

**KINEMATICS OF THE OROCLINAL BENDING OF JALALPUR  
AREA EASTERN SALT RANGE, PUNJAB, PAKISTAN**



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AMEEN.

## **Abstract**

The NW Himalayan folds and thrusts belt of northern Pakistan is present at the western periphery of main Himalayan belt, exhibiting strike changes from north-south to northwest-southeast to the west and east direction, respectively. The Salt Range represents the youngest southernmost Himalayan deformation and is present in the apex of major Himalayan oroclinal deflection. The stratigraphic sequence of the area ranges in age from Precambrian Salt Range Formation to Quaternary Lei Conglomerate with four prominent unconformities. This research work deals with the oroclinal bending developed in the Eastern Salt Range with special emphasis on the kinematic relationship of different trending regional structures and its restoration to an undeformed state has been accomplished with the help of 2D and 3D modules of the Move software.

The study area has gone through different stages of strike slip tectonics with zippered junction zone and associated thrusting and folding produced an unusual deformation and rotation to hold variance in the displacement vectors. The overall structural geometry of the area has undergone through three major phases of deformation, the older southward propagating stress phase has uplifted the Salt Range Front and Jogi Tilla Ridge, whereas the younger phase of stress vector propagating from the southeast-northwest direction towards hinterland has brought Chambal Ridge as a Back-Thrust sheet over younger Mollase sequence of the Range Front. The current oroclinal bending developed in the research area shows In-sequence and out of sequence thrusting phenomena with break back sequence and forward breaking sequence of faulting, though prominent strike slip faults have facilitated them at the later stages.

The Sinistral sense of Jalalpur Sharif lineament has displaced the Salt Range Front and Jogi Tilla Ridge from each other with simple shear component parallel to its strike, that

has lateral displacement within the Mollase sequence. The dextral sense of Pind Sawika lineament present at the northern margin of Chambal Ridge has facilitated the younger compressive stress vector to move Chambal Back-Thrust sheet towards hinterland side, it has finally joined the Jalalpur Sharif lineament in the NW direction as a closing zipper junction zone. The concavity developed in the NW corner of the mapped area shows another dextral strike slip fault that has translated the region towards NE direction and merged with the older strike slip lineament. Besides the crowding of major thrust faults, a large synclinal structure known as Kotal Kund Syncline occupies the central and northern half of the study area and finally terminates near the zippering of strike slip faults. The amount of shortening calculated through cross section balancing techniques shows a total of 46 % and 49 % shortening along cross section lines.

### 1.1 General description

The mountain ranges of north Pakistan is located at the western periphery of main Himalayan belt. It has marked shifting in the regional structures from north-south to NW-SE trending thrusts and folds to the west and east respectively. The Salt Range is located in the apex of main Himalayan oroclinal deflection (Fig. 1.1). The east-west oriented Salt Range was uplifted along thin skinned detachment which led to the horizontal shortening and vertical thickening of continental shelf sediments above decoupling surface (Butler, 1987). The eastern and western arms of the Salt Range have almost north-south oriented structural trends as compared to the central portion. Regionally it is bounded by South Potwar Deformed Zone (SPDZ) in the north, Punjab Plain in the south, Sub-Himalayan ranges in the east, Kalabagh strike slip fault in the west. Whereas locally the study area (Jalalpur Sharif village and surroundings) is bordered by Dil Jabba and Domeli Thrust in the north, SRT and Punjab Plains mark its southern periphery, while Jhelum River and Khewra gorge is present at the east and west, respectively (Davis and Lillie, 1994; McDougall and Hussain, 1991).

The study area is a part of Eastern Salt Range having low elevation and irregular topography with thick stratigraphic sequence ranging in age from Precambrian (evaporate) to Pleistocene (mollase) (Gee, 1989). The recent Himalayan shortening in the form of Salt Range has received shed of alluvial mollase through Jhelum and Indus River from high elevated Himalayas since start of collision. The study area is marked by the hinterland and foreland verging thrusts and folds, which make them among the most complex structural scenario, so the research work has focused on sequence of deformation and kinematic relationship of the oroclinal bending of Jalalpur Sharif area.

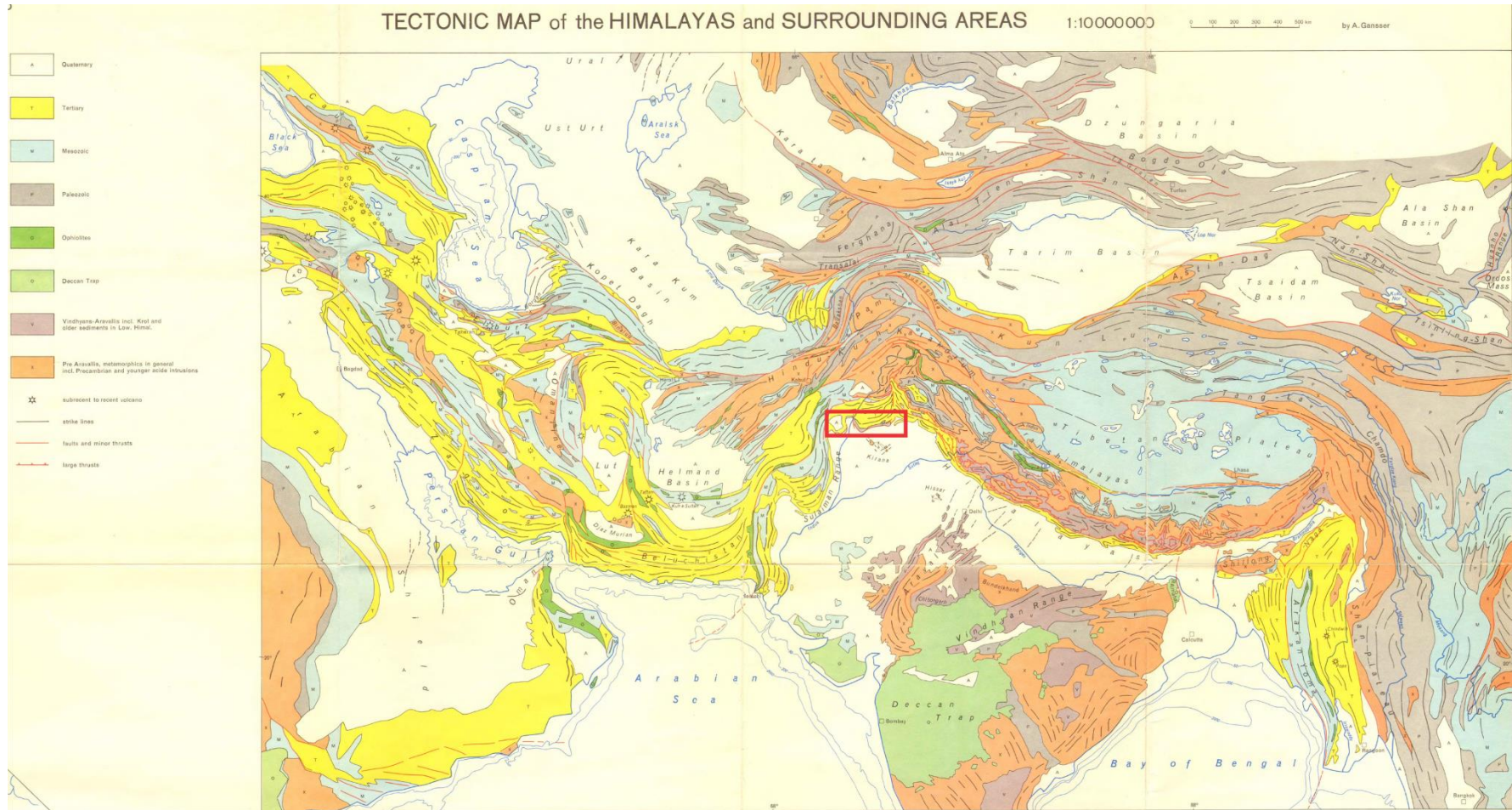


Fig1.1 Tectonic map of Himalayas and surrounding areas, red inset shows Salt Range present in the apex of main Himalayan oroclinal deflection (modified from Gansser, 1964).

## **1.2 Location and Accessibility**

The study area is situated in Jalalpur Sharif, a union council of Pind Dadan Khan about 48 km southwest of Jhelum city, District Jhelum, Punjab, Pakistan. The Baghanwala, Jutana, Kotal Kund, Dhok Chanda, Pind Sawika villages are located within the study area. The area can be easily accessed from M2 motorway to Pinddadan Khan-Mandibhaurin road (Fig. 1.2). At first main roads were followed to get general image of the area. The Salt Range front geology were traversed along Gharenwal Chak Mujahid road connecting a snake shape road which is passing from Rawal and Baghanwala villages. The Chambal ridge was studied along Chak Rajgan-Wagh road, while Jogi Tilla ridge was studied along Hasnoot Pind Sawika road. Random traverses were made easily within the gorges, nallas and small roads.

## **1.3 Topography**

The study area shows moderate topography with different trending ridges and valleys. Topography of the study area is associated with deformation and lithologic units. The competent stratigraphic units of the Carapace has formed peaks such as Jutana Dolomites whereas soft and friable units of Rawalpindi Group and Siwaliks Group such as Chinji Formation, Salts of Precambrian age has occupied low laying places. Unfortunately the flow of Bunha River has covered and eroded margins of different trending ranges. At places thick vegetation cover has created problem in analysis of the area. The mountains front are steep and covered with eroded materials. The elevation of the Siwaliks mollase and carapace carbonates ranges in 375 m, 957 m respectively (Fig.1.3).

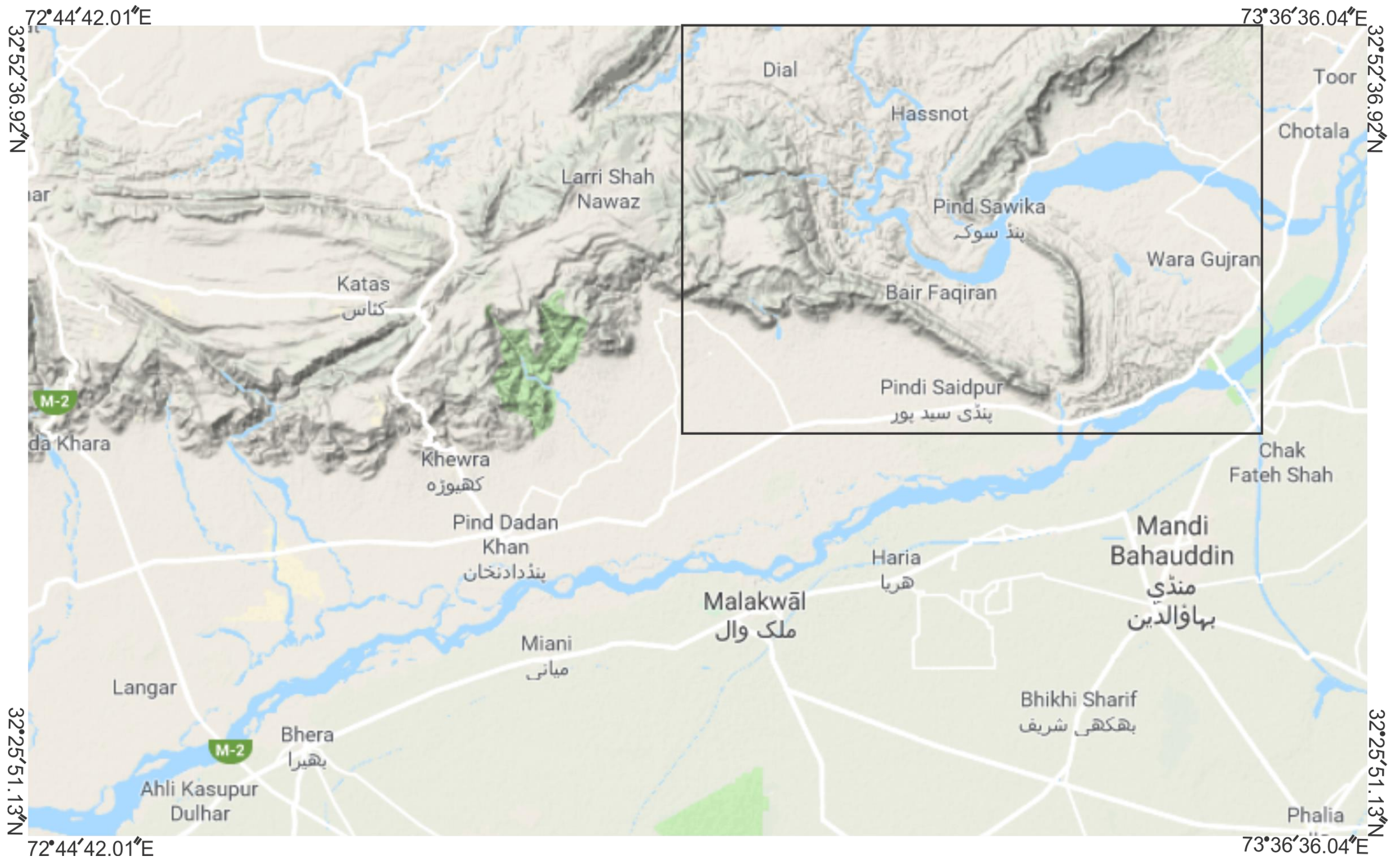


Fig. 1.2 Accessibility map of the study area (inset) and surrounding regions.

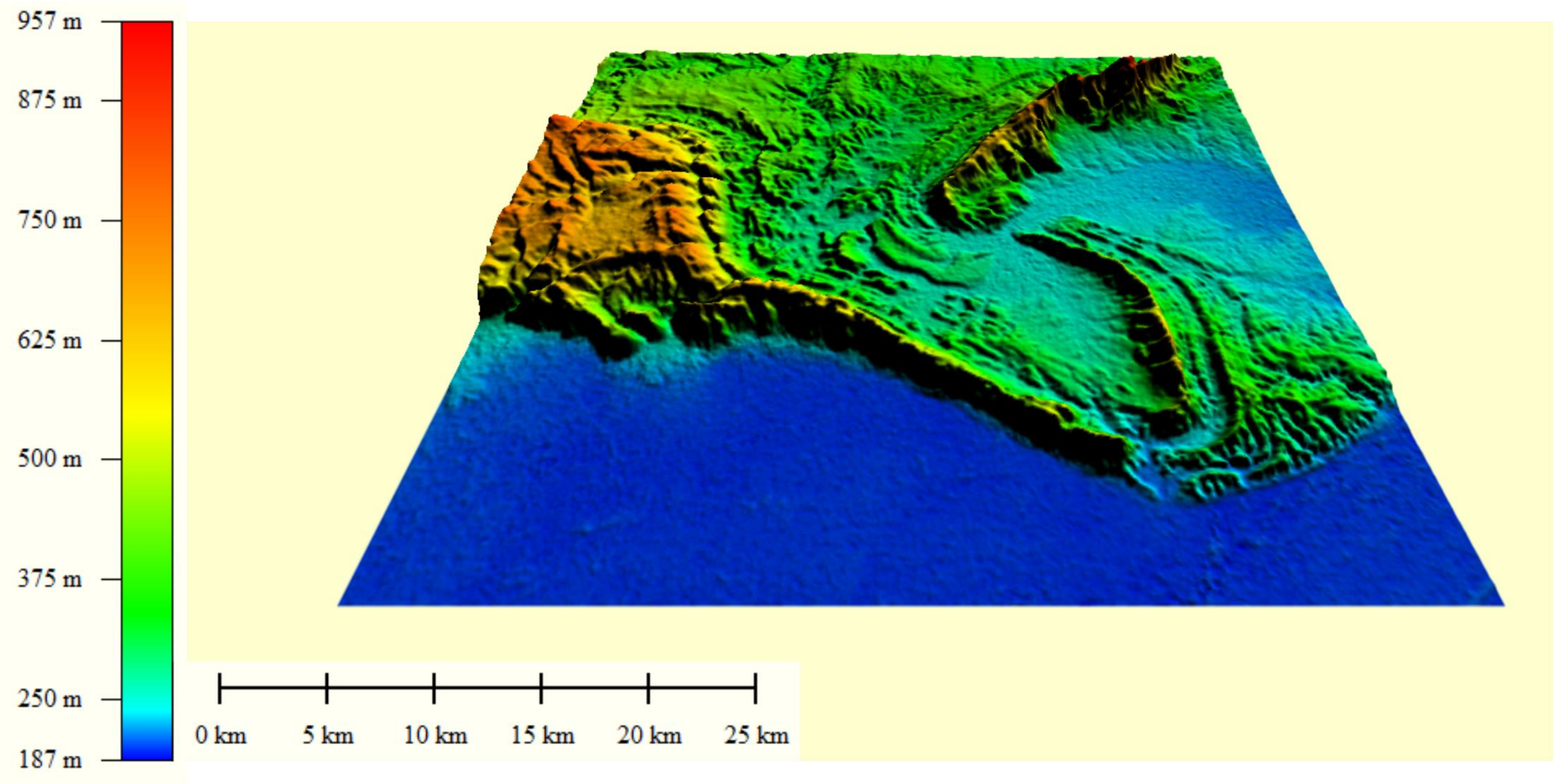


Fig. 1.3 Digital Elevation Model (DEM) showing topography of the study area

#### **1.4 Climate**

The Jalalpur Sharif village and surroundings of the study area have all four weather conditions. The summer is very hot and blazing but winters prevails coldness. The summer temperature normally ranges in average from 30<sup>0</sup>-45<sup>0</sup> Celsius and in winters average temperature ranges from 4<sup>0</sup>-17<sup>0</sup>. Heavy rainfall occurs during monsoon with an average rainfall/year is 60-66 cm.

#### **1.5 Problem Statement**

The proposed research work on structural model will focus on the area displaying a regional E-W trend with sinus bending towards the eastern part. The eastern side of the research area marks unusual behavior of SRT. The well-known loop in the Salt Range Thrust with multiple vergences along the same trend line indicate the tricky situation near the Jalalpur Area, which cannot be explained by simple south verging regional tectonic push.

The south verging fore-thrust component of SRT is continuous till Jalalpur Village where it takes a sudden loop towards north (Fig. 1.4). The SRT die out near the village Jalalpur Sharif. The eastern prominent north-south oriented ridge (Chambal Ridge) was formerly believed to be the extension of the SRT but the idea could not explain the sudden shift in vergence of the SRT near the Jalalpur Village. Current study will systematically explore the sequence of tectonic events, the kinematic relationship for the different trending structural ridges present in the study area and also the reason because of which these differences were seen over the SRT.

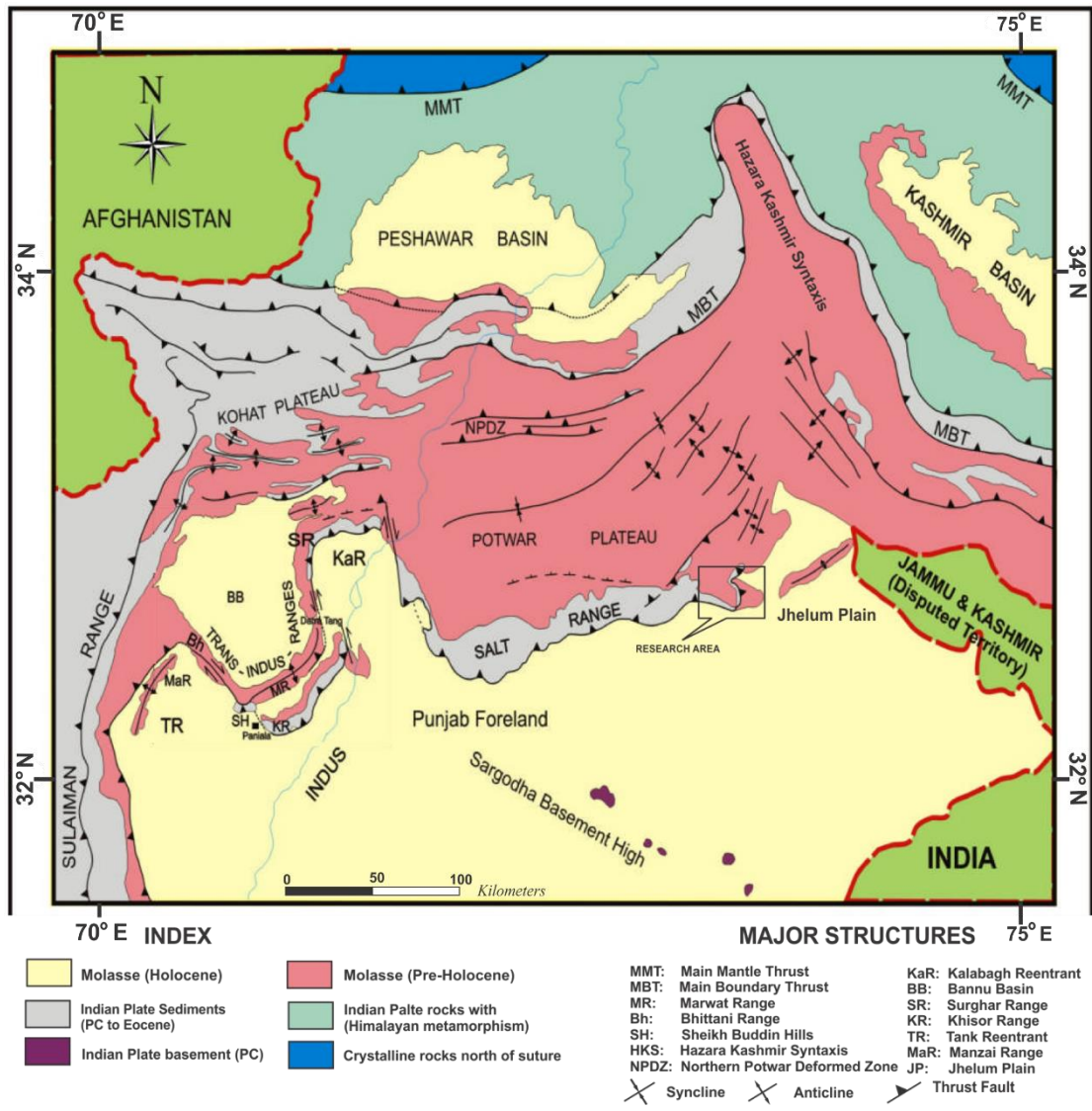


Fig.1.4 Tectonic map of northern Pakistan showing the location of study area (after Kazmi and Raza, 1982).

### 1.6 Aim and Objectives

This research work was aimed with the following objectives;

1. To accomplish detail structural mapping of the area at 1:25000 scale.
2. To work out the nature and factors responsible for producing Jalalpur knot in the eastern Salt Range.
3. To develop a comprehensive subsurface model for the structural evolution of the area.

4. To sort out the style of décollements liable for the structuration of the area.

## **1.7 METHODOLOGY**

The current research work was accomplished with the help of published Geological Survey of Pakistan maps, 30 m resolution satellite images, 30m DEM from NASA and published literature to get general picture of the area. Geological fieldwork of two weeks were planned, where different set of traverses across the strike of geologic units were drawn using GPS and Silva Range compass to record orientation data. The movement on predefined paths such as Nallas, Gorges and streams were used to understand structure geology of the area.

After the completion of geological fieldwork, raw data was analysed and assessed through different software. At first the contact lines for different trending structural ridges were drawn with the help of GPS points and attitude data on Google Earth. The KMZ file format for the line working were then brought to Global Mapper to obtain its shape files for further processing in ArcGis. The stratigraphic and structural features in the form of polygons, lines and points were finally drawn in ArcGis 10.4.1.

Accomplished digitized map and DEM (Digital Elevation Model) of the study area was brought to the MOVE 2013 software, where 2D cross section modelling in terms of construction and restoration was achieved with the help “fault parallel flow” and “flexural slip” module of MOVE. Finally 2D cross sections and Geologic map of the study area were combined to get subsurface condition in 3D view. An attempt was made in this study to make kinematic relationship between different trending ridges and then the deformed state was restored to an undeformed state (previous geometry) with the help of “object loop selection” polygon in Move software.

## **1.8 Interpretation and significance**

The above mentioned studies will lead to the following;

1. Update the geological map of the area at a detailed scale.
2. Define fold thrust relationship and sequence of deformation in area which may be eventually helpful in the hydrocarbon exploration activity in the area.
3. Define the nature of decollements in the evolution of the area.

## **1.9 Literature Review**

The youngest Himalayan deformation in the form of Salt Range has always been a place of attraction for structure geologist where complete stratigraphic sequence starting from oldest Precambrian to youngest Quaternary are exposed. The rock units of the exposed sequences are rich in faunas and floras with marked local and regional unconformities that is P-T boundary, K-T boundary etc have been a place for locals and foreigners to work with their objectives. Previous work on the Salt Range were led by Pinfold (1918), Cotter (1933), Gee (1945, 1947), Flemming (1953), Danilchik (1961), Waagen and Wynne (1878), Fatmi (1966, 1968), Yeats (1984). These innovators studied the Salt Range/Potwar Plateau in their limited resources and provided a base for further advanced structural interpretations. Broad scope of stratigraphy and structures was provided by Cotter (1933) to clarify the difference in style of Salt Range/Potwar Plateau with other surrounding regions. Gee (1980) produced first detailed map of Salt Range at 1:50,000 scale. Salt Range formed as a result of thin skinned deformation with lower decollement lies within the Precambrian Salt Range Formation (Lillie et al., 1987; Butler et al., 1987; Burbank and Beck, 1989). The seismic data across the Salt Range was analysed and interpreted that the basement normal fault is present in the subsurface beside this shortening percentages were also calculated by (Leathers, 1987; Baker,

1988; Lillie et al., 1987; Pennock, 1989; Qayyum, 1991) gave a detail account on the crustal shortening and evolution of Salt Range with the help of seismic data. In the recent times, the evolution of Salt Range and Potwar Plateau has been carried out through scaled sand-box modelling (Cotton and Koyi, 2000). The results showed that the difference in the structure style across the area may be because of nature of frictional and ductile substrate. Grelaud et al. (2002) gave a detail account on the episodes of deformation in the Salt Range and Potwar Plateau, where deformation was first concentrated on frontal thrust and then in the intervening episodes the deformation was distributed over the whole area, this analysis was executed with the help of Thrust-Pack Software.

**2.1 General Statement**

Eurasia consists of three extensive geological detachments as denoted by Laurasian, Tethyan and Gondwanian domains from north to south respectively. The origin of these traced to Late Paleozoic time (Wegener, 1924; Smith and Hallam, 1970; Smith, 1981; Irving, 1979). It is made up of various sized crustal blocks that are attached along ophiolite belts. Most of the blocks are detached from the Gondwana mother land, moved northward and finally collided with Laurasian Domain. This accreted land has been referred as Tethyan Domain by Sengor (1988). Southward, the Arabian and Indian Peninsular Shields are attached to this domain, which have detached from Gondwanaland and are the final accreted product to Eurasia. Pakistan is situated at the boundary between Gondwanian and Tethyan domains (Stocklin, 1977; Kazmi and Jan, 1997, Fig. 2.1).

**2.2 GONDWANIAN DOMAIN**

The amalgamated continental crust and crystalline basement of Gondwanian domain had formed in the Precambrian time, whereas the platform development occurred in the Paleozoic. In Asia it is signified to a greater extent by the Indian and Arabian Shields. The Indian Shields forms the Indo-Pakistan subcontinent with the crystalline thrust sheets marking the northern contact of the Himalayan orogenic belt. This belt sustains in the east and west direction and consists of a chains of oroclinal, distorted, peripheral fold belt in the Arakans, SR/PP (Salt Range/Potwar Plateau), Sub-Himalayan Siwalik Range, and Sulaiman Kirthar Ranges. The Indo-Pakistan subcontinent has three main geologic and physiographic divisions, mainly (1) Peninsular Region (2) Himalayan

Foredeep, present between Indian Peninsula and Himalayan ranges (3) Himalayas (Wadia, 1956).

### **2.3 TETHYAN DOMAIN**

The Tethyan domain is starting from the Pacific to the Mediterranean, covering India and northern boundaries of Arabia and Africa (Fig 2.1). This domain is comprised of huge orogenic mixture of several continental blocks, connected with the branching network of sutures and derived from the Gondwanaland as a result of rifting, fragmentation, calving and subsequent collision with the Laurasia across wide oceanic space. This makeup of the Tethyan domain started in Middle to Late Paleozoic, while the clustering of Pangea was in progression and is actually associated with the repetitive process of sea floor spreading, subduction and collision tectonics of continental blocks (Sengor et al., 1988).

In the Late Permian time, a Cimmerian microcontinent has formed through the process of rifting occurred along the northern margin of Gondwanaland and fragmented into separate island arc (Sengor et al., 1988). Finally the collision of these blocks with the Laurasia in Late Triassic is encompassed by the closure of Paleo-Tethys in Early Jurassic. The Eocimmerian events along with metamorphism and magmatism has affected the Paleo-Tehtyan sediments, melanges and associated ophiolites. The collision of India, Arabia and Eurasia had closed the Neo-Tethys along Indus-Tsangpo Suture Zone, these younger continental blocks along with Neo-Tehtyan suture has formed Alpine Himalayan mountain belt and is referred as Alpides, Sengor (1984).

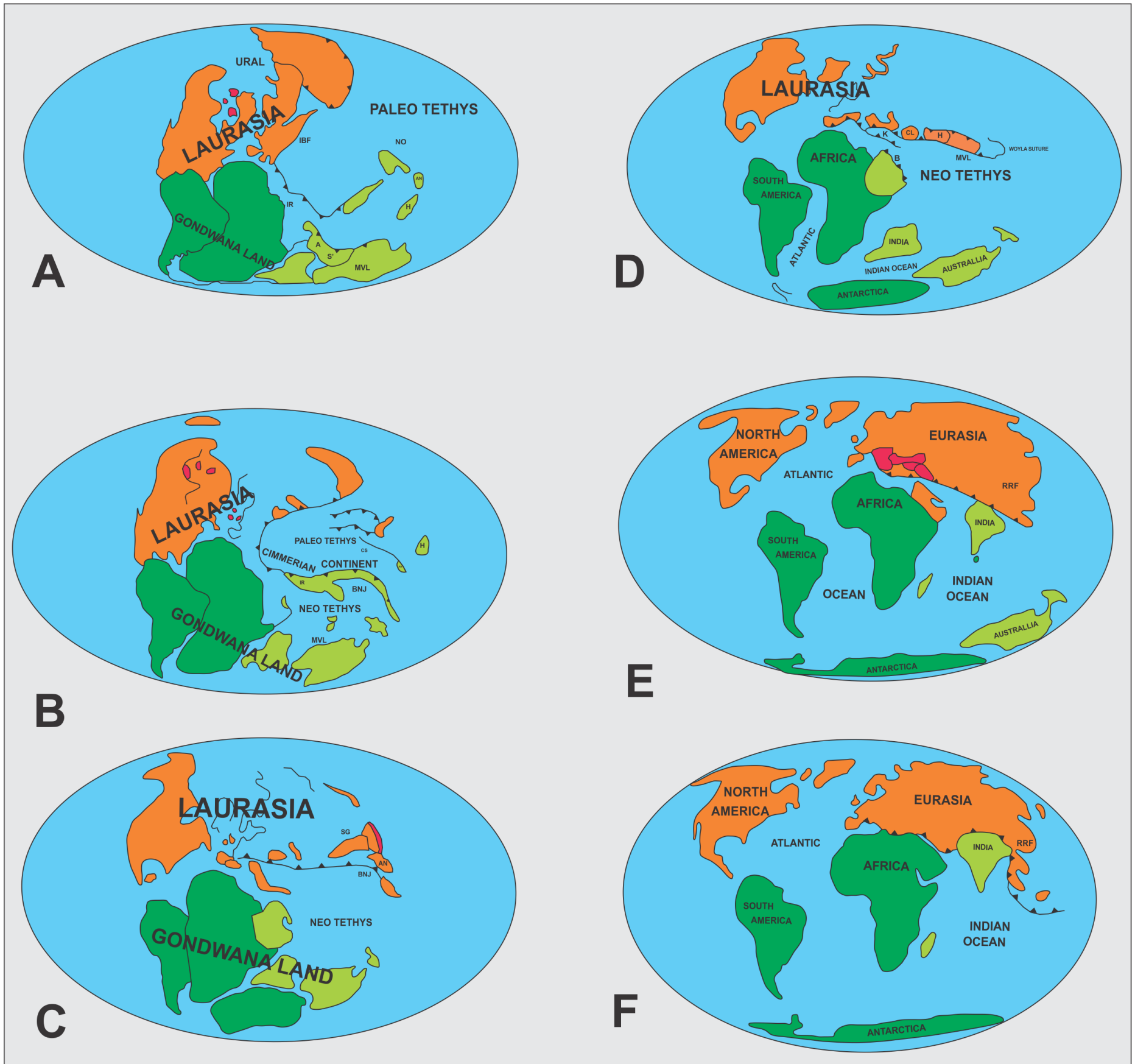


Fig. 2.1 Generalized splitting and reconstruction of continents of Gondwana and Tethyan landmass from Late Permian to Late Miocene (modified from Sengor et al., 1988). A-Afghan Block, An-Annamia, Cl-Central Iranian microcontinent, H-Himland Block, IBF-Istanbul Balkan Fragment, IR-Iranian Block, K-Kirsehir Block, MVL-Mount Victoria Land, NO-Northern Branch of Neotethys, RRF-Red River Fault, S'-Pamir West Quangtang Block, BNJ-Waser/Rushan Pshart/Banggong

## **2.4 HIMALAYAS**

The Himalayas signifies the most widespread and active collisional belt in the world. The Himalayan fold and thrust belt ranges from Burma passing through India, Nepal, Southern Tibet and into northern Pakistan (Bender and Raza, 1995). The Himalayan south directed thrust sheets produce erosional products into active foredeep that is from Ganga basin in India and Punjab Plain in Pakistan (Acharyya and Ray, 1982; Johnson et al., 1985, 2009; Raynolds and Johnson, 1985).

In the north and south verge of the Indo-Pakistan subcontinent, the most evident global feature known as the Indian Ocean and the Himalayas are produced through the process of continental drift, sea floor spreading and collision tectonics. The Indo-Pakistan's earth crust teared apart from supercontinent Gondwanaland and moved 5000 km northward through the process of geodynamic forces and finally collided with Eurasia (Johnson et al., 1976; Hodges, 2000). The subduction of the Indian's Plate northern margin has closed Neotethys and subsequent opening of Indian Ocean in south resulted in the formation of the Himalayas and surrounding mountain ranges. These ranges at its eastern and western limits forms syntaxial and sharp oroclinal bends, whereas north-south trending ramifying branches forms small less elevated mountain ranges (Kazmi and Jan, 1997). The continent-continent collision give rise to the wide Himalayan mountain ranges with quite complicated geology, where thick sequences of deformed Phanerozoic sediments and scattered thrust rocks of Proterozoic basement are in-turn intruded and affected by magmatic intrusions and metamorphic processes (Kazmi and Jan, 1997).

Different researchers gave distinctive characterization of Himalayas. DiPietro and Pogue (2004) characterized Himalayas into ten different zones but the location of Main Central Thrust raised confusion in this classification. Hodges (2000) classified

Himalayas into six different zones. Yin (2006) divided Himalayas into four distinctive units. Coward et al (1988) classified Himalayas into two distinctive units i.e Internal Himalayas having igneous and metamorphic rocks, External Himalayas constituting sedimentary units. The most accepted classification of Himalayas into four zones by Gansser (1981) is used as shown below (Fig. 2.2).

1. Tethyan Himalayas
2. Higher Himalayas
3. Lower Himalayas
4. Sub Himalayas

#### **2.4.1 Tethyan Himalayas**

The Tethyan Himalayan Zone takes place in the north of Higher Himalaya (Gansser, 1964). The Late Precambrian succession of turbidites, shelf and deltaic sediments grades into the analogous Cambrian and Early Ordovician sediments (Thankur, 1981). The Mount Everest, world's highest peak form the summit of Ordovician limestone. Towards north, the Tethyan Himalaya is constrained by the Indus Tsangpo Suture Zone, known as the Indus Suture in the northwest Himalaya. At the northern margin of the Indian Plate continental marine shelf deposits has been developed as the Tethyan sequence (Thakur, 1981).

#### **2.4.2 High Himalayas**

The high Himalaya is comprised of Precambrian Central crystalline thrust sheets, bounded by the Main mantle Thrust (MMT) or Indus Tsangpo Suture zone to the north whereas the Main Central Thrust (MCT) marks the southern position. the latter has thrusting substantially 10-15 km thick high grade metamorphic rocks over the Lesser Himalayan sequence, the MCT marks the base of these rock units (Gansser, 1981). The eastern and central portion of the Himalaya has well developed MCT but its western

extension on the far side of Kaghan is divisive in north Pakistan (Windley, 1983; Valdiya, 2002).

### **2.4.3 Lesser Himalayas**

The northern and southern extremities of this zone is marked by Main Central Thrust and MBT respectively (Windley, 1983). This zone in its western margin is composed of metasediments, volcanic and sedimentary units which is ranging in age from Eocambrian to Paleozoic. The thrust nappes of high grade gneisses obtained from Central Crystalline have been mounted on these metasediments (Valdiya, 1980, 1984, 1989, 1997; Sinha, 1981). Chiefly the Lesser Himalaya is formed by Upper Proterozoic to Lower Cenozoic terrigenous sediments derived from Indian passive margin and is interpolated with granites and acidic volcanics (Frank et al., 1977). Along the MBT these low grade sediments are thrust over the Sub-Himalaya. The Lesser Himalaya seems as tectonic window within the High Himalaya Crystalline Sequence. The southern peripheral portion of Lesser Himalaya (LH) in the form of sedimentary zone occurs along Kaghan, Pir Panjal, Hazara Kashmir Syntaxis and thrust over the southern Hazara, Kala chitta and Attock Cherat Ranges (Seeber and Armbruster, 1979; Seeber et al., 2013).

### **2.4.4 Sub Himalayas**

The foot hills of the Himalayan mountain ranges from Punjab to Assam form the Sub-Himalayan zone, constrained by the Main Boundary Thrust (MBT) to the north and Himalayan Frontal Fault (HFF) to the south (Valdiya, 2002). The Salt Range and Potwar Plateau is present within this zone. It has folded sequence of Neogene terrestrial sediments consisting of Rawalpindi Group and Siwaliks Group which are in-turn covered by Alluvium of Punjab Plains. These alluvium in the foot hills area are dissected by the traces of an active fault of Himalayan Frontal Fault (Yeats et al., 1984).

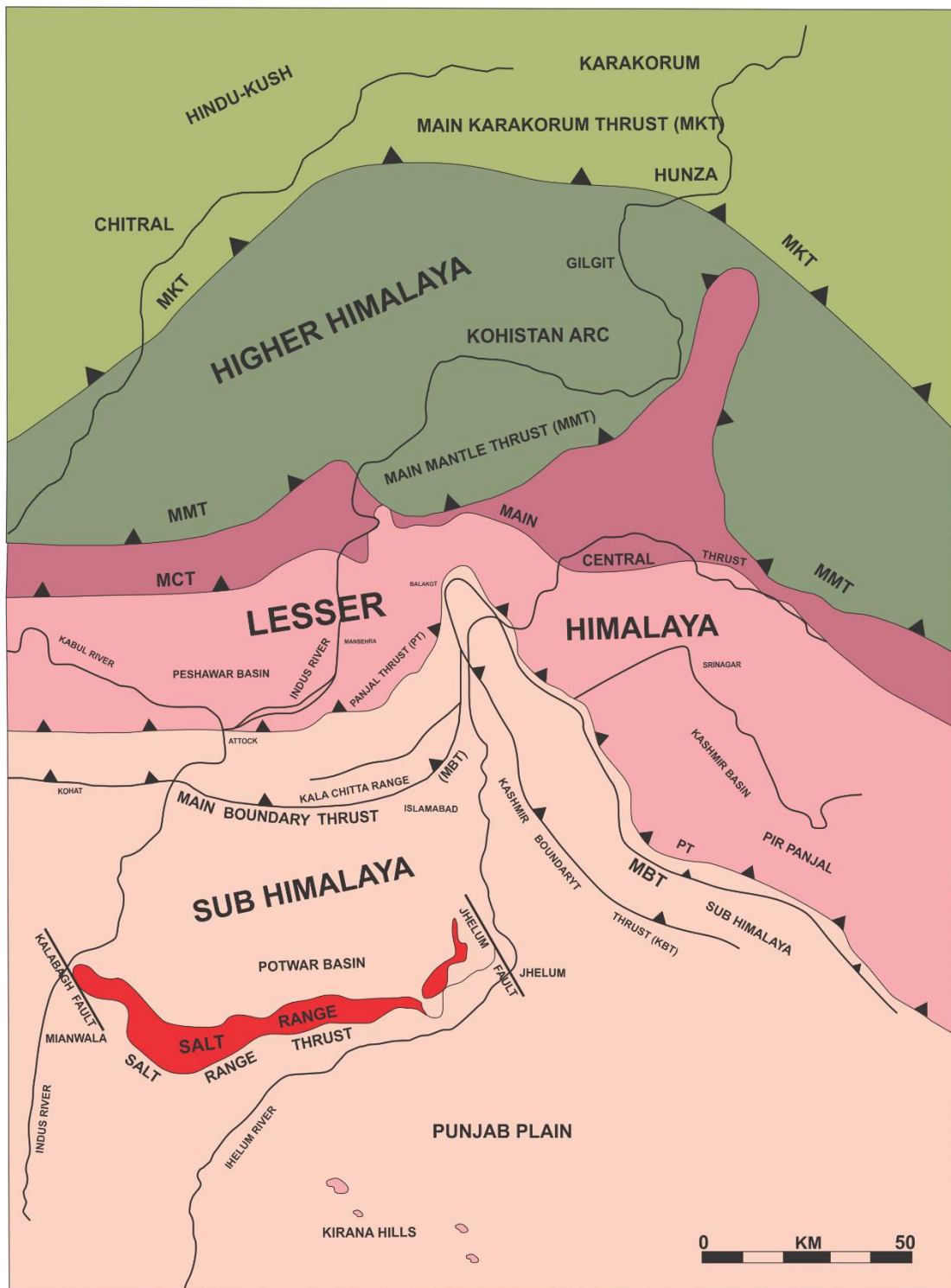


Fig. 2.2 Generalized tectonic map of north Pakistan, showing subdivision of Himalayas (modified after Gansser, 1981; Kazmi and Rana, 1982).

In Pakistan the Sub-Himalayas can be segmented longitudinally into east and west zones that is Kashmir and Punjab zone respectively. In a transverse section the Foreland is divided into the following zones (Ghazi et al., 2014).

1. Northern Potwar/Rawalpindi zone
2. The Soan Zone
3. Deformed Punjab platform to the south
4. Punjab Zone (known as Salt Range)

## **2.5 SALT RANGE**

The Salt Range shows step by step structural variation and leads to their different level of tectonic development. These variation in the structural features are actually the result of incompetent formation in the stratigraphic sequence. The Salt Range contains classical exposures of Eo-Cambrian and Paleozoic sequence and is basically a complex salt anticlinorium having series of anticlines, while Salt Range Thrust splits the Eo-cambrian sequence from the Proterozoic sequence. Its central part is wide between Khewra and Warcha whereas thins out towards east and west, respectively.

The Salt Range is characterized by two regional scale unique features; the presence of thick salt deposits and the occurrence of regional and local structures, the later non-depositional processes ranges in age from Precambrian to Pleistocene (Gee, 1989). The northwest trending Kalabagh Re-entrant in the westward direction is terminated from Trans-Indus Ranges through Kalabagh Fault, whereas the Salt Range Thrust marks its southern boundary (Sarwar and DeJong, 1979; Kazmi and Rana, 1982; Yeats et al., 1984; Coward et al., 1986; Gee, 1989; Yeats and Lawrence, 1984). This thrust becomes blind and decreases towards the eastern periphery of the Salt Range (Krishnan, 1966; Yeats et al. 1984). The southern boundary of the Salt Range is marked by the Jhelum Plain, where the southernmost ridges of about 800-900 m above plains shows

substantial deformation during Himalayan fold and thrust belt in Pakistan, though its northern periphery is passing progressively through gentle folds and thrusts of the Potwar Basin. The Salt Range and Potwar Plateau has been interpreted as a thrust and considerably rotated block along a decollement that overrides basement metamorphic rocks (Gansser, 1964; Crawford, 1974; Seeber and Armbruster, 1979; Yeats et al., 1984; Yeats and Lawrence, 1984; Lillie et al., 1987; Wadia, 1994; Grelaud et al., 2002; Seeber et al., 2013).

Krishnan (1966) has made four divisional zones for the Salt Range/Potwar Plateau i.e the Salt Range, Soan Syncline, Anticlinal Zone and Faulted Zone. The scarp slope of the Salt Range in the southernmost area has thick evaporate to clastics exposed stratigraphic sequence. In the southeast quadrant of the Salt Range within the Punjab Plains, the Precambrian outcrops of the Sargodha High having Himalayan trend interrupts the northward sloping Indian Shield (Farah et al., 1977; Yeats and Lawrence, 1984). The Jhelum River in the northern portion of Punjab Plain flows towards west-southwest direction and drains the Alluvial fans to the Himalayan Foredeep, these deposits are in-turn dissected by the Salt Range Thrust (Yeats et al., 1984). Structurally the Salt Range consists of wide synclines and dissociated by narrow sharp crest anticlines (Gardeszi and Ashraf, 1974; Yeats and Hussain, 1987; Krishnan, 1966). In regard to the faulting, the steep slopes of gullies consists of numerous small scale normal faults in the style of step faulting (Krishnan, 1966; Gardeszi and Ashraf, 1974).

## **2.6 Structural style**

The Salt Range is complex in nature and displays three fundamental structural styles

1. Compressional deformation (Thrusting and Folding)
2. Transform deformation (Strike faults)
3. Extensional deformation (Normal faults)

### **2.6.1 Compressional deformation**

The compressional deformation towards the south of Himalayan orogeny as a result of thrusting leads to uplifting of the Salt Range (Krishnan, 1966). The complete stratigraphic sequence along the youngest thrust has thrust older units over the Late Quaternary recent deposits (Baig and Lawrence, 1987). Though these structures are masked by the younger conglomerate deposits, but at few places obvious e.g at the eastern end of Salt Range. Near the foot hills, the Cambrian successions and the Precambrian evaporites are thrust over Late Tertiary sequence. An apparent reverse faulting is present at Kalabagh near Indus River (Yeats et al., 1984).

The clear evidence of recent earth's movement at several localities near the foot scarp are shown by the local outcrop of Late Pleistocene conglomerates overthrust by Paleozoic sequence (Yeats et al., 1984). Moreover narrow horsts bounded by high angle faults bring Salt Range Formation to the surface and is easily eroded, yet typical sections of Nilawahan, Khewra and Warchha gorges are found in deep gorges formulated through these horsts. The presence of detached zone beneath the Potwar Basin and Salt Range is supported by seismic and gravity data (Gee, 1989; Grelaud et al., 2002).

### **2.6.2 Transform deformation**

The transform deformation in the Salt Range produced strike slip faults. Two most important strike slip faults at the eastern and western margin of Salt Range is present, namely the Jhelum Fault and Kalabagh Fault. The mode of movements for the Jhelum fault and Kalabagh fault is Sinistral and Dextral respectively (Drewes., 1995). The south directed movement of the Salt Range is eased with the help of the Jhelum and Kalabagh fault, Moreover some tear faults that are high angle strike slip faults of local scale has facilitated in the case (Davis and Reynolds, 1996).

### **2.6.3 Extensional deformation**

The Salt Range shows extensional deformation in the form of normal faults. These salt related tectonics activity has brought the soft incompetent lithology of Salt Range Formation upward, known as “Salt Diapirism”

### **2.7 Subdivisions of Salt Range**

Salt Range on the basis of structural style, sedimentation and stratigraphy has been divided into three portions (Fig 2.3).

- 1. Eastern Salt Range**
- 2. Central Salt Range**
- 3. Western Salt Range**

#### **2.7.1 Eastern salt range**

The eastern portion of the Salt Range is laying between Jhelum and Khewra (Gee, 1989). The physique of the Salt Range in its eastward direction has been diverged into two slender northeast trending ridges known as the Chambal-Jogi Tilla and Dil-Jabba Ridges. The former embraces steeply dipping monocline which is surrounded by thrust and reverse faults, however the Dil-Jabba Ridge is structurally steeply dipping anticline that is crossed by Dil-Jabba Domeli thrust (Kazmi and Jan, 1997). The structural style in this area is controlled by northeast-southwest trending folds. Whereas the eastern margin of Jhelum Re-entrant is dominated by northwest-southeast trending folds. Based on stratigraphic and seismic investigations over Eastern Salt Range and Potwar Plateau, few imperative attributes are;

- I. Tight anticlinal structures are separated by open broad synclines. The axial zone of the anticlines dips from steep to overturn (Martin, 1962; Raynolds and Johnson, 1985).

- II. The north dipping gentle basement fault in the eastern Salt Range has shown that regional decollement designate within Salt Range Formation, it has not penetrated upward into molasses as indicated by thrusting and disharmonic folds (Davis and Engelder, 1985; Lillie et al., 1987; Butler et al., 1987). The salts squeezed and moved from synclines to the centre of nearby anticlines. These folds are penetrated by hinterland and foreland dipping blind thrusts.
- III. The common deformational structural styles are fault propagation folds, pop-up structures and triangle zones (Butler et al., 1987).

### **2.7.2 Central Salt Range**

The region laying in between Khewra and Warcha is marked as the central Salt Range (Gee 1989). The structural style is classified into the following five steps

- I. Axis of the minor folds is almost in parallel position to the range front
- II. High angle faults
- III. Insignificant faulting within the allochthon
- IV. Salt diapiric structures
- V. Transform zones or strike slip lineaments

The presence of minor east-west oriented folds advocate the same north south generated compressive stresses that has uplifted the Salt Range Thrust sheet. The greater part of this buckling gives off an impression of being concentric. Even though nonparallel buckling takes place locally, close to the range front. The amount of folding increases towards the front thrust in the south direction as well in the eastern Salt Range. In the central Salt Range three active strike slip faults gives the impression of tear faults and propagate obliquely to MFT (Yeats et al., 1984).

### **2.7.3 Western salt range**

The western Salt Range is marked in the region between the Warchha and Kalabagh (Gee, 1989). This Northwest trending change in the Salt Range towards west of Warchha matches with the strike variation of the exposed rock units and associated complex fault features (Gee, 1989). The Kalabagh Fault Zone has sharply terminated the Salt Range Thrust and is further extended 20 km to the north of Indus River, prior to its westward bend along north dipping reverse fault (McDougall and Khan, 1990; McDougall, 1989). The Salt Range Formation in the western part of the Salt Range and Kohat Plateau occurs in the form of confined diapiric intrusions especially along right lateral tear faults and high angle faults. The younger Siwaliks strata in a fold belt of northern Salt Range is overlain by late Quaternary gravels with an angular unconformable contact. These gravels of Kalabagh Formation are in-turn buckled and folded (Yeats et al., 1984).

### **2.8 Salt Range Thrust**

This fault turns its position at the southern verge of the Salt Range and lies in between Indus and Jhelum River. The older stratigraphic sequences of the Salt Range has been moved over less distorted Tertiary age sequence of the Jhelum Plain. Generally this thrust is concealed by recent conglomerate but exposed near Jalalpur and Kalabagh that shows thrusting Paleozoic rocks over Neogene/quaternary deposits of Jhelum Plain (Gee, 1945, 1989; Yeats et al., 1984). The SR/PP through Seismic, gravity and drill hole data shows that they are underlain by decollement zone within Eocambrian evaporates. The movement of a large mass of SR/PP towards south over Jhelum Plain has led decoupling of strata because of Salt Range Thrust, thus the surface articulation of the Salt Range represents forefront of a decollement thrust (Lillie et al., 1987).

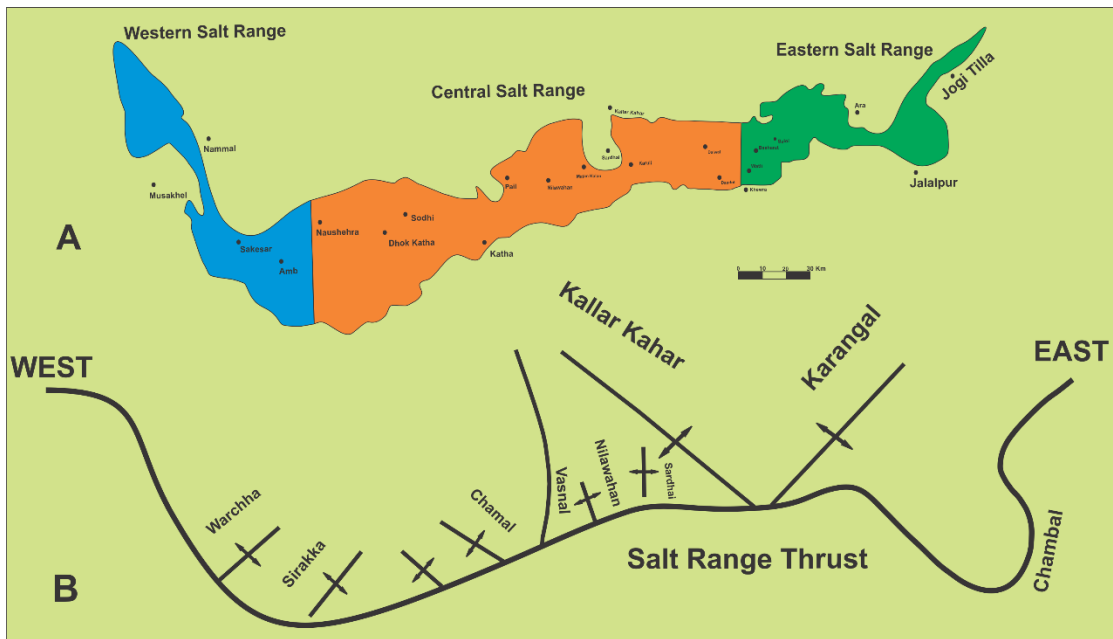


Fig. 2.3 (A) shows schematic subdivisions of the eastern, central and western Salt Range (modified after Gee, 1989) (B) shows regional structural trends in the Salt Range.

**3.1 Introduction**

The Salt Range is present at the southern margin of the Potwar basin, main Himalayan ranges, Pakistan. Historically the name of the Salt Range is derived from the huge salt deposits stratigraphically known as Salt Range Formation. The Salt Range in its central part is wide and thins out to the East and West. The geology of the range is easily accessible along the road side with few prominent gorges providing the excellent location for the study of sedimentary sequence of the Salt Range. The most well-known gorges are Nilawahan, Khewra, Nammal, Warcha, and Chichali gorges. The Salt Range has two unique regional scale characteristics features: the first one is the presence of thick saline series and the second one is the regional and local scale non-depositional proceedings ranging from Eocambrian to Plietocene (Gee, 1989).

In the Salt Range oldest and youngest stratigraphic sequence are the Salt Range Formation and recent conglomerates respectively. The basal portion of the oldest Eocambrian rock units is obscure, but the subsurface data has established the presence metamorphic rocks at the base of Salt Range Formation (Gee, 1989). The widespread exposed stratigraphic successions of the Salt Range and surrounding regions is interposed by gaps of local and regional unconformities.

**3.2 Unconformities**

The following described stratigraphy of the Salt Range is bounded by four unconformities (Fig 3.1); The basal eroded basement rocks is non-conformably overlain by the Neoproterozoic Salt Range Formation (Kazmi and Abbasi, 2008). The Indo-Pakistan landmass was a raised landmass at the end of Proterozoic, this uplifting caused

extensive fracturing, rifting and subsidence in the development of numerous sedimentary basins (Kazmi and Abbasi, 2008).

The shifting of non-marine and marine period resulted in the arid, restricted depositional environment for the Salt Range Formation upon the Proterozoic rocks. The long Hiatus gap at the end of Cambrian in the Salt Range and Potwar Plateau is marked by the absence of Early Ordovician to Late Carboniferous period. This Hiatus gap is represented by the predominant boulder bed of Tobra Formaton, an angular unconformity present at the base of Permian (Jadoon et al., 1997; Kazmi and Abbasi, 2008; Bender and Raza, 1995). The Eastern and Central Salt Range/Potwar Plateau has a paraconformity represented by a hiatus gap between Mesozoic shelf sediments and Paleozoic sequence (Jadoon et al., 1997; Bender and Raza, 1995; Kazmi and Abbasi, 2008). In the course of the Oligocene time, continental collision leads to the uplifting of north Pakistan and subsequent erosion (Kazmi and Abbasi, 2008). This unconformity shows the time break for the start of fluvial and end of marine sedimentation (Kazmi and Abbasi, 2008).

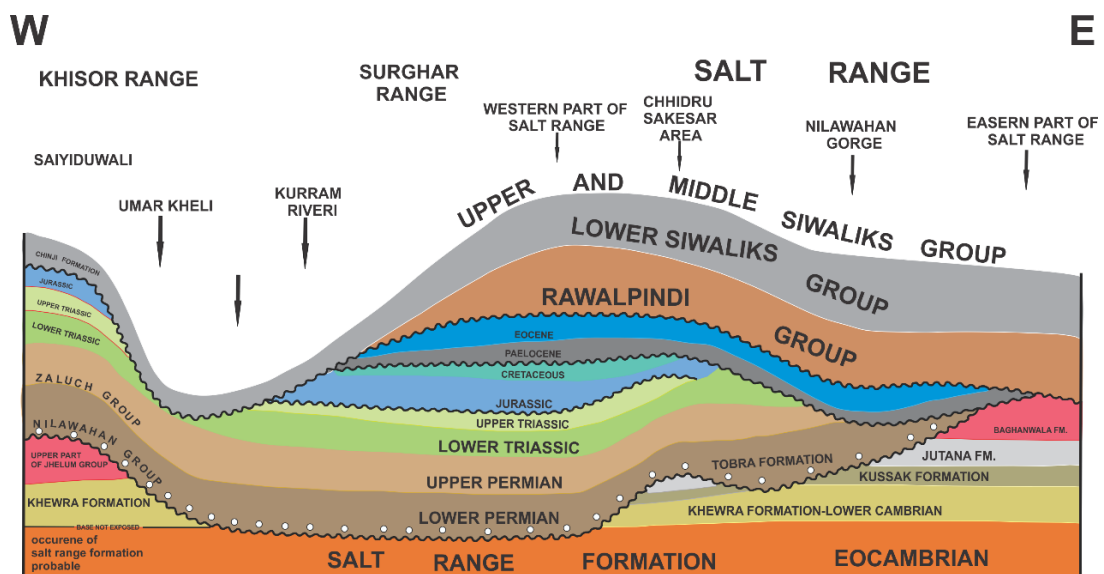


Fig 3.1 Pictorial section of the Upper Proterozoic to Tertiary sequences of the Salt Range and Khisor Range (after Gee, 1989, as cited in Bender and Raza, 1995; Kazmi and Abbasi, 2008)

### **3.3 Salt Range sequence and environment**

The Precambrian Salt Range Formation is extensively distributed in the Salt Range and represents a decollement zone between underlying basement and overlying Cambrian age rocks. The evaporitic sequence of the Salt Range Formation was developed in an arm of Tethys Sea that is cut off from the main body of sea and endorsed the shape of lake due to regression (Calkins et al., 1975; Latif, 1970). The development of evaporites under restricted marine environment was outstretched till Hazara (Calkins et al., 1975; Latif, 1970).

The Cambrian age rocks of the Salt Range represents variable cycles of sedimentation as Khewra, Kussak, Jutana and Baghanwala Formation, collectively known as the Jhelum Group (Yeats and Hussain, 1987; Noetling, 1901; Fatmi et al., 1984; Fatmi, 1973). These rocks are mainly shallow marine clastics and shows warm climatic condition (Shah, 1977). They are exposed along southern margin of the Salt Range. The Permian sequence in the Salt Range has been divided into the lower and upper units known as Nilawahan and Zaluch group. The Nilawahan Group shows continental environment and marine conditions (Ghazi et al., 2012). The Zaluch Group of the Upper Permian is developed in the Western Salt Range and is considered as highly fossiliferous shallow shelf carbonate deposits.

The Triassic sequence is well exposed in the Western Salt Range and consists of Mianwali, Tredian, Kingriali Formation collectively known as Musa Khel Group (Fatmi, 1973; Shah, 1977). The lower Triassic Mianwali Formation has underlying unconformable contact relationship with Upper Permian age rocks (Balme, 1970; Kummel and Teichert, 1970; Mertmann, 2003). During most of the period shallow marine conditions prevailed. A break in the deposition has occurred representing major unconformity in the Late Triassic to Early Jurassic time. The Jurassic sequence of the

Salt Range is comprised of Datta, Shinawri, Samana Suk Formation collectively known as Baroch Group (Fatmi, 1973). The Jurassic period represents diverse environments of sedimentation ranging from continental, deltaic to high energy oolite or reef. The start of the Jurassic is marked by deltaic deposits of Datta Formation followed by the marine transgression till Middle Jurassic resulting in the deposition of Shinawari and Samana Suk Formation (Fatmi and Haydri, 1986).

The sloping shelf of Punjab Platform and Eastern Salt Range shows lack of Cretaceous sedimentation which marks the boundary of final regression in Upper Cretaceous (Fatmi and Haydri, 1986). The Chichali Formation was deposited in the reducing environment in the period of Upper Jurassic and Lower Cretaceous followed by the shallow marine conditions for Lumshiwai Formation of the Lower Cretaceous. Near the end of Middle Jurassic regression and emergence process were followed by shallow marine clastic sedimentation in Late Jurassic and Early Cretaceous period (Fatmi, 1973; Hallam and Maynard, 1987). The last part of Cretaceous period observed regression of Tethys Sea to the northwest. The land surface at the end of Mesozoic time is comprised of Lower Triassic and Upper Permian formations over middle part of the Salt Range.

Before the onset of extensive marine transgression at Paleocene time, an impure bauxite and laterite formed due to the weathering of land surface at various places. The uplift, erosion and weathering of the land surface in the Late Cretaceous time were kept on by the Nummulitic marine transgression during extensive subsidence in the Early Tertiary time. In the Salt Range Makarwal Group deposition initiated with the variable sequence of Hangu Formation at the base subsequently followed by Lockhart and Patala Formation. During the Late Paleocene time, at some part of eastern and central Salt Range developed lacustrine environment for the deposition of subbituminous coal within Patala Formation.

The Chharat Group consisting of Nammal, Sakesar, Chorgali Formation showed stable marine environment in the Eocene time. At the end of Paleocene, another regression process of Tertiary age is apparent in different regions of the Salt Range. The predominant calcareous-argillaceous depositional sequence in the marine environment sustained within the upper part of Indus Basin. The Eocene strata rich in larger forams confirms the shallow oceanic conditions. .

The epirogenic movements resulted in the uplift of the area above sea level as signified by the missing of Upper Eocene strata in the Salt Range and had continued with erosion during the Oligocene time. Subsequent marine regression resulted in the lacustrine and fluvial environments for the deposition in the Late Eocene to Oligocene time. Until Late Pliocene, clastic sedimentation prevailed with no regional unconformities. The Salt Range stayed comparatively uplifted during Early Miocene time. The Murree and Kamli Formation collectively known as Rawalpindi Group represents fluvial and fluvio-deltaic environments respectively, which specify the start of substantial Himalayan uplift (Johnson et al., 1985).

The Siwaliks Group collectively known for Chinji, Nagri, Dhok Pattan and Soan Formation are the erosional production of south directed Himalayan thrust sheet, representing nonmarine time transgressive mollase facies in Plio-Pleistocene time (Yeats and Hussain, 1987; Wells, 1984). The Lei conglomerate is deposited as the valley fill having Eocene clasts and provide significant timing evidence for basal age of about 1.9Ma (Raynolds and Johnson, 1985).

### **3.4 Stratigraphy of the study area**

The Salt Range and surrounding areas have been divided into three zones on the basis of wide-ranging complex stratigraphy. The three zones from the north to south are the Potwar Plateau, Salt Range and Punjab Plain. The Potwar and Salt Range is separated

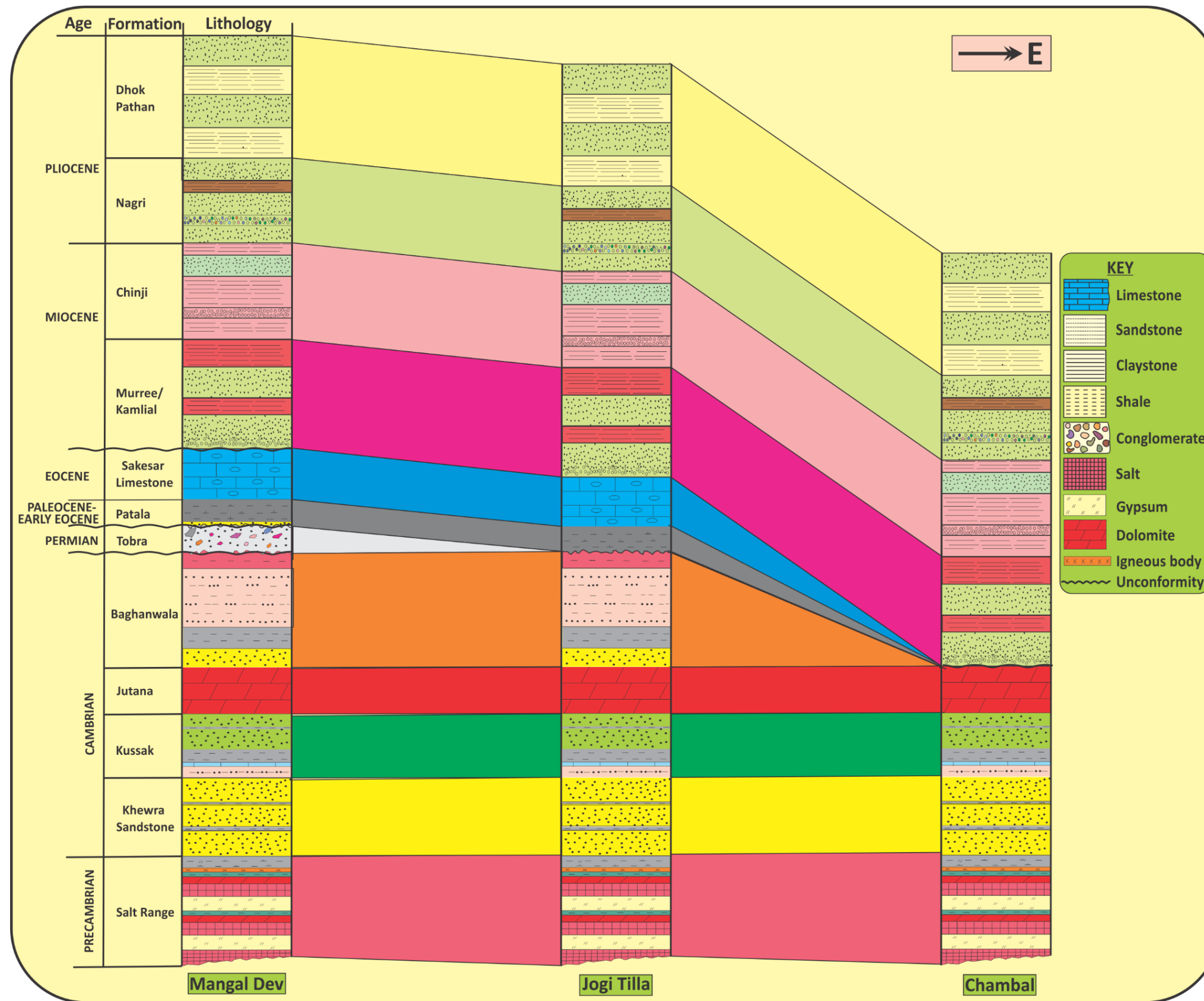


Fig.3.2 Stratigraphic column of the study area showing correlation between Mangal Dev, Jogi Tilla and Chambal Structural Ranges.

from one another due to the presence of monocline related to subsurface normal fault. The Salt Range is separated from the Punjab Plain by the Salt Range Thrust. The stratigraphic record of the study area ranges from Precambrian to Recent with major unconformities (Fig 3.2). The stratigraphic setup of the eastern salt range is described below;

## **Neoproterozoic**

### **3.4.1 SALT RANGE FORMATION**

The name Salt Range Formation has been designated by Asrarullah in (1976) for the type section located in the Khewra Gorge, Eastern Salt Range. The formation has been divided into the following three members.

#### **3.4.1.1 Sahiwal Marl Member**

This member consists of bright red coloured marl with scarce amount of gypsum and dolomite. The Khewra Trap is reported from the upper part of formation which is also known as Khewrite, a highly weathered six meters thick igneous body consisting of purple to green coloured radiating needles of pyroxene.

#### **3.4.1.2 Bhandar Kas Gypsum Member**

This member consists of dull red coloured marl with some amount of salt seams and about 10 m thick gypsum on the top.

#### **3.4.1.3 Billianwala Salt Member**

This member consists of red coloured ferruginous marl and thick seams of salt.

The formation is widely distributed in the Salt Range and Potwar area. The lower contact of the formation is non-conformable with metamorphic rocks of Precambrian age whereas the upper contact of the formation is conformable with the Khewra Sandstone. The age on the basis of stratigraphic superposition is considered as Late Precambrian.

## **Cambrian**

### **3.4.2 Jhelum Group**

The Cambrian sequence for the Jhelum group in the study area consists of (Fig 3.3, 3.4);

4. *baghanwala formation*

3. *jutana formation*

2. *kussak formation*

1. *khewra sandstone*

#### **3.4.2.1 Khewra Sandstone**

The name Khewra Sandstone was proposed by Fatmi (1973) and later on accepted by the Stratigraphic Committee of Pakistan. Khewra Gorge present near Khewra Town, Salt Range, Punjab is considered as the type locality.

Lithologically the formation consists of purple to brown, yellowish brown, fine grained, thick bedded to massive sandstone. The lower part of the formation is flaggy, red shale. Sedimentary structures like mud cracks, ripple marks etc are common features. The formation is widely distributed throughout Salt Range.

The lower and upper contact of the formation is conformable with Salt Range Formation and Kussak Formation, respectively, both the contacts are sedimentary in nature. Few trace fossils are present which are considered as Trilobite Trails in the formation, the above Kussak Formation is of Late Early Cambrian suggesting an Early Cambrian age to the underlying Khewra Sandstone.

#### **3.4.2.2 Kussak Formation**

The name Kussak Formation of (Fatmi, 1973) was accepted by the Stratigraphic committee of Pakistan. The type locality of the formation is present in the eastern part of Salt Range, Kussak Fort, Punjab.

The lithologic variation shows greenish-grey, glauconitic micaceous sandstone, greenish grey siltstone, interbedded with oolitic, arenaceous dolomite and light grey dolomite. Various layers of intraformational conglomerate and pink gypsum lenses at the top are present. The formation is extensively distributed throughout Salt Range with good exposure at the eastern part.

The lower part of the formation is in conformable relationship with Khewra Sandstone while the upper contact is conformable with Jutana Formation. The lithological unit in this formation is fossiliferous and has yielded “*Neobolus warthi*”, “*Botsfordia granulate*”, “*Lingulclla wanniecki*”, “*L. fiichsi*”, “*Hyolithes wynei*”, “*Redlichia noetlingi*”. The age on the basis of these faunas are considered as Early Cambrian.

#### **3.4.2.3 Jutana Formation**

The name for this units was formalized and accepted by the Pakistan Stratigraphic Committee, as Jutana Formation. The village of Jutana in the eastern Salt Range is considered the type locality.

Lithologically the lower part of the formation consists of light green, massive, hard sandy dolomite whereas the upper part constitutes light green to dirty white massive dolomite, at places brecciated dolomite.

The lower contact of the formation is conformably marked by Kussak Formation while the upper contact is conformable with Baghanwala Formation. The formation is well developed in the Eastern Salt Range but missing the Western part. In the middle part of the formation within shale unit some fossils were collected including *Lingulella fuchsia*, *Botsfordia granulate*, *Redlichia noetlingi* and gastropods. The presence of these fossils suggest a Late Early Cambrian to Early Middle Cambrian.

#### **3.4.2.4 Baghanwala Formation**

The name “Pseudomorph Salt Crystal Zone” was given by Wynne (1878) and later on approved as Baghanwala Formation by the Stratigraphic Committee of Pakistan. It is located near the village of Baghanwala, a section of Eastern Salt Range.

The formation is comprised of red coloured shale and clay with alternating flaggy sandstone beds showing variety of colours interms of blue, green, pink and grey at the lower part of the formation. The common sedimentary structures are ripple marks, mud cracks and Pseudomorph Salt Crystals, these structures are present along the bedding planes.

The absence of fossils record and sedimentary structures confirms lagoonal environment of deposition. The formation is well developed in the Eastern Salt Range. The lower and upper contact of the formation is conformable with the Jutana Formation and Unconformable with the Tobra Formation respectively. Based on the contact relationship, the age is considered as Early Middle Cambrian.



Fig. 3.3 (A) shows the contact between Khewra Formation, Kussak Formation and Jutana Formation having diapers of Salt Range Formation at the base near Jalalpur Sharif village. (B) Shows northward dipping contact between Salt Range Formation, Khewra Formation, Kussak Formation and Jutana Formation at Baghanwala village.

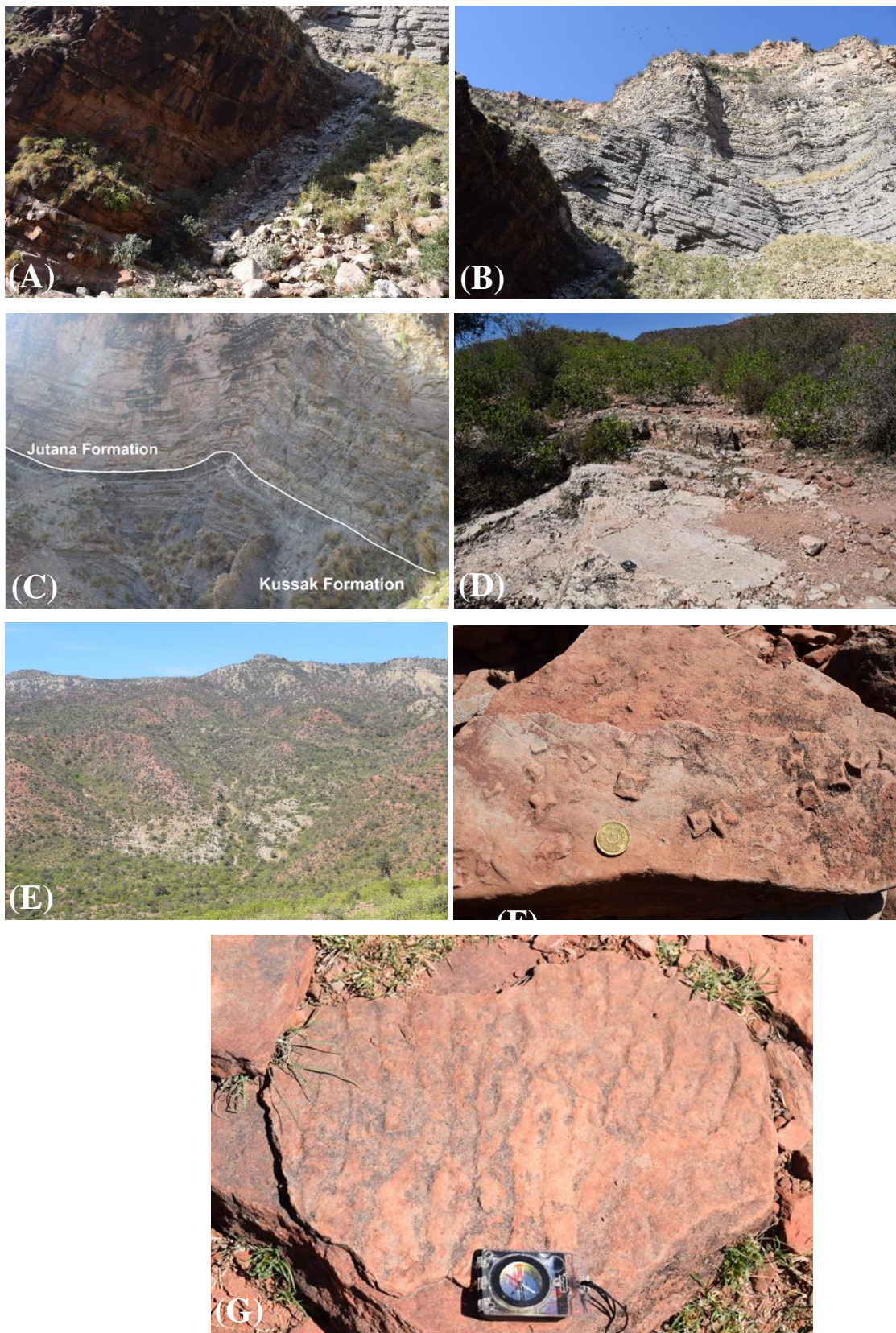


Fig. 3.4 shows the contact between Jhelum Group rocks. Red coloured clays shows Baghanwala Formation having “Salt Pseudomorph Crystals” and “Ripple marks” (E, F, G).

### **3.4.3 Permian**

The Permian units of the Salt Range are known for its richness in faunas. The Permian Strata of Nilawahan and Zaluch Group disconformably overlies the Cambrian Rocks of Jhelum Group while the upper contact with Triassic Rocks is also unconformable. In the study area, the Tobra Formation of Nilawahan Group have upper contact with Paleocene rocks, remaining units of both ages are missing (Gee, 1989).

#### **3.4.3.1 Nilawahan group**

The formations of the Nilawahan Group are;

4. Sardhai Formation (missing)
3. Warcha Sandstone (missing)
2. Dandot Formation (missing)
1. Tobra Formation

#### **3.4.3.2 Tobra Formation**

It shows mixed lithology which are divided into three facies (Fig 3.5);

##### ***1. Tillite Facies***

This facies represents marine sandstone having Eurydesma, Conularia fauna and are exposed in the Eastern Salt Range.

##### ***2. Freshwater Facies***

This facie represents alternating units of shale, siltstone with spore flora and few or no boulder. It is exposed in Central Salt Range.

##### ***3. Complex Facies***

This facie represents mixed lithology of sandstones and boulders. It is outcropped in the Khisor and western part of the Salt Ranges.

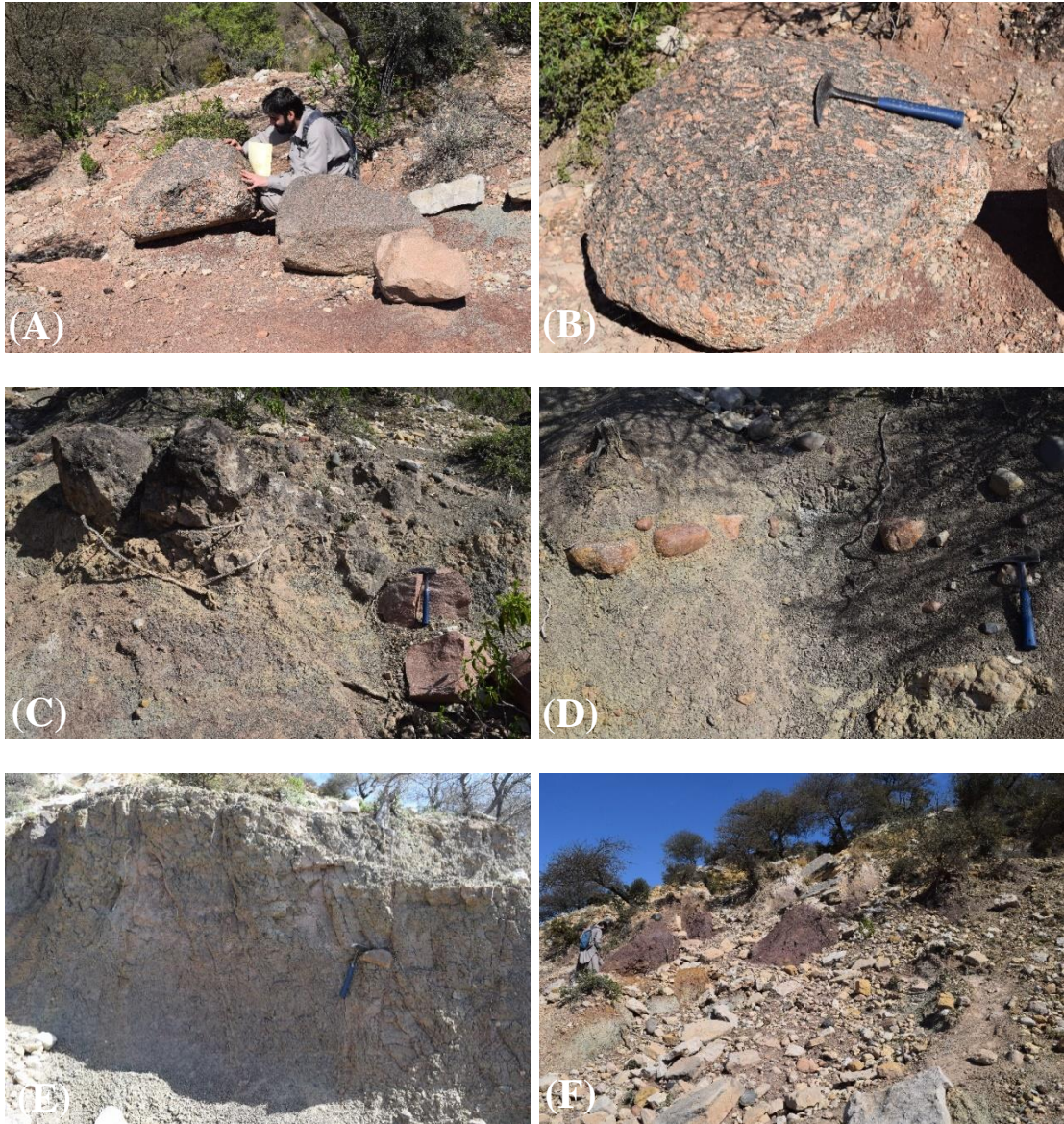


Fig 3.5 Shows three different facies of Tobra Formation.

The lower contact of the formation is unconformable with Jhelum Group rocks. The upper contact with Dandot Formation is conformable. The age of the formation on the basis of *Striatopodocarpites* and *Ptotohaploxypinus* is considered as Early Permian.

## **Paleocene**

### **3.4.4 Makarwal group**

The Paleocene Era is well preserved in the entire Salt Range. The Paleocene rocks are represented by Makarwal Group. A stratigraphic unit of the group exposed in the study area is discussed briefly (Fig 3.6);

3. *Patala Formation*

2. *Lochart Limesrone (missing)*

1. *Hangu Formation (missing)*

#### **3.4.4.1 Patala Formation**

The name of Patala Formation has been formally approved by the Pakistan Stratigraphic Committee for the section exposed in the Salt Range of Patala Nala.

The formation consists of shale and marl with minor amount of sandstone and limestone. Locally coal seams of economic value are being present and mined. The shale is characterized by greenish grey colour, at some places they are carbonaceous and calcareous in nature with marcasite nodules. The limestone is light grey to white and nodular. The sandstone are present in the upper part of the formation as subordinate interbeds characterized by yellowish brown colour and calcareous nature.

It is widely distributed in different areas of Hazara and Kohat-Potwar. The lower contact of the formation is conformable with Lockhart Limestone. The upper contact is marked as conformable and transitional with the Nammal Formation. The formation is rich in the fossil record of Foramaniferas, Molluscs and Ostracodes, which assigned Late Paleocene age.

## **Eocene**

### **3.4.5 Chharat Group**

The formations included in this group consists of;

3. *Chorgali Formation (missing)*

2. *Sakesar Limestone*

1. *Nammal Formation*

#### **3.4.5.1 Nammal Formation**

The name Nammal Limestone and Shale was used by Gee (in Fermor, 1935) and later on accepted by Stratigraphic Committee of Pakistan as Nammal Formation for the section exposed in the Nammal Gorge.

The formation lithologically consists of alternating units of shale, marl and limestone. The shale is grey to olive green in colour while limestone and marl are light grey to bluish grey in colour. At places limestone is argillaceous. The formation is widely distributed throughout Salt Ranges and Surghar Ranges. The lower and upper contact of the Nammal Formation is transitionally marked by Patala Formation and Sakesar Limestone respectively. The formation consists of abundant fossils of smaller and larger foramanifers, molluscs which has suggested an Early Eocene age (Fig 3.6).

#### **3.4.5.2 Sakesar Limestone**

Gee (in Fermor, 1935) introduced Sakesar Limestone and later this name was approved by the Pakistan Stratigraphic Committee. The type locality for the Sakesar Limestone is chosen as the Sakesar Peak, Salt Range.

Lithologicaly Sakesar Limestone dominantly consist of limestone with minor amount of marl. The limestone is light grey to cream, nodular and usually massive with chert in the upper part of the formation. The marl is light grey to creamy coloured and make continuous horizon near the top. This wide distributed formation in the Salt Range and

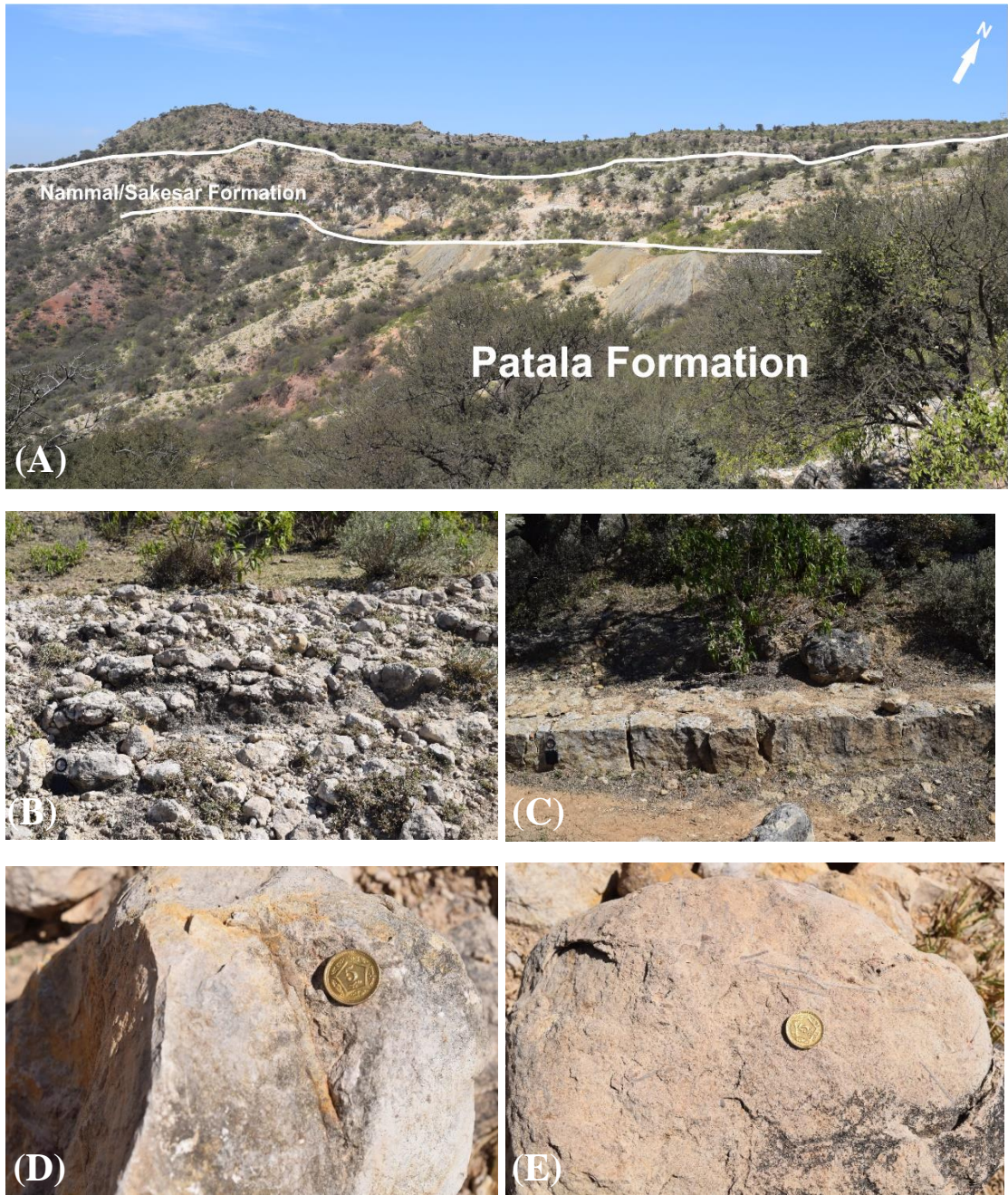


Fig. 3.6 (A) Shows NW looking regional view of Nammal/Sakesar limestone with low laying Patala Formation. (B, C, D, E) shows nodular limestone observed in Nammal/Sakesar limestone of Chharat Group.

Surghar Range has lower conformable contact with the Nammal Formation, whereas the upper contact is conformable with the Chorgali Formation. The rich accumulation of foramanifers, echinoids, and molluscs has suggested an Early Eocene age (Fig 3.6).

### **Miocene-Pliocene**

These age rocks are divided into two groups;

#### **3.4.6 Rawalpindi Group**

2. *Kamlial Formation (missing)*

1. *Murree Formation*

#### **3.4.7 Siwaliks Group**

4. *Soan Formation (missing)*

3. *Dhok Pattan formation*

2. *Nagri Formation*

1. *Chinji Formation*

##### **3.4.6.1 Murree Formation**

Pilgrim (1910) named the following compositional units as Murree Formation and later on accepted by the Stratigraphic Committee of Pakistan. The Dhok Maiki section of District Attock serves as the type locality.

Murree formation consist of repetitive stratigraphic sequence of dark red, purple clays and greenish grey to purple grey sandstone with intraformational conglomerate. The lower part of the formation has greenish grey, calcareous sandstone and conglomerates rich in larger foraminifera of Eocene age (Fig 3.7).

The formation is broadly distributed in Kohat Potwar Province. The lower contact of the formation is unconformable with Nammal/Sakesar Formation of Eocene age. The upper contact of the Murree Formation (Rawalpindi Group) is overlain by Chinji



Fig.3.7 (A) shows north-northeast looking regional view of Murree Formation. (B) Shows dark grey coloured sandstone beds of Murree Formation.

formation of Siwaliks Group. Murree Formation has poor fossils preservation but rarely few plant remains, fish remains, mammalian bones are present, suggesting an Early Miocene age.

#### **3.4.7.1 Chinji Formation**

The name adopted by Lewis (1937) for Chinji Formation was approved in the same manner by Pakistan Stratigraphic Committee. The village of Chinji, District Attock has been entitled as the type locality.

The formation consists of clays with subordinate sandstone. The sandstone is ash grey, brownish grey, fine to medium grained and is intermittently soft, gritty, cross bedded. The clay is red in colour with variable amount of sandstone interbeds at various places. The formation has intraformational conglomerate lenses with scattered quartzite pebbles at different horizons. The lower contact of the formation is marked sharp and conformable with the Kamlial Formation while the upper contact is conformably marked with the Nagri Formation. The late Miocene age has been assigned to the formation on the basis of rich vertebrate fossils (Fig 3.8).

#### **3.4.7.2 Nagri Formation**

Lewis (1937) proposed the name “Nagri Formation” which has been accepted by the Stratigraphic Committee of Pakistan. The Nagri village, District Attock has been entitled as its type locality.

The formation consists of sandstone with subordinate clay and conglomerate. The sandstone is greenish grey, bluish grey to dull red, medium to coarse grained, cross bedded and massive, at places consists of salt and pepper texture, calcareous and poor cemented nature. The variable amount of clay portion in the formation is sandy or silty, brown, reddish grey and pale orange. The conglomerate consist of pebbles of Eocene

limestone and igneous rocks that are highly variable in terms of composition and thickness (Fig 3.8).

It is far and wide in the regions of Quetta and Indus Basin. The lower and upper contact of the Nagri Formation is with Chinji Formation and Dhok Pattan Formation respectively. The formation is highly fossiliferous with vertebrate faunas, suggesting late middle Miocene age.

#### **3.4.7.3 DHOK PATTAN FORMATION**

The name “Dhok Pattan” by Pilgrim (1913) was redefined by Cotter (1933) and was later on accepted by the Stratigraphic Committee of Pakistan. The Dhok Pattan village, Attock District has been referred as the type section for the rocks of monotonous alternating cycles of sandstone and clays.

These cycles of sandstone-clays are about 6-60m in thickness.

The sandstone is grey to light grey, reddish brown, at places greenish grey or buff coloured, thick bedded, calcareous, soft and cross bedded. The clay is reddish brown to dull red, orange, at places yellowish grey, chocolate, calcareous and sandy. Minor amount of yellowish brown siltstones are present. The upper part of the formation consist of conglomeratic layers and lenses. The formation has underlying transitional contact with Nagri Formation. The upper contact with Soan Formation is disconformable in the Kohat-Potwar Province. The Dhok Pattan Formation yields rich vertebrate fauna that indicates Early to Middle Pliocene age (Fig 3.8).

#### **3.4.7.4 Lei Conglomerate**

The term Lei Conglomerate was introduced by Gill (1952) for post Siwaliks conglomerate in the Soan area. The type locality has been designated in the Lei River section, SE of Rawalpindi, Upper Indus Basin.

The conglomerates of the Lei has been considered as valley fill lacustrine, fluvial outw-



Fig. 3.8 (A) Shows Chinji Formation having interbedded sequence of maroon clays and thin beds of sandstone. (C, D) Shows monotonous sequence of sandstone and clays of Dhok Pattan Formation. (E) Regional SW looking view of north dipping Dhok Pattan Formation.

ash deposits present in the structural basins. It is made up of poorly sorted coarse boulders, pebble conglomerate of Eocene rocks, small amount of older sedimentary rocks, quartzite and igneous rocks with insignificant cross bedded sandstone and siltstone of pale brown colour. The larger fragments of the conglomerates are derived from the Tertiary and older rocks of the immediate areas. The lower contact with Soan Formation at various localities is marked as unconformable whereas the upper gradational contact with subrecent deposits is hard to define. It has no fossils except few fragments of vertebrates. The age has been assigned as Pleistocene.



Fig 3.9 shows derived fragments of boulders, pebbles and smaller matrix of Lei Conglomerate

**4.1 Introduction**

The study area lies in the Eastern Salt Range at about 15 km southeast of Choa Saidan Shah Town. The Salt Range, a part of the Himalayan foreland fold-and-thrust belt, have upper Proterozoic to recent successions and marks the southernmost position of the thrust front in the northwest Himalaya of Pakistan. It is 175 km long and 8 to 30 km wide area lying in between Jhelum River and Indus River in the east and west respectively. The Salt Range organizes a narrow zone of faulting, folding and uplift in comparison to the low structural relief of Potwar Plateau and no deformation at all in Punjab Plain at the south. The basic cause for the localization of this zone of deformation to the south of mountain front and abrupt change in structural style from northwest in Himalaya to the west-southwest in the Salt Range has been the most uncertain tectonic problem of Pakistan (Yeats, 1984). The Salt Range is divided into eastern, central and western sections.

The east-west trending structural pattern of the Eastern Salt Range is controlled by Salt Range Thrust, having south directed transport and is the southernmost tectonic lineament of the Himalayan orogeny. These compressional stresses in the Salt Range has resulted narrow fault cored anticlines exposing the Salt Range Formation with broad flat syncline exposing Paleocene-Eocene carbonates. Normal faulting as a result of salt tectonics has been observed at different localities in Pre-Cambrian Salt Range Formation.

The research work in this chapter deals with a part of eastern salt range (Fig 4.1), have special emphasis on the significantly unique deformational style with termination of the Salt Range Thrust and its implication for the kinematic linkages with the Chambal and Jogi Tilla ranges.

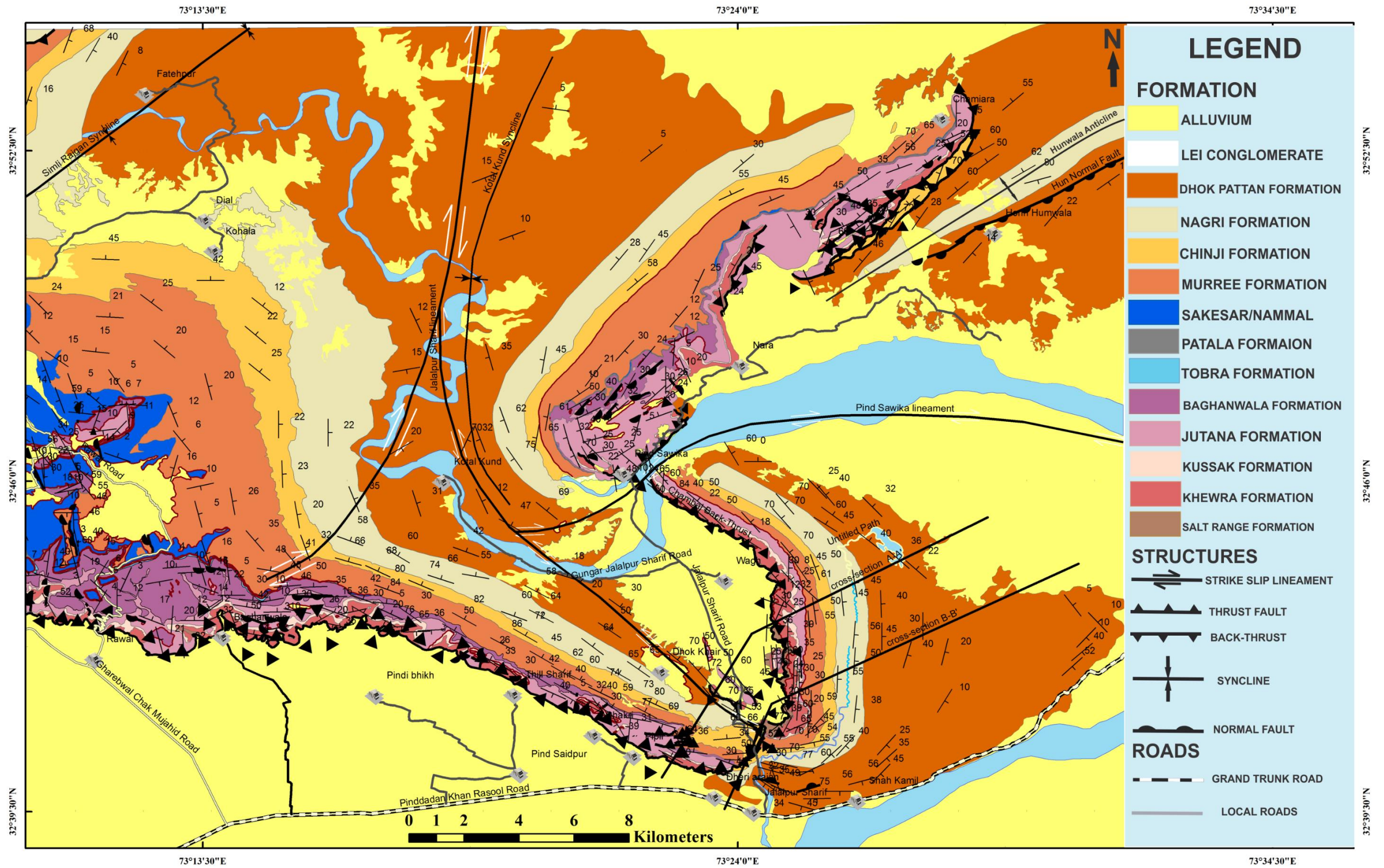


Fig 4.1 Geological map of the study area.

## **4.2 Structural setup of Eastern Salt Range**

The Research area is a part of Eastern Salt Range located at the southern margin of Potwar Plateau and is lying in between Dil Jabba and Domeli Thrusts, striking NE-SW in the northern margin of the study area while Jhelum River marks its southern limit. The uplifting of Himalayas and their subsequent compressive stresses resulted emergence of the Salt Range in late Cenozoic time, which formed east-west trending regional structures while the frontal structures in the east around Jhelum are mapped with an anticline in the south and widely spaced thrusts in the north. (Fig 4.2).

The stratigraphic successions of the study area ranges from Precambrian to Pliocene with major stratigraphic gaps of Basement to Precambrian, Ordovician to Carboniferous, Mesozoic to Paleocene and Oligocene. The surface structural framework and their complementary subsurface model has been explained one by one in detail in order to understand the current geometry and its interplay with the folds, faults and salt tectonics within the thrust sheets for better explanation of the structural geology of the area.

### **4.2.1 Surface Structures**

The Salt Range is ENE-WSW trending complex salt anticlinorium with successive salt anticlines and shows northward bending at both extreme ends to the east and west respectively. The stratigraphy of the study area shows three major units: the salt, overlying carapace and molasses. The competent lithologies of the Carapace make ridges whereas incompetent units of salt and molasses occupy valleys. The Salt Range complex structural feature is emergent along the south directed regional thrust, which is the leading edge of a basal fault present within Precambrian evaporites and has brought Phanerozoic sequence over Quaternary Fanlomerates (Yeats et al., 1984). The

fold pattern in the eastern salt range shows northeast to southwest regional trend as compared to east-west striking folds of central salt in the central salt range while eastern margin of Jhelum has northwest-southeast trending folds.

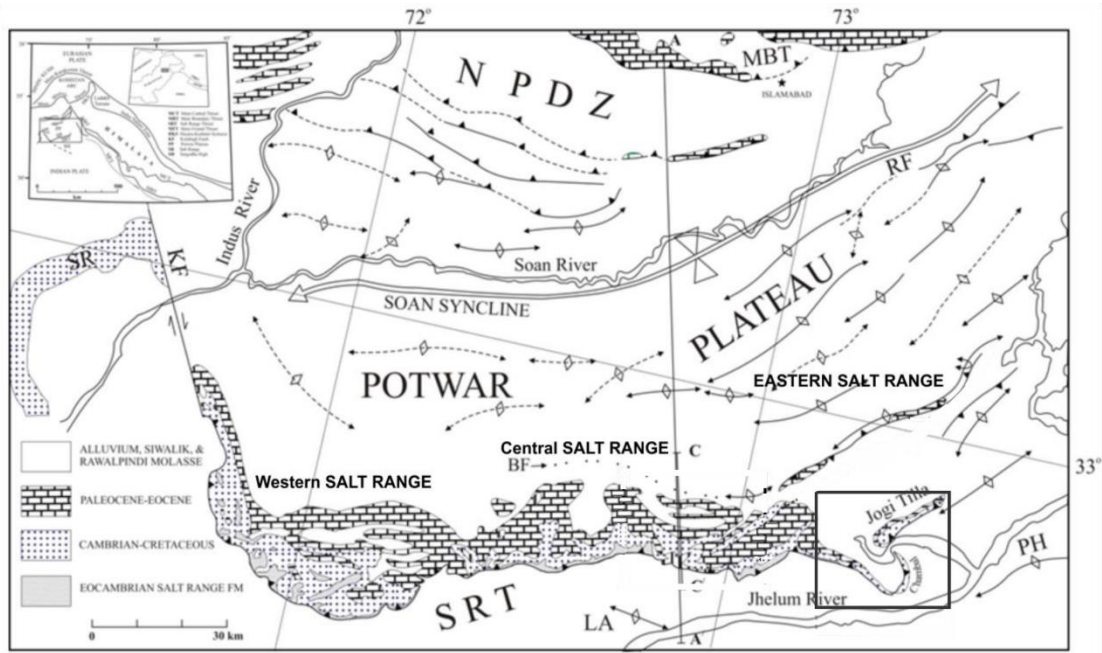


Fig 4.2 Geological map of the Salt Range (modified after Gee, 1989). The inset shows study area.

The Eastern Salt Range is lying in between Khewra and Jogi Tilla, here at the easternmost end of the Salt Range (study area), the SRT is completely a buried fault by recent Alluvium or Fanglomerate deposits. The roof sequence is highly folded in long narrow salt cored anticlines and wide flat synclines, whereas the southernmost part of it has been repeatedly disarranged by foreland and hinterland verging thrusts and vertical dipping normal faults. The anticline occupies deep eroded gorges and ravines with steep to overturn dips in its axial zones, whereas the synclines inhibited spurs and make transverse relationship to the main E-W trend of the Salt Range. At the later stages the most protuberant internal structures of the study area is the presence of different trending and variable sense of strike slip lineaments responsible for producing a crumpled shape in the form of “S” shape orocline.

The following mapped structures of the Eastern Salt Range are discussed in detail in order to understand the relationship of exposed stratigraphic units with the variable structural pattern of the area.

#### **4.2.1.1 Lateral variation in deformational style/Thrust Front collapse**

The evidence of the youngest earth's movement in the Himalayan frontal ranges is shown by the south directed tectonic push of the Salt Range Thrust which has brought allochthonous sequence ranging from Precambrian Salt Range formation and overlying younger carapace sequence onto the less deformed Late Cenozoic sequence. The buckling of the Salt range is uneven in trend along ENE-WSW direction whereas the central and western part of the Salt Range thrust is strongly exposed and developed, though it is completely submerged by recent Fanglomerates in the eastern part (study area) in between Khewra and Jalalpur. Near Mangal Dev to the west of Jalalpur Sharif village, the Salt Range Thrust is emergent and has brought Cambrian clastics and salts (evaporites) onto the Siwaliks (Gee, 1945, 1947; Yeats and others, 1984).

The study area has gradual decrease in the thickness of the Salt Range Formation where the thrust front dies out at the village of Jalalpur Sharif and two prominent emerging ridges known as Chambal Ridge, striking N-S and Jogi Tilla Ridge, striking NNE-SSE portrays a significant S shaped oroclinal structure. It shows variation in the compression within foreland and hinterland directed thrust sheets as compared to the rest of the less deformed Salt Range sequence. This lateral structural variation in the foreland front shows pinching of Permian-Eocene stratigraphic units near Thill Sharif, west of the Jalalpur Sharif village, thinning of salts as a results of Neogene Mollase load caused it to move from syncline to surrounding anticlines and has resulted in subsequent difficulties in thrust propagation, though small localized exposures of salts as diapers are brought up with the help of thrusts along Chambal Ridge and Jogi Tilla

Ridge (Fig.4.3). A parallel set of fault splays located in the north and eastern margin of the frontal fault (SRT), termed as Mangal Dev Faults. The reverse nature and swing in the map trace of the Mangal Dev Fault splays have brought Cambrian Jutana Formation and Baghanwala Formation in its hanging wall, whereas the Miocene Murree Formation marks the foot wall stratigraphy with varying dips from  $35^{\circ}$  to  $65^{\circ}$ . To the immediate north of frontal fault, a fault splay 1 and subsequent fault splay 4 at its western margin has outcropped Jutana Formation over Baghanwala Formation. These parallel series of four fault splays are separated at an average distance of 150 m with the strike length of 1.4 km, 0.5 km, 0.4 km and 1 km, respectively.

The southwestern portion of the study area in the Frontal Range shows gravity faulting that is related to salt tectonics, the salts has moved from trough into the nearby ridges as a result collapse of the carapace sequence at troughs has occurred. The Salt Range front shows northeast to southwest trending folds as compared to the central Salt Range which is trending east and west. At the Northwestern corner of the study area near a segment of the Dil Jabba Fault in the north, lies a broad valley named as Simbli Rajgan syncline of about 2.5 to 3.5 km width with long lateral extension upto Choa Saidan Shah (ranging out of study area). It is NE- SW trending fold showing swing in its trace farther west. The Nagri Formation and Chinji formation lies in the core and flanks of this syncline respectively. It has closure at its western end and opens towards Simbli Rajgan. The south dipping northern flank of the syncline dips with 200-400, whereas the north dipping southern flank dips with 250-400 (Fig.4.1). A segment of NE-SW trending Dil Jabba Backthrust far in the NW corner of the mapped area has thrust



Fig. 4.3 (A) Northwest looking view of collapsed/gravity faulting of the carapace sequence in the frontal ranges, pinching of Nilawahan group (Tobra formation) and Makarwal group (Patala formation) is evident at the top view of picture. (B) Southeast looking view of the Salt Range Thrust front bounded by low lying vast Punjab Plains. The outcrop picture has diapers of the Salt Range Formation followed by the older Jhelum Group. A localized normal faulting is evident in the outcrop picture.

Cambrian Khewra Formation and subsequent Carapace sequence in the NW direction over the Siwaliks Group (Pliocene Nagri Formation)

#### **4.2.1.2 Kotal Kund Syncline**

The mapped area of Kotal Kund, Hassnot, Mohal Patti and surrounding areas is predominantly run by a large synclinal fold and has outcropping Siwaliks Group rocks. It is located on few km's distance from Jalalpur Sharif in the Northwest direction and is present in the hanging wall of Salt Range Thrust with a swing in the trend of the fold axis from NNW- SSE direction. It is an open syncline with 1-2.5 km's width and about 25 km's in lateral extension. The south dipping northern limb dips range from ( $30^{\circ}$ - $70^{\circ}$ ), whereas the north dipping southern limb dips range from ( $15^{\circ}$ - $40^{\circ}$ ). Broadly, the Kotal Kund syncline is classified as lobate asymmetrical fold. The distribution of stratigraphic units on map shows younger rocks in its core, while older rock units occupy limbs of this syncline. It has Dhok Pattan Formation in the core, whereas Chinji Formation and Nagri Formation are present at the limbs.

In the study area Jalalpur Sharif lineament (left lateral strike slip fault) has been identified which is running from NNW-SSE direction with a zippered section in the north that is linking Dil Jabba Backthrust and Domeli Thrust. This fault is dragged through the north dipping limb of Kotal Kund syncline. The transpressional nature of this lineament in the study area provides displacement difference between Salt Range front and Jogi Tilla ridge. It has moved across the strike of contractional belt within the hanging wall of the thrust sequence and parallel to tectonic transport direction, though the Kotal Kund syncline has finally terminated contrary to the strike slip fault.

### **4.2.1.3 Chambal Ridge Structures**

#### **Chambal Back-Thrust**

The north-south trending Chambal Back-Thrust marks the south eastern periphery of the study area near Mangal Dev village and lies at the SE of the Salt Range thrust. In the study area, it is third largest fault next to the Salt Range Thrust and Jogi Tilla Thrust, extended for about 14 km's with 30-50° east-southeast dipping fault plane (Fig.4.4).

This fault has uplifted and exposed the rocks of Precambrian Salt Range formation followed by the Jhelum group (Khewra Formation, Kussak Formation, Jutana Formation), Rawalpindi Group (Murree Formation) and Siwaliks Group (Chinji Formation, Nagri Formation, Dhok Pattan Formation). Along this fault Jutana Formation formed peaks as compare to other exposed lithologies. The foot wall sequence in the central and northern portion is not exposed, which is almost covered by alluvium and Bunha River gravels, respectively.

The dips of the Jutana and Murree Formation on the hanging wall at the extreme northern edge of the Chambal ridge are overturned, whereas at the southernmost margin of the Chambal ridge, the Khewra Formation, Kussak Formation, Murree Formation, Chinji Formation and Nagri Formation are vertically exposed because of reduced displacement and close interaction between Chambal Back-Thrust and Salt Range Thrust and its closely spaced imbricates terminates at about 1 km north of Kas Saraggar village.

The Jutana Formation of the Back thrust sheet near the southern verge terminates before Salt Range Thrust imbricates. These pair of parallel small faults has thrust Kussak formation over Murree Formation and Murree Formation is further thrust over Chinji Formation. The southern verge of the Chambal Back-Thrust has clearly developed cross

cut relationship i.e between hanging wall sequence of the Chambal ridge thrust over folded hanging wall sequences of the frontal ridge (Fig.4.5).

A series of thrust fault splays in the hanging wall of Chambal Back-Thrust are located to NE of Jalalpur Sharif at the Dhok Chanda village. The trace of these parallel splays of fault has an oblique position to the Back-thrust with  $50^{\circ}$ - $60^{\circ}$  fault dipping planes, bounded the Dhok Chanda village to the west and east respectively. One fault splay to the west has thrust thin slices of Precambrian (evaporites), Cambrian (Khewra Formation, Kussak Formation, Jutana Formation) over Pliocene (Dhok Pattan Formation) and another fault splay to the east has thrust thin discrete slices of Cambrian (Khewra formation, Kussak Formation, Jutana Formation) over the hanging wall sequence of western fault splay.

#### **4.2.1.4 Jogi Tilla Structures**

The Jogi Tilla Ridge and its associated structures marks the northernmost position of the study area and is about 13 km's distance from Jalalpur Sharif to Pind Sawika village. It is more than 20 km long structure along its strike, whereas across the strike it is more than 15 km in width. The Jogi Tilla Ridge is NE-SW trending structure and is exposed along SE verging forethrust segment. The stratigraphic sequence exposed along this thrust ranging in age from Precambrian Salt Range Formation followed by the younger Cambrian (Jhelum Group), Paleocene (Makarwal Group), Eocene (Chharat Group), Miocene (Rawalpindi Group), Pliocene (Siwaliks Group). The Jogi Tilla Ridge front (southern periphery) is marked by the eastward flow of Bunha River which has covered the foot wall stratigraphic units.

The structure is divided into northeastern and southwestern segments. The northeastern segments near Chitti village is dominated by closely spaced parallel set of thrust fault

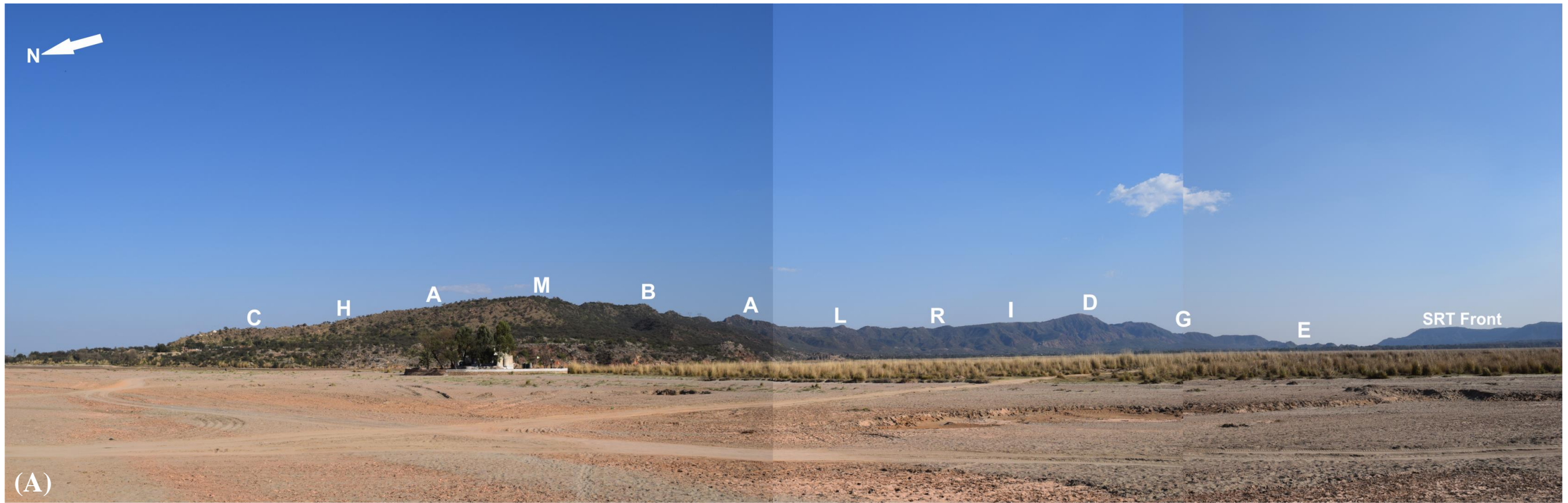


Fig. 4.4 (A) Panoramic view of north-south oriented Chambal ridge, peaks shows Jutana dolomites. (B) South looking side view of Chambal ridge shows south-southeast dipping orientation.

and its associated splays verging in SE direction, a large anticline is present at the foot hills of this segment known as Hunwala anticline, whereas the southwestern segment of Pind Sawika is devoid of these structures showing less deformed state.

The fault present near Mowala Kas is a thrust fault, which has emplaced Chinji Formation over northwest dipping limb of Humwala anticline. It is extended for about 10 km with  $30^{\circ}$ - $60^{\circ}$  north-northwest dipping fault plane. This fault at its northeastern and southwestern limits has out cropped Jutana Formation over Dhok Pattan Formation. A splay of this fault in the north has emplaced Khewra Formation and overlying younger carapace sequence in its hanging wall over the Chinji Formation in its foot wall with  $40^{\circ}$ - $70^{\circ}$  fault dipping plane. Further northward small/local parallel set of faults are present at about 170 m of distance from each other. The localized fault to the south has emplaced Kussak Formation over discrete patch of Baghanwala Formation and Jutana Formation. While the localized fault to the north has emplaced Khewra Formation over discrete patch of Baghanwala Formation which has marked the central position of this fault though Jutana Formation is present at their margins.

A large anticlinal fold structure is uplifted between Chitti and Hun villages known as Hunwala anticline which is present at the northeastern mapped area of the Jogi Tilla Ridge. It is NE-SW oriented anticline having 11 km long strike parallel lateral extension and about 6.5 km width in the study area. Stratigraphically the Nagri Formation and Dhok Pattan Formation lies in the core and limbs of this anticline, respectively. In fact it is an asymmetrical fold and has steeper NW dipping ( $45^{\circ}$ - $60^{\circ}$ ) flanks as compared to the gentle SE dipping ( $10^{\circ}$ - $20^{\circ}$ ) flanks. The NW dipping beds of the anticline is faulted against out cropping Chinji Formation, whereas the SE dipping limbs has a large normal fault.

The SW portion of the Jogi Tilla Ridge has relatively two large faults as compared to the NE portion. The fault near Nara village has thrust Precambrian Salt Range Formation and overlying younger carapace sequence over Cambrian Jutana Formation (Jhelum Group). The fault is covered by Quaternary Alluvium at its lower southern margin. The fault near Pind Savikka village has a trace length of about 3 km in mapped area with NW dipping fault plane, it has emplaced Cambrian Khewra Formation over Pliocene Lei Conglomerates. The major elevated portion of carapace sequence that is Jutana Formation is dominated by Normal faulting, secondary folds and overturned folds.

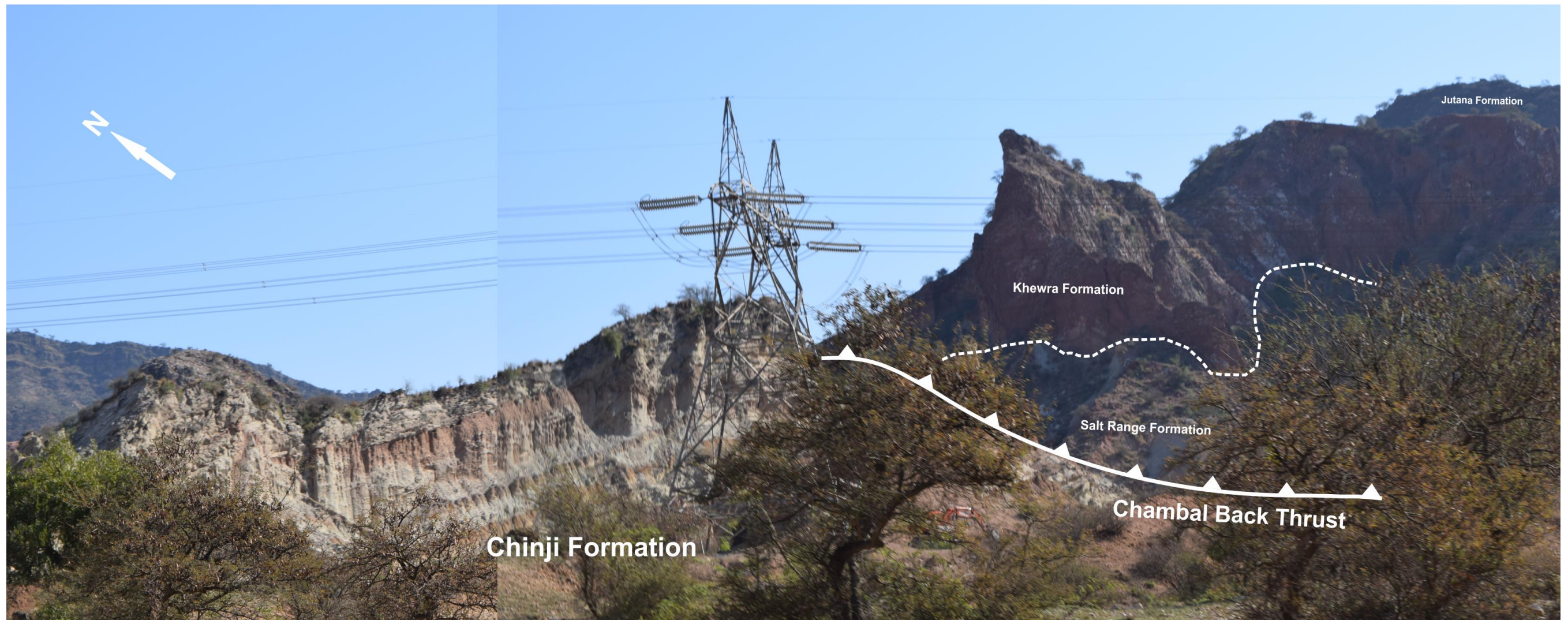


Fig 4.5 shows thrusting of Salt Range Formation and younger Carapace sequence over the Miocene Chinji Formation of Range Front. The thrust in the picture shows southern trace of the Chambal Back-Thrust.

### **4.3 2d Structural Modelling**

Two regional subsurface structural cross sections along lines A-A' and B-B' are constructed along contrasting structural orocline to reveal subsurface geometry from complex surface structural arrangements, in order to better understand their kinematic relationship. The detailed structural analysis with the help of field data has led in the accomplishment of 2d subsurface models. The cross section were drawn on the Frontal Salt Range sequence and Chambal Ridge Sequence, which is located to the southeastern half of the mapped area as described below.

#### **4.3.1 Cross section A-A'**

The basic requirement for making a cross section is to keep the section line parallel to the main tectonic transport direction, otherwise the movement of sedimentary packages would be biased. The mapped structures in the study area shows more than one tectonic direction of transport that's why the cross section line is drawn parallel to these stress vectors but with a jog.

The cross section line along A-A' lies in the ENE-WSW to NNE-SSW quadrants direction that controls the structural geometry of In-sequence and out of sequence thrusting. From ENE-WSW on a cross section line till a jog shows Forward-breaking sequence where the subsequent younger thrust faults and it packages have formed in the foot wall of the older thrust. The three observed faults in this section has same vergence direction to each other. A major thrust fault known as Chambal Back-Thrust have brought Precambrian Salt Range Formation and overlying younger stratigraphic sequence (Khewra Formation, Kussak Formation, Jutana Formation, Muree Formation, Chinji Formation, Nagri Formation and Dhok Pattan Formation) to the surface, whereas

the remaining stratigraphic units of surrounding ridges in the study area is missing in the Chambal Back-Thrust sheet.

Some minor secondary folds are formed in Carapace sequence above the gliding surface that is the Salt Range Formation. Onward an asymmetrical fold is present which has older Salt Range Formation in its core while younger rocks are present at limbs. It has comparatively gentle dipping SW limb as compared to steeply dipping NE limb. The sectional geometry of this anticline is covered by recent alluvium deposits and is bounded by 1<sup>st</sup> splay of fault (SW direction) emanating from Chambal Back-Thrust at a depth of more than 2 km. This fault is interpreted to occupy SW limb of anticline along which the Salt Range Formation and younger sequences are thrust over Jutana Formation of Cambrian age.

Another 2<sup>nd</sup> splay of fault lying in the SW direction to first splay of fault has breached at depth of about 1700 m and travelled sub-horizontally for some distance at the contact between Salt Range Formation and underlying Murree Formation, later on the fault moved upward and emplaced Salt Range Formation, Khewra Formation, Kussak Formation and Jutana Formation at the surface. The sequence of faulting in this sectional part has been interpreted on the basis of cross cut relationship which shows that Chambal Back-Thrust is older primary fault from which younger splay 1 and splay 2 of the same order is originated subsequently (Fig 4.6).

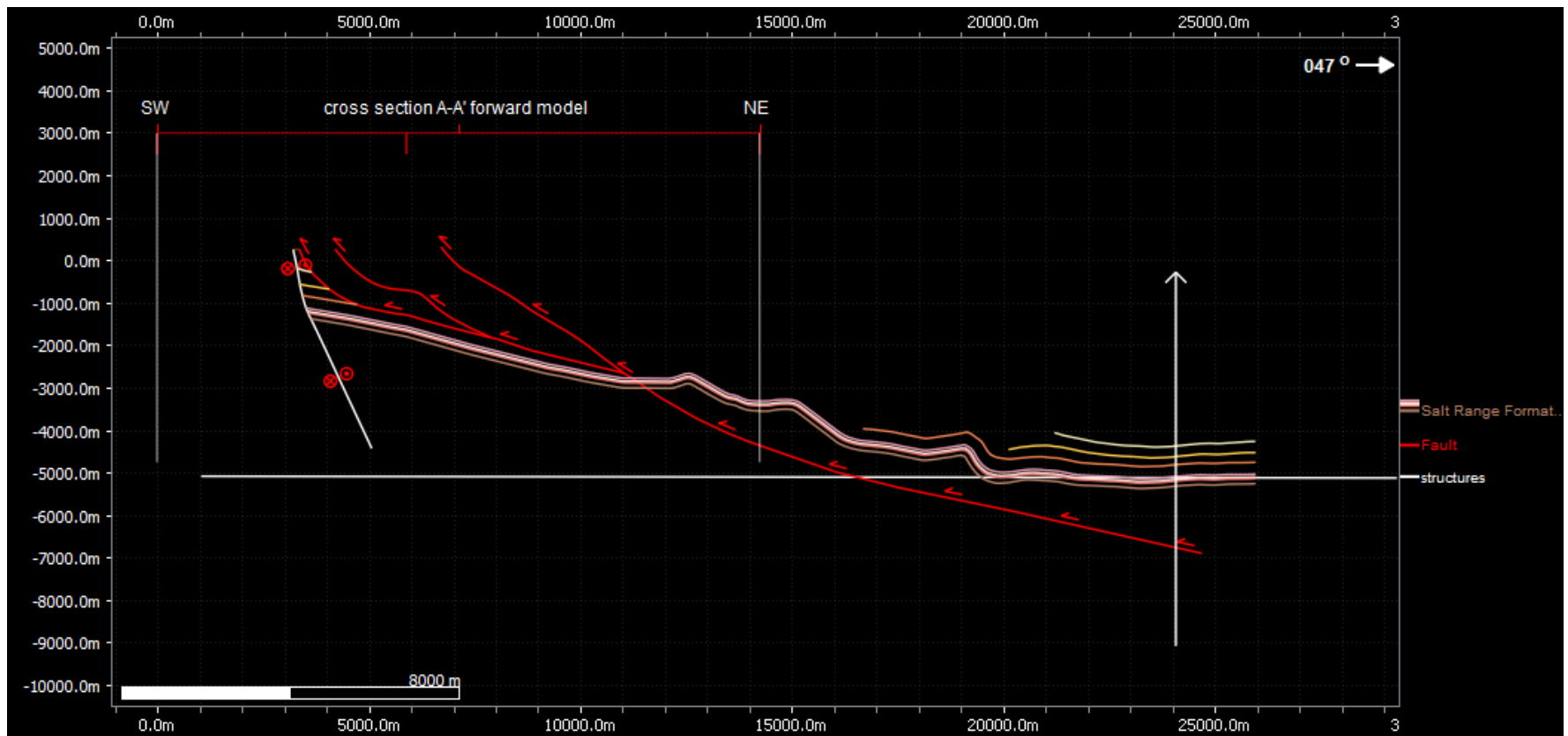
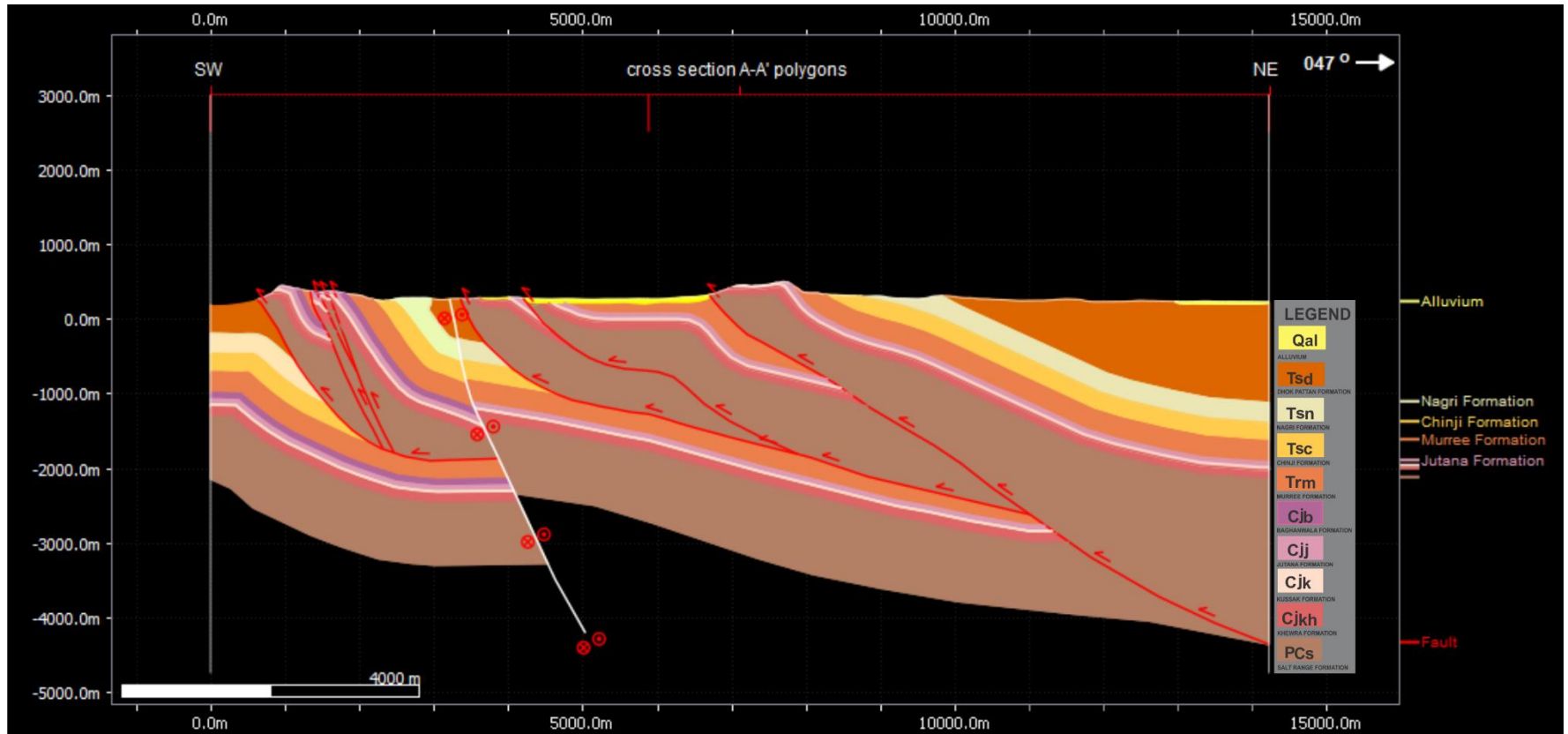


Fig. 4.6 Geological cross-section along line A-A' (First), Forward model of cross-section A-A' (second)

The extreme left corner of the cross section is almost different from the one which is explained above. The section drawn on the range front shows break back sequence of faulting which shows that the subsequent younger thrusts have formed within the hanging wall packages of the older thrust that is the fore thrust component of the Salt Range Thrust. Along this thrust Precambrian Salt Range Formation and overlying younger Jhelum and Siwaliks Group are thrust as a hanging wall units. The sectional geometry of this sequence has well developed Baghanwala Formation which is completely missing in the above discussed section.

It is made clear that the sequence of faulting on basis of cross cut relationship for 1<sup>st</sup> splay, 2<sup>nd</sup> and 3<sup>rd</sup> splay of fault is progressively backward with consecutive thrusting of Jutana Formation over Murree Formation to the surface has occurred. These parallel splays of thrust fault has spread out with steeper angle at a depth of about 1800 m from older main thrust front The cross section line in this part is crossing through a left lateral strike slip fault named as Jalalpur Sharif lineament which is transpressional in nature and shows a component of pure shear across and simple shear component parallel to it.

#### **4.3.2 Cross section B-B'**

The cross section line B-B' is drawn on Chambal Ridge and Salt Range front, which has shown almost same geometrical features as that of A-A' section but the structural configuration to the lower half of B-B' section near Jalalpur Sharif and Kas Saragar village is more complex, where the Salt Range Thrust termination and opposite verging thrust has come in close association. The cross section line at the juncture of Chambal Ridge shows forward breaking sequence which has thrust Precambrian Salt Range Formation and overlying Jhelum Group (Khewra Formation, Kussak Formation, Jutana Formation), Rawalpindi Group (Murree Formation), Siwaliks Group (Chinji

Formation, Nagri Formation, Dhok Pattan Formation) over the Miocene Murree Formation. Here the Jutana Formation has pinched in the subsurface as shown in the map expression. A splay fault of same vergence has breached at a depth of about 1700 m and thrust Salt Range Formation over folded hanging wall sequence of Salt Range front that is Chinji Formation (Fig 4.7).

The left corner of the cross section has portrayed difference in vergence style along a regional thrust and its associated packages as compared to the right segment because the cross section line turned with a jog and is again passing through the lowermost southern portion of Chambal Ridge stratigraphic sequences with varying orientation pattern for attitude values as compared to the central and northern half of Chambal Back-Thrust sheet, though it has overlapped the Salt Range Thrust and its packages sideways.

The component of Chambal Back-Thrust at its southern portion has emplaced Precambrian Salt Range evaporites, Jhlem Group (Khewra Formation, Kussak Formation), Rawalpindi Group (Murree Formation), Siwaliks Group (Chinji Formation, Nagri Formation, Dhok Pattan Formation) over folded hanging wall Sequence of Salt Range front. It has been interpreted with the evidence from map expression that the two parallel splay faults as a fore-thrust component has been bifurcated from the tip of the Salt Range Thrust with similar vergences into the Chambal Back-Thrust packages. These two splay faults have vertically outcropped the Back-Thrust units. The First splay of fault has emplaced Kussak Formation over Murree Formation to the surface while the second splay has brought Murree Formation over Chinji Formation. These faults have spread out from a depth of about 1100 m (Fig 4.7).

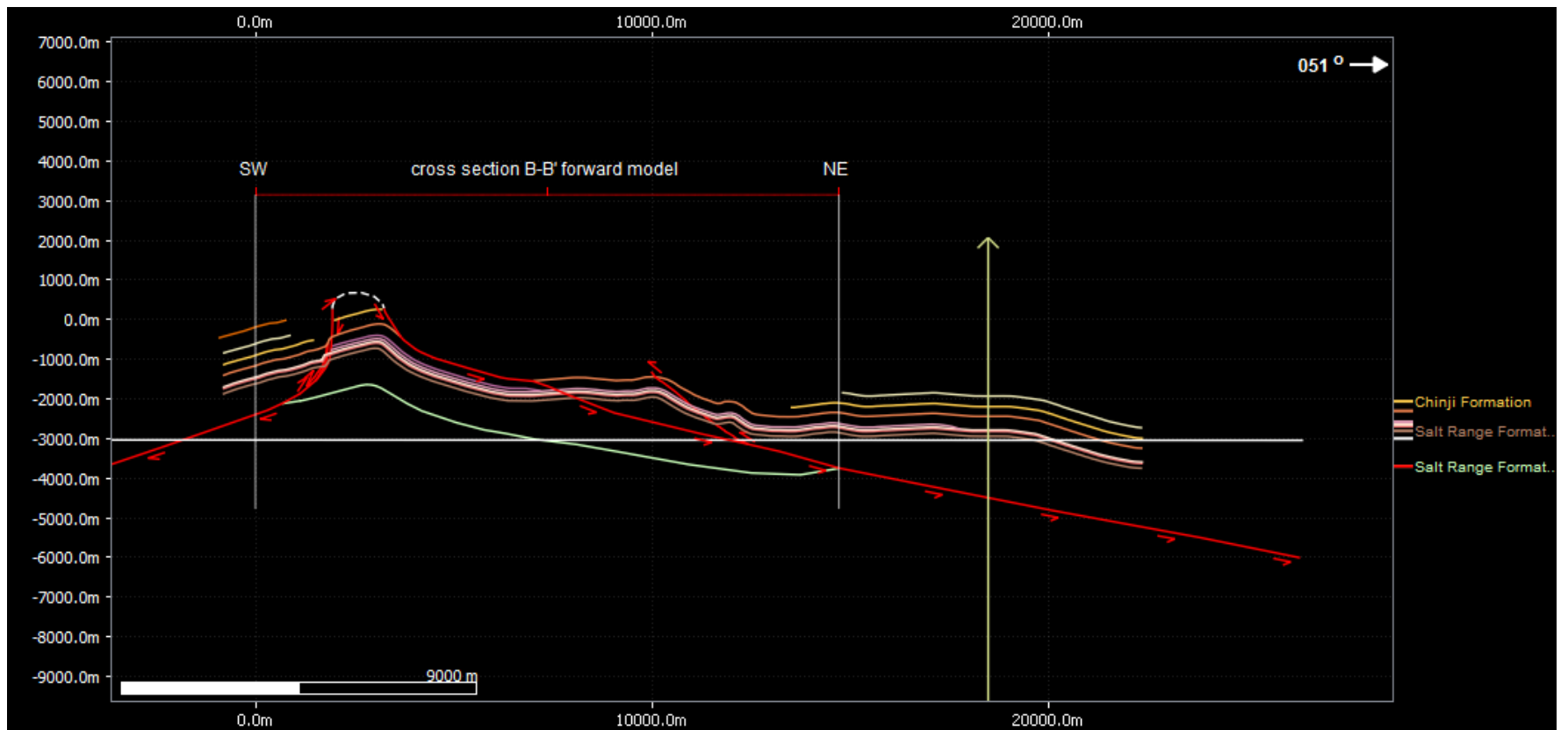
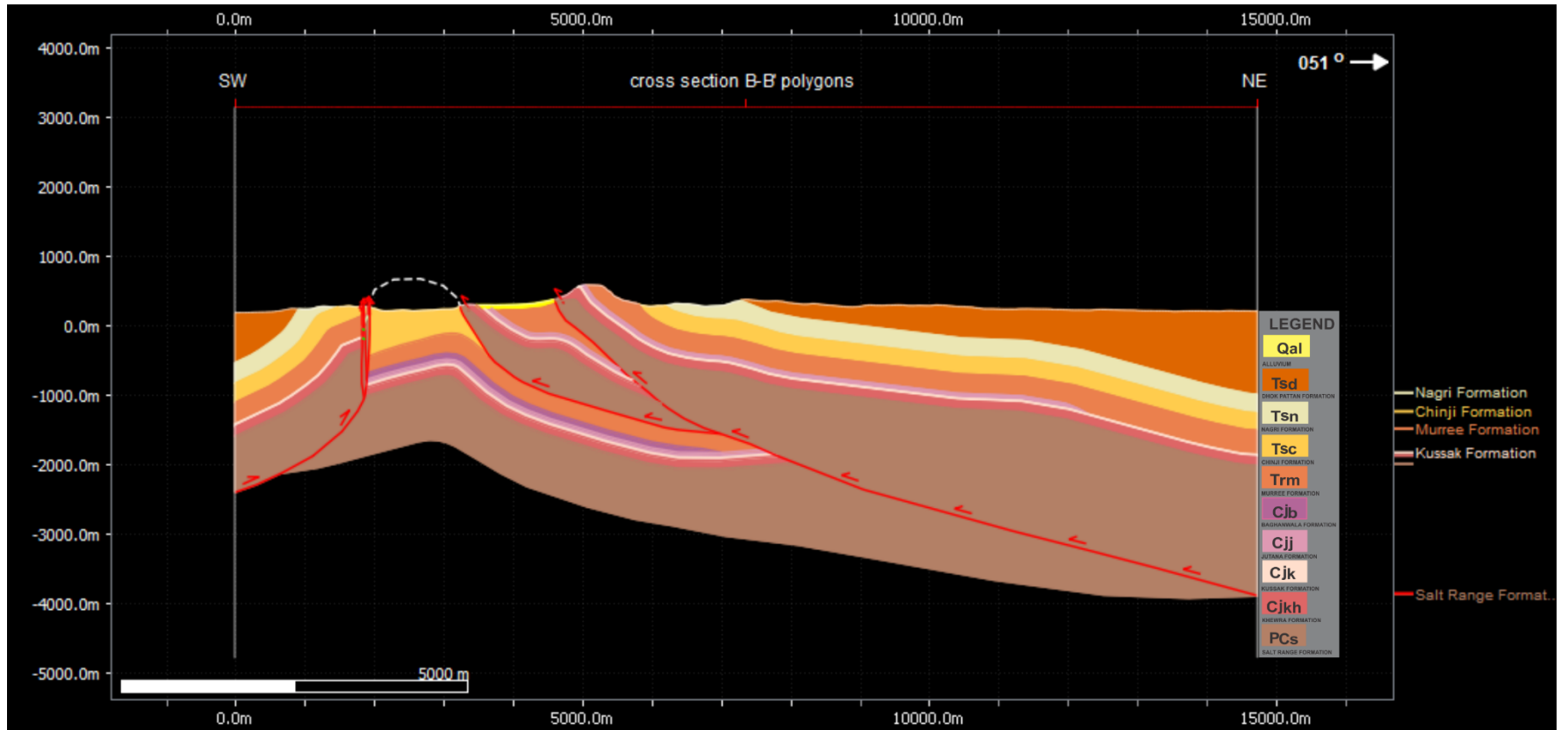


Fig. 4.7 Geological cross-section along line B-B' (First), Forward model of cross-section B-B' (second).

#### **4.4 Restored Cross-sections**

The cross sectional geometry along line A-A' and B-B' is passed through the Palinspastic restoration technique with the help of 2D module of move software, which is used to undeform a cross section progressively so as to validate its deform state. The following restored and balanced cross sections were made in order to calculate the amount of shortening took place during folding, faulting and their overall percentage of shortening in the studied area (Fig 4.8).

##### **4.4.1 Cross-section A-A'**

In order to reinstate the deform cross section, it was first subjected under forward modelling technique to make balanced faults cut-off with displaced stratigraphic sequence. The thrusts were analysed with "Fault parallel flow" under "Move on fault" module, later on subjected to "Flexural slip" under "Unfolding" module. As a result the deformed state of cross section having length of 14290 m restored to a length of 26550 m. The total amount of shortening calculated along thrusts, its associated splays and unfolding is 12260 m, but the percentage of shortening along cross section is 46%.

##### **4.4.2 Cross-section B-B'**

The cross sectional geometry along line B-B' were analysed and restored in the same manner and technique of "Move on fault" and "Unfolding module. The deformed state cross sectional length portrays a total length of 11529 m except for left corner of section because it is the same lower portion of Chambal Ridge but with difference in vergence style to the other half of the structures as discussed in previous sections. After applying above attributes the cross section restored to a length of 22459.5 m. The total amount of shortening achieved along thrusts and unfolding is 10930.5 m whereas the percentage of shortening is calculated as 49%. The Remaining portion of the cross

section with different style were calculated separately, which shows a total length of 1953.25 m. The restored length, shortening amount and percentage is 1375 m, 578.25 m and 30%, respectively.

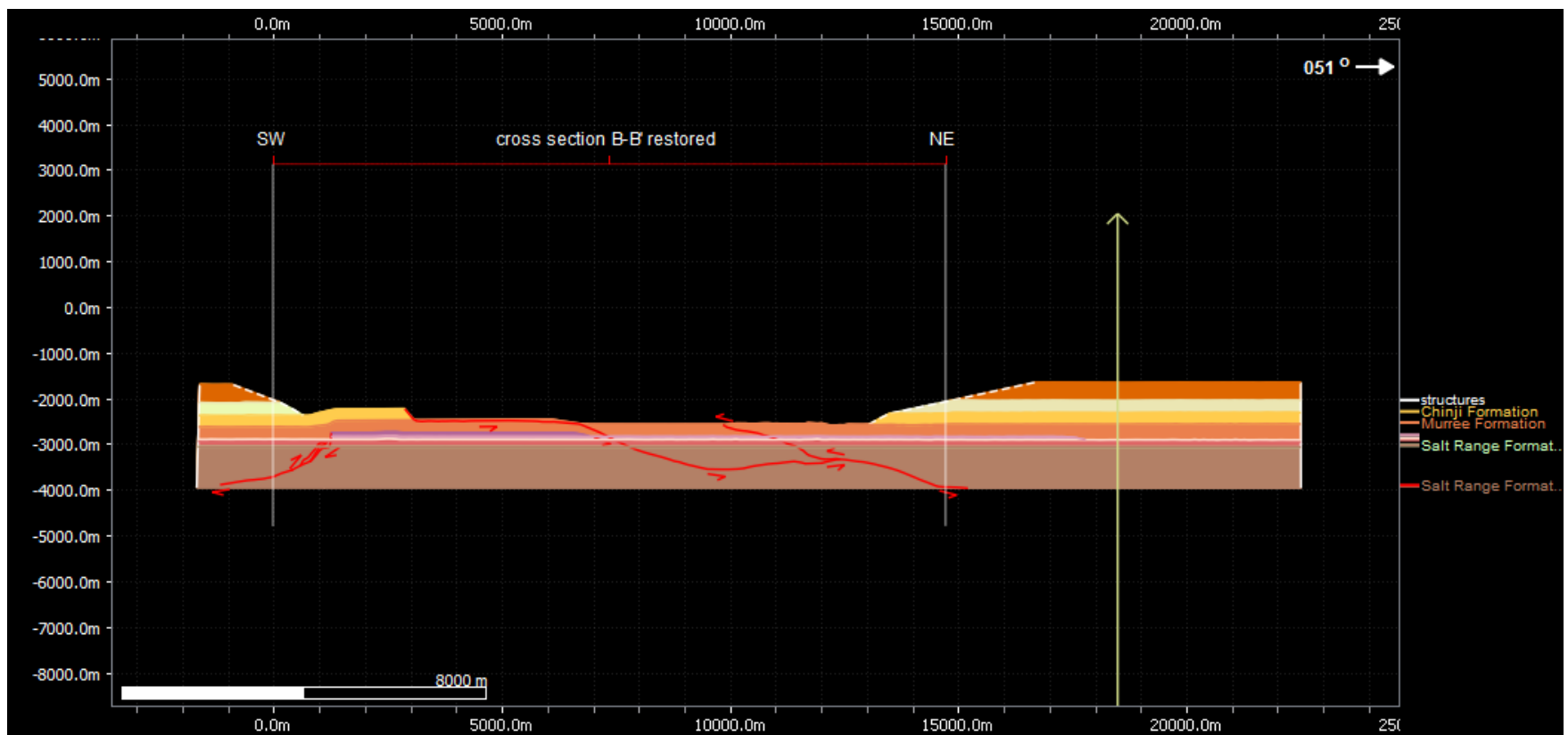
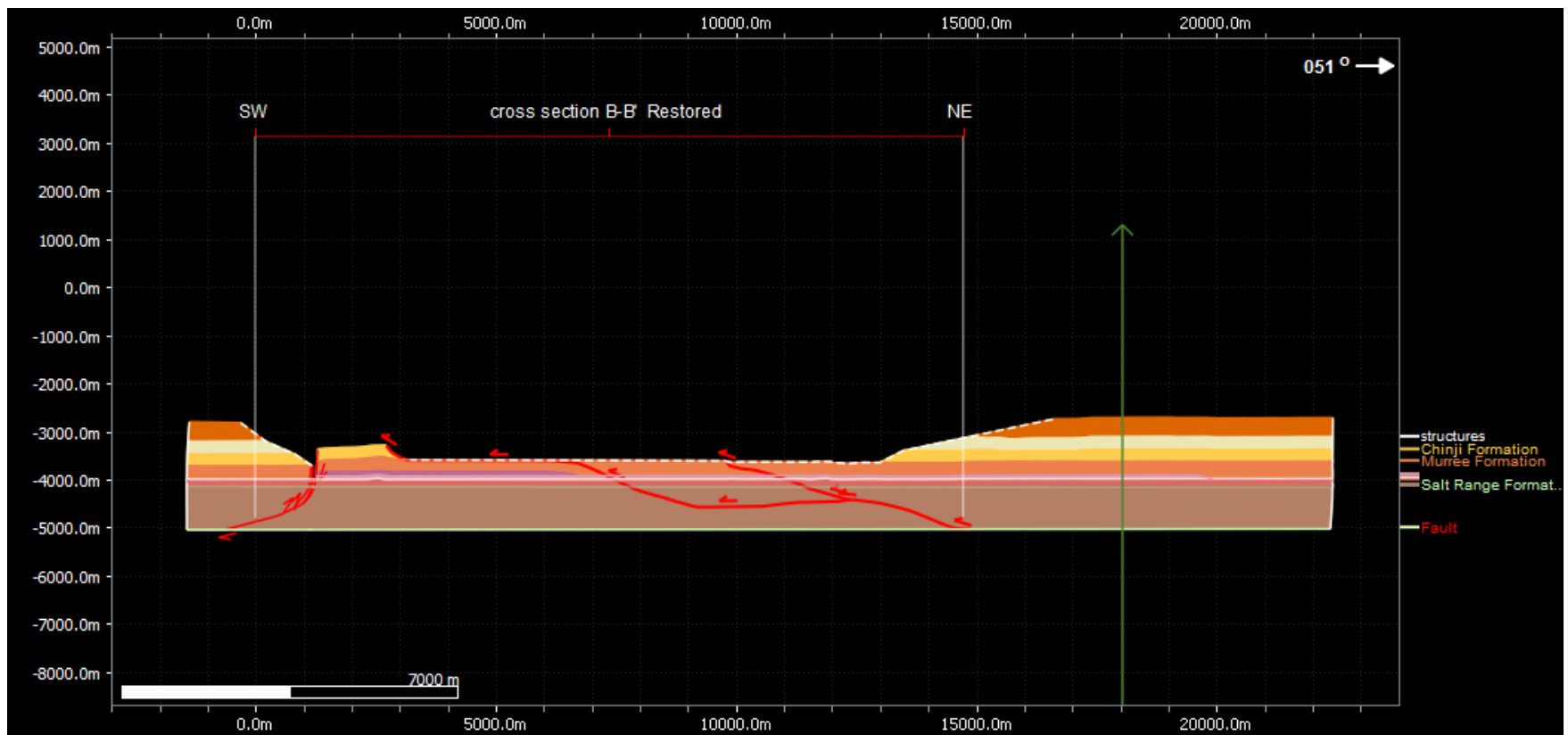
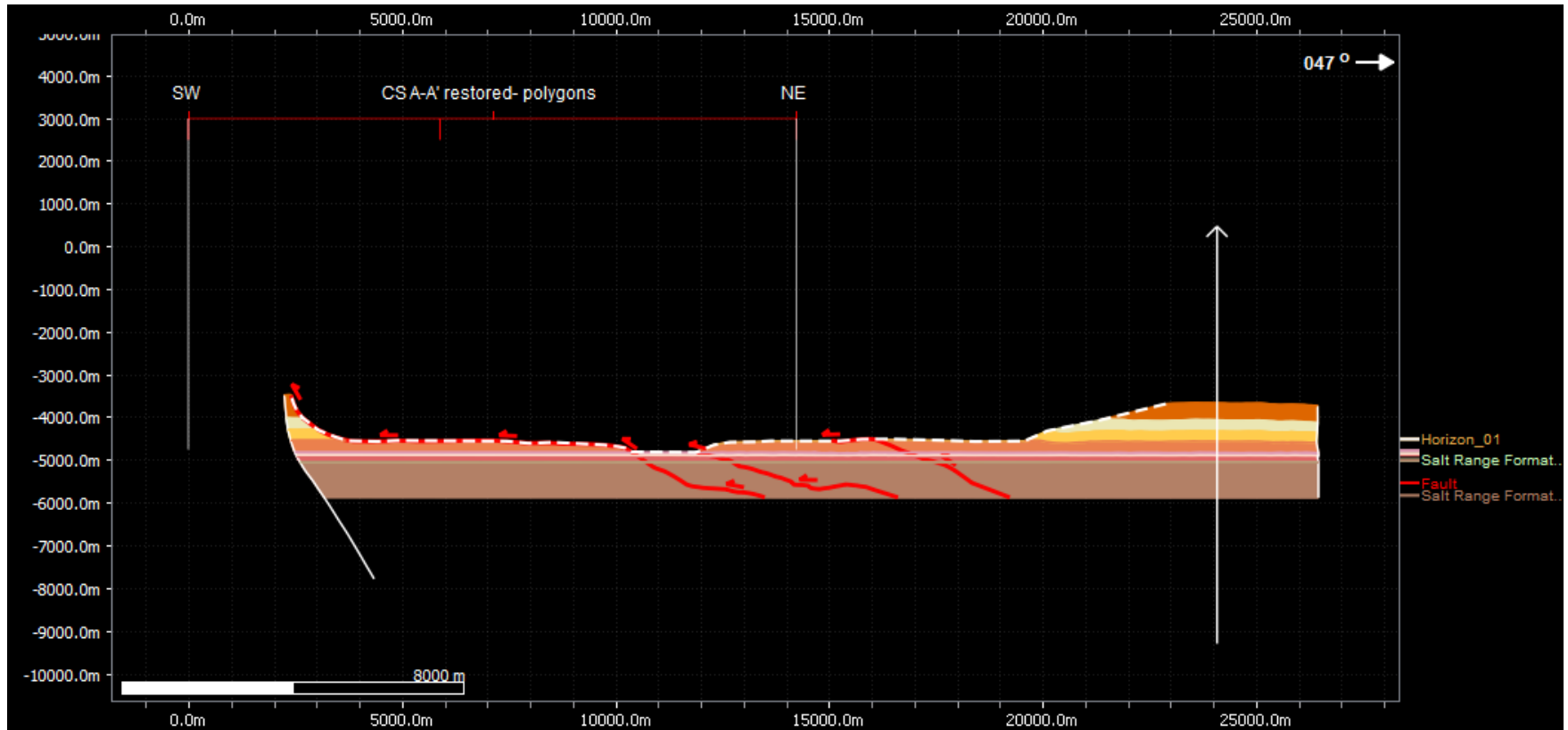


Fig. 4.8 Restored geological cross-sections.

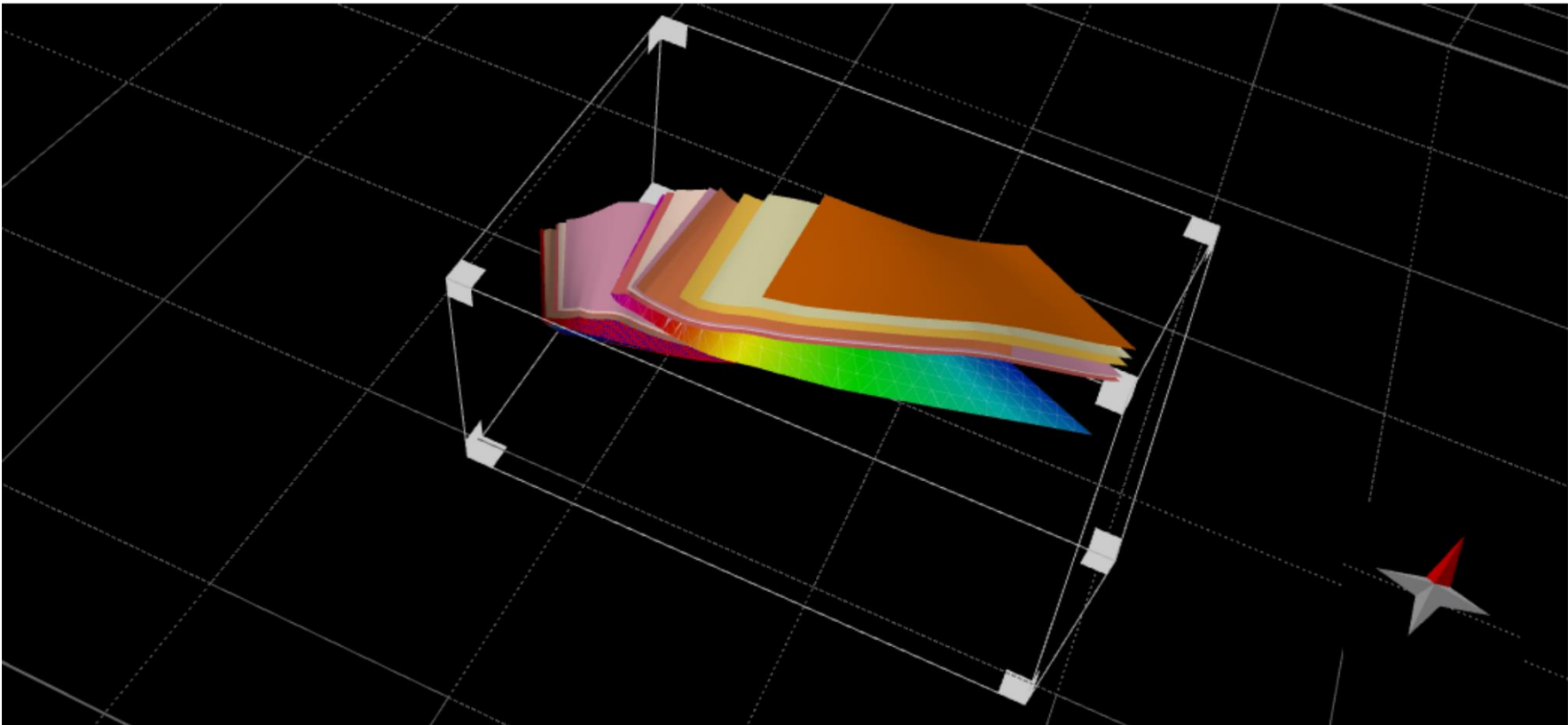
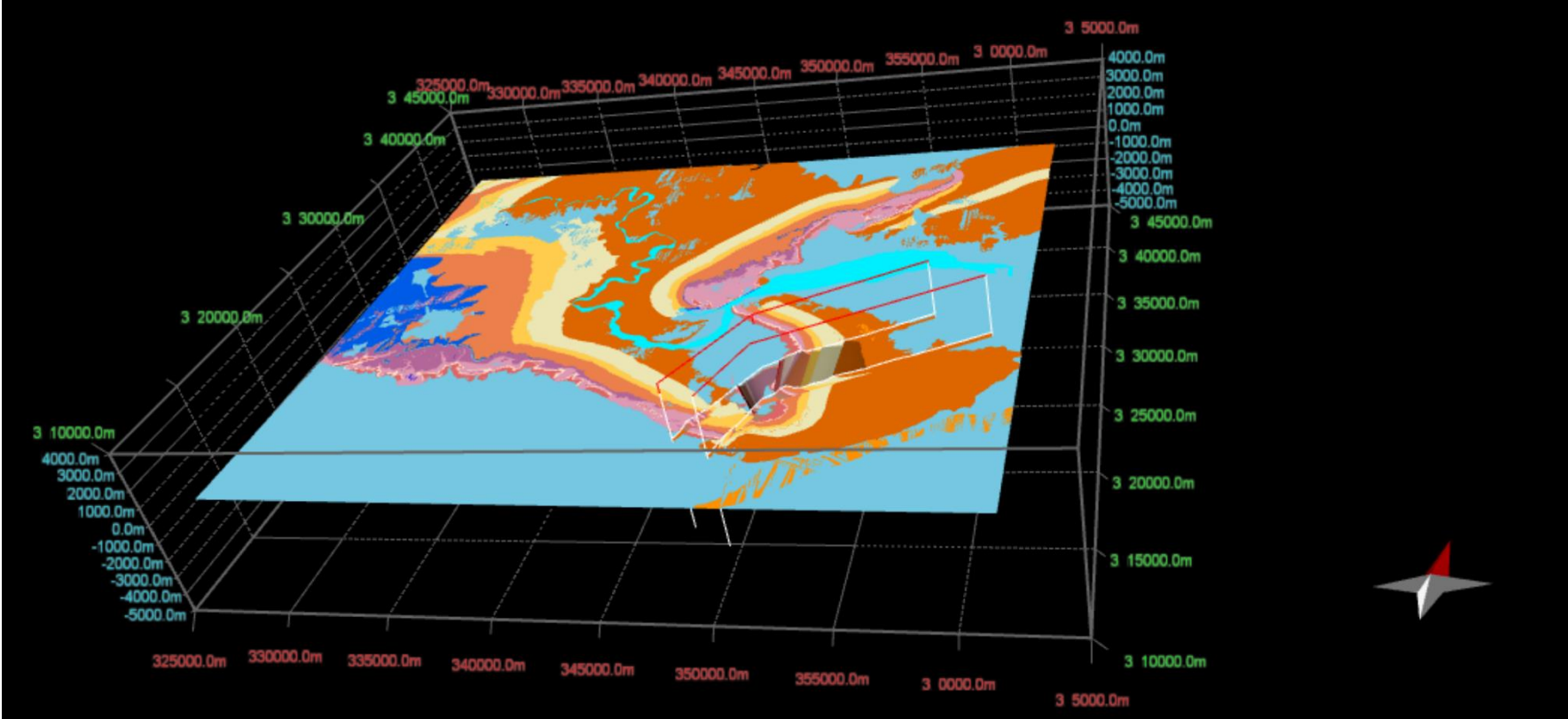
#### **4.5 3D Structural Modelling**

A modelling technique for 3D portrayal of any object and surfaces can be accomplished with the help of computer generated programme. Construction of 3D models may lead to disclose hidden geological structures and its varied geometries. The three dimensional (3D) structural geometry of the study area has been accomplished with the help of field data, curved surfaces of geological map and subsurface cross sections. Although transforming two dimensional geological data into three dimensional geological model is quite complicated which may lead to speculations. So for this reason currently available two dimensional data were combined into a constant 3D work flow to better explain the overall extension and propagation direction of regional structures.

The 3D modelling of the study area has the following work flow:

1. Construction of deformed cross sections
2. Redrawing the cross section for balancing purpose (Forward Modelling)
3. Construction of undeformed state cross section.
4. Cross section rectification and overlaying on geologic map.

Figure 4.9 Shows northwest and southwest looking view of 3D rectified sections along Chambal Back-Thrust and Salt Range front ridges, which shows variation in the structural style and termination of associated splays. The 3d model of the study area was developed along regional faults and associated packages to interpret the disharmony of the structures in the subsurface. The 3d models of main fault particularly along Chambal Back-Thrust shows variation in strike from north to south and that is



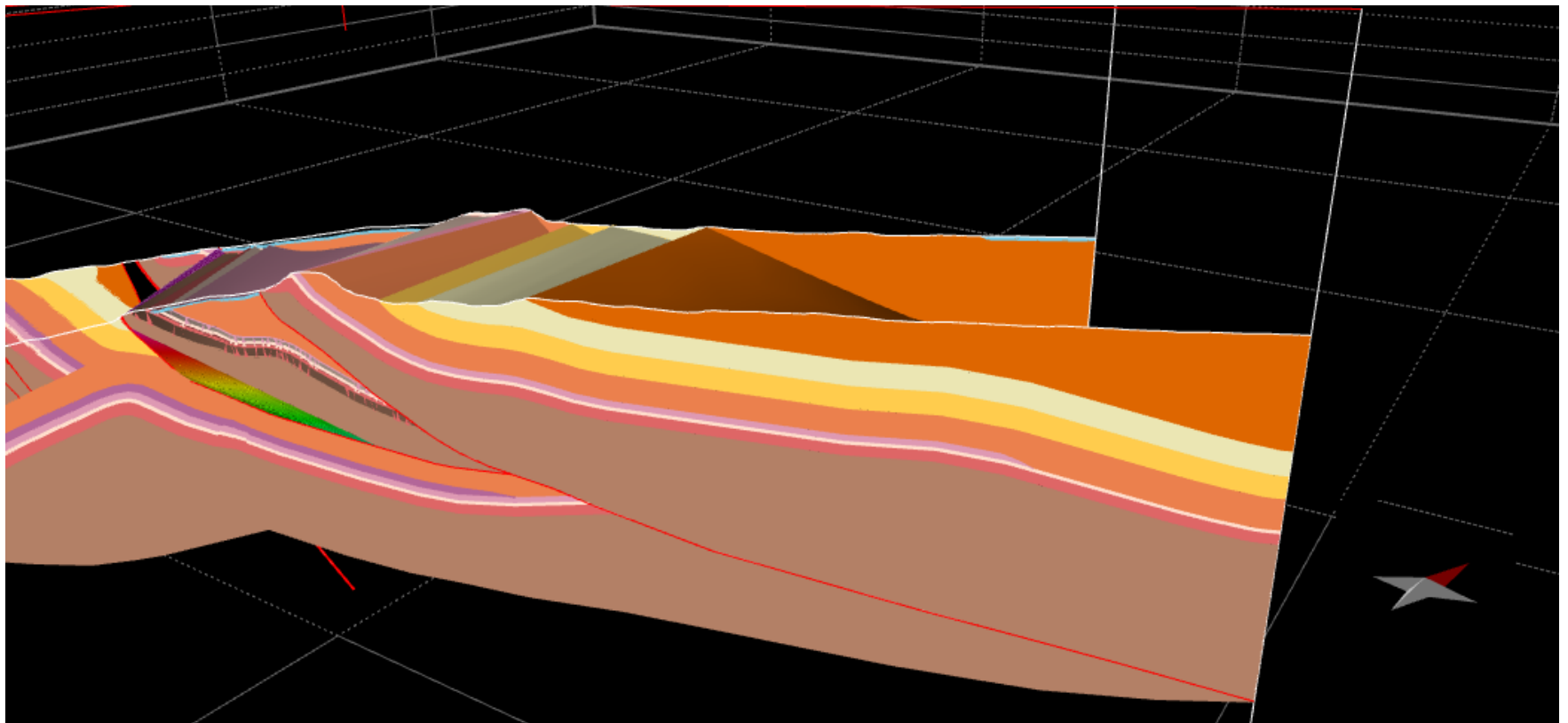
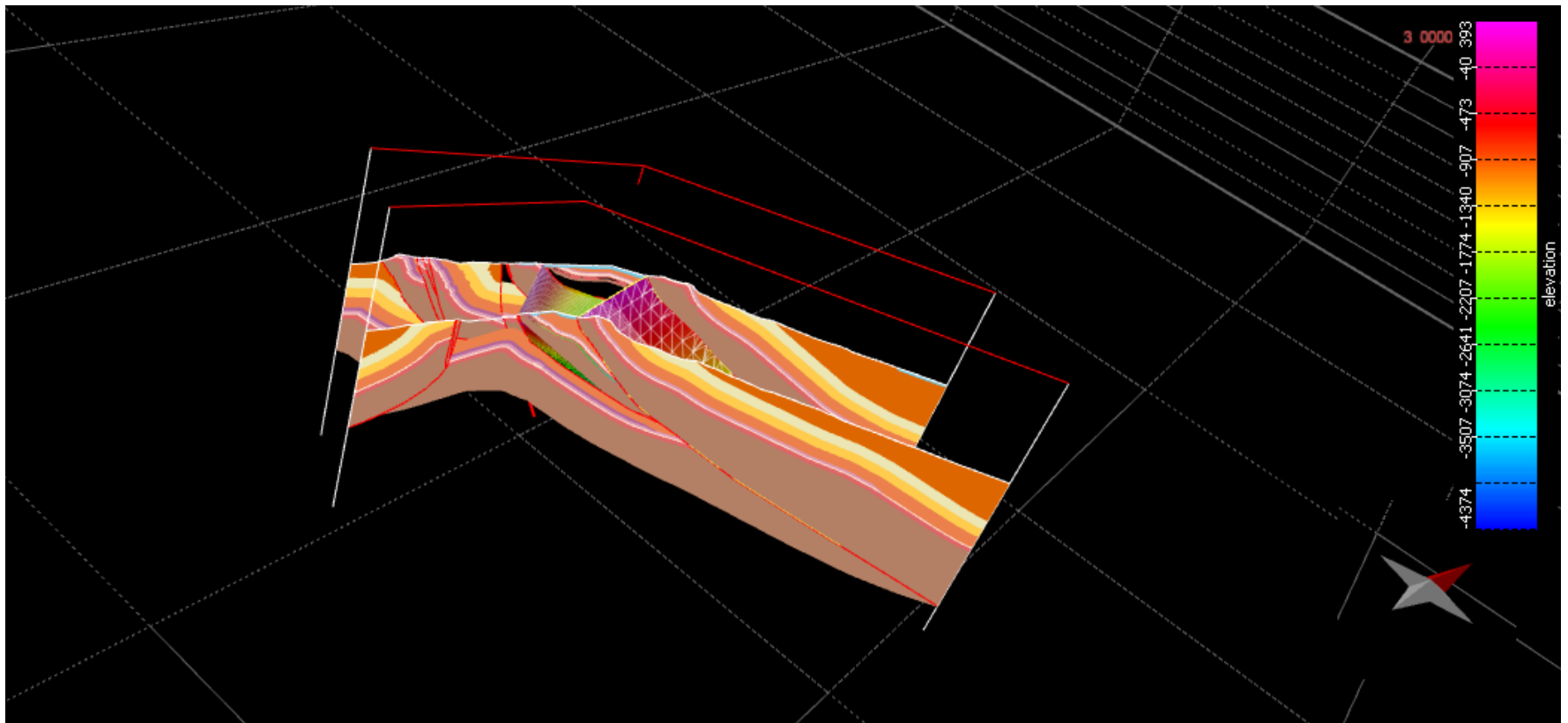


Fig 4.9 3D models of the study area showing regional fault propagation, fault splays and associated stratigraphic packages (coloured strip shows elevation in meters).

because of more intensified deformation and displacement in south than the northern portion of the main fault.

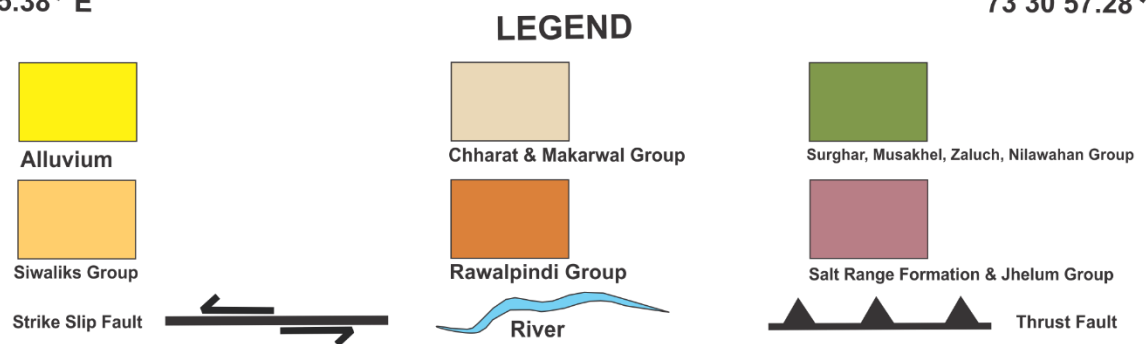
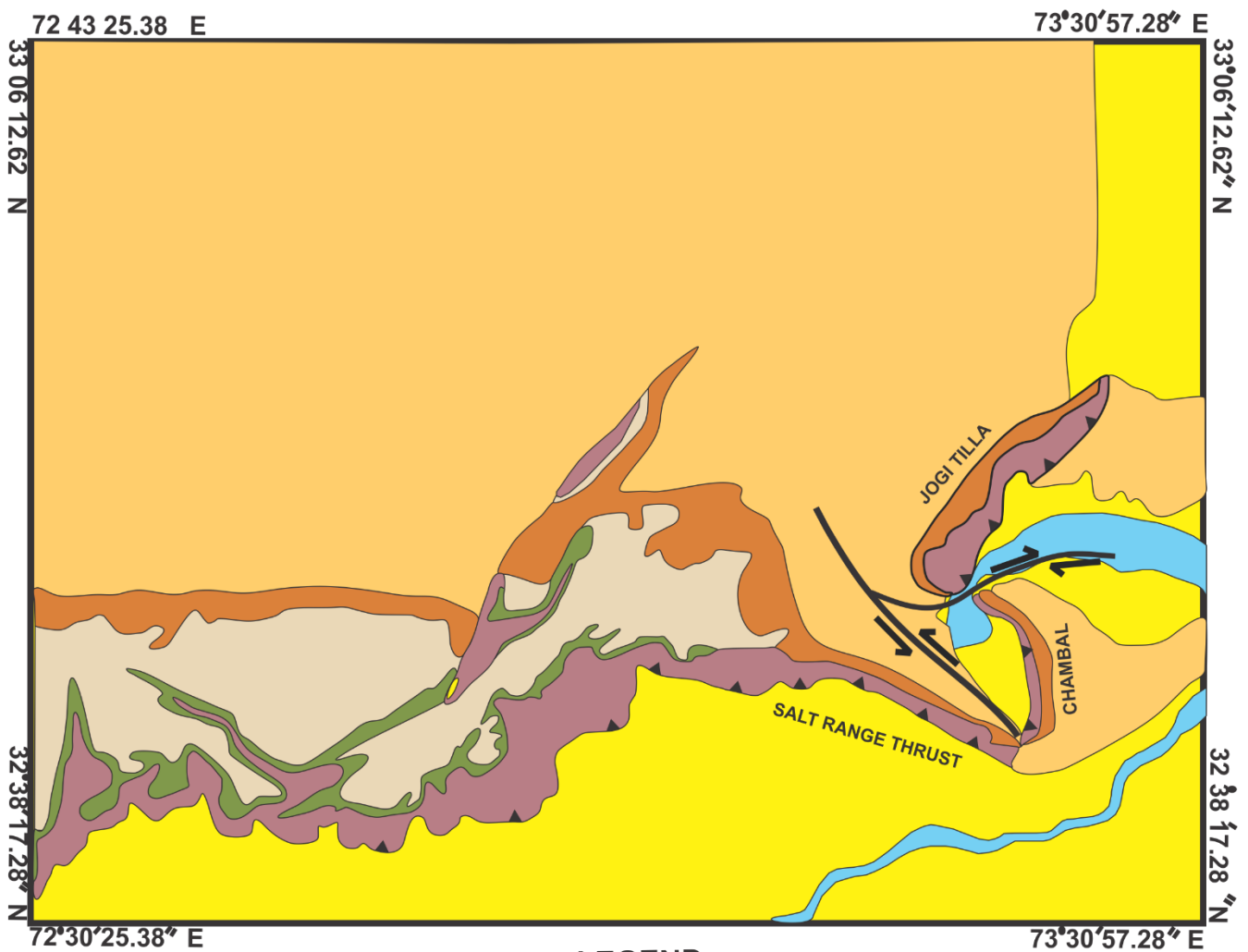
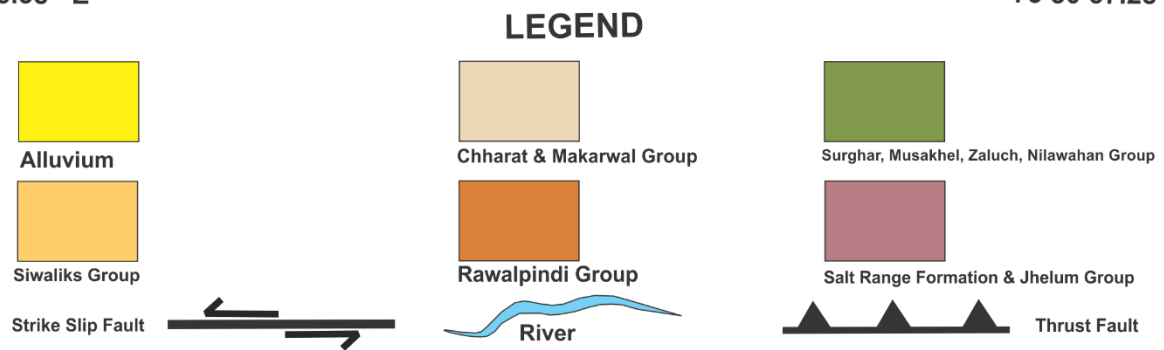
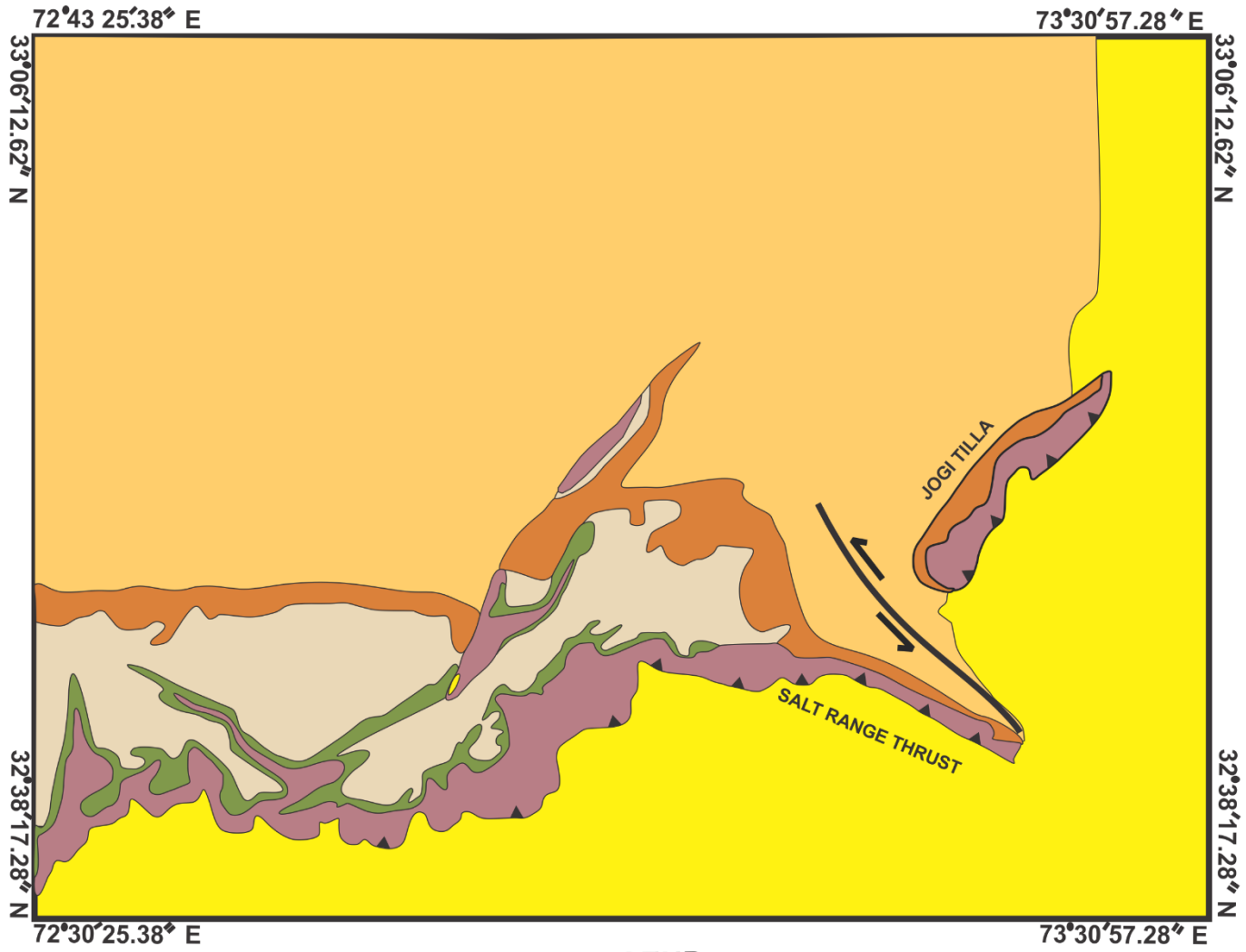
#### **4.6 Kinematics of Orocline and its implication from Strike Slip Faults**

An orocline is the curvature or bend observed in the mountain belt of the study area. The curvature or bent is present among three different trending structures of the Salt Range front, Jogi Tilla and Chambal ridge. An attempt has been made on the basis of field data and map impression to sort out its kinematic relationship with each other. Two pronounced structural ridges that is Salt Range front and Jogi Tilla ridge have comparable stratigraphic arrangements, though Chambal ridge is unique in arrangements as compared to two. The stratigraphic sequence in between Salt Range front and Jogi Tilla ridge is marked with Precambrian evaporites, Jhelum Group, Nilawahan Group, Makarwal group, Chharat group, Rawalpindi Group and Siwaliks Group. Whereas the Chambal ridge is marked with Precambrian evaporites, Jhelum Group, Rawalpindi Group, Siwaliks Group. The successive pattern of strike slip faulting in the study area has produced remarkable Jalalpur Sharif Orocline as shown in the fig (4.10).

The Jalalpur Sharif lineament is about 17 km long, trending NW-SE direction and cross cut the Salt Range frontal and Jogi Tilla sequence in an oblique manner. This pronounced lineament on the map is extended from NW of Kotal Kund village to further SE of Bair Faqiran village. It shows simple shear component parallel to its strike having lateral displacement within mollase sequence, which has separated these two regional structures from one another, whereas the pure shear component across the left lateral strike slip zone has provided further movement in the development of Salt Range fore-thrust and its associated splays near Mangal Dev.

Following another phase of strike slip faulting known as Pind Sawika lineament which is trending WNW-ESE in between Jogi Tilla and Chambal ridge with right slip sense of movement and finally merged with the Jalalpur Sharif lineament in an oblique manner. The Jalalpur Sharif and Pind Sawika lineament has bounded Chambal Back-Thrust sheet, though its movement is further facilitated towards the hanging wall sequence of Salt Range front. The opposing shear sense of these two lineament have juxtaposed in the NW direction of Kotal Kund and produced the dextral opening zipper junction zone. According to Platt and Passchier (2016) the merged strike slip faults in an area may results in the unusual deformation and rotation to hold the variance in displacement vector. Therefore the Salt Range front, Chambal ridge and Jogi Tilla structures have NW-SE (Mangal Dev and surroundings), N-S, NE-SW regional trends, respectively.

The map expression of the Salt Range frontal ridge shows remarkable shift along Jalalpur Sharif lineament, though its NW mapped portion has different trend as compared to the Mangal Dev and surrounding areas. As a matter of fact the NW portion is bounded by parallel set of two right lateral strike slip fault, one dextral fault is located out of the study area near Choa Saidan Shah, which was previously explained that Choa Thrust and Karangal Back-Thrust of opposite vergences is terminated by a right lateral strike slip fault (Hassan, 2011 and Ali, 2007). The second dextral fault is located in the NW portion of the study area where it has formed a zippered junction zone with the Jalalpur Sharif lineament and dragged the same thrust sheet to the opposite direction towards hinterland side. The lineament has further moved across the outcropped NW verging and SE verging Dil Jabba Back-Thrust and Domeli Thrust, respectively. The analysis is drawn with the conclusion that the study area has gone through systematic deformation and subsequent anticlockwise rotation in the above ridges.



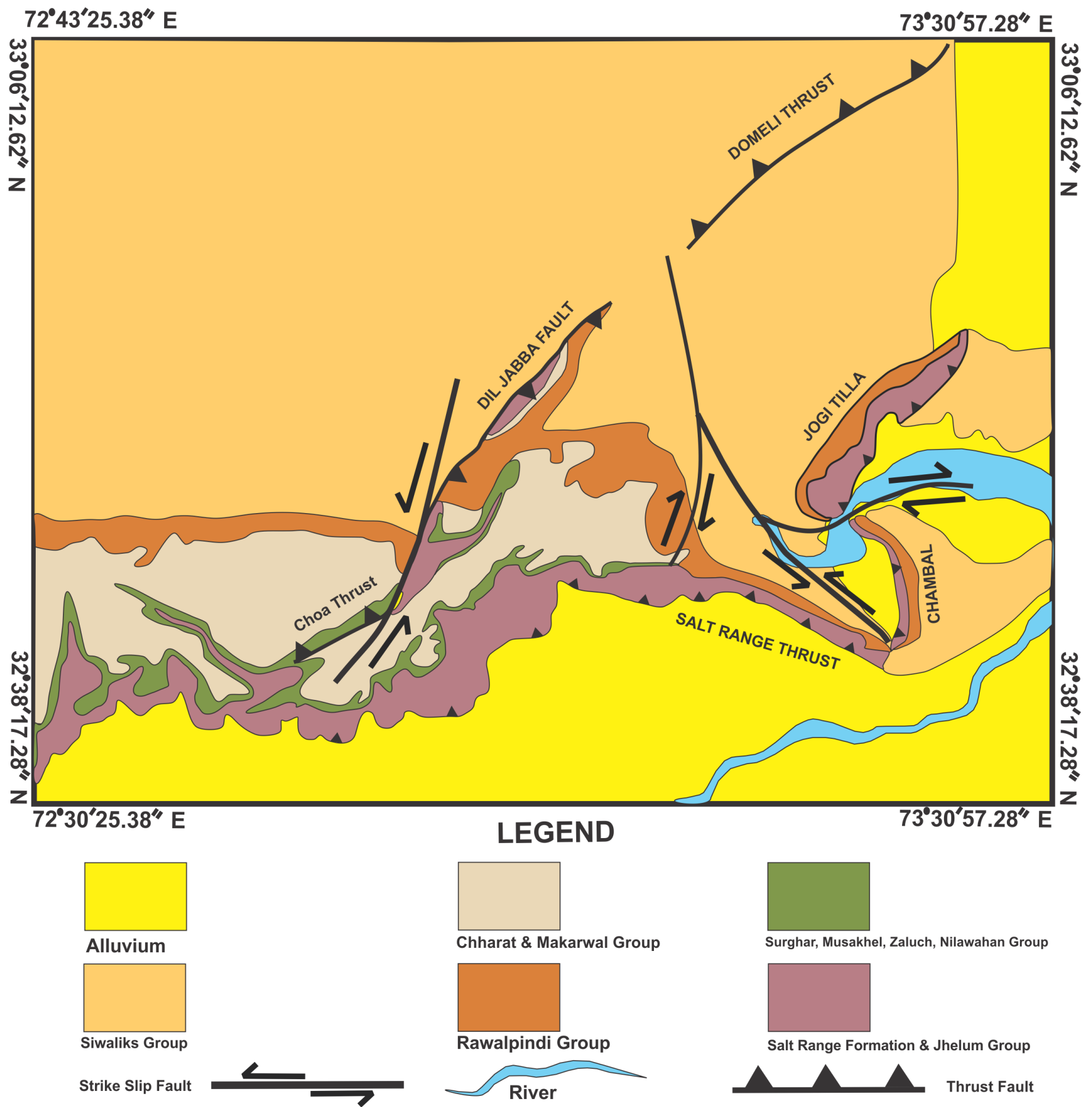


Fig. 4.10 Sequential map representation showing kinematics of oroclinal bending near Jalalpur Sharif village, Eastern Salt Range. (A) North-South compressive stress emplaced Salt Range front and Jogi Tilla, later on separated by Jalalpur Sharif Lineament. (B) An oblique (NW) directed stress vector developed Chambal Back thrust, Pind Sawika lineament at later stages supported further movements and rotations. (C) North-Western portion of the map shows dragging of thrust sheet towards hinterland side by dextral fault (within study area), sinistral fault (present at Choa village) and associated fore thrust, back thrust development.

#### **4.7 Palinspastic Restoration**

In this standard technique/procedure present-day deformed state of a geologic domain is figured out into progressively undeformed state and it is assumed that movement on faults is rigid translation and rotation. The mosaic pattern of fault bounded blocks override each other in a compressional regime.

The study area is dominated by bivariate shortening direction, the older and main phase of shortening direction is progressively from hinterland to foreland (north to south) along which Salt Range thrusting has occurred about 5-1.9 Ma (Grelaud, 2002), whereas another younger phase of shortening direction is interpreted to prevail towards northwest direction in an oblique fashion to the main tectonic transport direction. These variable stress vectors has caused an unusual situation in the study area by creating contrasting bend in “S” shape structure. It is formed by the different trending geologic structures of Salt Range front, Chambal Ridge and Jogi Tilla ridge. The deformation within these ranges involves emplacement along faulting with significant sinistral and dextral shear component at later phases has modified these ranges into “S” shape structure (Fig. 4.1, 4.10). The models presented above shows that the faulted structural blocks of the study area are bounded by different sense of strike slip faults with closing zipper junctions that have supported distortion, bending and subsequent rotation. These faults have an important role in establishing the complex structural geometry and physiography of the study area.

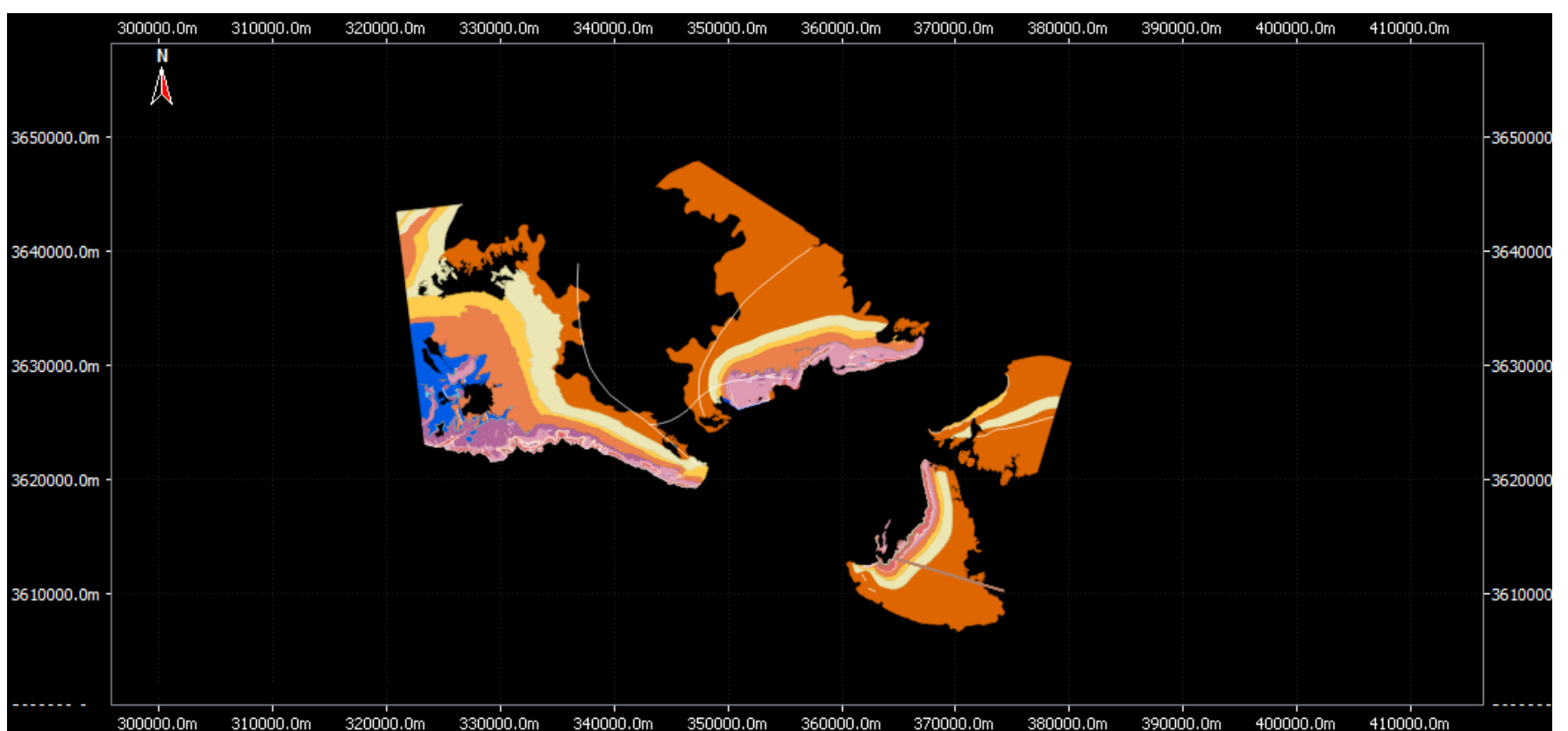
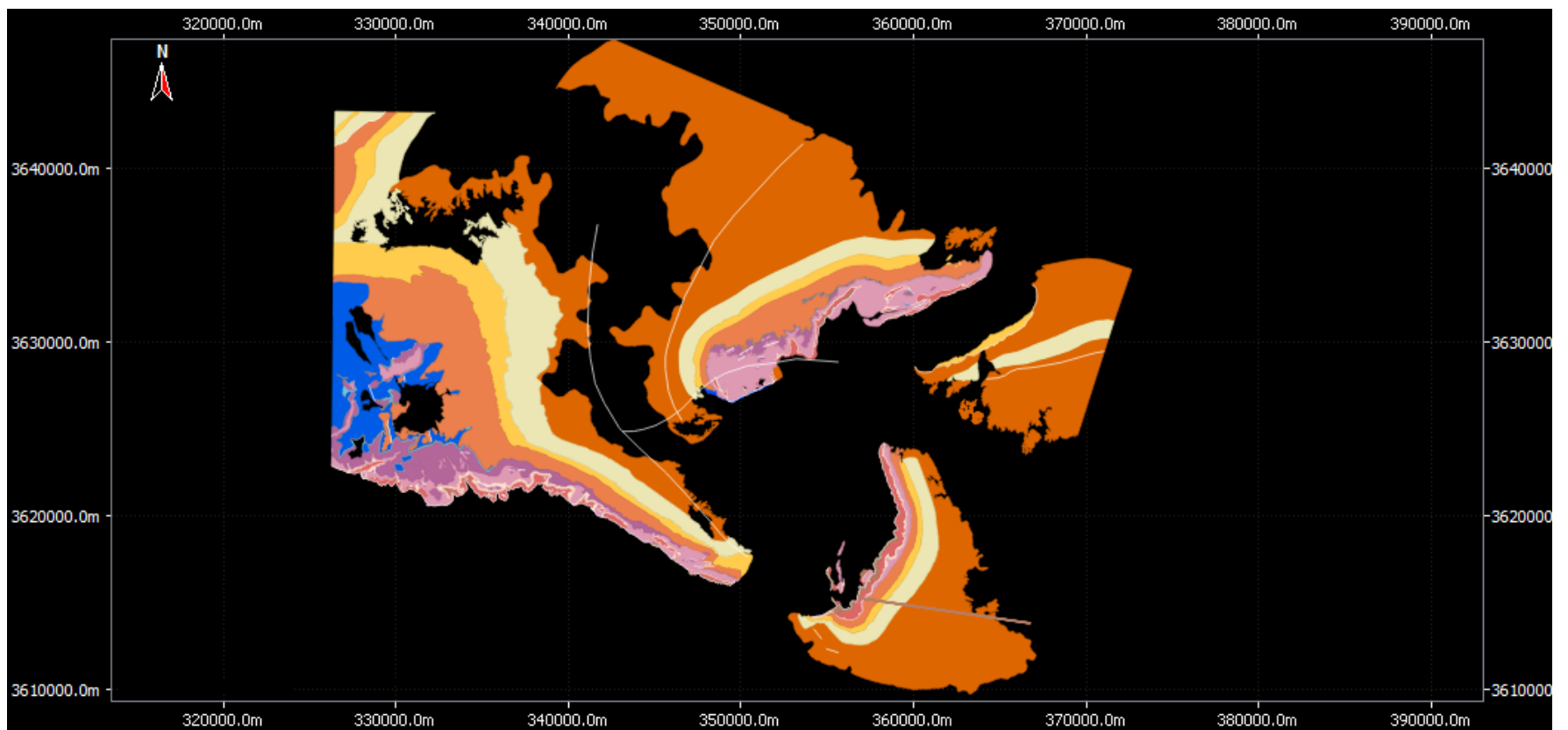
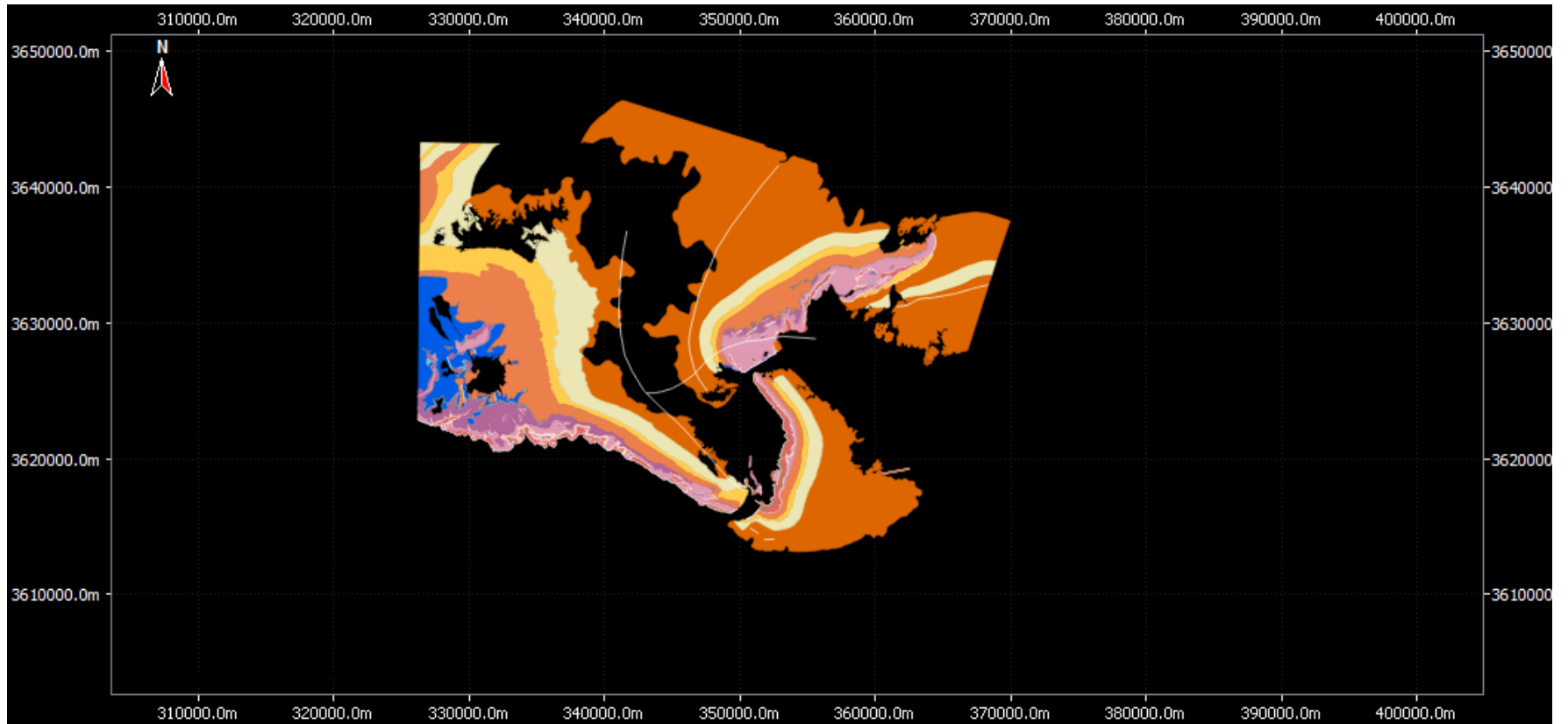
The Palinspastic reconstruction of the study area is accomplished with the help of the Midland valley Move software, 2013, in order to locate the previous geometric position of these structural ridges. In this progression geological field attributes of regional thrust faults, strike slip faults, dip and dip direction of the different exposed stratigraphic units has been considered for restoration. Using the 2d module of the

“Move” software followed by the “object loop selection” in the model building menu, polygons for different structural blocks have been drawn and then displaced back to its juxtaposed structural features. The selected polygon with complete stratigraphic sequence of the Range Front have been palinspastically restored to its former position by reversing the Jalalpur Sharif lineament, as a result the Range Front has been coordinated and matched with the stratigraphic sequence and structural trends of the Jogi Tilla selected polygon. After matching the polygons of two congruent structural ridges there is still convexity and tilting in the Jogi Tilla ridge with the Range Front (making V-shape), which has been interpreted due to an oblique younger resistive stress vector operating towards northwest in an opposite direction to main tectonic transport direction. The overlaps and gaps indicates the area of contraction and extension respectively.

The restoration procedure for the SE portion of the study area is advocated similarly as discussed above. It is marked by the north-south trending Chambal ridge lying in between Jalalpur Sharif and Rasool village. The Chambal ridge is considered as a younger deformational event as compared to the other arms of “S” shaped structure that is the Salt Range front and Jogi Tilla. The reason is upheld by the cross cut relation and out of sequence thrusting phenomena. It has been found that the northwest trending Pind Sawika lineament is present at the northern outskirts of Chambal ridge, where it has zippered with older Jalalpur Sharif lineament. The dextral sense and inward push segment uphold the movement of Back-Thrust and subsequent anticlockwise rotation (Fig 4.10, B).

Now to re-establish the structural and stratigraphic geometry of Chambal ridge to the undeformed position. A polygon of the Chambal ridge has been drawn with the help of “object loop selection” in model building of 2d module, where a reverse sense of Back-

Thrust and Pind Sawika lineament has been applied in the 2d model of map restoration. It is demonstrated that Chambal ridge succession and the Mollases now isolated through Bunha river has been restored and coordinated with the Siwaliks sequence of the Chambal ridge. Expelling the anticlockwise rotation in the Chambal ridge place it in the SSE quadrant which may actually be its unique position from where it began thrusting and rotation. The anticlockwise rotation shown in the models of current study are consistent with the previous interpretation of paleomagnetic studies of Johnson et al., (1979).



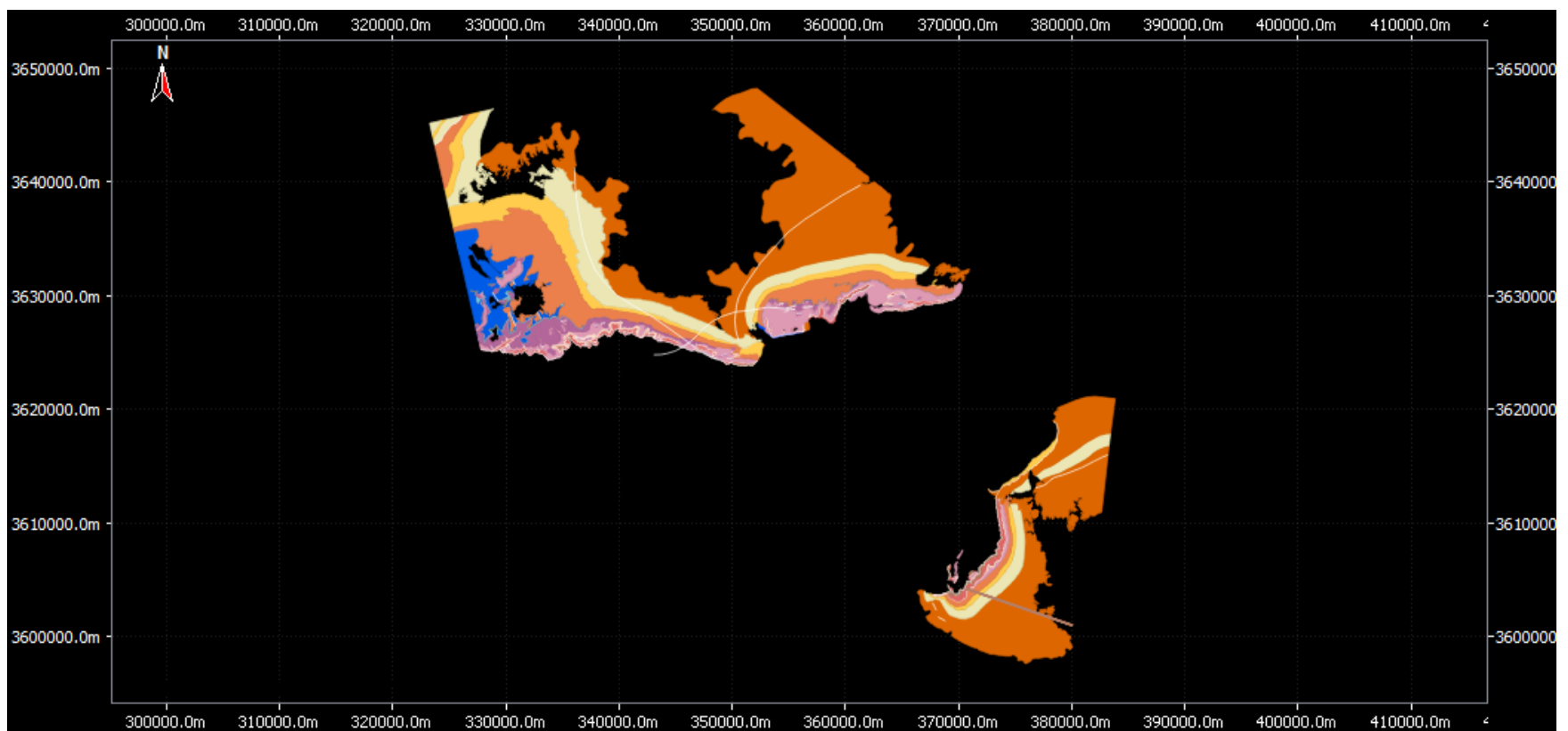
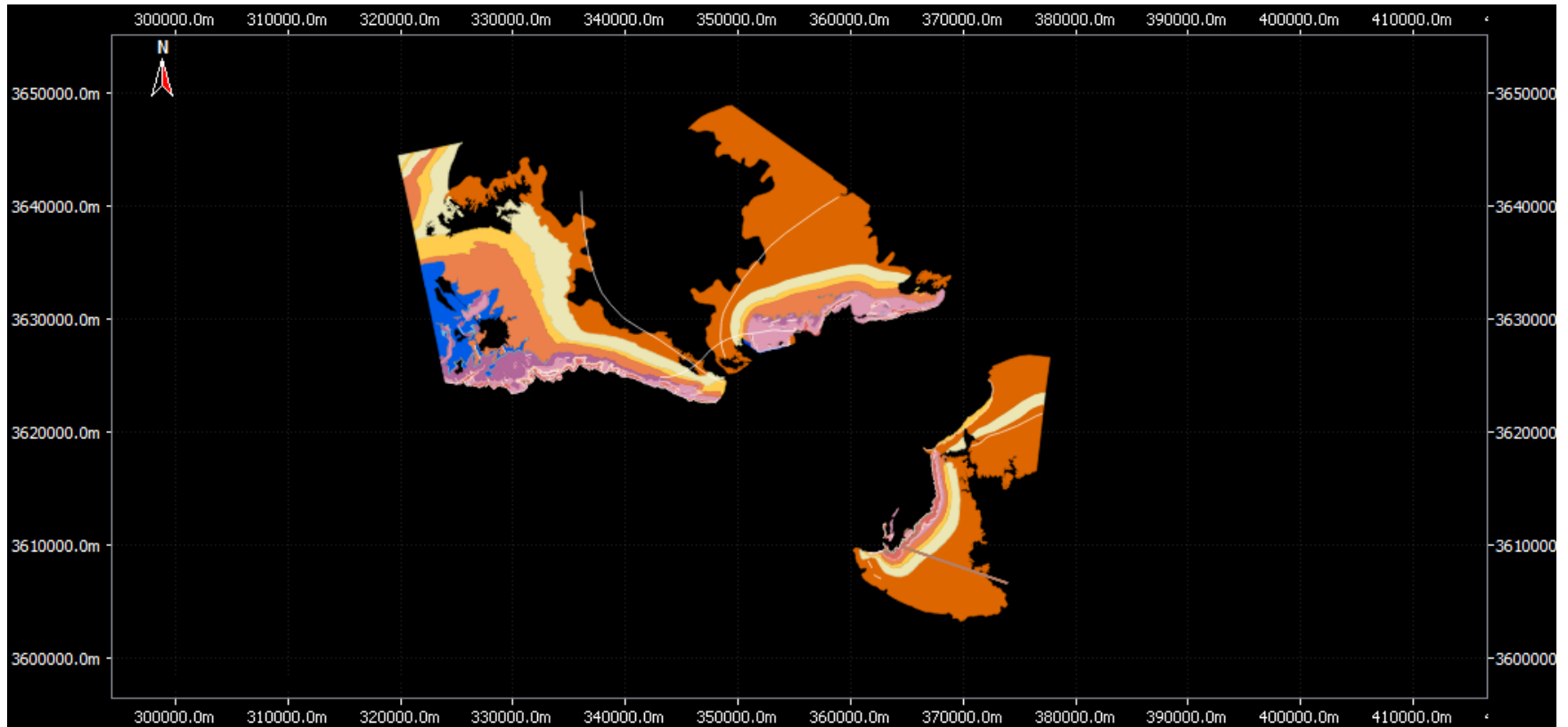


Fig. 4.11 Palinspastic reconstruction with the help of 2D module of Move software for contrasting structural style of three prominent structural ridges that is Salt Range front, Chambal ridge and Jogi Tilla ridge. First and second image shows Back-Thrust restoration in the SE direction, further progressive movement in the image three has shown removal of tilt in Jogi Tilla and reconstruction of rotation in the Chambal ridge. Image fourth and fifth shows progressive movement and juxtaposing of the Salt Range front and Jogi Tilla ridge.

## Conclusions

The kinematics of contrasting structural style of the study area in-terms of three different trending structural ridges led to the following conclusions;

- During the compilation of detailed geological map for the research area it has been concluded that the stratigraphic sequence ranging in age from Precambrian Salt Range Formation to Quaternary younger units are involved in the process of deformation.
- The oroclinal bending of three different trending structural ridges depicts varied stratigraphic sequences. The Frontal Range and Jogi Tilla ridge ranges from Precambrian Salt Range formation at the base followed by the younger carapace sequence, whereas the Chambal Ridge is devoid of Upper Cambrian unit, Makarwal group and Chharat Group.
- The area has undergone through three different phases of deformation, an older deformational phase is directed from hinterland towards foreland (south verging), whereas another younger phase of deformation is directed towards hinterland (NW verging) and later on followed by the strike slip tectonics.
- The In-sequence thrusting observed in the Frontal Range and Jogi Tilla Ridge has been later on displaced to the existing position by left lateral strike slip fault known as Jalalpur Sharif lineament. The outcropping sequence of these ranges shows break back sequence of faulting. The parallel set of fault splays have developed in the backward direction from the main thrust near Mangal Dev of the Frontal Range and depicts transpressional deformation.
- The out of sequence thrusting phenomena in the easternmost corner of the study area has been observed in the form of Chambal Ridge, the associated parallel splays has developed in the footwall of the main thrust and depicts forward breaking

sequence. A right lateral strike slip fault occupying the northern margin of the Chambal Ridge known as Pind Sawka lineament is running from southeast to northwest direction and has advocated the Back-Thrust.

- The “Palinspastic Restoration” for south verging Frontal Range and southeast verging Jogi Tilla Ridge has been achieved with the help of Move 2013 software by reversing the thrust faults and Jalalpur Sharif lineament that have been matched collectively in-terms of structures and stratigraphy and placed in the northern position, whereas the Chambal ridge with its associated splays and Pind Sawika lineament have been restored farther to the southeastern position.
- The opposing sense of different strike slip faults has produced shear zippered junction zone in the NW position of the study area, an unusual deformation and subsequent rotation is supported by these merged shears that holds the variance in the displacement vectors.
- Utilizing the “move on fault” and “unfolding” module of the Move 2013 software, the average shortening calculated in the study area is 47.5 %.

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