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Geological constraints on the Western Kohat foreland basin, Khyber Pakhtunkhwa, Pakistan: Implication from 2D and 3D structural modelling

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Abstract

The Kohat Foreland Basin is an outcome of continental collision between Indian and Eurasian plates defining the southern edge of Himalayan Orogenic System in the north-western Pakistan. This study constrains the structural geometry and kinematics in 2-D and 3-D workflow, evaluation of the role of multiple detachments and the structural correlation between surface and sub-surface geology of the western Kohat Foreland Basin. The structural style of the western Kohat Foreland Basin evinces the thin skin deformation associated with a couple of structural detachments i.e.i) base-Eocene shale/ evaporite sequence ii) the upper interface of crystalline basement. These detachments separate the outcropping and buried stratigraphic sequence of the Kohat Foreland Basin into upper and lower structural-stratigraphic domains. The lower domain has a series of north-dipping or south-verging fold-thrust assemblages incorporating a rigid rock sequence of EoCambrian to Paleocene. The comparatively more ductile rocks of the upper domain comprising of Eocene to Pliocene are deformed into tight, overturned, doubly plunging and internally faulted anticlines intervened by broad synclines. The two domains dictate different deformational behaviour and structural style, deforming in total disharmony; hence the structural geometry of shallow units does not match the sub-surface rocks. The total 37% of shortening in the sedimentary cover was revealed by structural balancing in 2-D and 3-D kinematic modelling. Stress analysis of Gurguri Fault unveiled 40% failure susceptibility and recorded positive values of effective normal stress (σ_n) with an orientation of maximum principle stress (σ_1) as N17°.
Keywords: *Kohat Foreland Basin, Khyber Pakhtunkhwa, Pakistan, Structural Modelling*

1. Introduction

The Kohat Foreland Basin (KFB; Fig 1) lies about 100 km south of the main part of the western Himalayan Foothills (Pivnik and Wells 1996) formed as a result of Indo-Eurasian onward collision, started in the Eocene (Najman et al. 2010; Qasim et al. 2018). It was the main depocenter of the Himalayan synorogenic sediments influx during Early Miocene, now uplifted and deformed, which preserved the imprints of Himalayan Orogeny (Najman et al. 2001; Ghani et al. 2018; Ikram et al. 2020). The KFB is the westernmost of the east-west trending Himalayan Foreland Basin chain containing a thick sequence of Paleocene to Pleistocene sedimentary rocks (Gee 1945; Fatmi 1973; Sameeni et al. 2009; Shah 2009). The ongoing collision between the Indian and Eurasian plates continuously propagated the thrusting and compressional forces southward (Gansser 1964; Powell et al. 1973; Molnar and Tapponnier 1975). The regional structures in KFB with all folds and faults having their fold axes and fault planes trending east-west are the clear indication for the southward movement of Himalayan Deformation (Wells 1984; Pivnik 1992; Rehman et al. 2009; Ghani et al. 2018). The presence of a large number of thrust faults and tight-to-overturned folds makes KFB one of the most structurally complex areas in northern Pakistan.

Evidences of transpressional deformation envisaged in this compressional regime, which makes the structural geometry of pre-existing structures even more complicated in the KFB (Verma and Chandrasekhar 1986; Pivnik and Sercombe 1993; Sercombe et al. 1998; Mona Lisa et al. 2002; Ahmed et al. 2004; Mona Lisa et al. 2004; 2005; Yazdi et al. 2015; Mollai et al. 2019;).
The study area is about 793 km^2 and covers the western part of KFB (Fig 1). The Main Boundary Thrust (MBT) and Kohat Range (KR) border the KFB in the north (Khan et al. 1986) and uplifted the Mesozoic-Paleocene sediments against the Tertiary sediments of KFB. The north-south trending Kurram Fault marks the western boundary of KFB, while river Indus confines it to the east and separates it from its eastern equivalent i.e. Potwar Foreland Basin. The southern limit of KFB is defined by the Bannu Basin (McDougall and Khan 1990; Pivnik and Khan 1996; Ghaffari et al. 2015). Previous research regarding the structural evolution of KFB is based on surface investigation, well data correlation and 2-D seismic sections for integrating surface geology with sub-surface data (e.g., Meissner et al. 1974; Abbasi and McElroy 1991; McDougal and Hussain 1991; Pivnik 1992; Pivnik and Sercombe 1993; Sercombe et al. 1994a; 1994b; Khan and Najeeb-uz-Zaman 2003; Ahmad et al. 2004; Paracha 2004; Chen and Khan 2009; Bazoobandi et al. 2016). Research work regarding a structural model of the western KFB in 3-D to validate the sub-surface structural geometry is currently lacking. Therefore, in

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this paper we focused on surface geology to develop sub-surface cross-sections and to construct 3-D structural Model of the western KFB. We also have examined the previously constructed structural models (e.g. Abbasi and McElroy 1991; McDougal and Hussain 1991; Pivnik 1992; Pivnik and Sercombe 1993; Sercombe et al. 1994a; 1994b; 1998) and adopted work that is similar to our investigations. Our structural model is a reinterpreted approach in 3-D and an integration of our findings with previous models. Furthermore, we calculated the total amount of shorting along the selected profiles and to carry out the stress analysis by using Mohr's stress Diagram.

2. Tectonic Setting and Previous Structure Models

Himalayas, the twenty-five hundred kilometres long mountainous belt, formed 65-50 Ma ago as a result of collision between the Eurasian Plate in the north and the Indian Plate in the south. It is the youngest and perhaps the most impressive product of continent-continent collision all over the Earth (Gansser 1964; LeFort 1975; Molnar and Tapponnier 1975; Fraser et al. 2001). The northward departure of Indian Plate from the Gondwana land started about 130 Ma ago (Johnson et al. 1976), resulting in the shrinkage of the Neo-Tethys which was situated between the Indian and Eurasian plates (McKenzie and Sclater 1971). The Nuristan, Kandahar and Kohistan-Ladakh arcs were formed due to an intra-oceanic subduction at the time of Neo-Tethys closure (Searle 1991; Treloar and Izzat 1993). This arc magmatism sustained for a time of almost 40 Ma (Petterson et al. 1985) and resulted in the closure of back arc basin. Kohistan-Ladakh Arc collided with Eurasian Plate forming an Andean type of continental margin (Coward et al. 1986). According to Powell (1979) the subduction of Neo-Tethys underneath the Kohistan Island Arc (KIA) was nonstop and totally consumed the leading edge of Indian Plate that finally collided with the remnant of KIA during Eocene.

After the aforementioned processes, four regional scale fault systems were generated i.e. Main Karakorum Thrust (MKT), Main Mantle Thrust (MMT), the MBT and the Salt Range Thrust (SRT) and/or Trans Indus Range Thrust (TIRT), which divided the Pakistani Himalayas into five litho-tectonic domains (Kazmi and Jan 1997; Ahmad et al. 2004) (Figs 1, 2). The Karakorum Block, KIA, Northern Fold and Thrust Belt (NFTB), Southern Fold and Thrust Belt (SFTB) and Punjab Foredeep are the said litho-tectonic domains (Kazmi and Jan 1997; Ahmad et al. 2004) (Figs 1, 2). The research area lies in the western KFB, which itself is a part of SFTB (Fig 1), covering the Manzalai and adjoining areas. The tectonics of the study area is mainly characterized by folds and faults due to the compressional stresses resulting from the northward and clockwise movement of the Indian Plate. In an effort to understand the structural evolution of the KFB, a first organized approach was adopted by McDougal and Hussain (1991) through a balanced cross section illustrating the thrust sheets forming duplexes, translated above blind or partially emergent thrusts, fault-bend folds and detachment folds (Fig 3a). Abbasi and McElroy (1991) constructed a double décollement model to analyse the structural style of KFB. The Infra-Cambrian to Paleocene sequence is considered as north-dipping duplex structure between a passive-roof thrust at base of Eocene strata and deep-seated sole thrust at upper interface of crystalline basement. The rocks above Eocene shale and evaporites are interpreted as passive-roof stratigraphy (Fig 3b). Pivnik and Sercombe (1993) and Sercombe et al. (1998) define the structural kinematics of KFB into two distinct phases; fold and thrust belt subsequently followed by transpression (Fig 3c).

3. Stratigraphy and Décollement Levels

The stratigraphic record of the KFB reveals three major evolutionary phases. In the first phase, the sedimentary rocks of Paleozoic to Mesozoic were deposited on the northern passive margin of the Indian Plate. It was followed by a Paleogene fore deep basin formation which filled during Late Cretaceous to Early Eocene. Finally, as a result of Indo-Eurasian collision, the east-west trending structures associated with the main north-south compression, originated an intra-continental foredeep basin, which filled up during Miocene-Pliocene ((Khan et al. 1986; Kazmi and Abbasi, 2008; Shah 2009).

The detailed surface investigation of the KFB indicates that the area is dominated by Eocene platform rocks which have an unconformable contact with the overlying Miocene to Pliocene Molasse sediments comprised of Rawalpindi and Siwalik groups (Gee 1945; Fatmi 1973; Meissner et al. 1974; Sameeni et al. 2009; Shah 2009). The oldest rock unit exposed in the study area is the Panoba Shale of Eocene, whereas, the well data suggests that Datta Formation of Early Jurassic is the unexposed oldest rock unit (Fig 4). The sequence comprising the EoCambrian to Triassic rocks are not exposed nor drilled in the KFB. Stratigraphic details of the Early Eocene to Early Pliocene rocks is based on the field observations and literature review, whereas, the unexposed rock knowledge from Jurassic to Paleocene is mainly acquired from the available published data (e.g. Meissner et al. 1974; 1975; Shah 1977; Wells 1984; Ahmad and khan, 2012; Ghani et al.2018; Yazdi and Sharifi Teshnizi 2021).

On the basis of seismic data of the western KFB, two different décollement levels were interpreted; i) basal décollement ii) secondary décollement. The basal décollement lies on the upper interface of crystalline basement/ base EoCambrian rocks. The Early Eocene shale/evaporite sequence have an average thickness of about 2000 m.

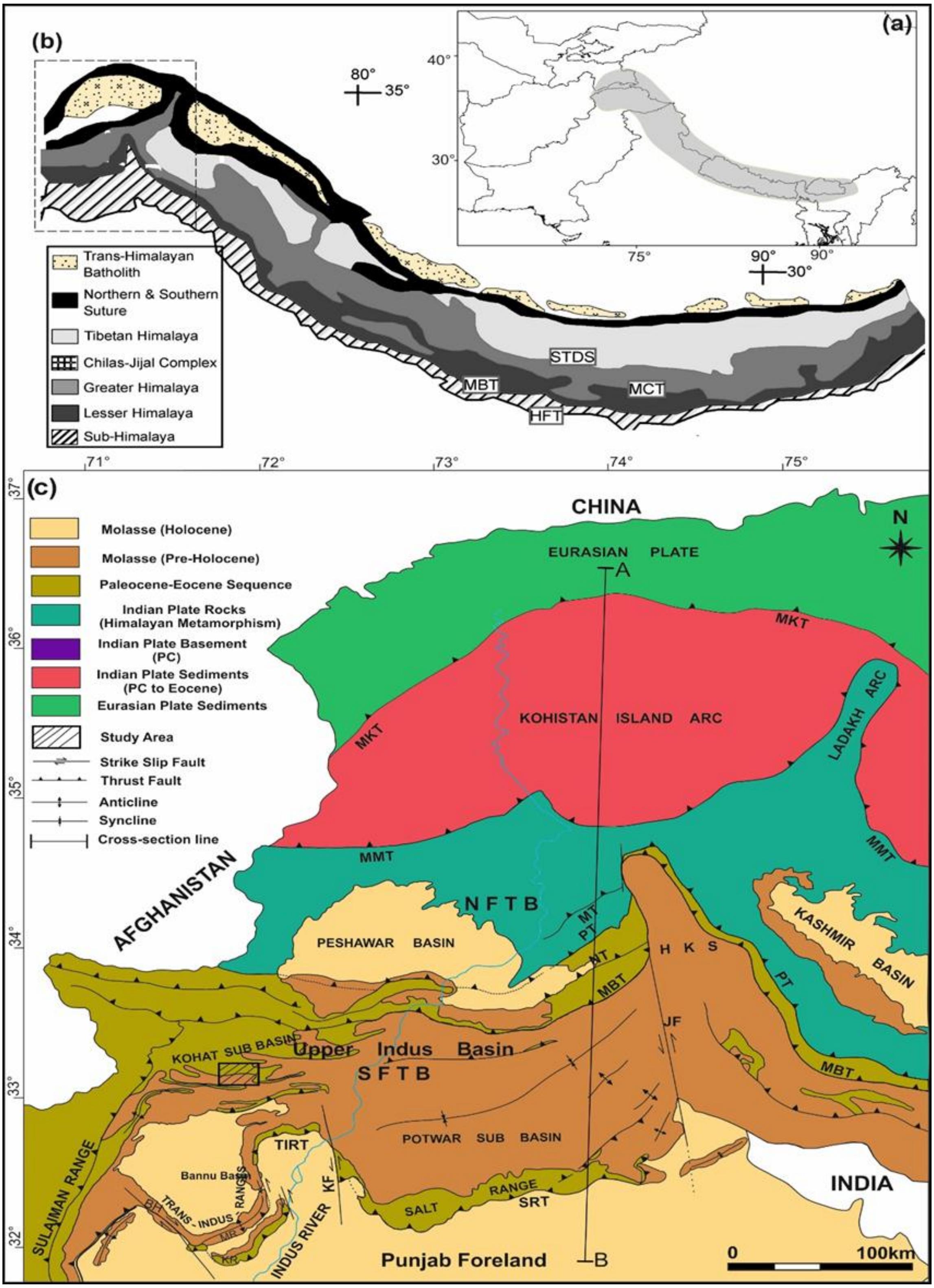

Fig 1. (a) Regional location of Himalaya. (b) Overview of Himalayan geology with location of (c). (c) Generalized geological map of the NW Himalayan foreland fold and thrust belt, modified after Kazmi and Rana (1982). Inset shows the location of study area. MKT: Main Karakorum Thrust, MMT: Main Mantle 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, BH: Bannu Highs, MR: Marwat Range and KR: Khissor Range.

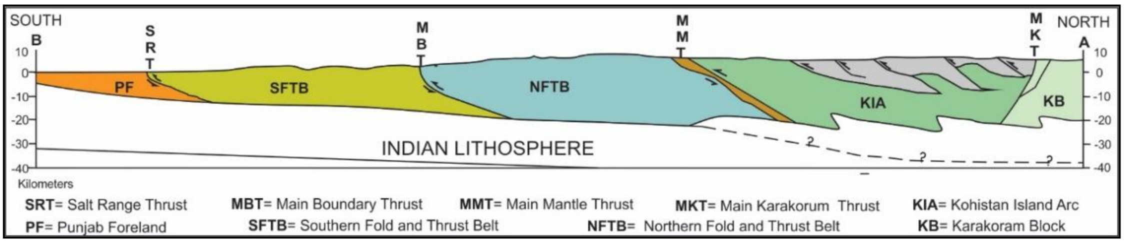

Fig 2. Cross-section along line AB of Fig 1. showing different tectonic terrains of North Pakistan separated by regional faults (Modified after Hauck et al. 1998).

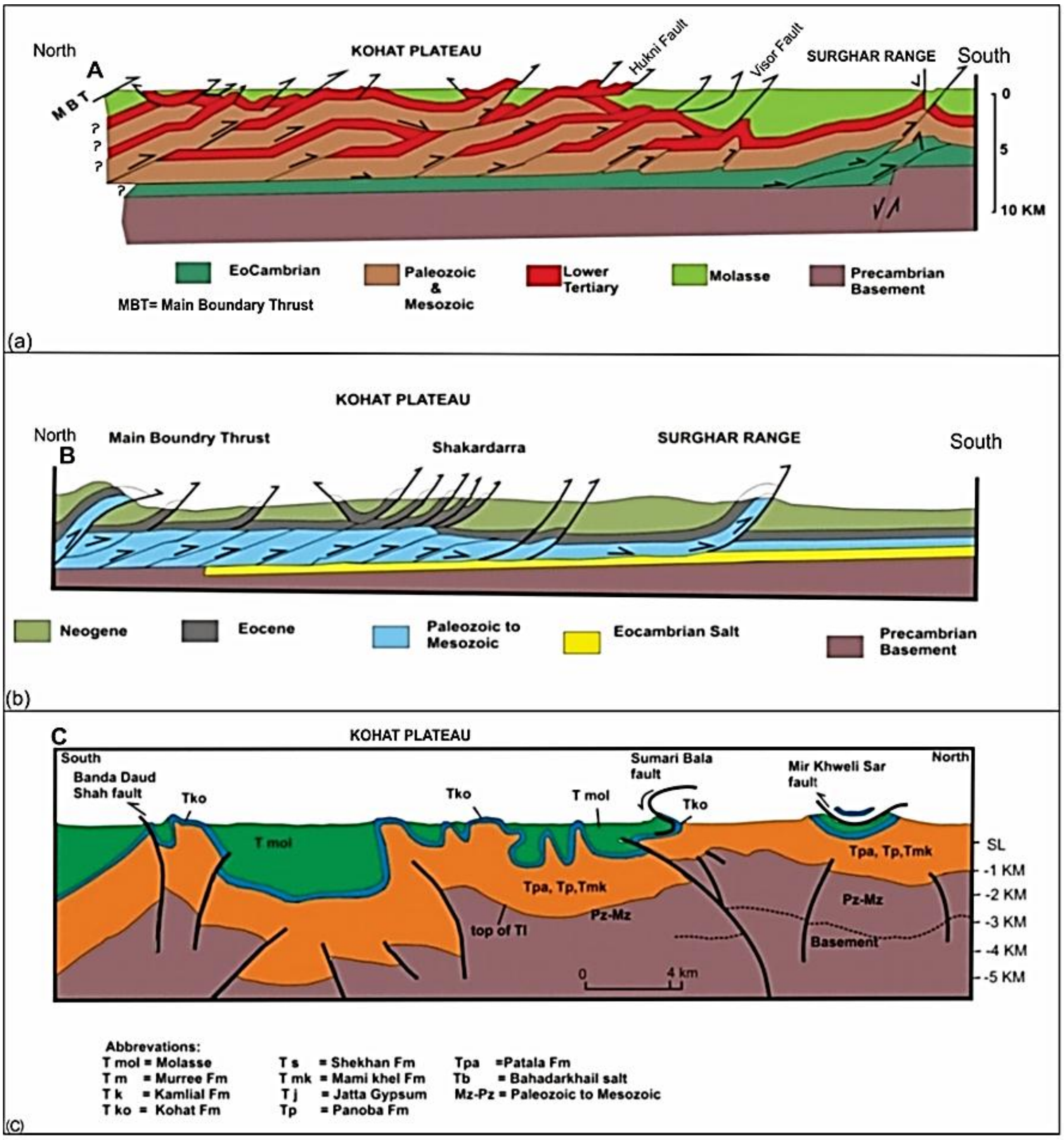

Fig 3. Tectonic evolution models of the KFB. (a) Balanced cross-section A of the KFB constructed by McDougall and Hussain (1991) illustrates shortening caused by severe folding and faulting below molasse deposits. (b) Abbasi and McElroy (1991) suggested a concept of double décollement in section B, controlling the deformation style in the KFB. (c) Section C of Pivnik and Sercombe (1993) shows the structural evolution of KFB has been influenced by the transpressional tectonics. The deep-rooted oblique-reverse faults which are exposed at surface as doubly-overturned and tight anticlines.

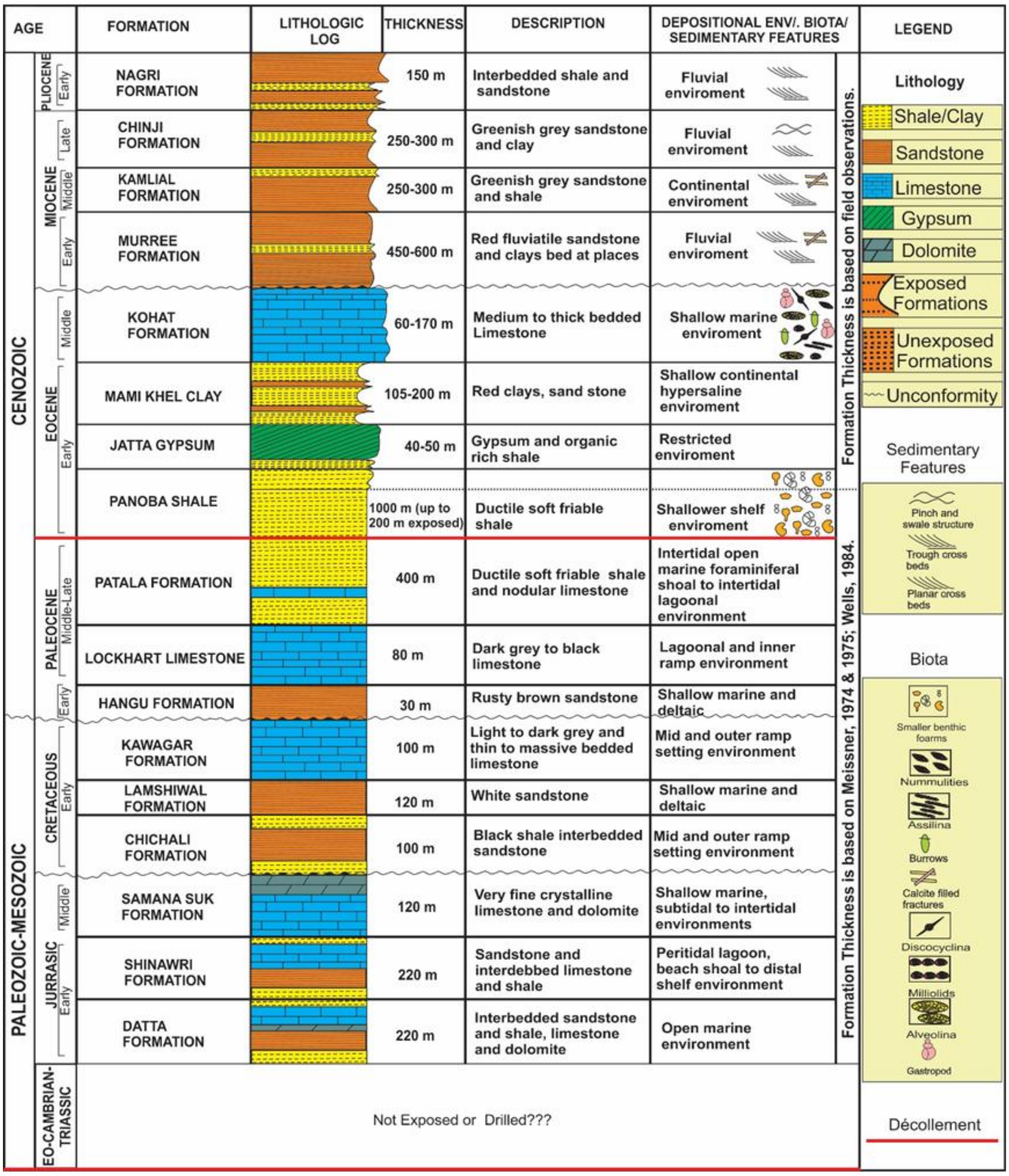

Fig 4. Generalized stratigraphic column of the KFB.

This massive deposit behaves plastically, which accommodates the stress associated with the splays, originated from the basal décollement and acting as secondary décollement. These décollements divided the stratigraphic sequence of the western KFB into upper structural-stratigraphic domain (USSD) and lower structural-stratigraphic domain (LSSD). The USSD comprising of Early Eocene to Early Pliocene rocks characterized by tight-overturned folds and faults related to the secondary décollement level. The rocks of lower series consist of EoCambrian to Paleocene are relatively stiff than the upper series. The deformation in the lower series is mainly controlled by the basal décollement illustrating the north dipping ramp-related fold-thrust assemblage (Fig 6).

4. Structural Framework of the Western KFB

The study area is located in the south of the MBT, which covers the western KFB between Pongi Banda Syncline in the north and the Dargai Anticline in the south (Fig 5). Tectonically, the area is severely deformed as a result of southward propagation of the Himalayan orogeny, which formed the east-west trending regional structures. The rocks exposed in the study area are of Eocene to Pliocene age, comprising of shale, limestone, sandstone, gypsum and conglomerates, which makes low topographic relief and rugged mountainous landscape. Surface structural geometries and their corresponding subsurface model are separately discussed to comprehensively explain the structural framework of the study area.

4.1. Surface Geology

The surface structural geology of the study area is mainly controlled by the north-south compressional stresses. The east-west trending anticlines are separated by broad synclinal valleys filled with the Neogene fluvial foreland basin deposits i.e. Rawalpindi and Siwalik groups (Fig 5). The folds in the study area are east-west trending, open to tight-overturned, doubly plunging and their fold-axis verging towards north or south. The faults are east-west trending, reverse, back and fore thrusts with their fault planes dipping at an angle ranging from 30°- 80° to the north or south. The geological map of the western KFB (Fig 5) is compiled through the integration of available published maps (Meissner et al. 1974, 1975) field observation and Google Earth imagery.

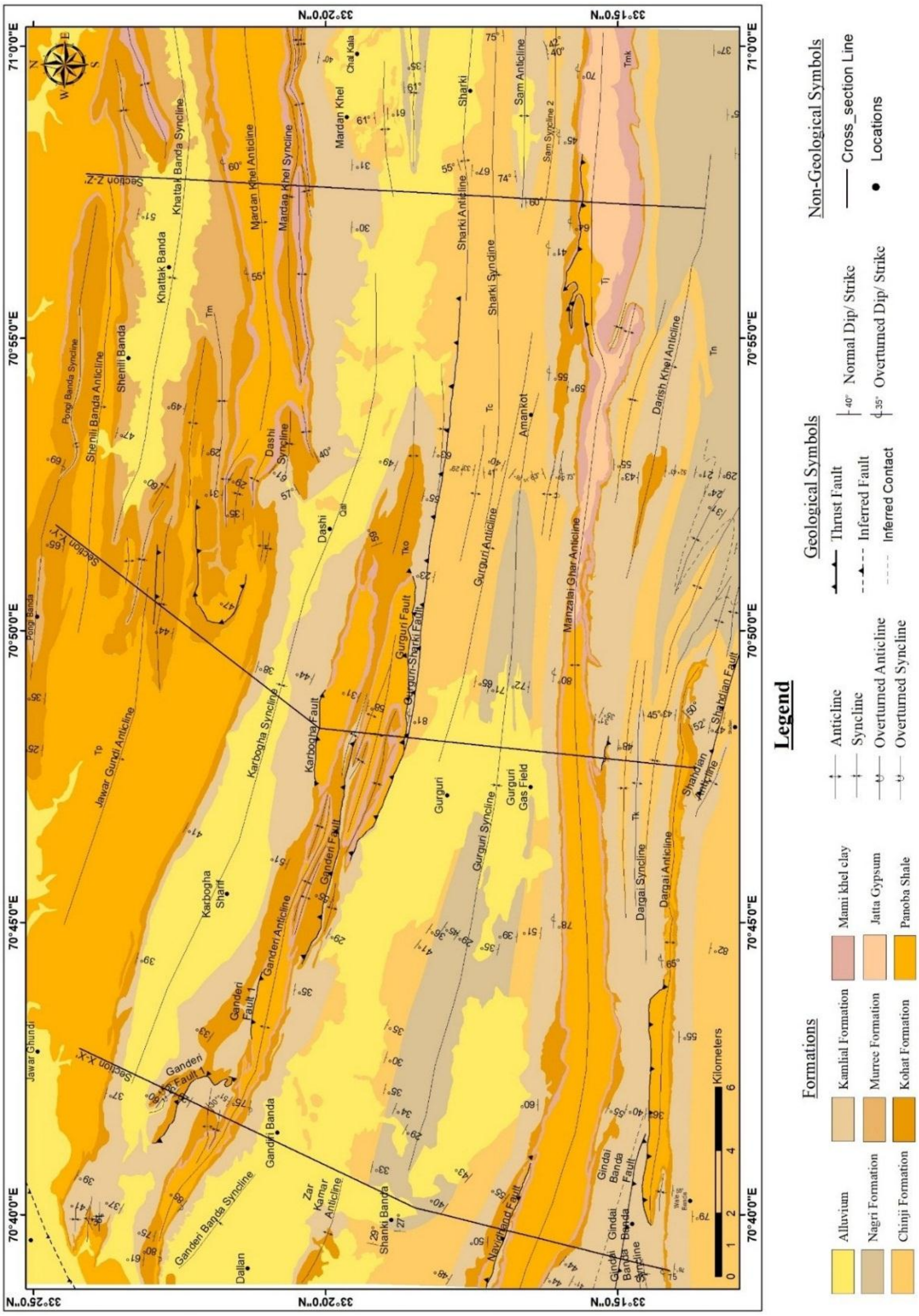

Fig 5. Geological map of the western KFB.

4.2. Seismic Interpretation

Two seismic sections (YXT-19 and YXT-35) are presented in this paper (Fig 6) to demonstrate the subsurface structural framework of the western KFB with their location in Fig 6(E), however, total seven seismic lines were interpreted. The available subsurface seismic data is of poor quality and feeble resolution; therefore, it is difficult to mark the prominent reflector showing the basement on these lines. Our interpretation of crystalline basement in the western KFB is mainly based on the seismic interpretations of McDougall and Hussain (1991) and Ghani et al. (2018) and assumption of flattened reflectors near 4.5 s two-way travel time (TWT) (Fig 6). Our interpretation of seismic sections YXT-19 and YXT-35 (Fig 6) shows a couple of décollement levels; i.e. at 2.0 to 2.5 s TWT (secondary décollement) and at 4.5 s TWT (basal décollement). The surface structures involving Eocene to Pliocene rocks are interpreted to originate above the Eocene base/ secondary décollement. The reflectors between 2.5 s to 4.5 s are interpreted as north dipping duplexes forming stacks of thrust-bounded rocks of EoCambrian to Paleocene (Fig 6).

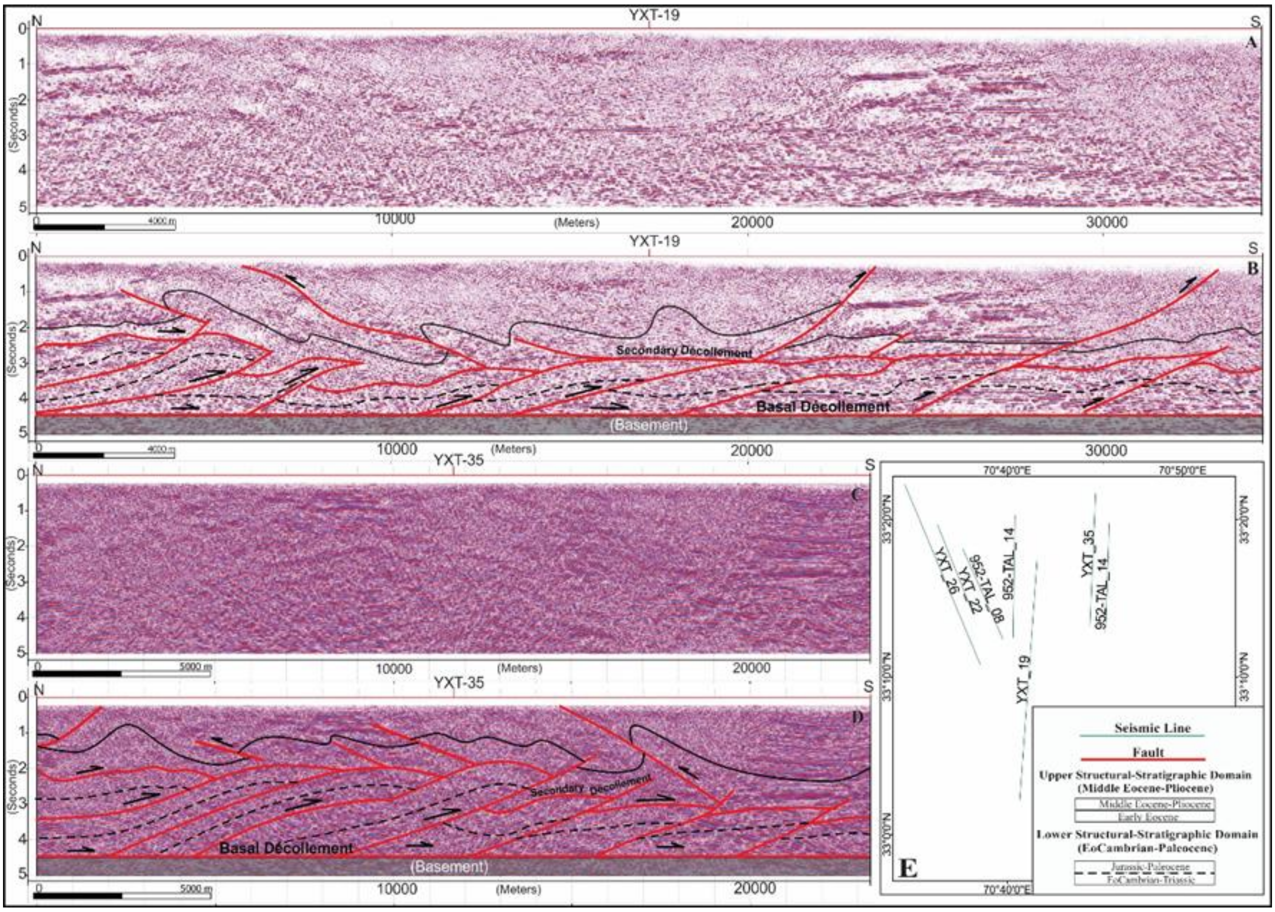

Fig 6. A and B showing the uninterpreted and interpreted seismic profile (YXT-19), whereas, C and D representing the uninterpreted and interpreted seismic profile (YXT-35) from the western KFB. E is the location map of seismic lines.

4.3. Cross-sections

To construct structural cross-section and to understand the subsurface structural framework in western KFB, we adopted the structural style as interpreted on the selected seismic lines (Fig 6). Three structural cross-sections along the lines X-X´, Y-Y´ and Z-Z´ (Fig 7) of Fig 5 are built, balanced, restored and analysed by using 2-D kinematic modelling module of MOVE 2015.1. Considering the principles of area and line length balancing, the geological structures are brought to their undeformed state with the help of 2-D kinematic algorithms.

We interpreted the structural geometry and the displacement of different lithological units in USSD with the help of mapped structures. However, the structural geometry of rocks lying between the basal and secondary décollements are interpreted as north dipping duplexes based on seismic interpretation. The displacements along faults emanating from basal décollement accommodated and die out in thick and mechanically soft assemblage of shale/ evaporites sequence of Early Eocene. While, the structures in the USSD are tight to overturned folds and fore and back thrust/ reverse faults mainly controlled by the secondary décollement (Fig 7). It depicts the disharmony of the structures between the surface and

sub-surface. The sub-surface data related to the stratigraphic sequence of the Pre-Eocene rocks and the basement depth are deduced from Sercombe et al. (1998) and Ghani et al. (2018). The contact between sedimentary rocks and crystalline basement in the undeformed state is about 10 km deep in the study area with a regional northward dip of 1.4 to 1.5° (Khan et al. 2012).
The cross-sections along the line X-X´, Y-Y´ and Z-Z´ were restored and balanced in order to calculate the bulk shortening. The actual length of the cross-section X-X´ is 19667 m, and 31172 m after restoration. The amount of shortening is 11504 m and percentage of shortening is 37% along the cross-section line X-X´ (Fig 7). The cross-section Y-Y´ is 21885 m in length, which has been restored and the length changes to 35766 m. The amount and percentage of shortening along Y-Y´ is 13880 m and 39%, respectively (Fig 7). The cross-section Z-Z´ is 19608 m long, whereas, its restored length is 31244 m with a shortening amount of 11635 m. The percentage of shortening along the cross-section Z-Z´ is 37% (Fig 7). According to the restored sections X-X´, Y-Y´ and Z-Z´, the average shortening percentage in the study area is 37.7%.

4.4. 3-D Models

Two-Dimensional available data was integrated into an internally consistent 3-D workflow, which was then easy to incorporate and conclude beyond known points to better constrain structural interpretation and validation. For structural interpretations, and to develop 3-D fault and horizon models of the western KFB, the 3-D Kinematic Modelling module of the MOVE 2015.1 software was used. The sub-surface structural geometry of the project area is illustrated by the proposed 3-D structural models of the western KFB. These are constructed by the integration of field data, geological map and structural cross-sections developed along the lines X-X´, Y-Y´ and Z-Z´. These 3-D models explicate the extension and propagation of the regional structures in the sub-surface (down to 10 Km) with the correlation of surface data. It shows the variation in the structural style and the termination of the structures across the cross-section lines X-X´, Y-Y´ and Z-Z´ (Fig 8, 9).
Geocellular volumes of Late Paleocene (Patala Formation) is generated in both deformed and undeformed state (Fig 10) with the help of "create volume" tool in MOVE. The purpose of this model is to illustrate the shortening in 3-D and change in geometry of rocks as a result of deformation. The geocellular volume is 3-D mesh of cells in the form of cubes at undeformed state (Fig 10a), which modified to rectangular shape after the strata is deformed (Fig 10b). This model exemplifies the behaviour of rocks in 3-D to accommodate volume when stresses applied and represents the difference in elevation before and after the deformation.

5. Stress Analysis

As discussed above, the study area has a south verging fold and thrust system, which is consistent with the north-south compression. The stress components i.e. normal stress and shear stress are determined by using the "Stress-Analysis" Module in MOVE 2015.2. This module is based on the Mohr´s Stress Circle Diagram (MSCD) overlapped on the Coulomb's Failure Envelope (CFE) for 3-D state of stresses and the general equations to calculate the normal and shear stresses are mentioned below:

$$\sigma_n = \frac{(\sigma_1 + \sigma_3)}{2} - \frac{(\sigma_1 - \sigma_3)}{2} Cos(2\theta)$$

$$\tau = \frac{(\sigma_1 - \sigma_3)}{2} Sin(2\theta)$$

The "σ_n" is the normal stress and the "τ" defines the magnitude of shear stress, whereas, σ_1, σ_2 and σ_3 are the maximum, intermediate and minimum principal stresses, respectively (Davis and Reynolds 1996).
The extensive network of south verging fold and thrust faults provide the grounds to develop the orientation of σ_1 by averaging their dominant orientation in 3D. The calculated σ_1 was applied on 3-D surface of Gurguri Fault (GF) generated between the cross sections (Fig 11). The GF was selected for the stress analysis because it best represents the regional stress vector and hence qualifies for further analysis which would be applicable to the rest of the structures within the KFB. Software calculated the σ_n and τ by applying the σ_1 on GF by taking multiple samples plane from the 3-D fault surface with different orientations. Each separate plane is represented by a black cross (+) which is marked on the center of the plane. The stress data of each point was plotted on the MSCD which was overlapped with CFE. It was found that the CFE slices the significate part of the MSCD marked by the red color. The region above the plane is failure envelop or slip envelop, which shows instability (shear Stress) and high slip tendency. The MSCD of a 3-D surface of the GF is constructed with the effective normal stress (σ_n) is on x-axis and shear stress (τ) is along the y-axis (Fig 12). There are 48787 different points selected by the software on the basis of different dip direction domains of planes of fault surface. Total 22476 points lies in the in the intersected red color region of the MSCD and the CFE (Fig 12). This means that the stress analysis of the GF shows that total 40% of planes are susceptible to failure. The normal stresses in 3-D surface of the GF is positive because the minimum principle stress (σ_3) is greater than zero, which illustrates the compression related slip (Fig 12). The stress analysis of GF revealed that the direction of maximum principal stress i.e. σ_1 is N 17° illustrating the ~ N-S regional compressional stresses (Fig 12).

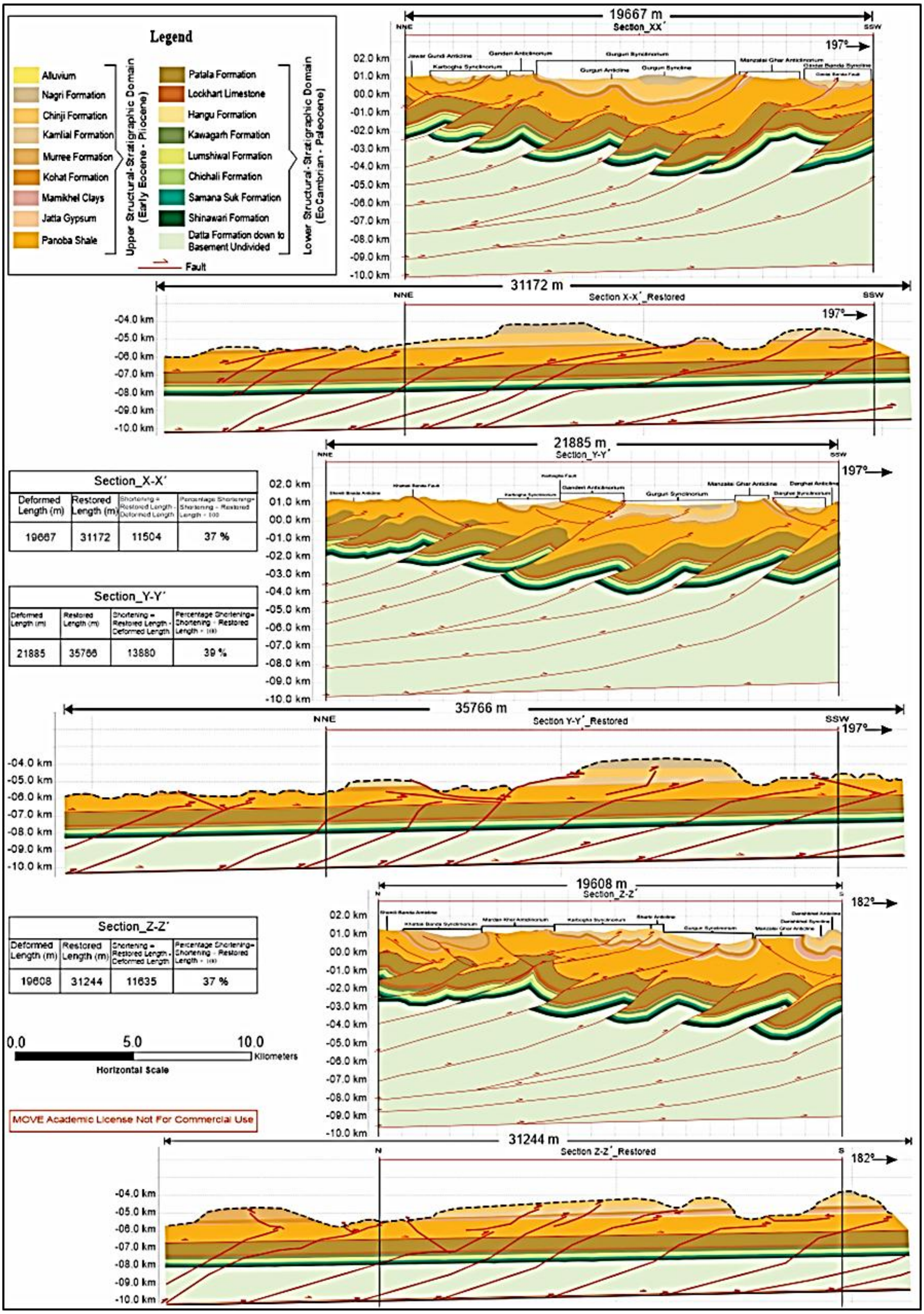

Fig 7. The structural cross-sections and their restored sections along the lines X-X´, Y-Y´ and Z-Z´ of the Fig 5.

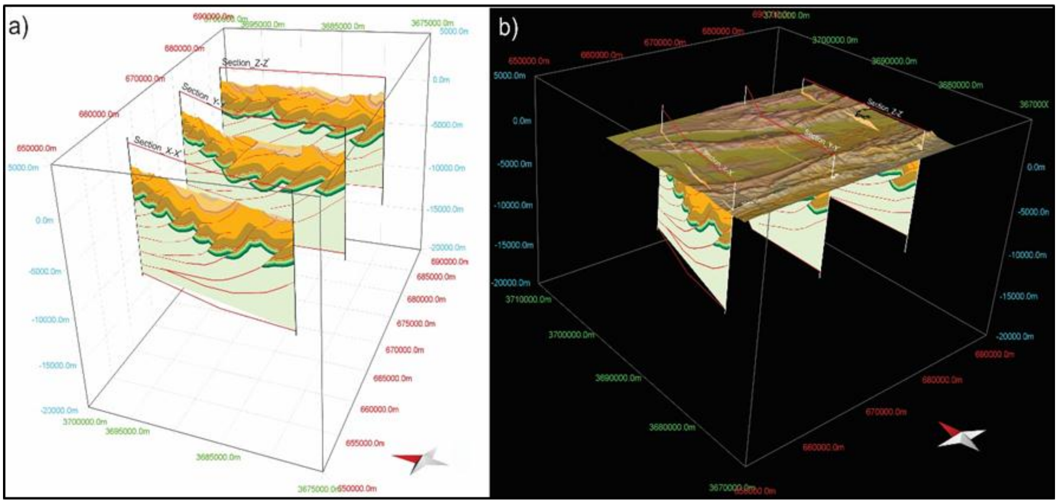

Fig 8. 3-D models of western KFB. a) showing the cross-sections along lines X-X´, Y-Y´ and Z-Z´ of Fig 5. b) showing the interaction between surface geology and cross-sections along lines X-X´, Y-Y´ and Z-Z´ of Fig 5.

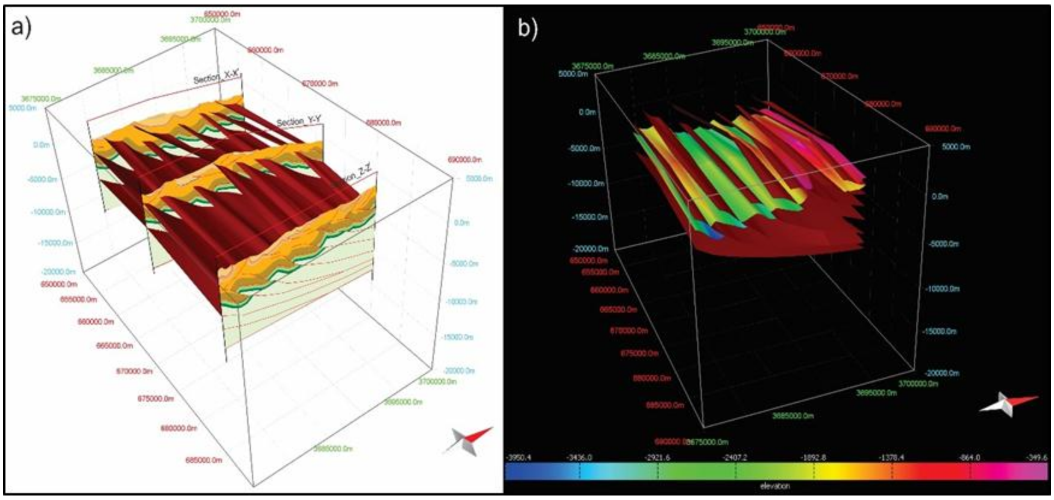

Fig 9. 3-D models of western KFB a) Fault model showing a regional thrust system. b) Horizon model at the level of the Paleocene cut by the faults.

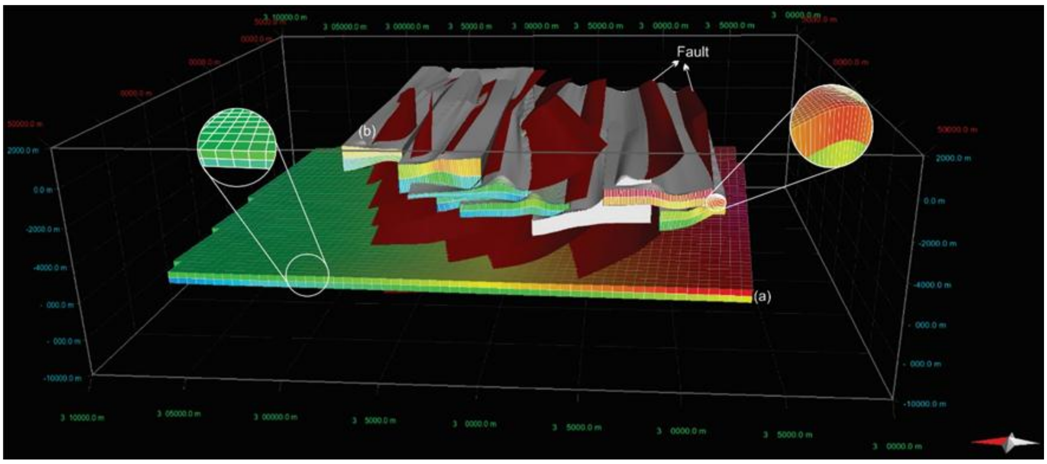

Fig 10. 3-D geocellular model of Late Paleocene (Patala Formation). (a) 3-D geocellular volume representing the rocks of Patala Formation at undeformed state. (b) The rocks of Patala Formation after folding and faulting in the form of 3-D geocellular volume.

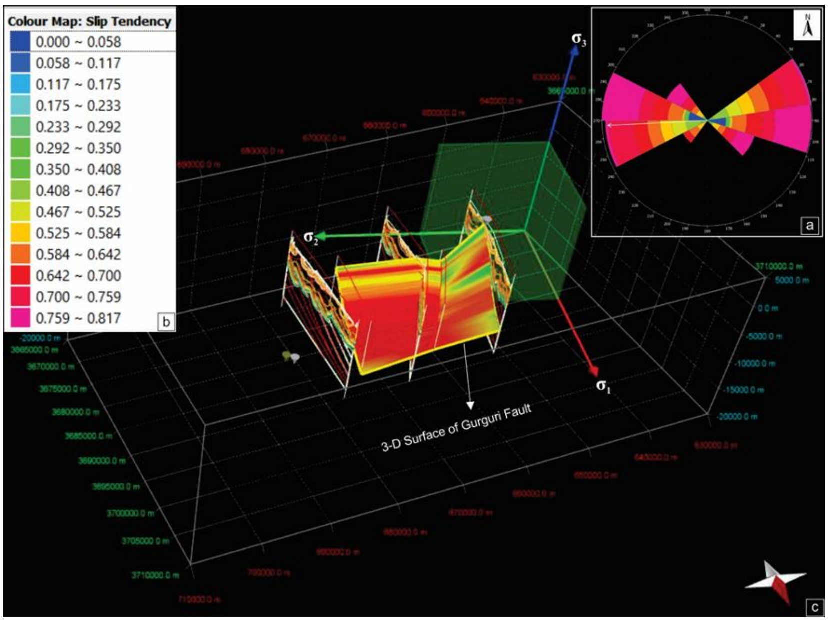

Fig 11. (a) The Rose plot diagram showing the slip tendency of different strike domains on 3-D surface of GF. (b) showing different colours with slip tendency values. (c) 3-D Model showing surface of Gurguri Fault with respect to slip tendency.

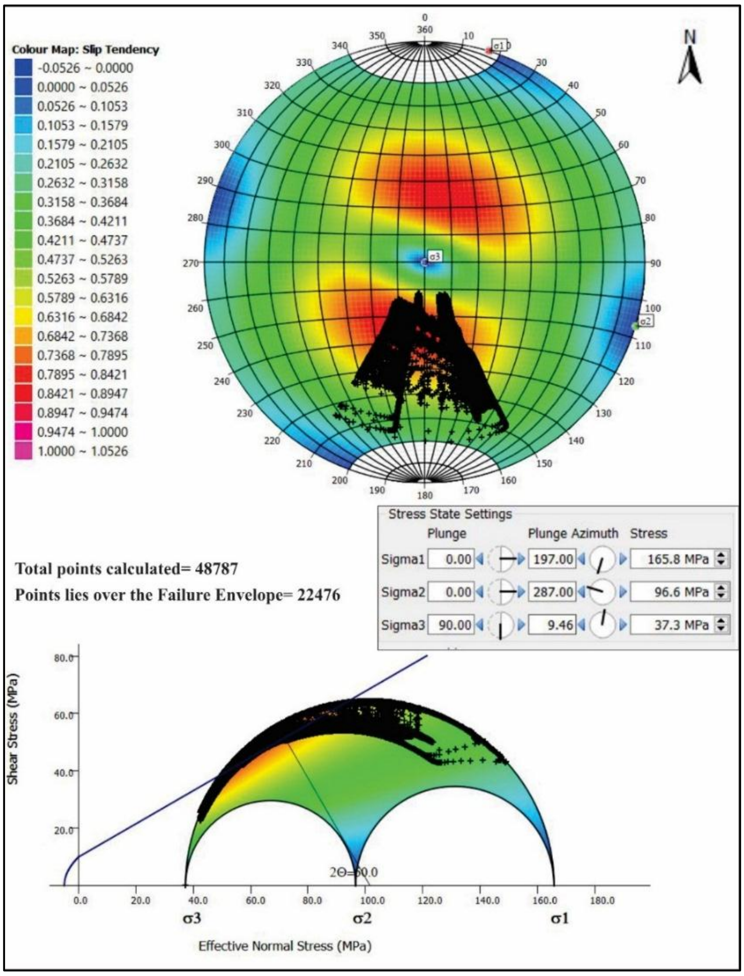

Fig 3. The regional MSCD of the western KFB explaining the slip tendency of Gurguri Fault with positive (compression) normal stresses.

6. Discussion

The study area is focused on the western part of the KFB, which itself is the westernmost of the east-west trending Himalayan Foreland Basin Chain in Pakistan. The sedimentary record of KFB exhibits different evolutionary phases marked by regional unconformities. The Paleozoic-Mesozoic rocks were deposited on northern rifted margin of Indian Plate. It was followed by Paleocene-Eocene sequence deposited in Paleogene fore deep basin formed as a result of Indian-Eurasian plates convergence. Finally, in Miocene, the KFB was believed to be a major depositional centre of the east-western Himalayan sediments, which were further deformed as a result of ongoing orogenic processes and recorded a southward propagation of the Himalayas. The exposed rock sequence in the western KFB comprising of molasse deposits of Miocene to Early Pliocene unconfirmably underlain by the Eocene platform sediments.

The study area is located in the south of the MBT, which covers the western KFB between Sarozai East Syncline in the north and the Dargai Anticline in the. Tectonically, the area is severely deformed as a result of southward propagation of the Himalayan Orogeny, which formed the east-west trending regional structures. Surface structural geometries and their corresponding subsurface model are separately discussed to comprehensively explain the structural geology of the area. The surface geology in the western KFB explains the fold geometry as asymmetrical, open to tight, plunging and overturned with their east-west oriented fold axis. Whereas, the faults are north or south dipping fore and back thrust/ reverse in nature (Fig 13).

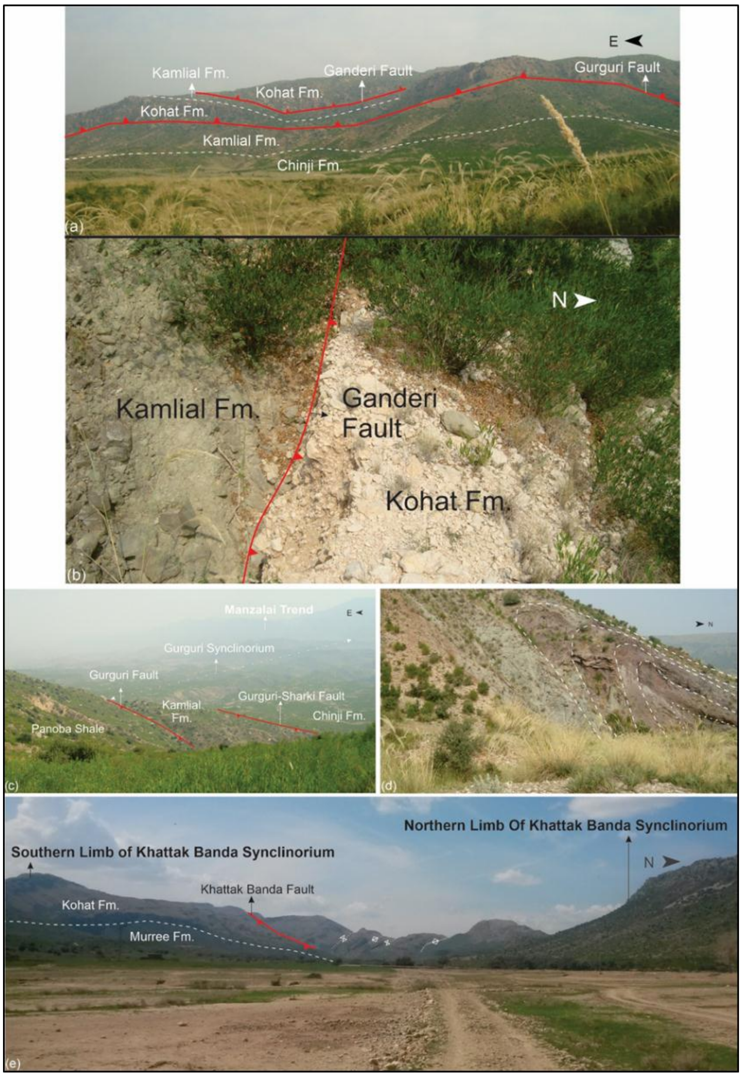

Fig 13. (a) Field photograph showing the regional view of the Gurguri and Ganderi faults. (b) Showing the north dipping Ganderi Fault between the Kohat Formation and the Kamlial Formation. (c) The south-west regional view of the Gurguri Synclinorium, Gurguri-Sharki Fault and the Gurguri Fault. (d) The south-west facing field photograph showing the core of the Gurguri Anticline within the Chinji Formation near the Amankot village. (e) An eastward facing regional view of the western end of the Khattak Banda Synclinorium from its core is shown by the field photograph. The Khattak Banda Fault and small folds are marked at the western closure of the synclinorium.

Three different evolution models of the KFB have been suggested to understand the subsurface structural kinematics. i) The out of sequence thrusting over younger rocks forming duplex structures shown in balanced cross-section constructed by McDougall and Hussain (1991). ii) Abbasi and McElroy (1991) introduced the concept of double décollement at base Eocene and Infra-Cambrian rocks. iii) Pivnik and Sercombe (1993) interpreted the structural geometries in the KFB is mainly controlled by compressional- and transpressional-tectonics. Based on our interpretations, a conceptual model is proposed to understand the structural evolution of western KFB (Fig 14). Seismic- and geological cross-sections suggest two décollement levels i.e. Basal and secondary at the upper interface of crystalline basement and base Early Eocene rocks, respectively. These décollements divided the stratigraphic sequence into USSD and LSSD. The deformation in the rocks (EoCambrian-Paleocene) of LSSD adopted the duplex mechanism controlled by basal décollement. The USSD consists of Early Eocene to Early Pliocene rocks. Whereas, the rocks of Early Eocene comprising of about 2000 m thick assemblage of shale/evaporites which behave plastically and accommodated the stresses emanating from the basal décollement and distributed into the cores of anticline during shortening. The fault splays generated from the interface of sedimentary and basement rocks, tip out at the base of Early Eocene sequence. The mechanically soft rocks of Early Eocene acting as decoupling surface between USSD and LSSD. Hence, the structural geometry in the western KFB has a mismatch between surface and subsurface rocks (Fig 14).

Seismic interpretation illustrates a series of fault propagation folds were interpreted in LSSD, which are mainly south vergent and faults having displacement varying between 250 m and 2000 m. The fold geometry in the USSD indicates that the folds are asymmetrical, open to tight, plunging and overturned with their fold axis dipping towards north or south. The faults in USSD are mainly fore and back thrust/reverse with the displacement varies from 20 m to 1600 m. The structural style of the study area typifies a regional level thin-skinned deformation controlled by the pair of décollements.

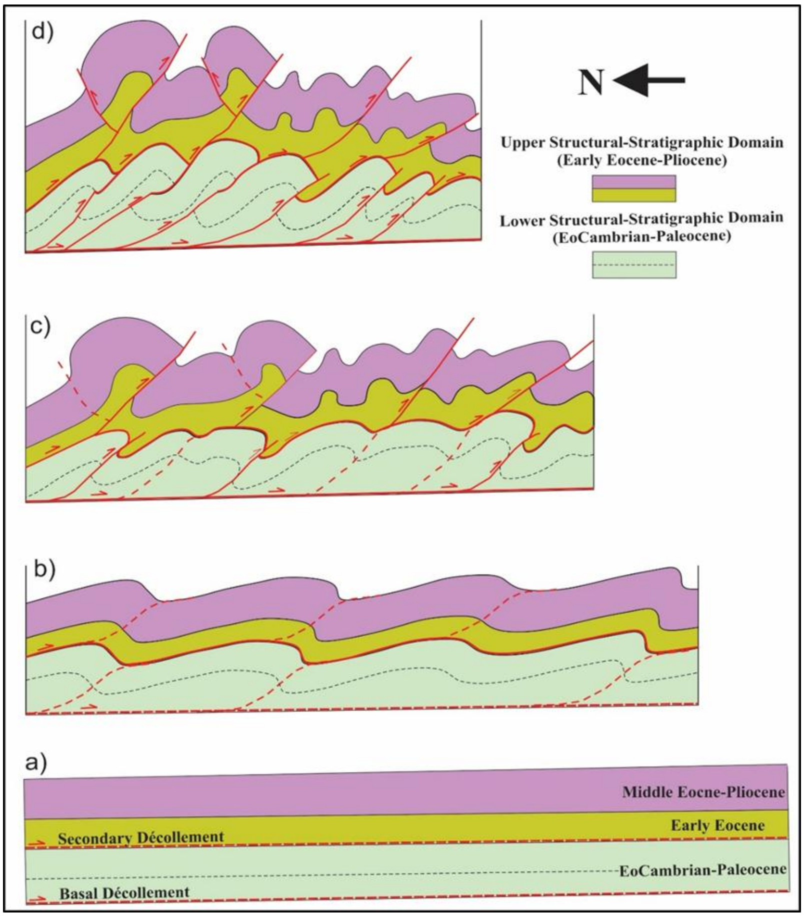

Fig 14. Proposed structural evolution model of the western KFB. a) Undeformed rock sequence and location of décollements. b) Uniform folding prior to faulting. c) Movement on basal and secondary décollements towards foreland. The rocks in LSSD deformed to duplex structures in contrary with the deformation in USSD. d) Showing disharmony between the geological structures of USSD and LSSD.

Previously, the total calculated shortening is reported 50% by McDougal and Husain (1991) in eastern KFB, 51% by Abbasi and McElroy (1991) from MBT to Surghar Range and 33% by Ghani et al. (2018) in central and southern KFB. However, our structural interpretation suggests 37% of average shortening in the western KFB. Stress Analysis of the GF shows that the fault has a 40% slip tendency which is quite high. Geometrically, the GF is the most comparable to the overall structural style of the study area, therefore, it could be concluded that the KFB is tectonically active and the deformation is ongoing.

7. Conclusions

The western KFB has a complex east-west trending thin-skinned deformation as a result of north-south oriented stresses. The structural evolution is controlled by the basal, and secondary décollements divided the KFB into USSD and LSSD. The Eocene to Early Pliocene rocks of USSD deformed into fore and back thrust/reverse faults and open to tight, overturned, and plunging folds. The EoCambrian to Paleocene rocks formed a series of north dipping duplex structure bounded by basal and secondary décollement in LSSD. A thick assemblage of mechanically soft rocks of Early Eocene behaves plastically to accommodate the stresses originated from the basal décollement resulted in structural disharmony between the USSD and LSSD. The average calculated shortening in the study area is 37%. The stress analysis of Gurguri Fault revealed 40% of planes are susceptible to failure and the direction of maximum principle stress i.e. σ_1 is N17°.

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