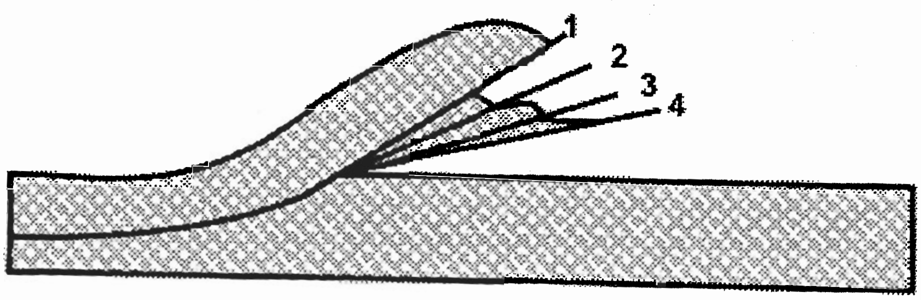

Fig. 5.2 Piggyback development of imbrications in the footwall

sole thrust deforms the roof thrust (Figs. 4.4a and 4.4b). The overlying Eocene beds in effect ride up the roof thrust forming a fold panels above the upper detachment. These structurally higher folds are caused by the bends in the roof thrust, so its dip panels terminated at the upper detachment. As the sequence above the roof thrust remains stationary, relative to the duplex structure, the shortening of the duplex sequence is accommodated in the roof sequence by uplift and folding. This type of structure style is called passive – roof duplex (Banks and Warburton, 1986). It shows that the structural model of the Eastern Kalachitta Range is a "passive-roof duplex".

According to Morely (1986), the development of passive-roof duplex geometry is the result of the mechanical properties of the rocks. The deformation that occurs in sedimentary basins is primarily controlled by brittle (low temperature) deformation processes. Davis et al. (1983), and Dahlem and Suppe (1988) formulate a frictional, or brittle theory of crystal deformation that applies to both compressional and extensional regimes. According to this theory, in more competent or strong rocks, the fractures will form at high angles to the bedding, and in the incompetent rocks, such as shale, the fractures tend to develop parallel or sub-parallel to the beddings (Fig. 5.3).

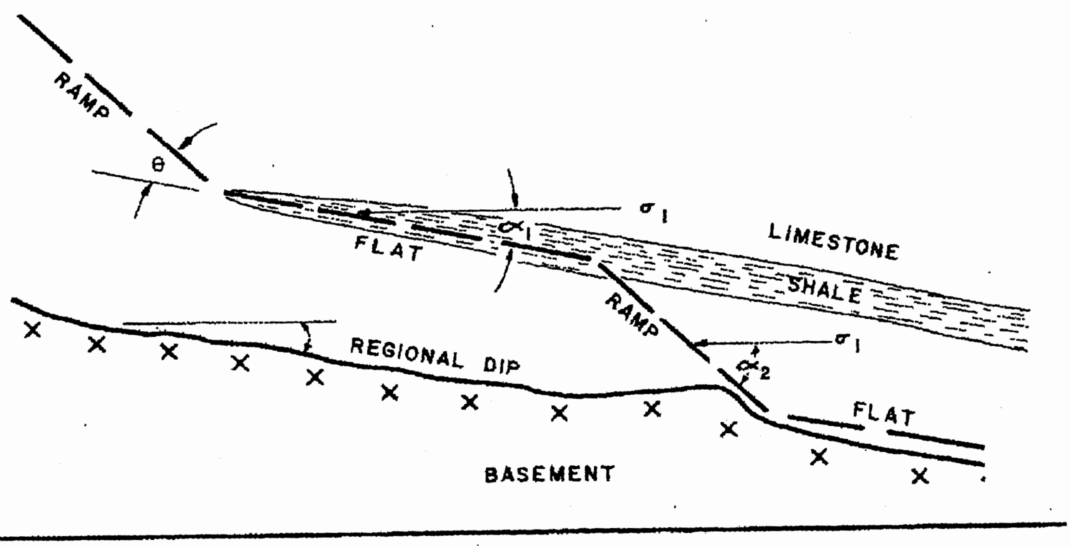

Fig. 5.3 Cross section of ramp geometry, showing how the competent incompetent layers are affected by thrust faulting.

If the motion along these fractures cause them to coalesce (come close and unite), the detachment will form along the flat lying bedding and follow incompetent (shale or evaporite) for ten or even hundred of kilometer (Davis and Engeldger 1985). Where the ramp connects to a weaker layer on a higher structural level, the ramp transforms into flat once again. Once a network of ramps and flat form and a large force is applied to the back of wedge – shaped region (Fig. 5.3). The strata above the flats and ramps will being to move along the fault. Material will begin to slide along the flats and up the ramps, forming a fold in the hangingwall block.

In my study area a competent Eocene limestone lies above the incompetent Patala Formation, supports the idea of development of "passive-roof duplex structure". The folding within the Eocene formations is due to its passive behavior, not affected by thrusting, but the upper detachment cause them to fold and lift above, as in the case of Margalla Hill limestone. Below the Patala Formation are lying the competent (brittle) limestone sequences, causing the development of ramp structure at high angle and joins the upper Patala shale in the form of a flat during thrusting (Fig. 5.3). Same passive duplex structures have been reported by Banks and Warburtion (1986) and Jadoon (1991) from the Suliman Kirther Thrust belt. This shows the style of deformation in the mountains front of Pakistan is similar.

As the thrust belt moves progressively over the foreland, new thrust faults forms near the toe (front) of the thrust belt. Where a thrust fault forms below pre-existing faults, motion along the deeper fault causes the shallow faults and overlying structure to fold. The deformation produces interesting and complex geometry of stacked fold (Fig. 5.9). A similar type of fold structure is observed near Katha Colony, called Kaltha Colony stacked anticline structure (Fig. 4.2-Annexure 1).

To some extent shortening of the duplex sequence is accommodated in the roof-sequence by uplift, folding and erosion (Figs. 4.4a and 4.4b). Banks and Warburton (1986), have suggested that a roof-sequence, instead of extending over large number of horses, can imbricate. The Eastern Kalachitta Range shows similar structures. North of Katha Colony a NW verging recumbent fold is observed within the Margalla Hill Limestone. At the higher relief the faults are back folded (Plate 4.5). These structures suggest that the area has experienced a north directed sense of compression. The source of this compression is thought to be above a regional roof thrust of a large duplex (Fig. 3.6). In the first phase of deformation south verging thrust were formed that ended in fault propagation folds.

According to Cotter (1933), the structure of the Kalachitta Range is an anticlinoruim, having fan shaped geometry, characterized by north-south verging folds (Fig. 1.4). The structures developed in response to the swelling of Kalachitta mass due to lateral compression and the Precambrian slate has acted as lubricant (Cotter, 1933).

The north verging structures are shown by the rocks of Paleocene to Eocene is due to the passive back thrust at the roof detachment level.

Hussain (1990), at many places of the Kalachitta Ranges rocks has shown that Eocene units are involved in imbrication. The involvement of Eocene units in the thrust imbrication can be attributed to the variation in the style of deformation of thrust sheets.

Along the strike of the Kalachitta Ranges there is change in the strike of structures. In the east around Fatehjang it is 090°-080° while in the west it gradually swing around and become 130° (Izatt, 1990). Shows a change of 35°-40° in the strike. This swing in the trend of the Range is due to the differential movement in the two detachment levels and can developed in two ways:

a. By pinning both the ends of the Potwar-Kohat to the east and west respectively (Fig. 5.4), minor anticlockwise rotation occur in Hazara and clockwise in the west. This attributed to the difficulties encountered in the southward propagation of Salt Range Thrust due to the thinning of Salt Range Formation to the east or because of the decrease in the angle of basement dip (Jaume and Lillie, 1988).

b. By pinning in the central Kalachitta Ranges and due to the increasing amount of shortening in west and east producing a hinterland verging sense. This change in strike occurs above the roof thrust. The east rotates anticlockwise while the west rotates clockwise.

In the first phase of deformation event in the Kalachitta Ranges the thrust faults were south verging that terminated in the fault propagation folds. Due to the displacement on Main Boundary Thrust (MBT) the south verging structures were deformed above the roof thrust. Then back-folding developed above a regional roof thrust due to which the MBT plane and its splays were deformed (Fig. 3.6). Continued deformation above the regional roof thrust uplifted the area to the present strike of the Kalachitta Ranges.

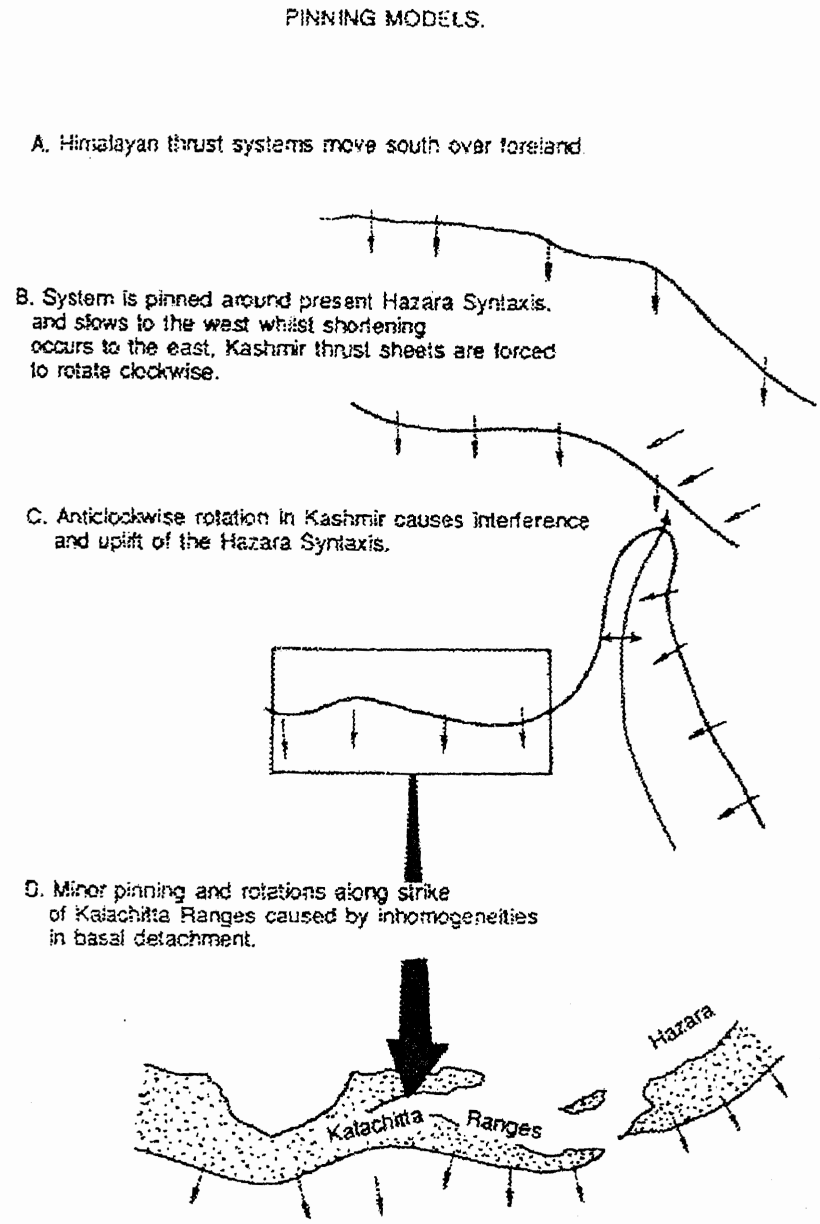

Fig. 5.4 Pinning model for the deformation style of Kalachitta Range (Izatt, 1990).

5.2 STRUCTURE MODEL OF NORTHERN POTWAR DEFORMED ZONE (NPDZ)

This area is intensely folded and faulted, especially the northern part. The structure of NPDZ is same as discussed above (passive-roof duplex). The only difference between them is the varying detachment levels. Here the lower detachment lies within the Salt Range Formation while the upper detachment in the Rawalpindi Group, while in the Eastern Kalachitta Range, the upper detachment lies at the base of Paleocene (Patala Formation) and the lower detachment at the base of Samana Suk Formation (Fig. 5.5-Annexure 2).

In this area the sole thrust ramped upward from the Salt Range Formation and flattened along the bedding at the base of Kamlial Formation, forming a wedge structure. Between these lower and upper detachments lies the competent (Permian-Eocene) limestone, called the platform sequence (Fig. 4.7). The passive roof thrust at the northern limb of Soan Syncline develop at the base of Kamlial Formation. Because of the transfer of slip from lower detachment to the upper detachment cause the sequence above the roof detachment to bend upward and in response developed the Soan Syncline (Jones 1987). Due to the continued convergence from the hinterland, the northern limb of the Saon Syncline is steeply dipping. The disharmonic structures within this area are because of the Salt Range Formation, which flowed into the core of the anticlines from the adjacent synclines. The pop-up structure is developed as the Salt Range Formation flowed into its core. The NPDZ has developed prior to 2 Ma, as the foreland strata were progressively accreted onto the overriding thrust sheet by duplex formation north of the northern margin of the evaporites Formation (Jaswal et al., 1997).

The stacking of folded blind thrust under the passive roof thrust give rise to the development of a triangle zone and foreland syncline (Bank and Warburton, 1986; Morely, 1986). Passive roof duplexes (or triangular zones) have also been reported from the frontal parts of Sulaiman and Kirthar ranges of Pakistan (Banks and Warburton, 1986) and eastern Rocky Mountain foothill of Canada (Price, 1981, 1986 and Jones, 1982).

The southward migration of the deformation front across the foreland of Pakistan occurs at varying rate. Initially deformation south of the Hill Ranges is assumed to have taken place in the NPDZ. The intense deformation in this area indicate relatively slow rate of propagation of the decollement. When the decollement developed in the salt layer it encountered the basement buttress. This added resistance to the sole thrust and temporarily ceased foreland propagation. Due to the basement buttressing resulted in the out-of-sequence deformation in the NPDZ (Baker, 1988). This deformation is responsible for the steep to overturned strata of Rawalapinid Group and the its unusual thickness in this area.

The structures within Kohat Plateau are a blind duplex located to the west of the study area. The roof thrust of the duplex is a backthrust passively accommodating shortening beneath it (Abbasi and McElroy, 1991). The deformation in the sequence above the roof thrust is not related to the structures of underlying duplex (Banks and Warburton, 1986). The minimum shortening estimated is 55±5 km in the Kohat Plateau (Abbasi and McElroy, 1991) as compared to the shortening calculated from Eastern Kalachitta Range to Soan area (68-km), which seems to be consistent. The Kohat Plateau is much more intensely and heavily faulted, having narrow outcrop width and high structure relief (Abbasi and McElroy, 1991). Due to the deeper basal detachment level in the west of Kohat Plateau and normal stress on basal detachment due to overlying strata, offers greater resistance to sliding. This resulted in intense deformation of the overlying wedge as compared to the thinner wedge of the Potwar (Abbasi and McElroy, 1991).

The NPDZ constitutes a relatively homogenous structural province, being entirely detached from its underlying substratum along a continuous decollement level made up by the Precambrian salt. In size and geometry, it is quite similar to the Jura Moutains and adjacent Molasse Basin, which indeed developed in front of a major Alpine thrust, deformation propagating towards foreland over a long distance due to an extensive intra-Triassic ductile layer (Phillippe, 1994).

5.3 AMOUNT OF SHORTENING

Making use of the restoration technique of the 2DMove software, the horizontal shortening calculated along the line (A – B) of the Eastern Kalachitta Range is about 25-km (Fig. 5.6).

Along the Section line B – C total shortening is about 28-km (Fig. 5.7). While along the line C – D a total of 15-km shortening is calculated (Fig. 5.8). Total estimated shortening along line (A-D) from the Eastern Kalachitta Range to the Soan River is 68-km (Fig.5.5-Annexure 2)

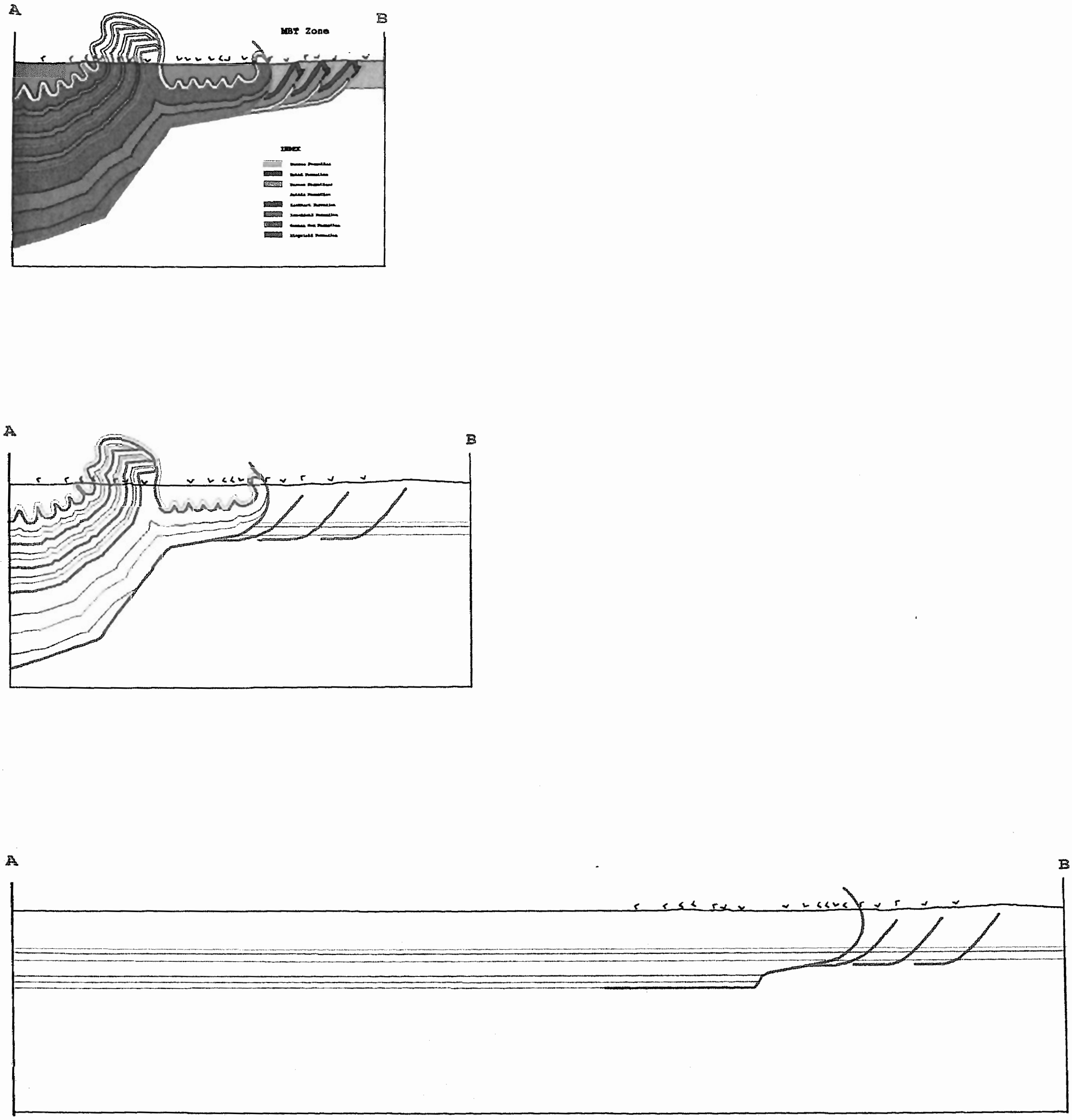

Fig. 5.6 Restored section along line A-B

x axis = 1:173381, y axis = 1:173381

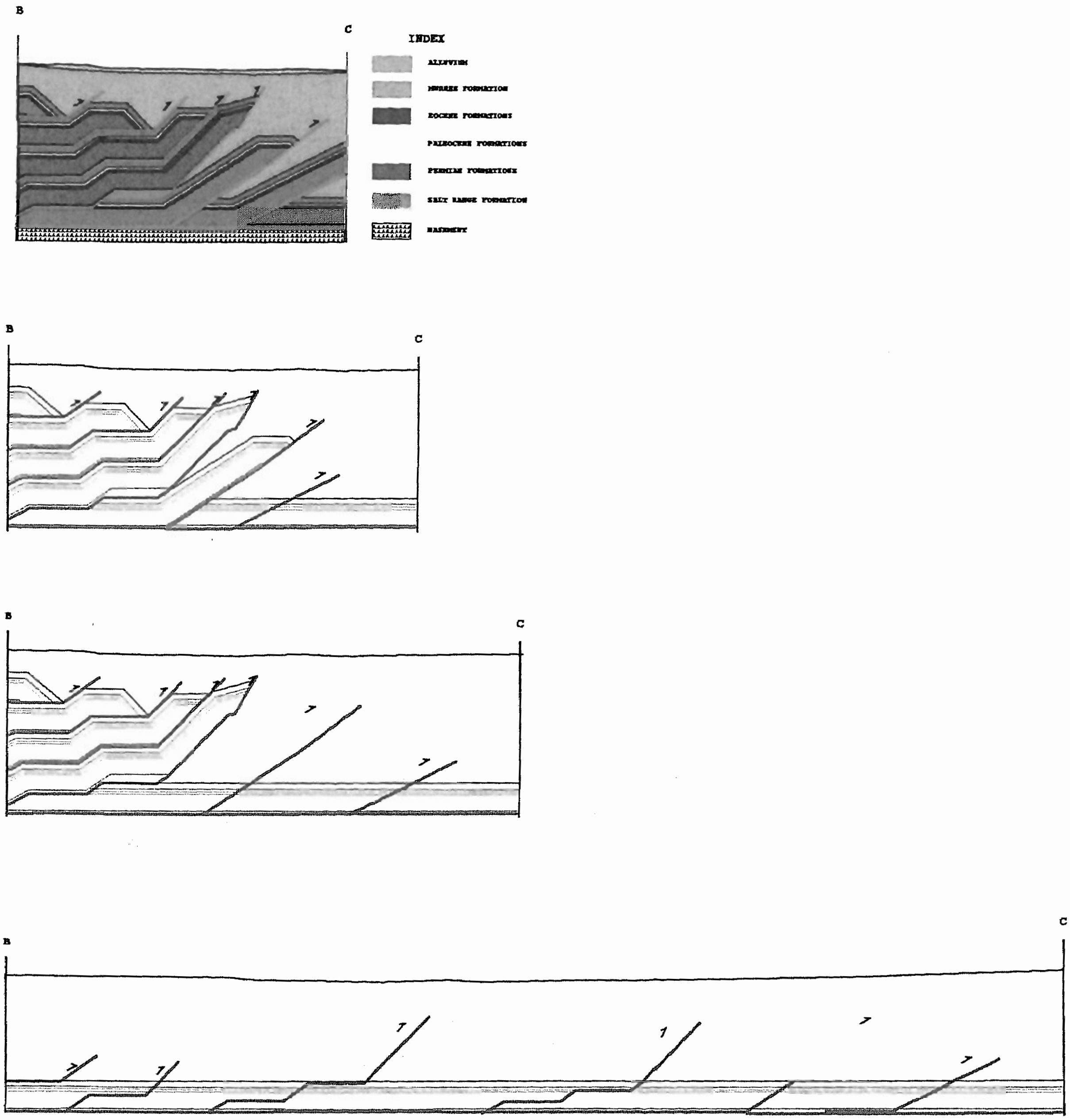

Fig. 5.7 **Restored section along line B-C.**

x axis = 1:260858, y axis = 1:260858

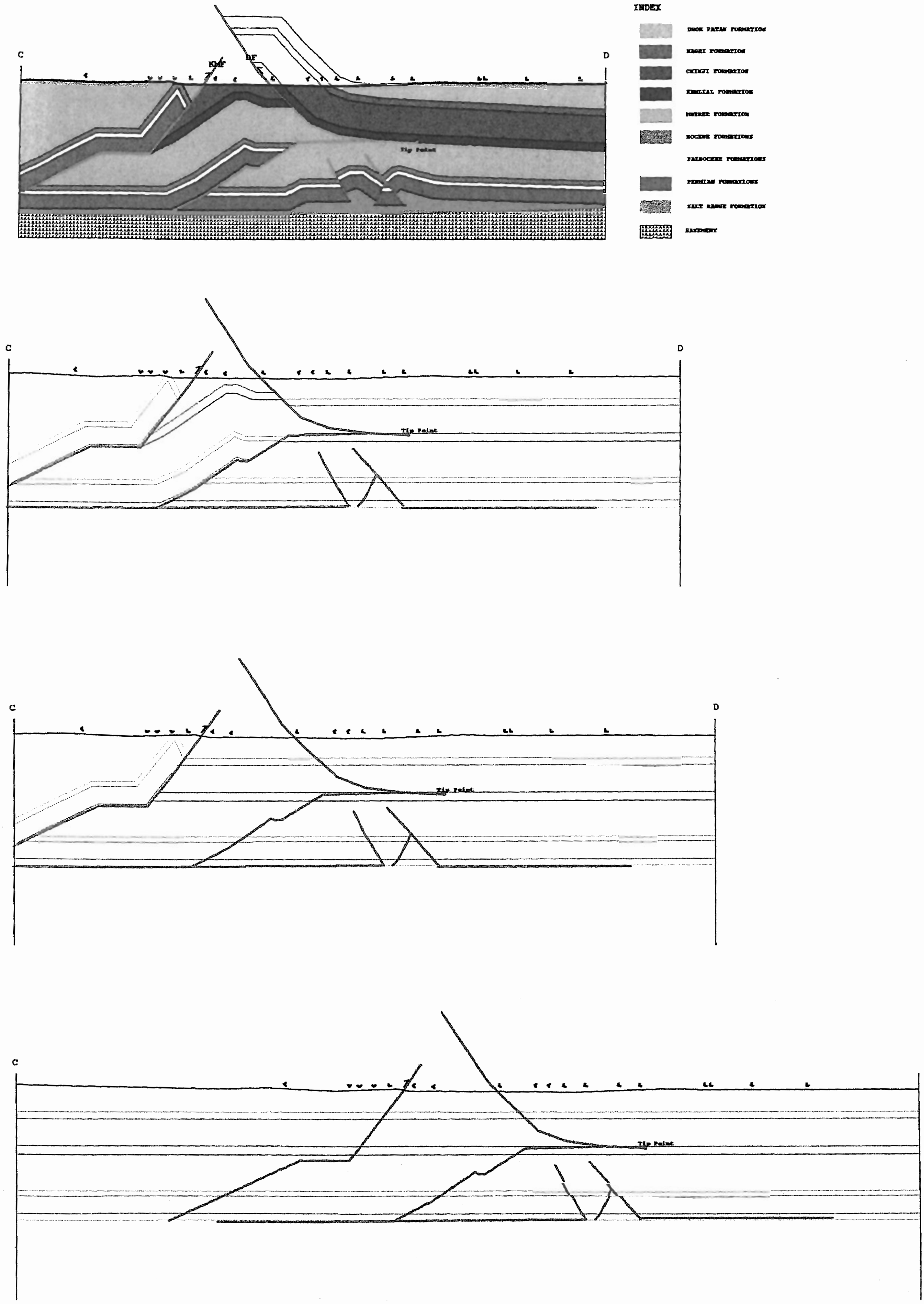

Fig. 5.8 Restored section along line C-D

x axis = 1:250949, y axis = 1:250949

5.4 Conclusions

Surface and Sub-Surface data are integrated to compare the structure style of eastern Kalachitta Range and Northern Potwar Deformed Zone. Based on this study the following conclusions are made:

1. The structural geometry of the study area is of a passive roof duplex, related to thin-skinned deformation.
2. In the Eastern Kalachitta Range the lower detachment lies at the base of Samana Suk Formation and the upper detachment is within the Patala Formation. In case of NPDZ the lower detachment lies within the Salt Range Formation and the upper detachment at the base of Kamlial Formation.
3. The Katha Colony anticline of Eastern Kalachitta Range is a stacked anticlinal duplex.
4. The progressive steepening of thrust faults from south to north, in the Eastern Kalachitta Range is due to piggyback style of deformation, prograding southward.
5. The "triangle zone" geometry north of Soan Syncline is also developed due to piggy back blind thrusting beneath a passive roof thrust.
6. A pop-up structure developed below the northern limb of Soan Syncline is the result of Salt Range Formation, which flowed in its core and lifted it up.
7. Kalachitta Range is separated from NPDZ by a regional thrust fault called the "Main Boundary Thrust" (MBT). MBT is the major emergent thrust exposed north of Fateh Jang.
8. The anticlines of the Eastern Kalachitta Range is fault related structure cored by Patala Shale, while the anticlines of the NPDZ are salt cored as the salt has moved from the adjacent synclines.
9. The unusual thickness and steep to overturned beds of the Murree Formation is due to imbricated thrust sheets and fault-propagation folds know as out of sequence deformation.
10. Khairi Murat Fault (KMF), the major emergent fault of NPDZ exposed north of Soan Syncline and is responsible for the uplifting of the triangle zone. KMF soles out from the Salt Range Formation at the depth of approximately 7500 m.
11. The Soan Syncline is a foreland dipping monocline.
12. Loading of the thick molasses sediments within the Soan Syncline has caused salt flow towards the south.

13. The thrust fault at the northern limb of Soan Syncline is back thrust, the tip of which lies at the base of Kamlial Formation at a depth of approximately 3200 m.

14. About 62-km of horizontal shortening has been calculated from Eastern Kalachitta Range to the Soan River.

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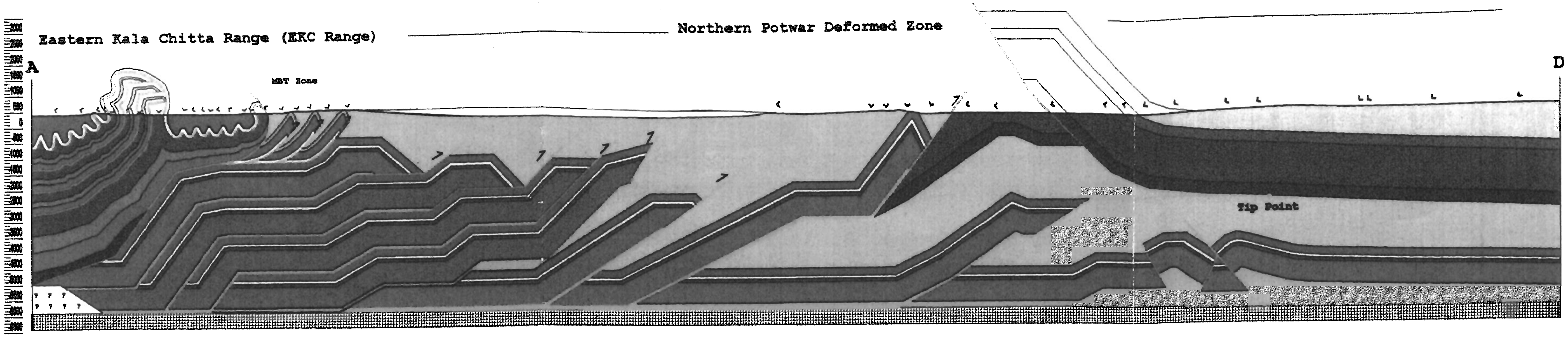

FIG. 5.5. Cross section along line C-D from eastern Kalachitta Range to Soan River.

X axis = 1:133262, y axis = 1:133262

Scale (V=H)

0 1 2 3 4 km

INDEX of EKC Range

- ALLUVIAL
- MURREE FORMATION
- KOHAT FORMATION
- EOCENE FORMATION
- PATALA FORMATION
- LOCKHART FORMATION
- LUMSHIWAL FORMATION
- SAMANA SUK FORMATION
- KINGRIALI FORMATION

INDEX OF NPDZ

- DHOK PATAN FORMATION
- NAGRI FROMATION
- CHINJI FORMATION
- KAMLIAL FORMATION
- MURREE FORMATION
- EOCENE FORMATION
- PALEOCENE FORMATION
- LOCKHART FORMATION
- PERMIAN FORMATION
- SALT RANGE FORMATION
- BASEMENT