

Two and Three-Dimensional Structural Modelling of Central Kohat Plateau, Northwestern Himalaya, Pakistan



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Abstract The Kohat Fold and Thrust Belt (*KFTB*) lies in the north western margin of Himalayan arc in the Pakistan. It covers a part of outer Himalayan Foreland Basin where 800 m thick Eocene package is predominantly exposed at the surface forming different structures. Current research describes the structural geometry and kinematics of the central *KFTB* and identifies the role of mechanical heterogeneity in defining the surface structuration as well as its impacts on the deeper horizons. The east west trending, open to tight and overturned folds having curvilinear axes associated with thrust fault system dominates the exposed structural geometry of the area. Three mechanically different stratigraphic packages have been identified in the research area. The thick middle (Late Paleocene to Middle Eocene) clayey and mechanically soft package is sandwiched between upper and lower mechanically competent packages. The upper package comprises of Middle Eocene to Late Miocene rocks while the lower package consists of Paleozoic up to Paleocene rocks. Our structural modelling suggests that the deformation within the exposed upper competent stratigraphic package is disharmonic in structural relation to the lower stratigraphic package, which is comprised of south verging, ramp-related fore-folds. The middle, soft and plastic stratigraphic package is acting as surface of fault-fold decoupling between the lower and upper competent packages. The structural balancing reveals

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that the area has undergone 42.35% shortening. The mode of deformation is thin-skinned, while the facing of structures show southward propagation of deformation as a result of the Indo-Eurasian plates collision.

Keywords Structural geology · 2D and 3D structural modelling · Stress analysis · Central Kohat Plateau · KP Pakistan

1 Introduction

The study area lies in the central part of Kohat Fold and Thrust Belt (*KFTB*). The *KFTB* represents the western segment of the Upper Indus Basin of Pakistan and lies in the north western margin of Himalayan arc (Fig. 1). The Himalayas formed about 57 Ma ago due to Indian and Eurasian landmass collision (Gansser 1964; LeFort 1975; Molnar and Tapponnier 1975; Fraser et al. 2001). The *KFTB* is an east west trending foreland basin comprised of Eocene to Plio-Pleistocene sediments (Gee 1945; Fatmi 1973; Meissner et al. 1974; Sameeni et al. 2009; Shah 2009). The lack of igneous and metamorphic rocks makes this region a part of the external zone of Himalayas (Coward et al. 1986).

The *KFTB* is characterized by tens of kilometers extended anticlines and synclines (Meissner et al. 1974) and the limbs of many of these structures shows thrust/reverse faulted relation with younger rocks (Khan et al. 1986; Gardezi et al. 2017). During the orogeny of Himalayas, the *KFTB* was the major depositional center of eastwestern Himalayan sediments in the Miocene age (Dutta et al., submitted). Gradually, it uplifted tectonically and became folded and faulted, recording the southward propagation of Himalayan deformation as a result of ongoing collision between Indian and Eurasian plates (Wells 1984; Pivnik 1992).

The stratigraphy of the western Himalayan collision zone is predominantly preserved in the Kohat region. The stratigraphy of this region and adjoining areas reveals a broad spectrum of oceanic and continental environment facies ranging from Triassic to Recent (Fig. 2). The continental rock units of the Miocene to Plio-Pleistocene mark a regional unconformity with the underlying marine rock units of the Eocene age. Jatta Gypsum of the Eocene is the oldest exposed rock unit in the study area. The northern and north western border of *KFTB* is demarcated by the Main Boundary Thrust (*MBT*) (Khan et al. 1986), the Bannu Basin and the Surghar Range mark its southern boundary. The axial belt of Kurram accretionary wedge, which is transpressional left lateral fault, delimits its western boundary while the Indus River marks its eastern frontier and separates it from the Potwar Plateau. The present research focuses on the detailed study of structural geology of the central *KFTB*, which lies in the north west of outer Himalayas in the north Pakistan. The structuration in this area is the result of southward propagating deformation due to Indo-Eurasian collision. These structures are mainly anticlines, synclines, thrust faults and their associated back thrusts. The overall structural trend is east west with local exceptions (Fig. 1).

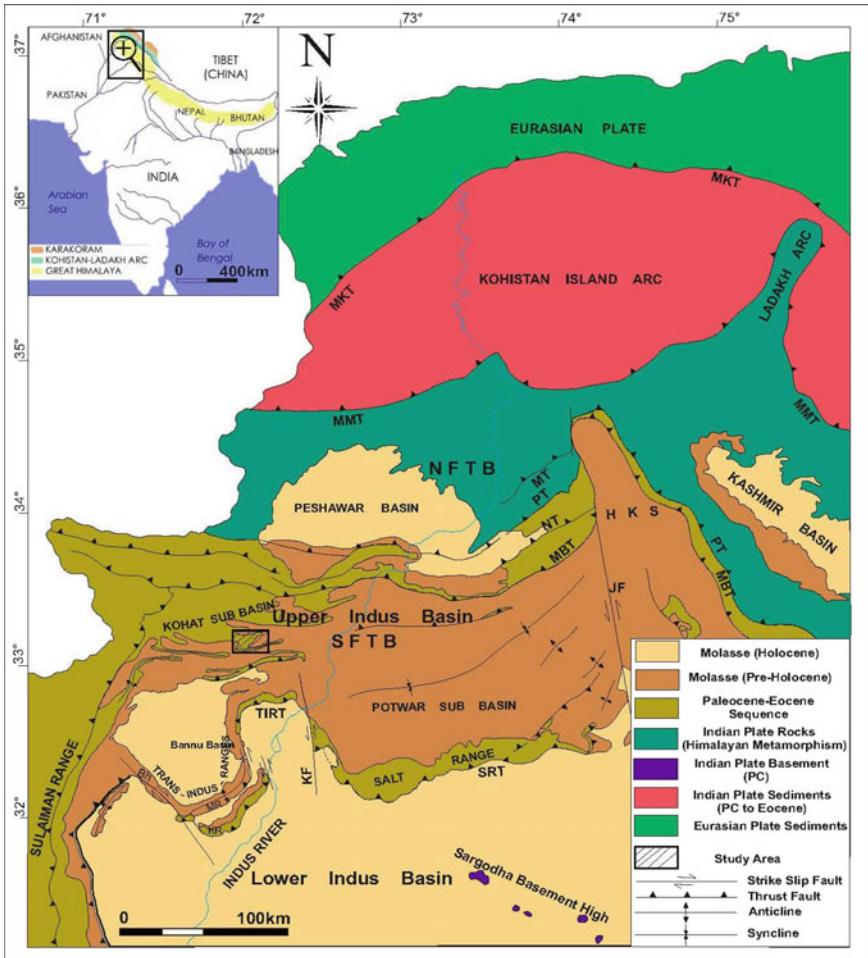


Fig. 1 Generalized geologic map of the NW Himalayan foreland fold and thrust belt, modified after Kazmi and Rana (1986). Inset shows the location of study area. *MKT* Main Karakorum Thrust, *MMT* Main Mantle Thrust, *MBT* Main Boundary Thrust, *NFTB* Northern Fold and Thrust Belt, *SFTB* Southern Fold and Thrust Belt, *MT* Mansehra Thrust, *PT* Panjal Thrust, *NT* Nathiagali Thrust, *HKS* Hazara Kashmir Syntaxis, *JF* Jhelum Fault, *KF* Kalabagh Fault, *SRT* Salt Range Thrust, *TIRT* Trans Indus Range Thrust, *MR* Marwat Range and *KR* Khissor Range

The *KFTB* has been explored by many researchers mainly because of its extensive salt, gypsum, oil and gas occurrences (Burnes 1832; Davies 1926; Gee 1945; Pinfold 1918; Raza and Khattak 1972). Fatmi (1973) carried out a detailed work to establish the lithostratigraphy of this geological province. In 1974, Meissner et al., mapped this region on a scale of 1: 50,000. Wells (1984) published his worked on the depositional environments of the Early Eocene strata of the *KFTB*. Yeats and Hussain (1987) worked on the timing of structural events in the Himalayan foothill of NW Pakistan.

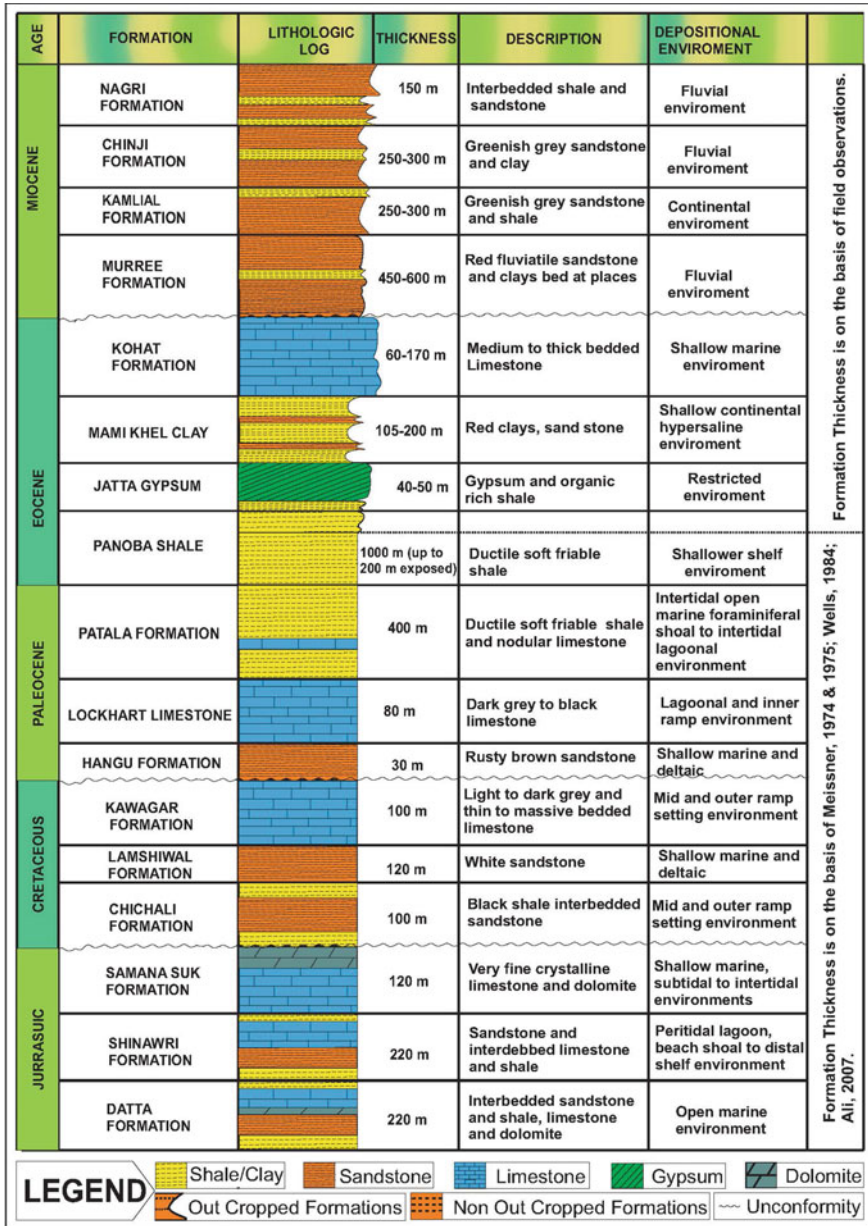


Fig. 2 Generalized Stratigraphic column of the *KFTB*, modified after Meissner (1974, 1975), Wells 1984

Abbasi and McElroy (1991) conducted the structural modelling of some parts of the Kohat region. McDougall and Hussain (1991) discussed the thrust kinematics of the region. Other workers described the *KFTB* as a complex, hybrid terrain consisting of wrench faults and compressional structures (Pivnik 1992; Pivnik and Sercombe 1993; Sercombe et al. 1994a, b). Saleemi and Ahmed (2000) have worked on the chemical and mineralogical composition of mudstone of the Karak area. Hussain et al. (2004) work on the geological map of the *NWFP*. Paracha (2004) published a research paper on the *KFTB* with reference to the Himalayan Tectonics. Gardezi et al. (2017) worked on the structural styles of western *KFTB*. They concluded that the area has undergone thin-skinned style of deformation which is the result of compressional stress generated from on going collision between Indian and Eurasian plates.

2 Tectonic Setting and Stratigraphy of the Study Area

The collision between the Indian and Eurasian plates have produced ~2500 km long Himalaya having *NW* to *SE* in India which switches to *NE* to *SW* orientation in Pakistan (Fig. 1). The Indo-Eurasian convergence is still sustained since Eocene at the rate of 5 mm per year due to which, uprising of Himalaya and establishment of a chain of foreland fold-and-thrust belts thrust over the Indian craton (Kemal 1991). The Himalayas in the north Pakistan are divided into five major tectono-stratigraphic terrains, separated by thrust system. The northern most fault of the thrust system is the Main Karakorum Thrust (*MKT*), which separates the Karakorum Block in the north from the Kohistan Island Arc in the south (Tahirkheli 1983). Coward et al. (1986) named it as the Northern Suture Zone that formed during Late Cretaceous. Due to collision and subsequent subduction of the Indian Plate underneath the Kohistan Island Arc (*KIA*), the Main Mantle Thrust (*MMT*) or the Indus Suture Zone formed (Tahirkheli et al. 1979; Tahirkheli 1982, 1983). The *MMT* and the *MKT* combinedly forms the Indus-Sangpo Suture (*ITS*) of the central Himalaya in the India and the Tibet.

The continent-arc-continent convergence that deformed the Indian crust remained continued with the formation of the *MMT* (Fig. 1). This convergence developed a regional foreland fold-and-thrust belt situated in south of the *MMT*. This foreland fold-and-thrust belt is further sub divided into a northern fold-and-thrust belt (*NFTB*) which is 260 km wide along *NS* and extends around 500 km along *EW*. This northern belt is comprised of severely deformed rocks of sedimentary, meta-sedimentary and igneous origin displaying festoon geometry. The *NFTB* is bounded by Kashmir Basin in the east and the Kurram area in the west. The *MBT* demarcates its southern boundary and separate it from the southern fold-and-thrust belt (*SFTB*). The *SFTB* is underlain by sedimentary rocks and because of the presence of petroleum system the area is very important for oil and gas exploration. The study area is located within the western premise of the *SFTB* i.e. in the central *KFTB*. This external part of the foreland basin is thrust southward over the undeformed sediments of the Punjab Foreland Basin along the *SRT*.

The *KFTB* and the adjacent areas represent a complete depositional record from Mesozoic up to Pleistocene (Fig. 2). The stratigraphic framework of the central *KFTB* demonstrates that until Middle Eocene it was a restricted sedimentary basin followed by the Late Eocene to Oligocene exposure marked by a regional unconformity. Since Miocene, it has become a syn-orogenic foreland basin filled with fluvial sediments mainly derived from north. The Eocene, Miocene and Pliocene rock units are exposed, which are mapped during the current field work (Fig. 4). The Pliocene rocks are not deposited throughout the entire mapped area but their presence in the extreme south shows that the foreland basin migrated southward due to the Miocene onward slip associated with the *MBT* (Burbank 1983).

The rock sequence exposed in the study area includes Eocene age platform rocks unconformably overlain by Miocene to Mid Pleistocene molasse sequence (Fig. 2). The Early Eocene Panoba Shale is the oldest formation that is exposed in the core of the anticlinal folds. The study area shows a complete stratigraphic record from Eocene to Early Jurassic Datta Formation (Fig. 2). The stratigraphic description of the exposed Eocene to Miocene rock sequence is based on the field observations whereas the description of the non outcropping Paleocene to Jurassic rock sequence is based on the literature review (Meissner et al. 1974, 1975; Wells 1984).

3 Methodology

3.1 Reconnaissance and Travers Selection

Google Earth imagery (30 m resolution), already published literature and maps as well as Digital Elevation Model (DEM) (30 m resolution) were analyzed to understand structure, geology and drainage pattern of the area. Different systematic traverses were marked in the Google Earth throughout the study area by following road network and drainage in the study area for detail geological mapping.

3.2 Field Data Collection

Different field trips were planned to collect geological and structural field data. This field data included determination of attitude of bedding planes and different structures (folds and faults) and marking different contacts along systematic traverses. Sketches of different faults and folds were drawn during field in order to visualize the true pictures of the outcrop. Photographs were taken of different faults, folds and formations during field work.

3.3 Remote Sensing

The field data was plotted on Google Earth to pick color tone of different geological contacts along the systematic traverses. That is how the normal as well as faulted contacts were extended between the systematic traverses.

3.4 Surface Geological Map Construction

Geographic Information System (GIS) software was used to construct a comprehensive geological map at scale 1:50,000 of the mapped coordinates by incorporating field data and Google Earth work.

3.5 Structural Study

Two different structural models were proposed by previous author to explain the structural style of the *KFTB*. One model considers the structures to be part of a passive thin-skinned fashion roof thrust translating southwards. It overlies a passive roof duplex formed by an active wedge of thrust slices directed southwards deforming Pre-Tertiary stratigraphy (McDougall and Hussain 1991; Abbasi and McElroy 1991). The second model suggests that the thick-skinned deformation has greatly influenced the structural evolution of the *KFTB*. This thick-skinned deformation is

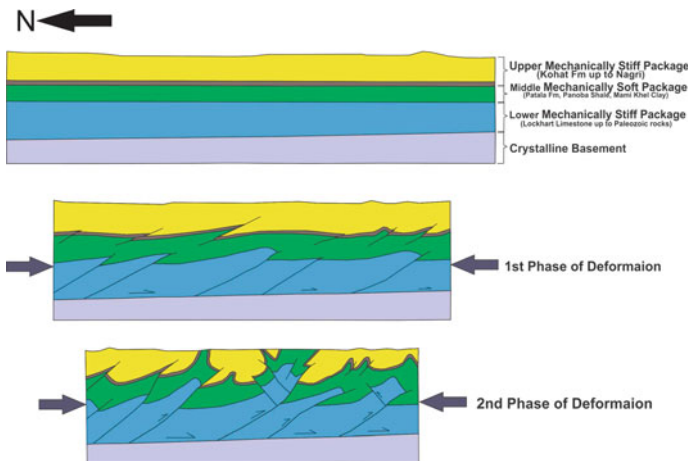


Fig. 3 Model showing structural evolution concept and mechanical stratigraphy of the *KFTB*

demonstrated in strike slip faulting recognizable only in the subsurface and exposing themselves in the Eocene cover as anticlinal trends (Pivnik 1992; Pivnik and Sercombe 1993; Sercombe et al. 1998). The proposed structural evolution model of the study area (Fig. 3) deduces that the subsurface structures do not mimic the surface structures. The stratigraphy of the study area is presumed in three different stratigraphic packages on the basis of stiffness i.e. the upper mechanically stiff package, the middle mechanically soft package and the lower mechanically stiff package (Fig. 3). This mechanical stratigraphy has a vital role in the structural architecture of the region.

3.6 Two and Three Dimensional Structural Modelling

Surface geology is always helpful for understanding the subsurface structural geometries especially in the areas where the surface structuration systematically passes down into subsurface. In the study area the stress vectors do not penetrate homogeneously into the depth (Fig. 3) which makes it tricky to interpret the subsurface using the surface data. But the relationship does exist between the surface and the subsurface structures, which once figure out, becomes the key while making admissible subsurface structural geometries. For two dimensional structural modelling, 2D module of MOVE software was used. This modelling consisted of preparation of 2D balanced geological cross sections (XX' , YY' and ZZ') and their restored sections. For the construction of geological cross sections *DEM* (30 m resolution) and surface geological map were used.

The *DEM* is used to generate the topographic profiles along cross section lines. By utilizing apparent dips the contacts and faults along profile lines interpolated in subsurface using “construct horizons from template objects” tool of MOVE software. Horizon thicknesses from Nagri Formation of Miocene age up to Mami Khel Clay of Eocene age are according to field observations. While the rest of horizon thicknesses are according to previous literature (Meissner et al. 1974, 1975; Wells 1984). On the basis of previous data, the basal detachment is inferred to be located at 9000 m depth dipping towards north having slope of 1.6° in the study area (Sercombe et al. 1998). Restoration of geological cross sections was performed in two steps. The first step includes restoration along faults by sequentially removing the movements on each fault using “Fault Parallel Flow” method of “Move on Faults” algorithm. In “Move on Faults” algorithm different values for heave were fed into the software until the horizons were fully restored and were continuous across the fault. In the second step the beds are unfolded to their undeformed state using “Unfolding” method of “Flexural Slip” algorithm. In “Flexural Slip” algorithm a pin is inserted at the relatively less deformed area and horizons were unfolded on template bed. Restored sections were used to calculate the magnitude and percentage of shortening strains. For 3D structural modelling, 3D module of MOVE software was used. The 3D structural

modelling consist of 3D fault and horizon models. By utilizing same horizon or fault lines in different 2D sections using “Spline curves” method different 3D surfaces were generated.

3.7 Stress Analysis

The “Geo-Mechanical” module of MOVE software was use to perform the stress analysis of the Sumari Payyan Anticline. This module works on the theory of the Mohr’s stress circle diagram which is overlapped on Coulomb Failure Envelope. Plunge, plunge azimuth and stress amount (MPa) of different principal stress axis (σ_n) i.e. the maximum stress (σ_1), the minimum stress (σ_2) and the intermediate stress (σ_3) were calculated form 3D surface of Sumari Payyan Anticline of existing model. These values along with 3D surface used by the software to generated the final stress model. The software convert whole 3D surface into large number of planes on the basis of different dip direction domains. Each separate plane is represented by a black dot which is mark on the centre of the plane. The software calculate the stress analysis of each plane using the input values. The stress data of each point was plotted on the Mohr’s stress circle diagram in the software. The Coulomb Failure Envelope was plotted over the Mohr’s stress circle diagram and they intersect each other. The intersected region is marked by the red color. The points which fall within the red color region of Mohr’s stress circle diagram are the plane where the failure can occur.

4 Results

4.1 Surface Geology

It has been found that the structuration in the study area is mainly controlled by east west trending open to tight normal and overturned folds. Major folds in the area having curvilinear axis. The faults is the area are thrust and back thrust in nature. The vergence of major structures is towards south (Fig. 4). Dominated dip directions in the area is in north and south.

4.2 Two-Dimensional Structural Modelling

On the basis of structural evolution model of the study area (Fig. 3) three structural cross sections along lines XX' , YY' and ZZ' (Figs. 6, 7, 8) are selected which are approximately perpendicular to the major structural trend in the study area (Fig. 4).

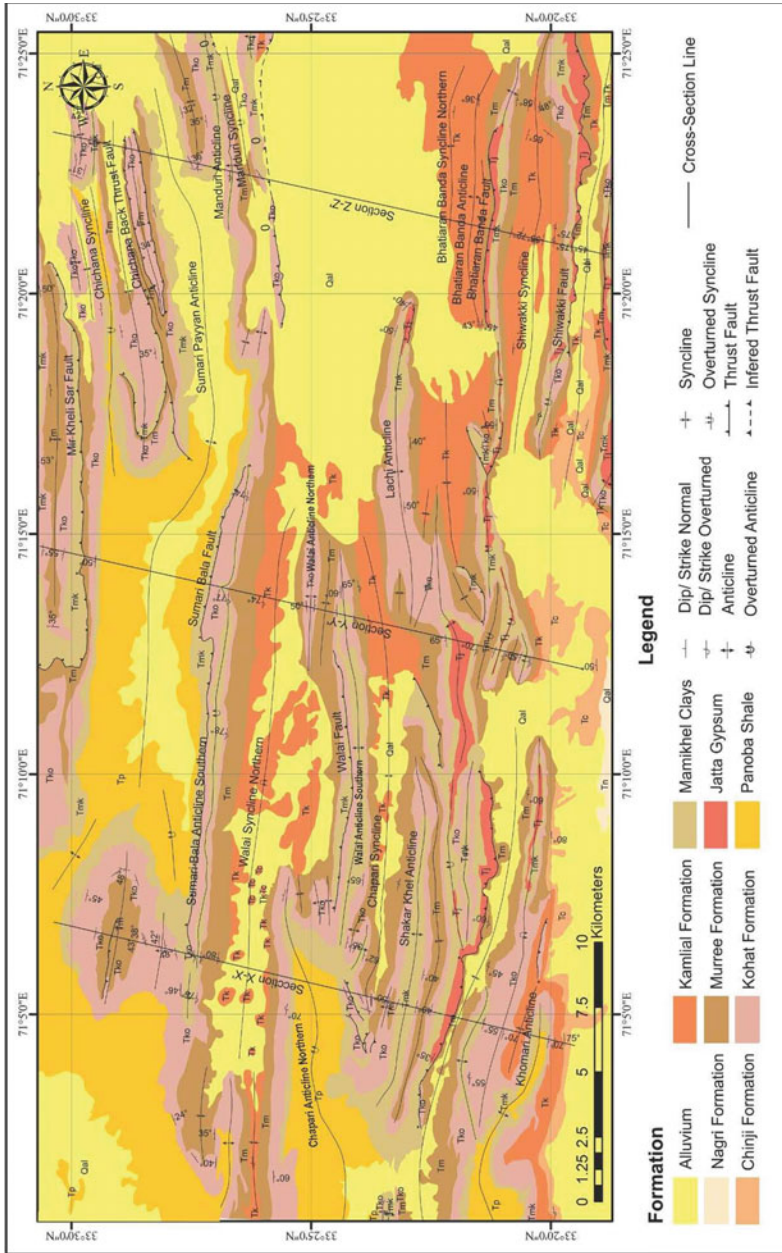


Fig. 4 Geological map of the study area

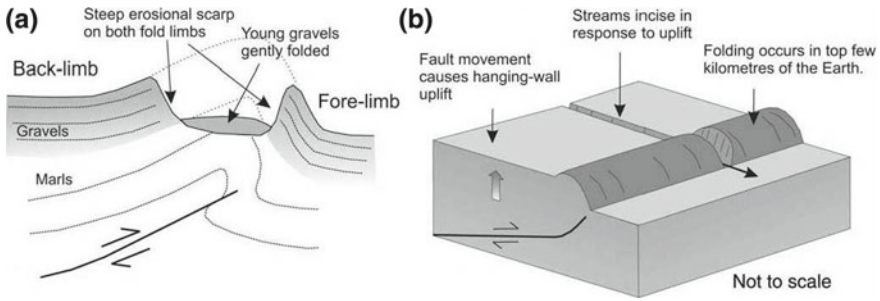


Fig. 5 a Schematic cross-section and b block diagram of a ‘blind’ thrust fault (Stein and Yeats 1989)

The east west trending flat-topped ridges and valleys are commonly interpreted to be alternating low-amplitude anticlines and synclines in the study area. Anticlines are mostly uplifted by sub-cropping blind faults, the slip on which is in most of the cases accommodated by the tight folding in the upper stiffer package (Stein and Yeats 1989) (Fig. 5).

Three cross sections (Figs. 6, 7 and 8) were constructed for the better understanding of subsurface structural geometries, kinematics, and behavior of the various stratigraphic units across different structures of the study area. The structural model constructed along the lines XX' , YY' and ZZ' suggests that within the Eocene carapace the disharmonic folds of varying amplitudes dominate the subsurface structural geometry of the area (Figs. 6, 7 and 8). As the Panoba Shale occupies the base of the Eocene, its plastic nature has resulted in thickening of the anticlinal cores. Maximum folds are overturned and south verging. The cross sections suggest that the dominant structures style within the area is comprised of a series of south verging alternate anticlines and synclines.

Restoration and balancing of cross sections estimate the amount and percentage of shortening along the lines XX' , YY' and ZZ' of lengths 20,482.3 m, 21,321.4 m and 21,810.8 m, respectively (Figs. 6b, 7b, 8b). The total amount of shortening occurred along folds and faults of the cross section XX' is 18,383.6 m so the percentage of shortening is 47.3%. The shortening amount occurred along folds and faults of the cross section YY' is 15,473.1 m with calculated percentage of shortening is 42.05%. The total amount of shortening occurred along folds and faults of the cross section ZZ' is 13,197.5 m with calculated percentage of shortening is 37.69%. Average amount and percentage of shortening along the cross sections XX' , YY' and ZZ' are 15,685.07 and 42.35%, respectively. The percentage of shortening along cross sections XX' , YY' and ZZ' indicated that in that area the rate of deformation increases from east to west in the study area.

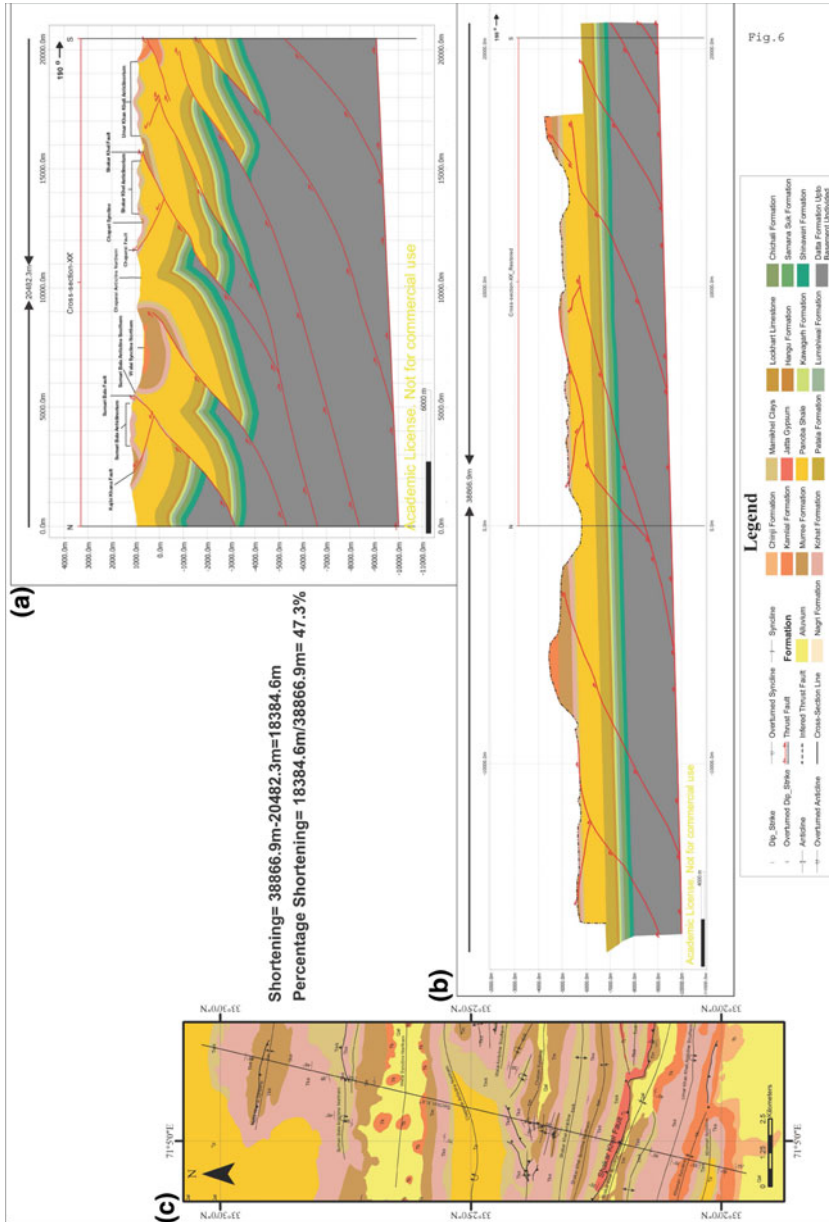


Fig. 6 a Structural interpretation before restoration, b final stage of restoration and c base map of cross-section XX'

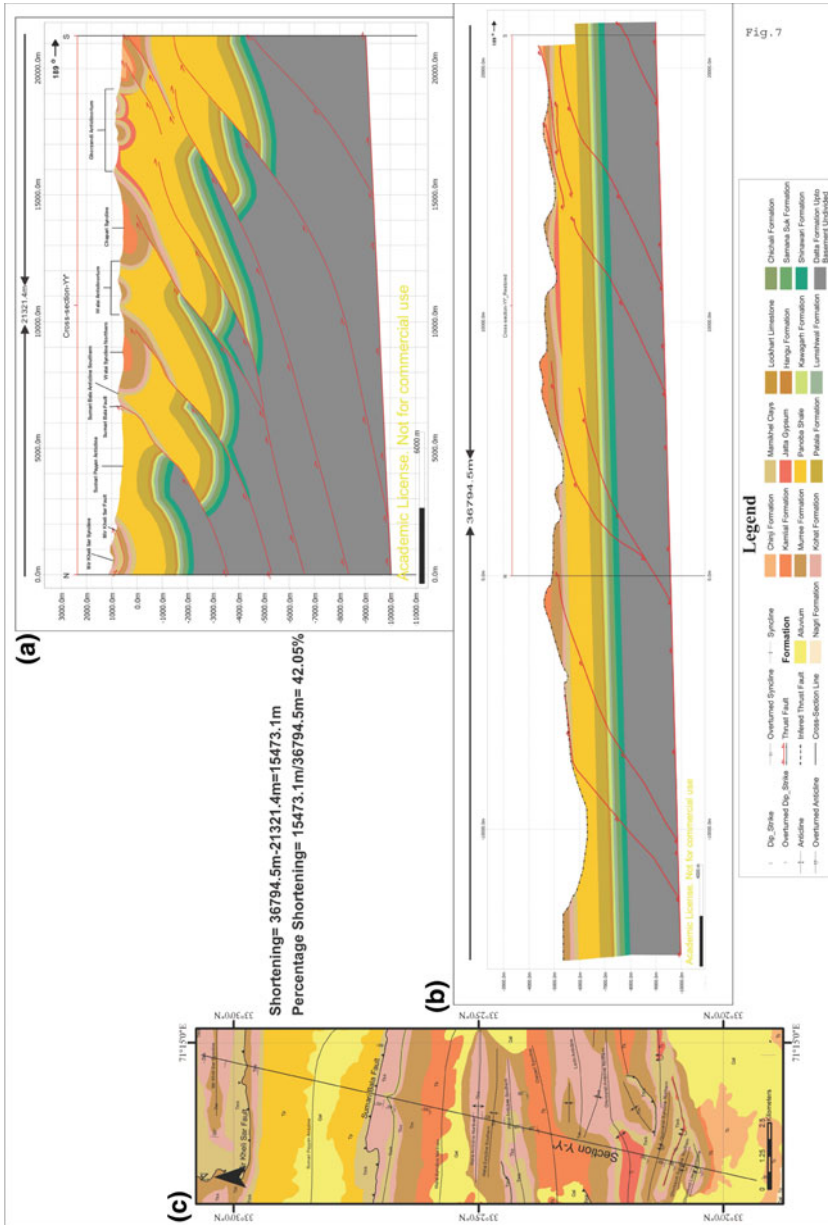


Fig. 7 a Structural interpretation before restoration, b final stage of restoration and c base map of cross-section YY'

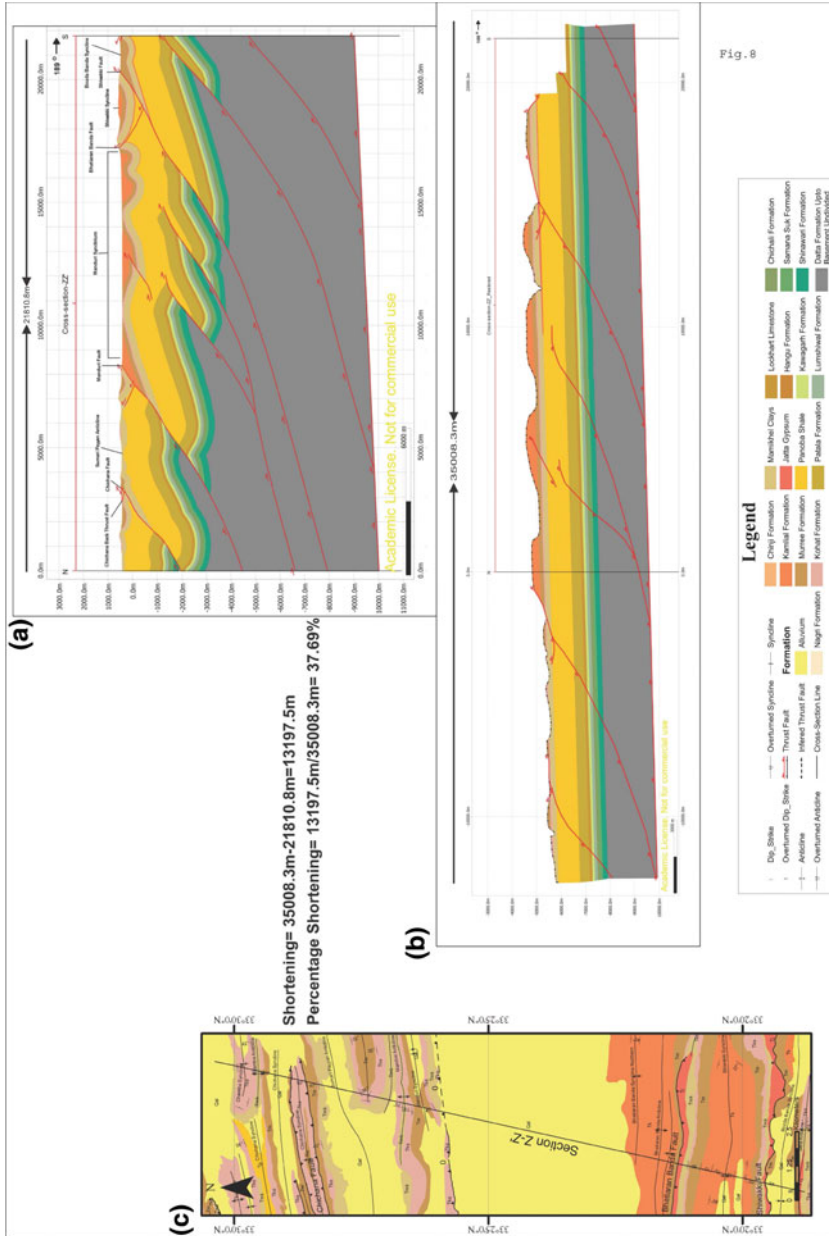


Fig. 8 a Structural interpretation before restoration, b final stage of restoration and c base map of cross-section ZZ'

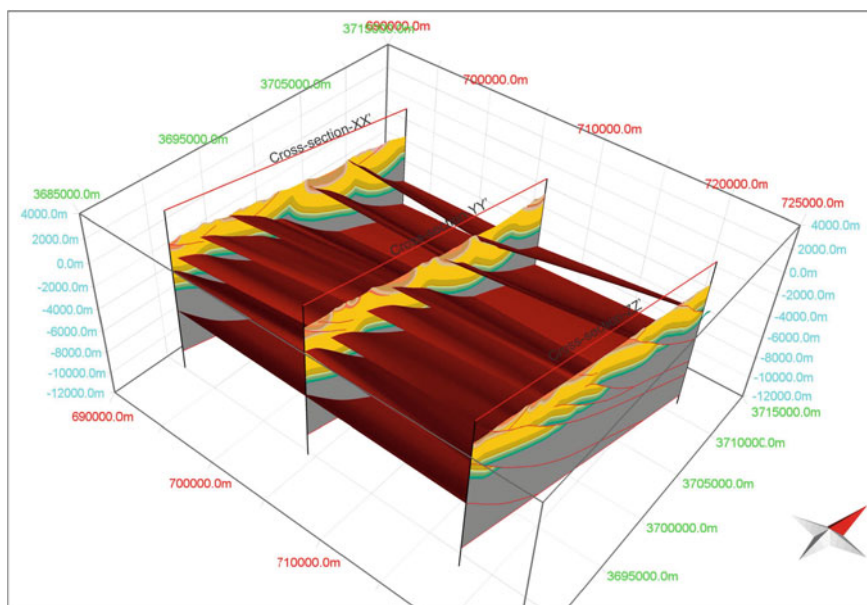


Fig. 9 Image showing south eastern view of 3D fault model of the study area

4.3 Three-Dimensional Structural Modelling

Total, 21 fault planes from 2D sections were used to generate 3D fault model of the area (Fig. 9). The model consist of seven fault surfaces which shows trend and behaviour of different faults in subsurface. This shows that the major faults in the area are east west trending and south verging. The 3D fault model shows that the fault system in the study area is the thrust related faults. The strike direction of the fault system is ENE (N80°E) with the dip angle varying 35°–40°. The majority of the faults have seen as “blind faults” and only a few faults cuts up section at the surface in the entire model.

The 3D horizon model of top of the Lockhart Limestone (Paleocene) was generated according to the developed fault model (Fig. 10). The model shows the relation between four major anticlinal folds with intervening depressions and fault system. These anticlines can be suitable traps for hydrocarbon accumulation. The 3D horizon model also describes the petroleum play concept of the area where fault plane can act as the path for primary migration of hydrocarbon from source rock to reservoir rock.

The 3D model shows majority of structural trend is EW and some with minor tilt. This structuration is the result of southward propagation of deformation as a result of NS compressions and localize lateral forces due to Indo-Eurasian plates collision.

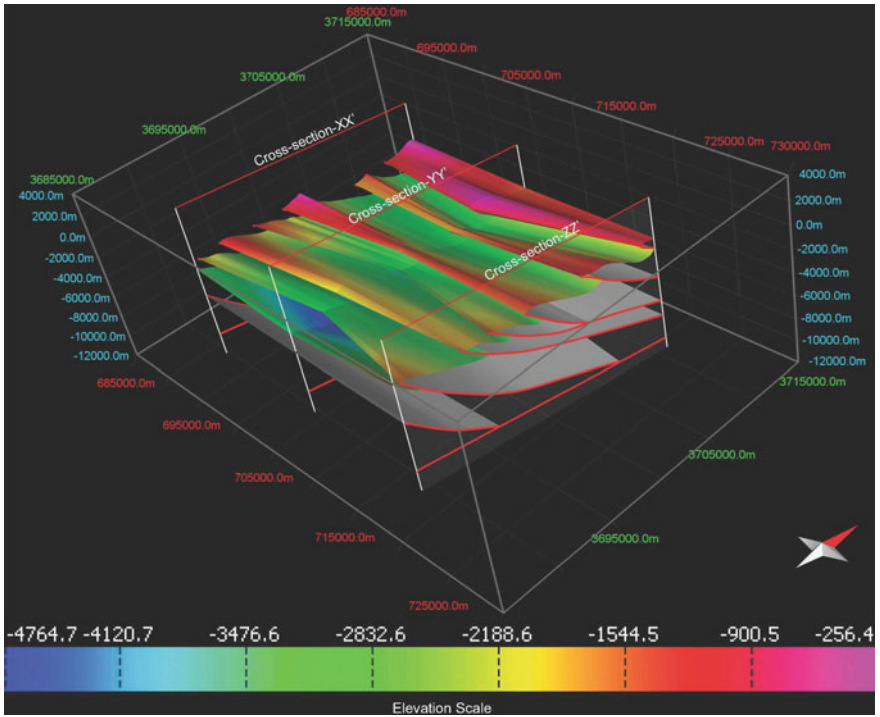


Fig. 10 Image showing south eastern view of 3D horizon model at the top of the Lockhart Limestone

4.4 Stress Analysis of the Area

Stress analysis of a 3D surface of the Sumari Payyan Anticline (Fig. 11) at a level of the Lockhart Limestone was performed (Fig. 12). This structure covers an area of about 30 km² and it rest on the Sumari Bala Fault at the depth of 1700 m. There are

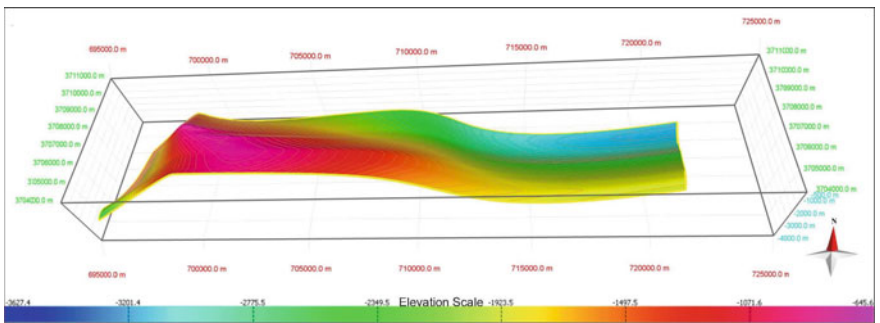


Fig. 11 Image showing 3D surface of Sumari Payyan Anticline at the top of the Lockhart Limestone

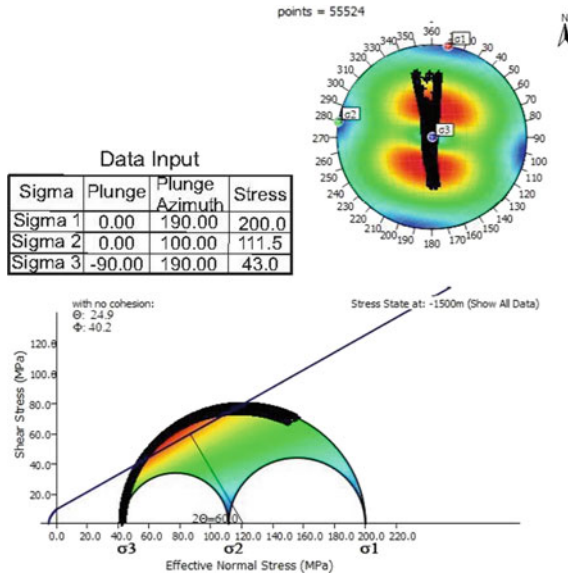


Fig. 12 Stress analysis of the Sumari Payyan Anticline at the top of Lockhart Limestone

55,524 different points selected by the software on the basis of different dip direction domain of planes of 3D surface. Total 22,209 points lies in the intersected red color region of the Mohr’s stress circle diagram and the Coulomb Failure Envelope. This means that the stress analysis of the Sumari Payyan Anticline at a level of the Lockhart Limestone shows that total 40% of plane are susceptible to failure.

5 Discussion

In this study, field and remote sensing data sets are utilized for detailed structural analysis of the central *KFTB*. Different softwares e.g. Google Earth, *GIS* and *MOVE* (2D and 3D) for the construction of geological map and structural cross sections, 3D models as well as to perform stress analysis of the area. The study area lies in the western part i.e. *KFTB* of the Upper Indus Basin. The *KFTB* lies of the north western margin of Himalayan arc in the Pakistan. The rock sequence that is exposed in the study area include Eocene age platform rocks unconformably overlain by molasses sediments of Miocene to Plio-Pleistocene age. The structural geometry is well developed in the area as a result of southward propagating deformation due to Indo-Eurasian collision.

The structural fabric is dominated by east west trending open to tight folds and southward verging thrust faults system as well as back thrust faults. Our 2D and 3D structural modelling deduced that there is disharmonic relation between surface and

subsurface structures. Thrusting related to decollement tips within Paleocene and older rocks. This folding is complicated further by shale diapirism. Based on the relative stiffness and mechanical aspect, the stratigraphy of the study area is presumed in three different stratigraphic packages (Fig. 3). This mechanical stratigraphic arrangement and thick shale sequence have a vital role in the structural architecture of the region. These three distinct mechanical lithic packages include:

- (i) Uppermost mechanically stiff package having Kohat Formation and overlying molasse sediments up to the Nagri Formation.
- (ii) Middle mechanically soft package consisting of Patala Formation, Panoba Shale, and Mami Khel Clay, and
- (iii) Lower mechanically stiff package comprising of Lockhart Limestone up to Paleozoic rocks.

The structural disharmony between the upper and the lower units is mostly credited to the middle soft package. The predominant fold-thrust system verging southward at the surface is characterized by the structures within the upper unit. Shale diapirism has modified this fold thrust system. These local decollements provided by the soft mechanical strata at shallow depth are greatly responsible for the structural disharmony between the underlying and overlying strata. Although, overall structural trend is east west which is the result of regional north south stresses but because of an echelon spread of the folds (Fig. 13) it can be inferred that lateral component of stress also present in the area. The Sumari Payyan Anticline, Walai Syncline Northern, Walai Anticline Northern, Walai Anticline Southern, Chapari Anticline, Chapari Syncline, Shakar Khel Anticline, Shakar Khel Syncline, Khomari Syncline and Khomari Anticline plunged eastward in an en echelon fashion. This shows that right handed lateral movement acting over here along line AA'. Same type of movement can be inferred along line BB' which changed the trend of Chapari Anticline toward NE-SW. This proves that the structuration in the *KFTB* is the result of both north south compression stresses and the lateral stresses components.

Many authors worked on the structure geology of the *KFTB* but their work was on the regional scale also they not incorporate the role of the mechanical stratigraphy in their analysis (Meissner et al. 1974; Yeats and Hussain 1987; Abbasi and McElroy 1991; McDougall and Hussain 1991; Hussain et al. 2004; Paracha 2004). Previous authors did not use advance softwares for structural modelling and no one perform the 3D structural modelling of the area.

6 Conclusions

- Three different stratigraphic packages based on their mechanical response to deformation are presumed to control the structural disharmony within the central *KFTB*. The uppermost package is mechanically stiff and is comprised of Kohat Formation (Eocene) up to Siwalik Group (Miocene) which is underlain by a middle, mechanically soft mobile package of Mami Khel Clay, Jatta Gypsum and Panoba

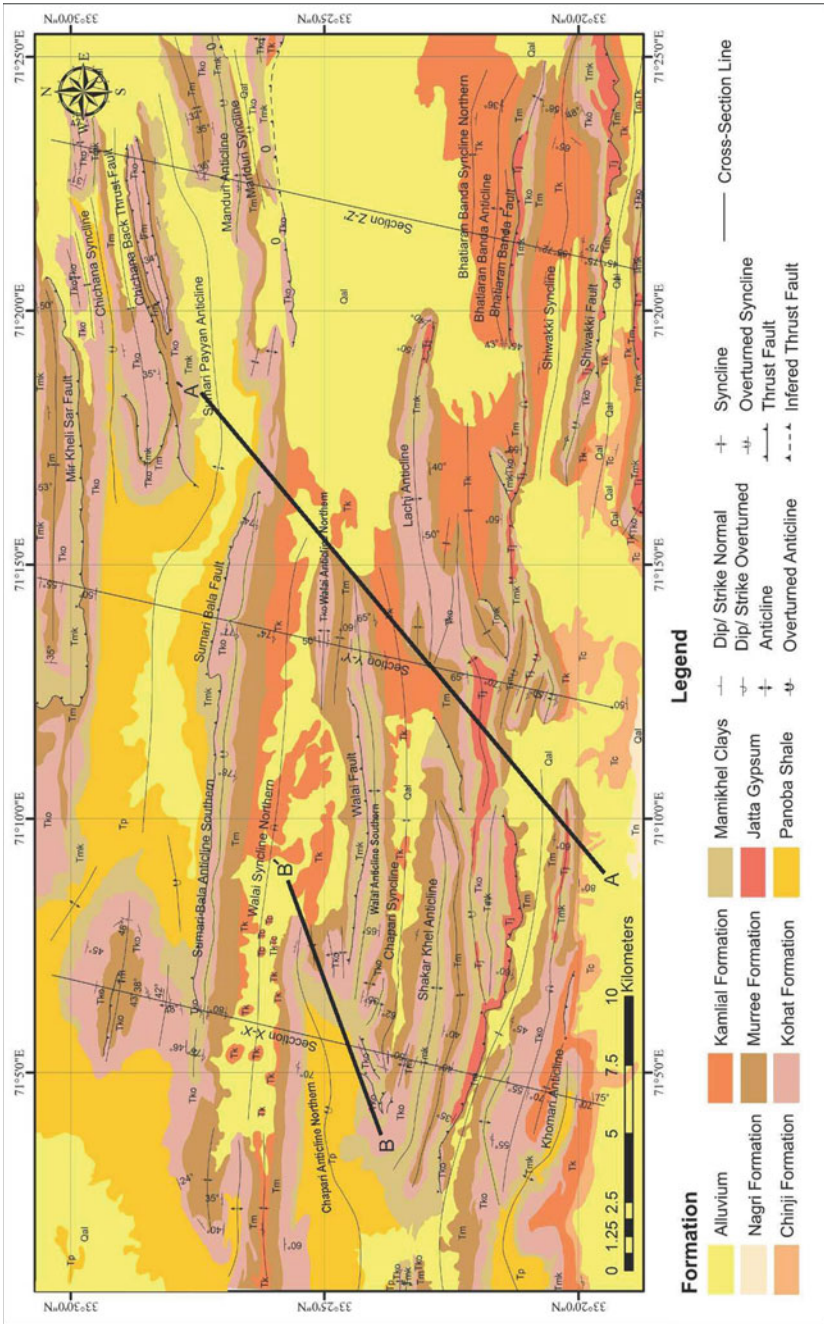


Fig. 13 Geological map of the study area showing concept of lateral stresses acting along lines AA' and BB'

Shale (Eocene) and is underlain by a lower stiff package of Lockhart Limestone (Paleocene) and older rock units.

- The structural geology of the area is dominated by east west (with minor exceptions) trending, south verging anticlines with intervening synclines with few blind and emergent thrust and back thrust faults.
- The structural architecture of the central *KFTB* is result of southward spread of north south compressional stress and localize lateral stress.
- Structural style within the exposed upper competent stratigraphic package is disharmonic and does not mimic the lower stratigraphic package which is comprised of south verging, ramp-related folds.
- The deformation in the area is thin-skinned.
- Calculated average shortening associated with above mentioned deformation is 15,685.07 km with 42.35% of shortening, which shows intense degree of deformation and orogeny in the area.
- The rate of deformation increases from east to west in the study area.
- The stress analysis of the Sumari Payyan Anticline at a level of the Lockhart Limestone demonstrates that the total 40% of planes where failure can occur.

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