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Development and Synclinal-Anticlinal Breakthrough of Fault-Propagation Fold: Insights from Borr Dhoro Section of the Ranikot Anticline, Southern Kirthar Fold Belt, Pakistan

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Abstract

The better understanding towards the structural development of the fault-propagation fold in a particular tectonic setting is critical to understand the deformation mechanisms, mountain building process, tectonic history, hazard assessment and resources exploration. Therefore, this study is aimed to development and tectonic evolution of fault-propagation fold with reference to the Ranikot anticline, Southern Kirthar Fold Belt, Pakistan. Kirthar Fold Belt is one of the important parts of the tectonic and structural system of the Pakistan that developed during Cenozoic due to the transpressional collision of Indian plate with Afghan block along the Ornach-Nal and Chaman fault system. This study employs structural forward modeling and reverse kinematic restoration techniques to reconstruct the deformation history of the structure on the basis of field data. The study indicates that, Cretaceous Pab Sandstone is the oldest unit exposed in the core of anticline, while youngest Holocene terrace deposits or deformed in the forelimb of the anticline. The anticline is developed as a result of eastward slip on the decollement, which is located at the top of Jurassic Chiltan Formation. Three deformation phases are identified during present study, which are development of anticline on the Kirthar Frontal Thrust with syncline breakthrough, anticlinal breakthrough of the hanging-wall block of Kirthar Frontal Thrust and deformation of foot-wall block of Kirthar Frontal Thrust. The anticline underwent intense deformation and balanced cross-section shows the 3Km or 43% structural shortening along the studied section. This research will make substantial contributions to the broader fields of structural geology with implications for tectonics, petroleum exploration, geological hazard assessment and scientific understanding of structural processes.

Keywords: Fault-propagation fold, Fault breakthrough, Borr Dhoro Section, Ranikot Anticline, Kirthar Fold Belt, Pakistan

INTRODUCTION

Asymmetrical folds having steep or overturned fore-limb, form and grow at the tip of propagating thrust fault are named as “fault-propagation fold” (Suppe, 1983; Suppe, 1985; Suppe and Medwedeff, 1990; Mosar and Suppe, 1992). Geometries of the fault-propagation folds are proved very useful to interpret the deep lithospheric structures in many fold-thrust belts and mountain belts. Fault-propagation folds are common features in foreland basins and fold-thrust belts across the globe (Suppe, 1983; Jamison, 1987; Suppe and Medwedeff, 1990; Mitra, 1990; Erslev, 1991; Al Saffar, 1993; Philippe, 1994; Outtani et al., 1995; Mercier et al., 1997; Spang and McConnell, 1997; Erslev and Mayborn, 1997; Ray, 1997; Hardy and Ford, 1997; Allmendinger, 1998; Cristallini and

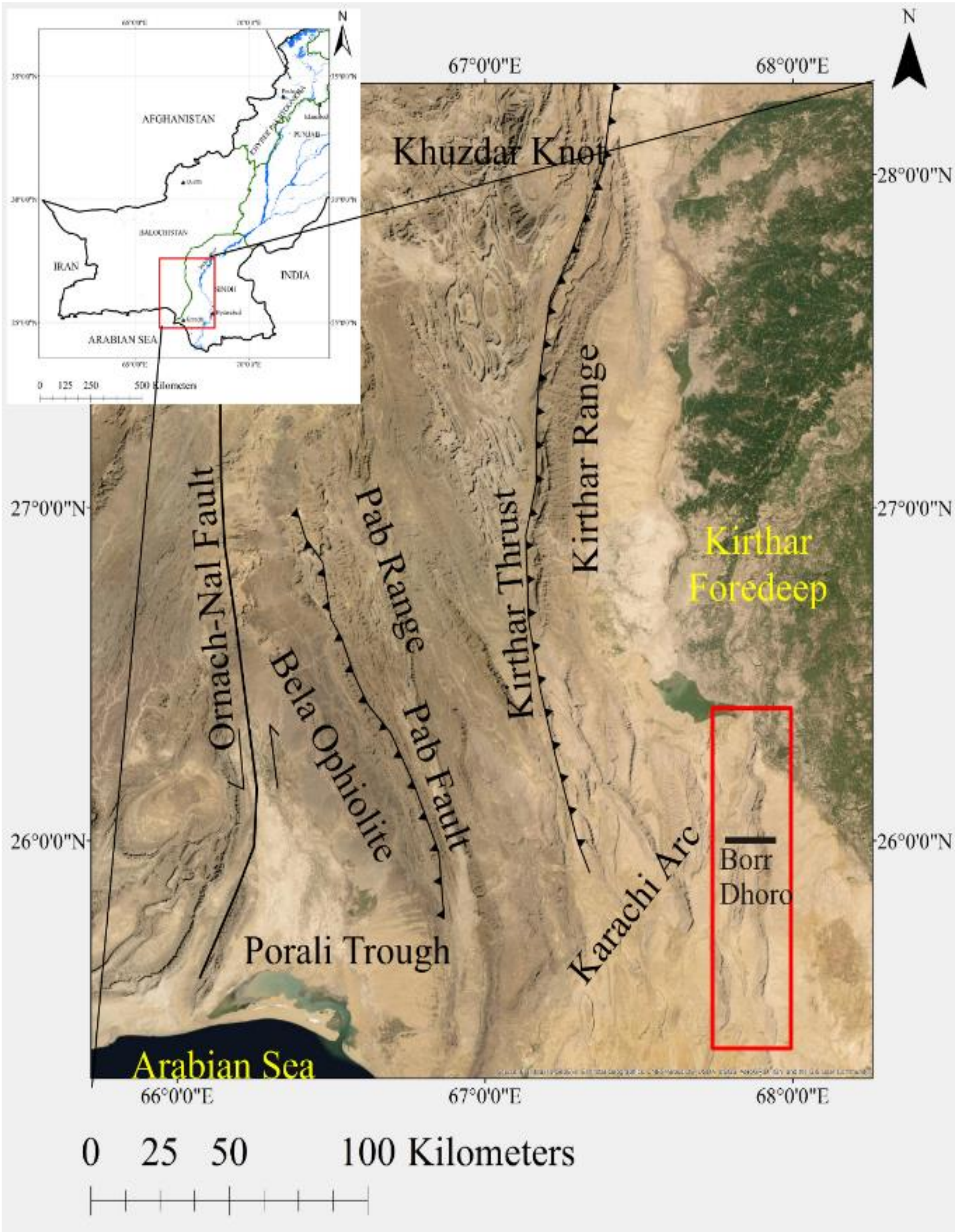

Figure 1: Map of Southern Kirthar Fold Belt showing location of Ranikot anticline in red rectangle and Borr Dhoro with bold line (After Hunting Survey Corporation 1960; Sarwar and De Jong 1979; Kazmi and Rana, 1982; Bannert et al., 1992; Halepoto et al., 2022) (Image Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community).

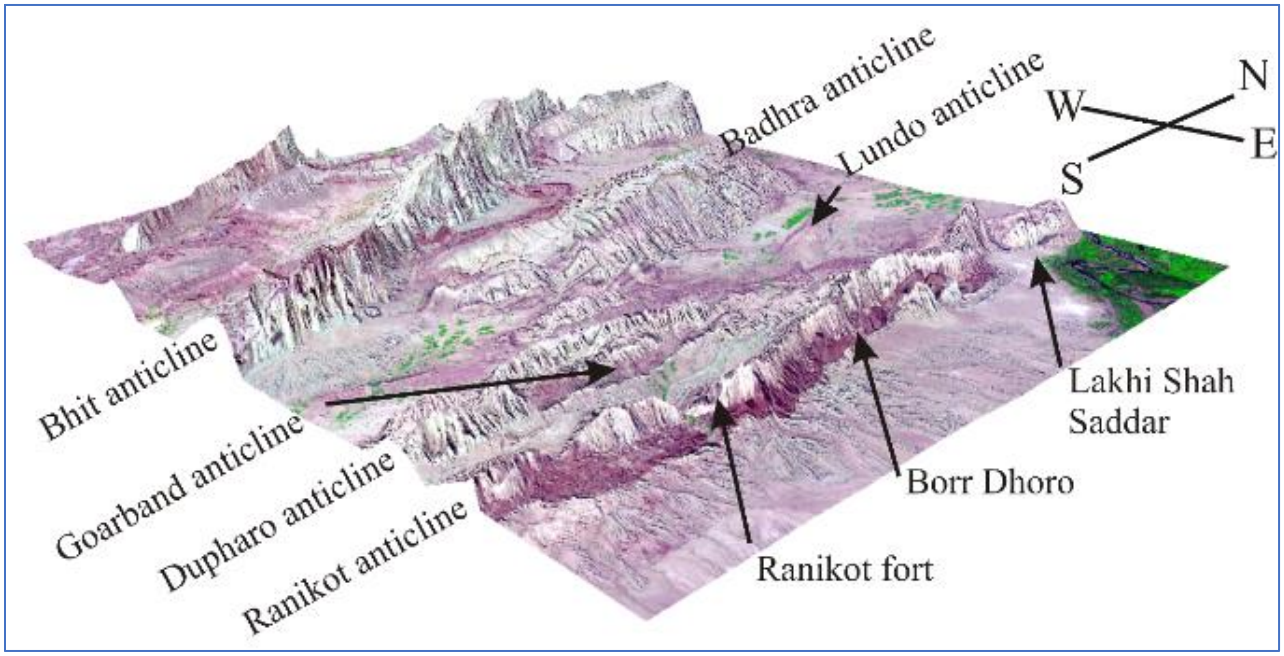

Figure 2: Landsat 8 (OLI TIRS) image draped over SRTM DEM to create 3D view of Ranikot anticline and adjacent structures (image source: earthexplorer.usgs.org).

Allmendinger, 2002; Cardozo et al., 2003; Wallace and Homza, 2004; Tavani et al., 2006; Carbonell et al., 2008; Mcclay, 2011; Tavani and Storti, 2011; Brandenburg et al., 2012; Jabbour et al., 2012; Hughes and Shaw, 2014; Bernal et al., 2018; Butler et al., 2018; Cawood and Bond, 2019; Jiang et al., 2020). Fault-propagation folds generally grow above an upward propagating thrust ramp as a result of foreland-ward horizontal slip of the sedimentary pile above a décollement. Therefore shape of the fault-propagation fold directly depends on the amount of horizontal slip along the basal décollement, the dip of the thrust ramp and the slip to propagation ratio (Suppe, 1983; Suppe, 1985; Suppe and Medwedeff, 1990; Mosar and Suppe, 1992; Mercier et al., 1997; Tavani and Storti, 2011; Jiang et al., 2020). It is observed that deformation is limited to the hanging-wall block of propagating thrust ramp, while foot-wall block remains un-deformed. The thrust ramp do not cut the surface in many cases where it remains as a blind thrust, but when it cut and emerge on the surface, then it is called as "breakthrough". The breakthrough can be "decollement breakthrough", "high-angle breakthrough" "low-angle breakthrough" "synclinal breakthrough" and "anticlinal breakthrough" (Suppe and Medwedeff, 1990). If thrust ramp propagates through and cuts the hinge of syncline or anticline, then it is called as "synclinal breakthrough" or "anticlinal breakthrough" respectively. Thrust breakthrough indicates the incompetent mechanical stratigraphy and intense deformation. Systematic understanding of the development of fault-propagation fold and its breakthrough will enable to understand the deformation history of the particular area.

Kirthar Fold Belt is located at the north-western plate boundary of Indian Plate that collided with Afghan Block during late Paleocene/early Eocene (Allemann, 1979; Sarwar and De Jong, 1984). Banks and Warburton (1986) proposed the passive roof duplex structural model for Suleiman and northern Kirthar Fold Belt. Schelling (1999) proposed the imbricate fan structural model for the frontal anticlines of Southern Kirthar Fold Belt. This fold belt remained an interesting and prospective area for the Oil and Gas exploration companies since 1990s. In this regard various workers such as (Raza et al., 1990; Ahmed and Ali, 1991; Bannert et al., 1992; Schelling, 1999; Hedley et al., 2001; Smewing et al., 2002; Smewing et al., 2011; Arshad et al., 2011; Ahmad et al., 2015; Hinsch et al., 2018; Hinsch et al., 2019; Halepoto et al., 2023a) worked on the tectonics, structural geology and stratigraphy of the Kirthar Fold Belt. This fold belt is divided into northern, central and southern parts on the basis of structural styles and shortening. Northern and central parts of the Kirthar Fold Belt consists of passive-roof duplexes, which accommodate more than 30% shortening (Banks and Warburton, 1986; Schelling, 1999; Hinsch et al., 2019), while Southern Kirthar Fold Belt consists of imbricate-fan, which accommodate less than 30% shortening (Schelling, 1999). Southern Kirthar Fold Belt is 200Km long and 50Km wide area between Karachi and Sehwan cities of Sindh (Kazmi and Jan, 1997). Tens of N-S trending en echelon anticlines are exposed in the Southern Kirthar Fold Belt. Ranikot anticline is the prominent structure for various geological studies in Pakistan, which is N-S trending structure that runs beside the meridian 68º between parallels 25º, 40′ N to 26º, 30′ N. The Ranikot anticline is more than 100Km long that can be outlined between Sehwan and Thano Bula Khan Cities of Sindh Province, Pakistan and along the western bank of Indus River (Figure 1 & 2). Hunting Survey Corporation (1960) and Fatmi (2009) used the term "Lakhi anticline" for Ranikot anticline. Schelling (1999) used the term "Ranikot anticline" for same structure, which is adopted in this work. The Ranikot anticline is previously studied by (Schelling, 1999) (Halepoto et al., 2022) and (Halepoto et al., 2023b) in terms of geometry and petroleum prospectus. But the sequential structural development of the anticline is poorly understood. Present work is aimed to understand the structural development of the Ranikot anticline constrained on the field data collected from the Borr Dhoro Section. In this paper, we adopted structural forward modelling to propose the deformation history needed to constrain the fold geometry during deformation as well as reverse kinematic restoration of the folding through time. This study will contribute valuable insights to the understanding of fold-thrust tectonics and the complex deformation mechanisms governing the evolution of fault-propagation folds in a specific geological setting. Borr Dhoro Section is an ephemeral water channel located in the central part of the anticline. The area of study can easily be accessed by the main highway N55 from Jamshoro to Sehwan city and associated link roads from where four wheel drive vehicles can lead through non-metalled road to the area in all favorable climatic conditions. Study area is located about 15 Km southwest of the Amri, district Jamshoro, Sindh, on the Survey of Pakistan's Toposheet No. 35 N/16.

MATERIALS AND METHODS

Fieldwork of the Borr Dhoro Section was carried out aimed to establish stratigraphic variations, stratigraphic younging direction, orientations of bedding planes, axial planes and structural features, such as faults and folds. The data were collected by employing different devices, such as compass clinometer, GPS device and high-resolution photography. Bedding and axial plane attitudes, fold axes orientations and their location were measured in the field with the help of compass clinometer and GPS device, while digital photographs were taken to capture the geometry of major geological features. Field data were processed and analyzed using different geological mapping and modelling software, such as ArcGIS, 2D-Move and Corel Draw. The

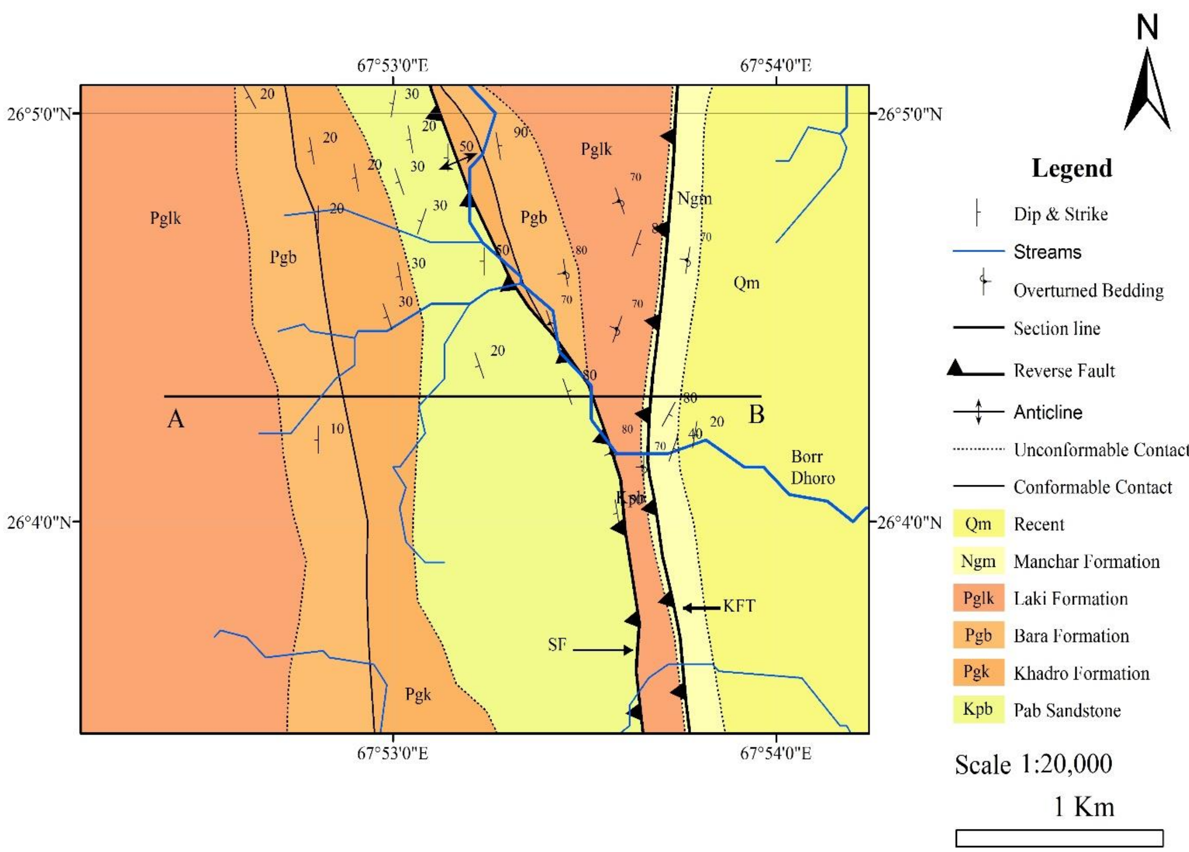

Figure 3: Geological map of Borr Dhoro Section, showing stratigraphy, structures and section line AB for balanced cross-section (KFT=Kirthar Frontal Thrust, SF=Splay Fault).

orientation of bedding planes, axial planes, fold axes and fault surfaces were analyzed to determine the history of structural development and the associated synclinal-anticlinal breakthrough of the Ranikot anticline. The cross-section is balanced by considering constant-thickness or parallel fault-propagation folding, assuming angular hinges and conservation of bed length. The balanced cross-sections were constructed with kink-style construction method by structural forward modelling to visualize the temporal structural development, surface and subsurface structural geometry and the relationships between different structural elements.

RESULTS AND DISCUSSION

Field Observations

Structural style of the structure is controlled by NS trending fold and thrust and associated splay faults. The Ranikot anticline at Borr Dhoro Section is asymmetrical because its forelimb is vertically dipping to overturned and back-limb is steeper near the hinge of the anticline and become gentle farther west. The overturning effect is observed in the Laki Formation and Manchar Formation, while older rocks are vertically dipping. This indicates the angular unconformity between Paleocene and Eocene rocks, which needs a detailed investigation to find out the Paleocene/Eocene deformation in the SKFB. Steepness of the back-limb near the fold hinge is

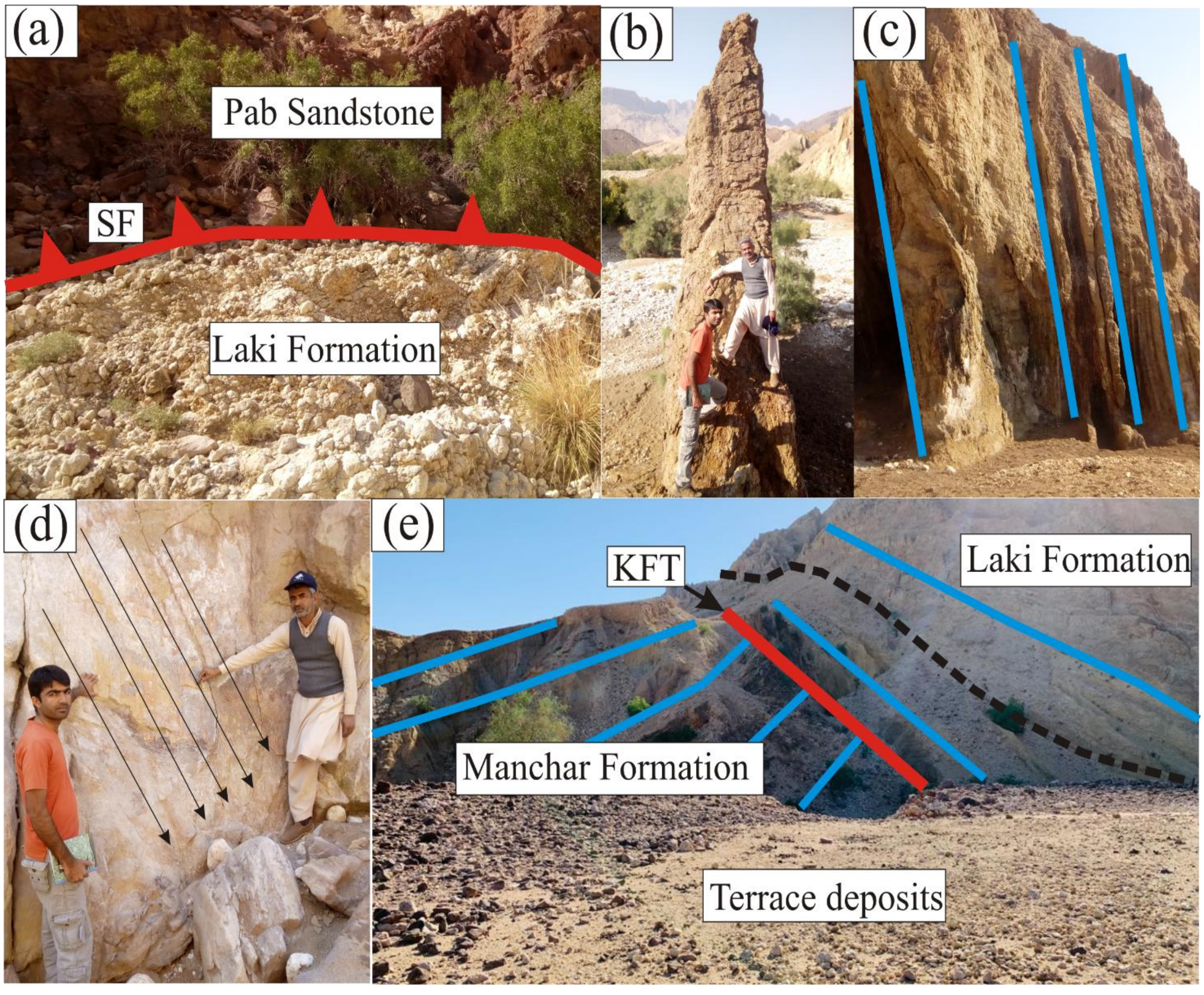

Figure 4: Field observations in the Borr Dhoro Section, **(a)** Upper Cretaceous Pab Sandstone is thrusted over the Eocene Laki Formation along the splay fault (SF); **(b)** vertical-dipping basalt of Lower Paleocene Khadro Formation; **(c)** vertical-dipping Middle Paleocene Bara Formation, where blue lines corresponding with bedding planes; **(d)** Slickensides or striations in the Eocene Laki Formation, where arrow-lines corresponds with striations and they are directed towards foot-wall block of splay fault; **(e)** KFT in the outcrop, where dashed black line shows the unconformable contact between Laki Formation and Neogene Manchar Formation and blue lines corresponding with bedding planes.

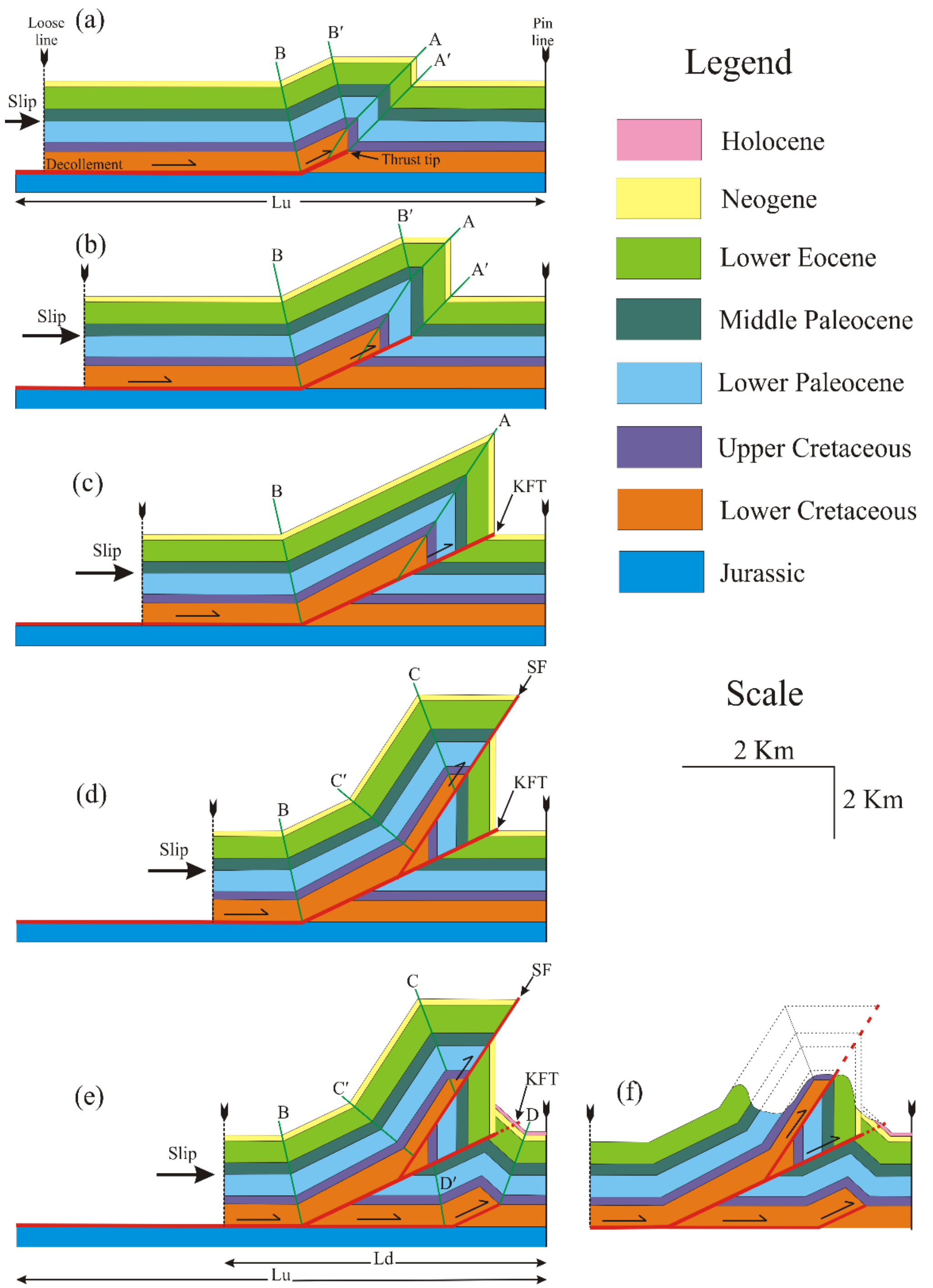

Figure 5: Balanced cross-sections depicting forward structural modelling of the Ranikot anticline, showing progressive development of the fault-propagation fold, its synclinal and anticlinal breakthrough along the Borr Dhoro Section.

a result of anticlinal breakthrough and emergence of splay faults.

Field studies indicates that Late Cretaceous (Maestrichtian) Pab Sandstone is the oldest formation exposed in the core of the anticline along Borr Dhoro Section (Figure 3). It is bounded by the splay fault in the east. The Pab Sandstone is thrusted over the Lower Eocene Laki Formation along this splay fault (Figure 4a). The hanging-wall block of the splay fault is back-limb of the anticline in studied section. Pab Sandstone is overlain by Khadro Formation of Danian age with a disconformable contact. Khadro Formation is exposed in the back-limb of the anticline while it is mostly under-thrusted in the forelimb, although some vertical dipping exposures are observed in the forelimb, where over-thrusted Cretaceous rocks are eroded (Figure 4b). The vertical exposures in the fore-limb of the anticline occurs as foot-wall block of the splay fault as well as hanging-wall block of the Kirthar Frontal Thrust (KFT). Bara Formation of Thanetian age overlies the Khadro Formation in studied section. Bara Formation has well exposure in the back-limb of the structure, but like Khadro Formation, it is also under-thrusted and has limited vertical dipping exposure in the forelimb (Figure 4c). Bara Formation is overlain by Laki Formation of Lower Eocene (Ypresian) age. The slickensides or striations are preserved in the Laki Formation along the hanging-wall block of splay fault, showing the movement direction of fault blocks (Figure 4d). Laki Formation is overlain by Neogene Molasse of Manchar Formation (Siwalik Group) in the forelimb. The KFT cut across the syncline hinge and emerges from the basal shale of the Manchar Formation (Figure 4e). Manchar Formation and Holocene Terrace deposits has steep east-ward dip in the footwall of KFT, which indicates that they are underlain by east-vergent blind thrust.

FORWARD STRUCTURAL MODELLING

Forward structural modeling (Figure 5) indicates that the Ranikot anticline is developed as a fault-propagation fold due to the propagation of KFT. KFT is the outer-most emergent thrust of the Kirthar Fold Belt, which stepped up from the décollement located at the top of Jurassic Chiltan Formation (Figure 5). Décollement at the top of Jurassic Chiltan Formation is also confirmed in the analogue seismic sections of the SKFB (Halepoto et al., 2023a; Halepoto et al., 2023b). The earliest fold geometry of the Ranikot anticline is shown in Figure 5a, with axial planes AA′ and BB′. These axial planes correspond with the first phase of deformation. Progressive propagation of the fault-tip in the hinges of syncline and its final emergence on the ground changed the fold shape as shown in Figure 5b-c. The first phase of fold development completed with the synclinal breakthrough. Further deformation is accommodated by the development of an splay fault (SF) along the hinges of anticline, because it is the zone of maximum stretching during folding (Suppe and Medwedeff, 1990). The balanced cross-section (Figure 5d) indicates that the splay fault (SF) is branched off from the KFT along the lower Cretaceous rocks. The Ranikot anticline underwent anticlinal breakthrough along this splay fault. This splay fault was named as “Rehman Dhoro Thrust” by Schelling (1999), because he identified and described it from the Rehman Dhoro, which is located north of Borr Dhoro Section. The development of splay fault and anticlinal breakthrough of the structure is interpreted to be the second phase of deformation. The axial planes CC′ correspond with the second phase of deformation. Third phase of deformation is marked by the eastward slip of the fault-propagation fold and stepping-up of another thrust fault from the décollement (Figure 5e). The axial planes DD′ in the foot-wall block of KFT correspond with the third phase of deformation. The younger thrust fault is blind, which folded as younger as Holocene terrace deposits in the fore-limb of the Ranikot anticline. Therefore, the development of this blind thrust fault is believed to be quite recent deformation phase. This indicate that study area is tectonically active in the present time as well. The present structural geometry of the Ranikot anticline along Borr Dhoro Section is shown in (Figure 5f). The balanced cross-section (Figure 5e) indicates the un-deformed length (Lu) of the section is 7Km and deformed length (Ld) is 4Km. This implies the structural shortening of 3Km or 43% along the section line AB. This shortening indicates that structure underwent intense deformation in Borr Dhoro Section.

CONCLUSIONS

The field observation indicates that the Pab Sandstone of late Cretaceous is the oldest unit exposed in the core of anticline and youngest Holocene terrace deposits or deformed in the forelimb of the anticline. Structural forward modelling suggested that anticline is developed as a result of east-west directed tectonic shortening. The anticline is detached from the top of Jurassic Chiltan Formation. Three deformation phases are identified during present study, which are development of anticline on the Kirthar Frontal Thrust with syncline breakthrough, anticlinal breakthrough of the hanging-wall block of Kirthar Frontal Thrust and deformation of foot-wall block of Kirthar Frontal Thrust. The anticline underwent intense deformation and balanced cross-section shows the 3Km or 43% structural shortening along the studied section.

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