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TECTONIC EVOLUTION AND STRUCTURAL MODELING OF BANDA DAUD SHAH-SURGHAR AND MARDAN KHEL-SOOR DAG TRANSECTS, KOHAT BASIN, PAKISTAN

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Abstract

The Kohat basin in the northwestern Pakistan is a sedimentary basin and a Fold-Thrust belt bounded by the Main Boundary Thrust in the north and the Surghar ranges in the south. Geological mapping, structural modelling and restoration have been conducted in central and southern Kohat basin to understand the evolution of the Fold and Thrust belt and its hydrocarbon potential. Surface geology of the area reveals the dominancy of thrust tectonics. Manzalai Anticlinorium, Karak fault zone and Surghar ranges are the prominent structural features of the area under discussion. Synclines are generally wide while anticlines are sharp, possibly due to the isostatic adjustment of ductile and incompetent Eocene evaporites, under the post Eocene stratigraphic column. This part of the Kohat basin is in the stage of initial deformation of the presently developed tectonic model in the northern Kohat basin, where it is believed to have formed by double decollement. The subsurface contour on top of the Paleocene shows promising traps in Manzalai anticline, Karak anticline, and Karak fault zone for the well-developed and proven petroleum system of the Kohat basin. The eastern and western structural transects (A-B and C-D) show crustal shortening of 15.19% and 6.63% respectively. Major crustal shortening and stress release is concentrated in the uplift of Manzalai structure and Karak fault zone. The un-mapable intra-formational en-echelon folding at the western part of the basin, toward the Kurram fault, represents transpressional tectonics.

Keywords: *Kohat Basin; Thrust tectonics; Manzalai Anticlinorium; Structural transects*

1. Introduction

The Himalaya is a majestic mountain range located in South Asia, spanning over 2,400 km across Afghanistan in the west and Burma in the east (Yin, 2006; Yuan et al., 2022). It is one of the most studied collisional orogeny in the world due to its complex tectonics and structural setting (Yin, 2006; Salam et al., 2023). The Himalaya mountain range is the result of the collision between the Indian and Eurasian plates, which began around 50 million years ago and is still ongoing today (Petterson, 2010; Rehman et al., 2011). The geology of the Himalaya is characterized by a variety of structural styles, including thrust faults, folds, and regional metamorphism (DiPietro and Pogue, 2004; DiPietro et al., 2008; Ali and Salam, 2019). In recent years, the Himalaya has become an important region of research for structural geologists interested in understanding the mechanics of mountain building and the dynamics of plate tectonics. Indo-Eurasian collision in the Early Eocene to Late Paleocene is believed to be the most recent continent-continent collision with some spectacular results in the form of Himalayan orogeny, and it has a visible effect on the foreland basins including Kohat basin (Gansser, 1964; Le Fort, 1975; Turab et al., 2017; Salam et al., 2023).

Based on the grade of deformation and metamorphism, the Himalaya (north to south) is divided into higher, lesser, and sub-Himalaya

(DiPietro and Pogue, 2004; DiPietro et al., 2008). Higher Himalaya is bounded to the north and south by Main Mantle Thrust (MMT, ~52 Ma) and Main Central Thrust (MCT, ~22 Ma) respectively. Lesser Himalaya is bounded between the MCT (in north) and the Main Boundary Thrust (MBT, ~11 Ma) in south, while the sub-Himalaya is bounded in south of MBT (Fig. 1) by the Main Frontal Thrust (MFT, ~4 Ma) (Meigs et al., 1995; DiPietro and Pogue, 2004; DiPietro et al., 2008; Petterson 2010; Faisal et al., 2014, Salam et al., 2023).

The Kohat basin is among one of the Himalayan foreland basin and it has been evolved into a Fold and Thrust belt due to the ongoing Himalayan tectonics (Ahmad, 2003; Pivnik and Wells, 1996). It is composed of thick sequences of Palaeocene to Miocene sedimentary strata (Ghani et al., 2018). The complex geology of Kohat basin is majorly dominated with fore- and back thrusts and a series of anticlines and synclines, which reflecting that the structural framework of the basin has important implications for the exploration and production of hydrocarbons in the area (Ahmad, 2003). The basin has been recently explored for hydrocarbon potential. Several prospective hydrocarbon deposits have been identified by). Some parts of the basin, however, are relatively unexplored in terms of tectonic development and hydrocarbon potential. The complex geology of Kohat basin is majorly dominated with fore- and back thrusts and a series of anticlines and synclines, which reflecting that the structural framework of the basin has important implications for the exploration and production of hydrocarbons in the area (Ahmad, 2003). The basin has been recently explored for hydrocarbon potential. Several prospective hydrocarbon deposits have been identified by (Ahmad 2003). Some parts of the basin, however, are relatively unexplored in terms of tectonic development and hydrocarbon potential.

This paper reports on the findings of a study that involved mapping of the surface geology of the central and southern parts of Kohat basin, which lies between the Manzalai trend and the Surghar ranges, through a combination of field investigation and remote sensing analysis. The identification and characterization of structural features are essential for understanding the geological evolution of the region. In addition, a balanced cross-section model that integrates surface data collected in the field with satellite images is also presented. These findings will be having important implications for regional tectonics and hydrocarbon exploration potential of the region.

Regional Geological Setting

The Himalayan mountain range in Pakistan is divided into five litho-tectonic zones by four major regional fault system: Main Karakoram Thrust (MKT), Main Mantle Thrust (MMT), Main Central Thrust (MCT), Main Boundary Thrust (MBT), and Main Frontal Thrust (MFT)/ Salt range thrust (SRT) (Ahmad, 2003; DiPietro and Pogue, 2004; Smith et al., 2012; Faisal et al., 2014; Jones and Patel, 2015). The rocks of Indian plate in the central Himalaya have been divided into orogeny-parallel tectonostratigraphic zones having westward decrease in Neogene shortening across the Himalayan Fold and Thrust belt (DiPietro and Pogue, 2004; DiPietro et al., 2008). Most of the shortening in the western Himalaya is concentrated in the un-metamorphosed foreland basins in contrast to the central Himalaya (DiPietro and Pogue, 2004). The Karakoram block, consisting of sedimentary, igneous, and metasedimentary rocks, is situated at the southern margin of the Eurasian Plate, and is flanked to the north and south by the Pamir and Kohistan-Ladakh Island Arcs (K-LIA), respectively (Faisal et al., 2014). The Main Karakoram Thrust (MKT), evolved ~100 Ma, is defined to be the suture zone between the Karakoram block in north and the K-LIA in south (Yoshida et al., 1997). It was followed by northward movement of the Indian plate during the Late Jurassic to Cretaceous, and subsequent collision with the K-LIA along the MMT (Pudsey et al., 1985; Petterson 2010; Rehman et al., 2011). The MMT is located in the north of the Northern Deformed Fold and Thrust belt along the K-LIA and affects the lower crust, with a fault plane that dips between 25 and 45 degrees toward the north (Le Fort, 1975; Bard, 1983; Malinconico, 1986). The exact location of the MCT is controversial with more than ten locations. There is no age equivalent thrust for MCT of central Himalaya, however, the tectonic stratigraphic extension of the eastern and central Himalaya shows the equivalency of Panjal-Khairabad thrust to MCT in western Himalaya (DiPietro and Pogue, 2004). The MBT, which runs from the Hazara Kashmir Syntaxis (HKS) to the Orakzai region in the northeast and southwest, respectively, is responsible for transporting Paleozoic and Mesozoic sedimentary and metasedimentary rocks over the Miocene foreland basin deposits (Khan, 2011). The Southern Deformed Fold and Thrust belt is an east-west trending fold and thrust belt covered by extensive fluvial deposits. It is divided by the Indus River into the Potwar basin to the east and the Kohat basin to the west, collectively known as the Upper Indus basin of Pakistan (Ahmad, 2003). The MFT delineates the southern borders of the Kohat basin and carries Jurassic rocks over the Punjab plain (Kazmi and Jan, 1997). The Kohat basin has a diverse array of structures, with thrust tectonics playing a substantial role in its tectonic evolution. The compressional forces brought on by the northward collision of Indian Plate have resulted in the formation of folds and faults, with the Surghar thrust, Karak fault zone, and Manzalai trend being the three most prominent structural elements. The MFT, known as the Surghar thrust, is responsible for carrying Jurassic rocks over the Punjab plain and serves as the southern borders of the Kohat basin. On the other hand, the Karak fault is a regional fault at the basin scale that runs from the Kurram fault to the Kalabagh strike slip fault in east-west direction (Bhatti et al., 2015; Shah et al., 2015; Ahmad et al., 2018).

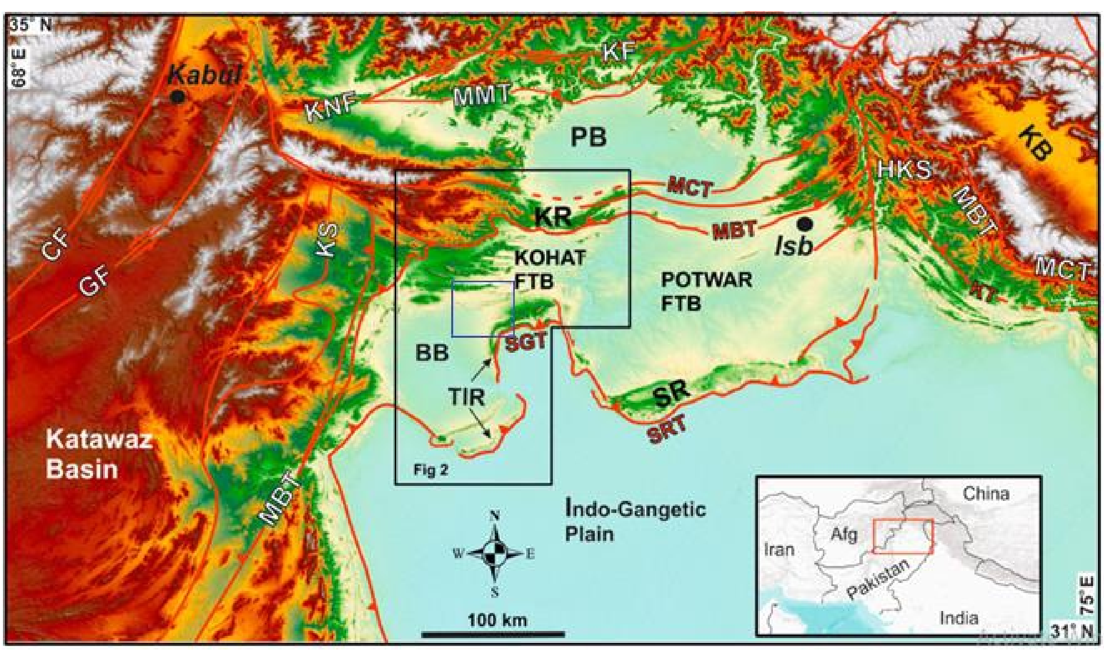


Fig. 1. Himalayan tectonic map illustrating key tectonic boundaries and the relative position of the Kohat and Bannu sub-basins (Ghani et al., 2021). Blue box shows location of the study area. In this figure: *KR=Khyber Ranges, KF=Karakoram Fault=Bannu Basin, SGT=Surghar Thrust, SRT=Salt Range Thrust, MMT=Main Mantle Thrust, MCT=Main Central Thrust, MBT=Main Boundary Thrust, TIR=Trans-Indus Ranges, PB=Peshawar basin, SR=Salt Range, KR=Khyber Ranges.*

Stratigraphy

The Kohat plateau only exposes rocks from the Younger or early Eocene age (Meissner et al., 1974). However, a thick succession of Mesozoic-Paleozoic deposits is found in the Surghar Range to the south and in the hinterland to the north, indicating that these older rocks likely underlie the Eocene deposits in the Kohat basin (Fatmi, 1973; Khan et al., 1986; Meissner et al., 1974. Khan et al. (1986) extrapolated the presence of Eo-Cambrian evaporites and a thin layer of Paleozoic sediments beneath the Kohat and Bannu basin, although they are not exposed elsewhere in the Trans Indus Ranges. This suggests that these deposits may be autochthonous beneath the Kohat plateau, with the range front thrusts cutting up-section from the evaporites to the base of the Paleozoic-Mesozoic succession to the north of Kohat basin (Butler et al., 1987).

The Potwar plateau, on the other hand, was translated along these Eo-Cambrian evaporites resulting in a broader, more open, and less deformed style of the Potwar foreland belt (Lillie et al., 1987; Baker et al., 1988). In contrast, the Kohat Plateau exhibits exposed thrusts that emplace Eocene evaporites over Miocene molasse sediments. The Bahadur Khel Salt and Jatta Gypsum are Eocene evaporites that are confined to the central Kohat plateau in a narrow-elongated belt called the Kohat salt zone (Khan et al., 1986). The Eocene rocks in Kohat basin shows variation from north to south with thick shales of Kuldana Formation and evaporites of Jatta Gypsum in the north, salt and gypsum in the central part to the thick carbonates exposed along Surghar thrust in the western Kohat basin. The Eocene evaporite sequence is overlain by Eocene shelf sediments of the Kuldana Formation (siltstone) and the Kohat Formation (limestone). These shelf sediments are unconformably overlain by 5 km of molasse deposits consisting of Rawalpindi group and Siwalik rocks.

Table 1: Exposed stratigraphy of the Kohat Basin are (modified after Ahmad, 2003).

ERA	PERIOD	EPOCH	FORMATION	LITHOLOGY
Cenozoic	Tertiary	Pleistocene	Soan Formation	Sandstone interbedded with conglomerates
		Pliocene	Dhok Pathan Formation	Sandstone with conglomerate lenses
			Nagri Formation	Sandstone and shale
			Chingi Formation	Shale and sandstone
		Miocene	Kamlial Formation	Sandstone and shale
			Murree Formation	Sandstone and red shales
		Eocene	Kohat/Nammal/Sakesar limestone	Limestone
			Mami Khel Formation	Red clays
			Jatta Gypsum	Gypsum and shale
			Panoba/ Bahadur Khel Salt	Shale/Salt
		Paleocene	Patala Formation	Black shales
			Lockhart Formation	Limestone
			Hangu Formation	Coal, sandstone, and black shales
Mesozoic	Cretaceous		Lumshiwal Formation	Sandstone
			Chichali Formation	Greenish shales, sandstone with belemnites fossils
	Jurassic		Samana Suk Formation	Limestone
			Shinawari Formation	Limestone and thin layers of shale
			Datta Formation	Black shales and sandstone

Materials and Methods

A preliminary map for comprehensive surface geology was created using Google Earth data, which delineated several formations. To verify contact of formations in the field, a geological fieldwork was conducted in the research region to collect various attitude data. The information from Google Earth data and outcrop data from the field were merged into Arc Map to create a detailed geological map at a scale of 1:25,000. Structural cross-sections of A-B and C-D oriented perpendicular to the strike of the geologic formation of the study region were constructed using orientation and surface geology data gathered in the field, incorporated into the 2-D MOVE module of the Midland Valley's MOVE software. Digital elevation model (DEM) imported to 2-D MOVE software is used for the creation of the surface topography along the geologic cross sections. The structural patterns on the section view were created with surface projection from the 2-D view. The stratigraphy in the section view is created by using function 'Horizon from the template' method in 2-D MOVE where the surface location of the formation contact is based on the projected data from the map view and the thickness of formation is based on the integrated map thicknesses and the thickness reported from the drilled wells in nearby areas.

A structural model was developed to analyze the evolution of various structures to understand the kinematics of the Kohat basin. A 2-D kinematic simulation phase was used to gradually restore the cross section in the MOVE application and assess the total shortening and tectonic development of the research area. The "move on fault" tool was used to reverse the stratigraphic throw along various faults, starting from south to north, bringing the section into a condition of folding prior to the faulting in early tectonic development. The Paleocene top was selected as the template line because of its preserved depositional length as it is not expose and eroded through the study area, and the other formations were employed as the passive line to be unfolded by the Paleocene template line, to restore the section back to its original depositional length. All horizons were flattened back to their deposition length using the unfolding. The difference of length of restored cross section to the deformed state was used to calculate the total percentage crustal shortening of the transect. Flow chart of the methodology is given in figure 2.

Results

Field Observation

Detailed geological field work was conducted on the predefined field traverses along the road cuts, stream cuts and routes to the mining sites as these features provide the best exposures of geologic structures and easy accessibility in the field. The study area is controlled by thrust tectonics with east west trending folds and dominantly south verging faults, coherent with Himalayan tectonic transport direction. The southern limbs and core of the folds are primarily faulted. The rocks exposed in the study area range from Eocene to Pliocene consisting of shale, sandstone, salt, gypsum, and limestone. The cores of anticlines are occupied by Eocene rocks mostly where Kohat Formation gives high terrain structures while synclines contain younger rocks from the molasses rocks in the core, mostly Siwaliks, giving low elevation to flat structures. The study of the Eocene and Miocene rocks in the Kohat basin revealed significant variations. The Kohat Formation, a prominent unit in the area, displays thickness variations, being relatively thicker in the Manzalai structure and only 1 meter-thick in the Karak fault zone. Furthermore, the formation is absent in the Surghar Ranges where its lateral variation is observed in the form of the Sakessar and Nummal Formations. Other evaporite horizons in the Eocene exhibit similar trends, with no exposure towards the Surghar thrust through the Karak fault zone. The formations generally strike in the east-west direction, perpendicular to the general tectonic stress vector in the region. The formations in the basin are characterized based on their texture, lithology, environment of deposition, and stratigraphic order, determined by the dip direction and structural geology of the area.

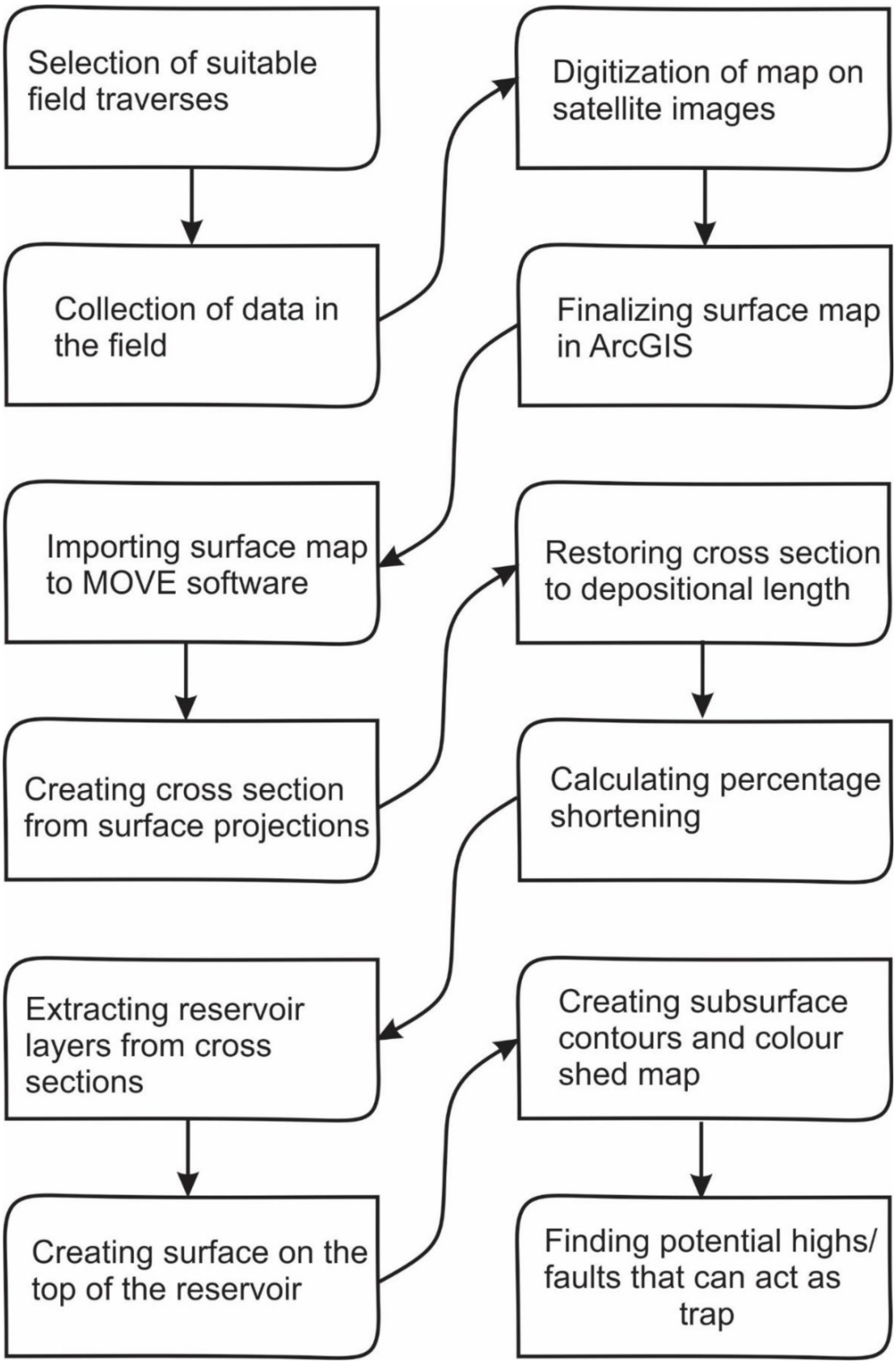


Fig. 2. Flow chart of the methodology used in this research.

Surface Geology

Surface geology of the area is dominated by compressive tectonics with south verging structures having sharp anticlines and broad synclines. The presence of salt tectonics and fault driven folding makes the anticlinal folds sharp and tight, with broad synclines. The southern limb or core of the anticlines is mostly faulted due to the south-verging tectonic stress regime. The surface stratigraphy is dominated by the Siwaliks group and Eocene rocks. The Eocene rocks are only restricted to anticlinal cores whereas the synclines are broad and wide with a thick sequence of Siwaliks rocks in the core.

A geologic map was constructed based on field data and surface interpretation of satellite images of Landsat from google earth. Based on the surface deformation in the study area, the geological map shows different structure domains from north to south. The area is characterized by major anticlinal and synclinal structures (i.e., Manzalai anticlinorium, Bahadur Khel anticline, Karak anticline, Nari Panos syncline, Painda Banda syncline, Handai Ghar syncline and Walaki syncline) bounded by major thrust faults (i.e., Nashpa back thrust, Idel Khel fault, Nari Panos back thrust, Kunghar back thrust, Karak thrust, Garori thrust and the Surghar thrust).

Manzalai anticlinorium is a major hydrocarbon producing geologic structure associated with dozens of small folds to the north and south of the main anticline. The structure is extended 47 km in the east-west direction, plunging towards east dying out in front of village Banda Daud Shah. The structure is bounded to the north and south by Nashpa back thrust and Idel Khel fault respectively, making it a pop-up anticlinal structure in the sectional view. The Nashpa back thrust is an east west trending, low throwback thrust mostly passing through Siwaliks group rocks. It passes between Painda Banda syncline and Banda Daud Shah thrust in the eastern part and to the north of the Manzalai structure in the west (Fig. 3)

In the eastern end of the Manzalai anticlinorium, the Nashpa back thrust thrusted Jatta gypsum of Eocene age in the hinging wall over the Chinji Formation of Siwaliks in the foot wall with westward decreasing stratigraphic throw. The associated small folds to the north of the Manzalai anticlinorium plunges in the west direction whereas a series of small folds to the south of the anticlinal structure plunges to the east.

Nari Panos syncline is a flat laying major syncline bounded to the north and south by Idel Khel thrust and Nari Panos back thrust respectively. It is a doubly plunging syncline that plunges towards southwest and southeast in the eastern and western part respectively. The axial plane is verging towards the south following tectonic transport direction (Fig. 3). The fault passes through Chinji Formation as an inter-formational fault in the common limb of the Speena Banda dome and Painda syncline, while further towards west it passes through the common limb of Nari Panos syncline and Manzalai anticlinorium.

Nari Panos back thrust is apparently out of sequence back thrust which adjusts the stress and shortening along the Karak fault. It extends from Speena Banda dome in the east to the Bahadur Khel crossing to the Ghol Dam in the west, towards where it merges with the Kurram strike slip Fault. The fault thrusted the Bahadur Khel salt of Eocene age in the hanging wall over the Nagri Formation in the foot wall, near Nari Panos village. Generally, the stratigraphic throw decreases from east to west direction.

Painda Banda syncline is an east-west double plunging syncline with Nagri Formation in the core and Chinji Formation on the limbs (Figure 2). Laterally it is located slightly south of the Manzalai structure and is bounded by the same fault structures sharing the same pop-up structural geometry in the sectional view. There is ongoing production and developmental activities of Nashpa oil field towards the eastern end of the structure while the western end is still unexplored.

Bahadur Khel anticline is a local anticline to the south of Bahadur Khel town. The western end of the structure is plunging towards the west and the eastern end is truncated by the Nari Panos back thrust. Bahadur Khel salts are the oldest exposed stratigraphic units located in the core while Mami Khel clays and Kohat limestone are present on the limbs of the structure. The southern limb of the structure is locally faulted near the Bahadur Khel tunnel where Bahadur Khel salt is thrusted over the Chinji Formation in the foot wall.

Handai Ghar syncline is in the high line Karak fault zone in the north of Karak city. The syncline is bounded to the north and south by Kunghar back thrust and Karak thrust, respectively, making it a pop-up syncline in sectional view. It is a west plunging syncline and having the Nagri Formation in the core.

Kunghar back thrust is out of sequence thrust parallel to the Karak thrust and Nari Panos back thrust in the Karak fault zone. It extends from Latamber area in the west towards Shahidan Banda in the east before it merges with the Karak Fault in the east, out of the study area. The oldest unit exposed along the thrust is Jatta Gypsum against the Nagri Formation in the east, while in the west near Surdag village it is intra-formational fault within Nagri Formation. The stratigraphic throw decreases towards the west with few exceptions in the middle part.

Karak thrust is an east-west trending basin scale fault in the north of Karak city. The stratigraphic throw generally decreases to the east and west, while the middle part has relatively high stratigraphic throw where it thrust Jatta gypsum in the hanging wall over Chinji Formation in the footwall.

Karak anticline is an east-west trending anticline that extends from Sarat Khel in the east to the Ambiri Kala in the west. It verges slightly to the south in accordance with the tectonic transport direction. The Karak anticline is bounded to the north by Mitha Khel thrust and to the south by Walaki syncline. The Mitha Khel fault is a north-east to south-west extended Fault that thrusted the Nagri Formation in the hanging wall over the Dhok Pathan Formation in the footwall.

Walaki Syncline is an east-west trending synclinal structure extending from the Ali Khel to Takht-e-Nasrati in the east and west respectively. The core of the syncline is occupied by Soan Formation with Dhok Pathan Formation on the limbs. The core of the syncline has a blind fault visible on the seismic section (Fig. 4).

Garori fault, which is mainly located to the east of the study area, extends in an east-west direction. Although the fault has a well-defined surface expression in the east, most of its part is concealed under alluvium. The presence of fault is evident in the seismic section depicted in Fig. 4.

Surghar thrust is an important component of the Himalayan collision, which has thrusted the Kohat basin stratigraphy over the Panjab plain in the footwall. The eastern segment of the Surghar thrust in the study area runs in an east-west direction, while the western segment runs in a north-south direction. The thrust fault places the oldest Jurassic Datta Formation over the Chinji formation in the footwall.

Construction and Restoration of Geological Cross Section

a) Construction of Geological Cross Section

To produce balanced structural cross sections, geological information from the surface was extrapolated into the subsurface along the A-B and C-D structural transects on (Fig. 3). Structural cross sections were created along the structural transects A-B and C-D to understand the underlying structural geometries, kinematics and the throw of different stratigraphic units exposed in the mapped area. The stratigraphic column beneath Paleocene is not exposed in the Kohat basin, however, it is present and reported in the oil and gas wells (i.e., in the Nashpa oilfield). This Pre-

Paleocene strata was extrapolated to the subsurface, in the cross sections, using the information from the well data. Part of the A-B cross section is aided with an interpreted seismic section after Ali Khan et al. (2008) (Fig. 4).

The study area deformational geometry is best represented by drawing cross-sections perpendicular to the strike of the structural features. Cross-section A-B extends from the Manzalai anticlinorium to the Surghar ranges, passes through Nari Panos town, covering the entire length of the study area (Fig 5). Cross-section C-D covers an area from the Manzalai anticlinorium to the Karak fault zone through Bahadur Khel village (Fig. 6). Both the cross sections show a decreasing trend of deformation from north to south, with the Eocene rocks being exposed in the north and Neogene rocks exposed in the south. The major deformation domains depicted in the sections are the Manzalai anticlinorium, Karak fault zone, and Karak anticline. To better comprehend the tectonic evolution and overall percentage shortening of the research area, sections A–B and C–D were restored to its depositional length.

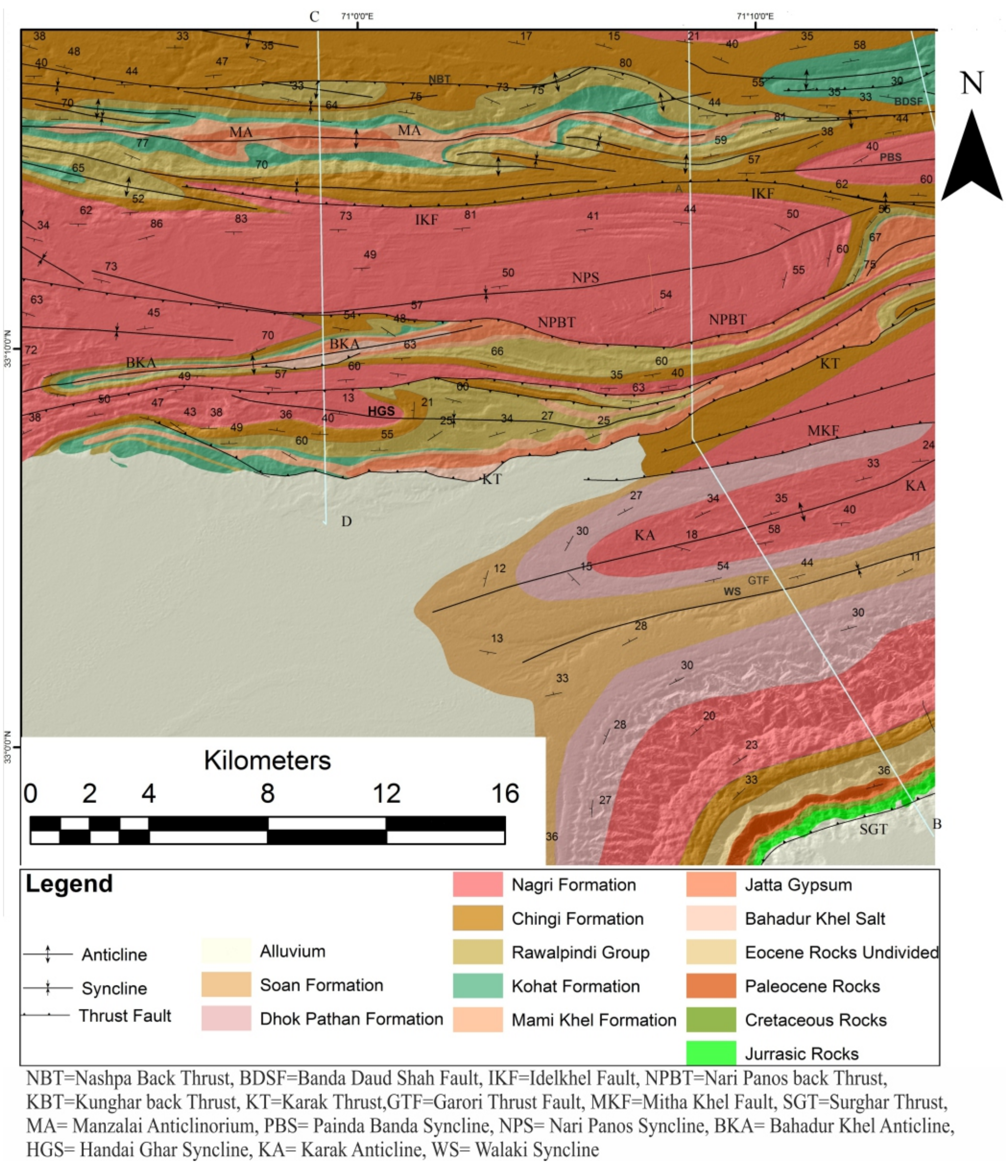
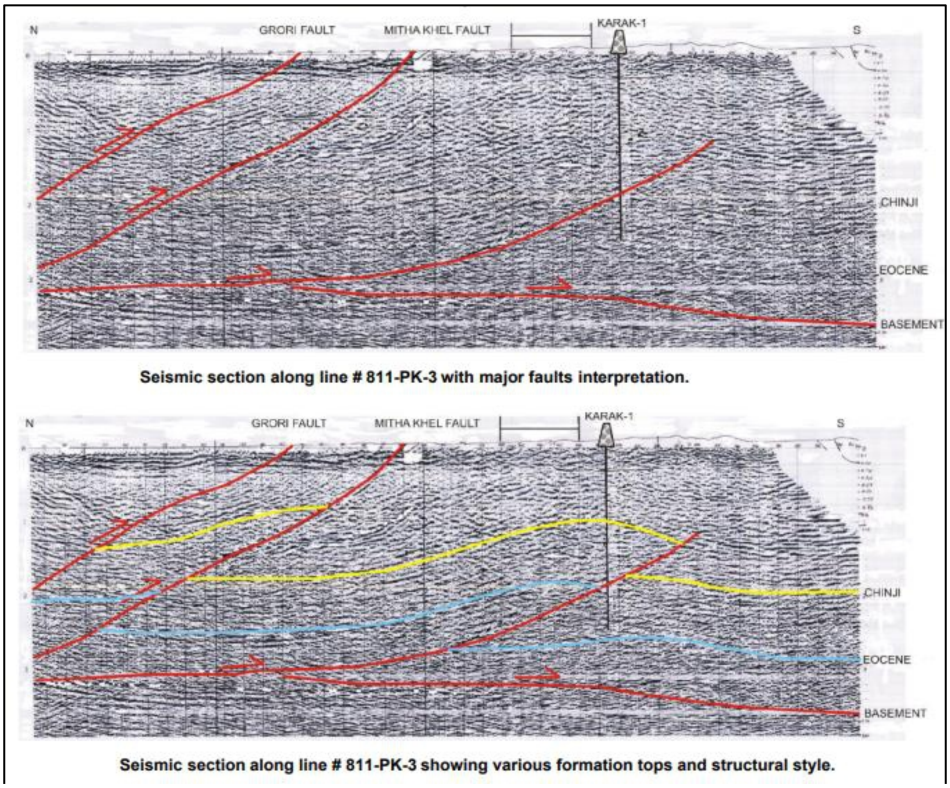


Fig. 3. Surface geological map of the study area showing different structural elements and the position of geologic transects A-B and C-D.



Seismic section along line # 811-PK-3 with major faults interpretation.

Seismic section along line # 811-PK-3 showing various formation tops and structural style.

Fig. 4. Interpreted seismic section along transect A-B between Karak thrust and Surghar ranges showing faults and stratigraphic horizons

b) Structural Restoration and Crustal Shortening

Rocks undergo deformation, which alters their original length and orientation. Measuring the degree of deformation can provide insights into the intensity and nature of the tectonic forces that acted on them. By comparing the original depositional length with the current deformed length of a rock unit, we can calculate the percentage change in length and gain a better understanding of the magnitude of tectonic deformation in the study area. Therefore, displacements along different faults of the deformed state cross sections were restored to their initial depositional stages for calculating the amount of shortening on each fault, and hence finding out the cumulative percentage shortening along the structural transects A-B and C-D. The deformed state length of the geologic cross-section A-B is 38400 m and after restoration the original depositional length is 44234 m (Fig. 5) Similarly the deformed state length for section C-D is 20707 m while restored length is 22080 m (Fig. 6). The total change in length for section A-B and C-D are 5834 m and 1373 m respectively. The percentage shortening in the sections is calculated by mathematical formula as:

$$\text{Percentage shortening} = \text{Deformed state length} - \text{Restored length} \div \text{Deformed state length} \times 100$$

The percentage shortening for section A-B and C-D as per above formula are as following:

$$\text{Percentage shortening } \mathrm{A-B} = 38400\mathrm{m} - 44234\mathrm{m} \div 38400\mathrm{m} \times 100 = 15.1927083\%$$

$$Percentage\ shortening\ C - D = 20707m - 22080m \div 29707m \times 100 = 6.63060800\%$$

The percentage shortening for section A-B is greater compared to C-D which follows the general trend of the basin where the shortening usually decreases to the flanks of the basin compared to its central part.

Well-Seismic Tying

Well-seismic tying, a pivotal process in geophysics, establishes a vital connection between well data and seismic information. This integration is fundamental for correlating subsurface details obtained from boreholes with seismic images, enhancing the accuracy of seismic interpretation and structural modeling for the hydrocarbon industry. At its core, well-seismic tying aligns seismic events with well log data, contributing to a more precise understanding of subsurface structures and properties. Through the process of evaluating seismic reflections and lowering uncertainty, geological models become much more reliable. Well-seismic tying is important for hydrocarbon exploration as well since it reduces risks by helping to identify possible reservoirs This study is based on surface geology projection to subsurface using surface orientations of the rock units except a part of the section A-B which is based on the already published seismic image from Ali Khan et al. (2008) (Fig. 4). Well-Seismic Tying can add a more realistic and accurate understanding of the subsurface structure geology.

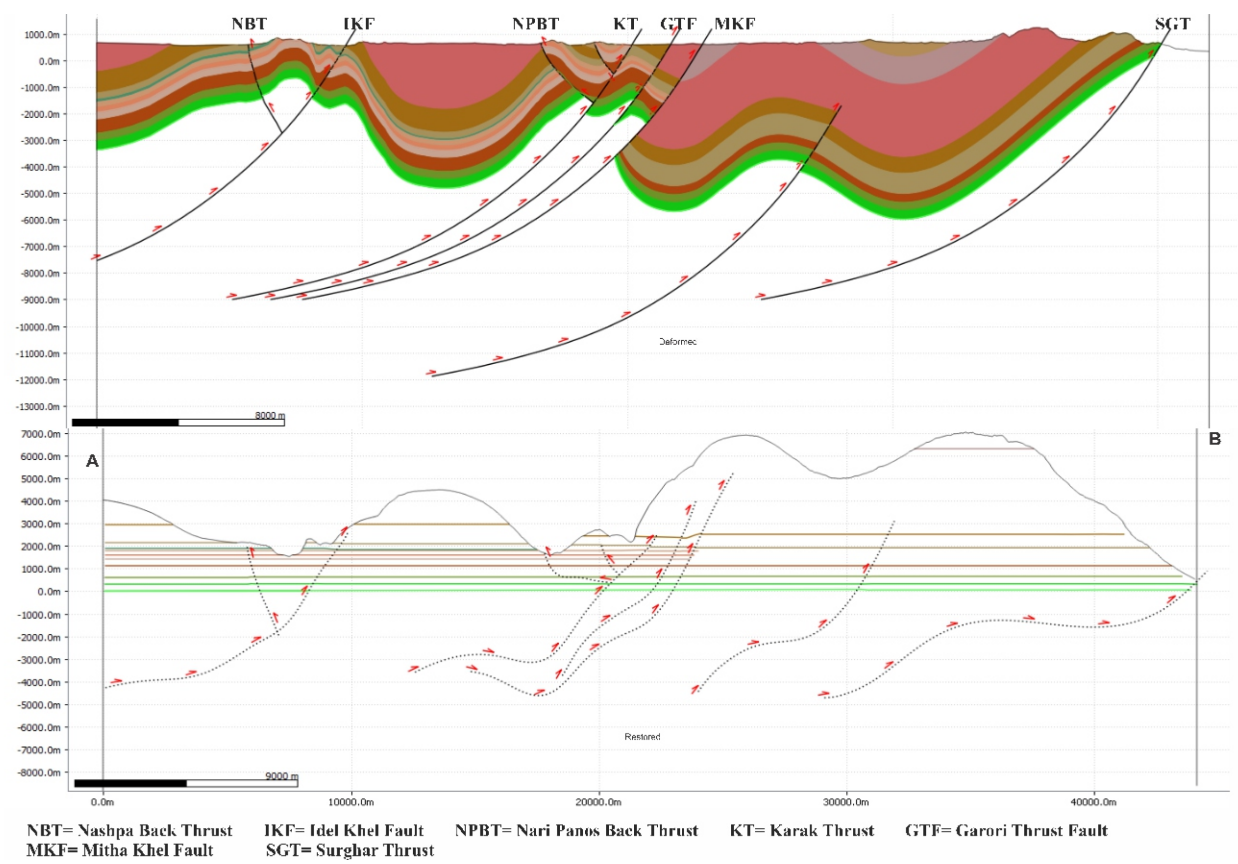


Fig. 5. 2-D structural model along structural transect A-B showing different Fault and fold structures, its deformed state and restored structural geometries.

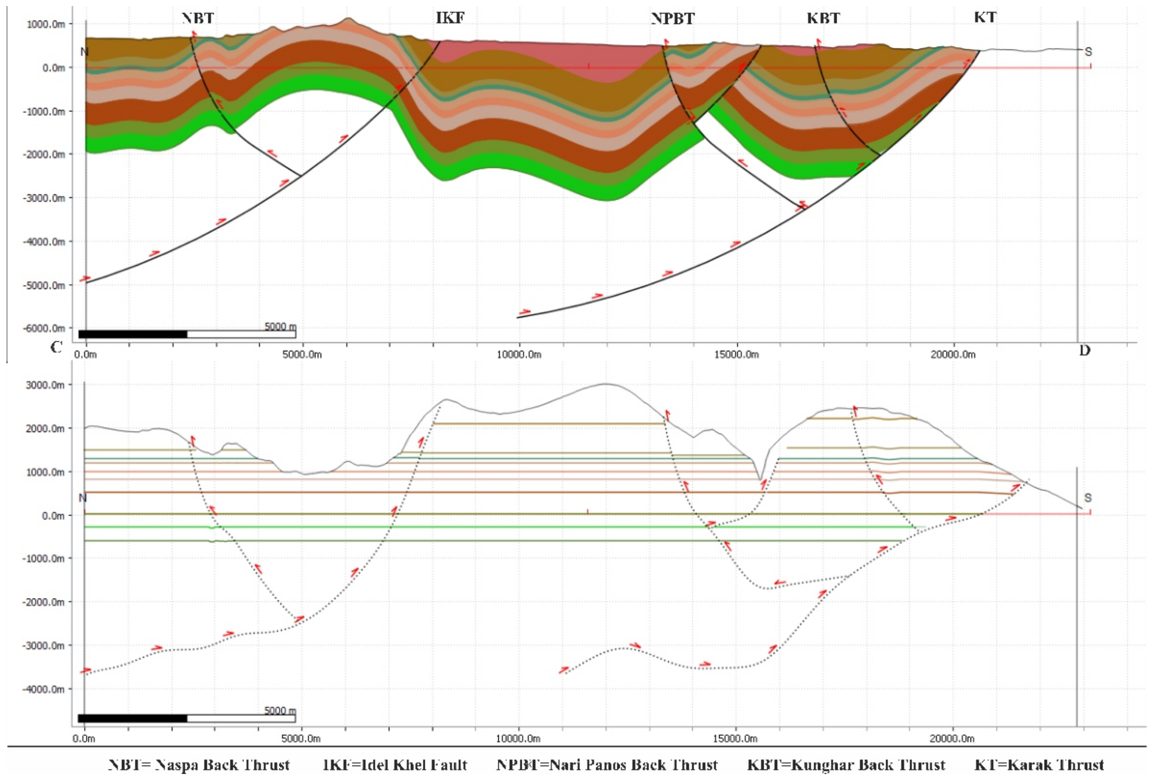


Fig. 6. 2-D structural model along structural transect C-D showing different Fault and fold structures, its deformed state and restored structural geometries.

Discussion

Structural and Stratigraphic Evolution

Previous research carried out specifically in the study area is unavailable. However, there are studies at the basin scale east of the study area that allow correlation with our results. According to Ghani et al. (2018), Kohat Fold and Thrust belt originated over an active roof thrust in Eocene evaporites that are ramp-stacked and passively carried to the foreland basin, resulting in the fault propagation folds. However, our studies in this part of the basin contradict with these findings suggesting initial phase of deformation before over thrusting and ramp stacking probably due to its location in the basin. Other studies by Abbasi and Mcelroy (1991) and Beek et al. (2006) suggest pop-up and triangular zones in seismic attributes and balanced cross section in line with findings of this study. Ahmed (2003) carried out basin scale studies suggesting thin skinned tectonics over major parts, pop-up, triangular zones, and double decollements in the base of infra-Cambrian and Eocene rocks. Double decollement can be true for certain parts of the basin and may not apply to the entire basin including our study area.

The Eocene rock units in the basin vary significantly, with shales and carbonates in the north, evaporites and carbonates in the central part, and thick carbonate sequences in the southern part as exposed in Surghar ranges. The youngest rocks in the basin are the Murree Formation in the north and the Soan Formation in the south. Due to lateral facies variations in the Eocene rock units and variable post Eocene stratigraphic column, it is difficult to define a single structural model for the entire basin. The structural models proposed by Abbasi and Mcelroy (1991) and Ahmad (2003) may fit best in areas with comparatively high deformation or closer to the northern tectonic margins of the basin. The present state model of the study area can be inferred as an early-stage model of the northern part of the basin discussed by Ahmad (2003) and Ghani et al. (2018). The study area is under initial tectonic development, and the Eocene horizon is not yet activated as a decollement. Instead, it is giving an internal movement due to isostasy of the evaporite horizon under the non-uniform thickness of the post Eocene stratigraphic column. Additionally, the southern part of the basin may not develop in the way as the northern part particularly and as rest of the basin generally due to mechanical variation in strata and differential deformation.

Hydrocarbon Potential

The Kohat Fold-Thrust belt is a well-known oil producing basin in the north Pakistan. Magyar Olaj (MOL) Pakistan and Oil and Gas Development Company Limited (OGDCL) are the major operators in the basin which collectively drilled more than 35 wells. The basin produces most of the total oil production in the country, due to which the basin is given more attention for exploring the unexplored parts of it. Part of the basin in this study is mostly unexplored except for the Manzalai structure which has approximately eleven producing wells, proving extreme potential for the exploration of more petroleum system.

The subsurface contour map on the top of the Paleocene and the reservoir horizon model (Fig. 7) shows three major potential reservoirs in the study area. The Manzalai anticlinorium, Karak fault zone and Karak anticline are three major structural highs surrounded by structural lows in the area and can be treated as the potential structural trap for the hydrocarbons. The Manzalai anticlinorium is a pop-up structure giving hydrocarbon production, however the study found that the structure still has exploration opportunities along the Fault traps in the north and south of the main structure. Karak fault zone is an extended east west structure with a major fault that can act as Fault traps and is the structural high in reservoir rocks on the subsurface contour map. It is bounded by Nari Panos syncline and Bannu basin to the north and south respectively which can significantly contribute to the reservoirs along the Fault traps in the Karak fault zone. Karak anticline and associated fault traps can be a good hydrocarbon reservoir as it is bounded to the west by a large area of structural low in the form of the Bannu basin. The study estimates that the depth of reservoir rock in the Karak anticline and related Fault traps is comparatively deeper because of the location more towards the frontal thrust and the presence of a thick Siwalik cover sequence. The block diagram (Fig. 8) represents the interaction of the faults to the reservoir layer of Paleocene and below it shows the Karak fault zone and Manzalai anticlinorium as a pop-up structure in three-dimensional space.

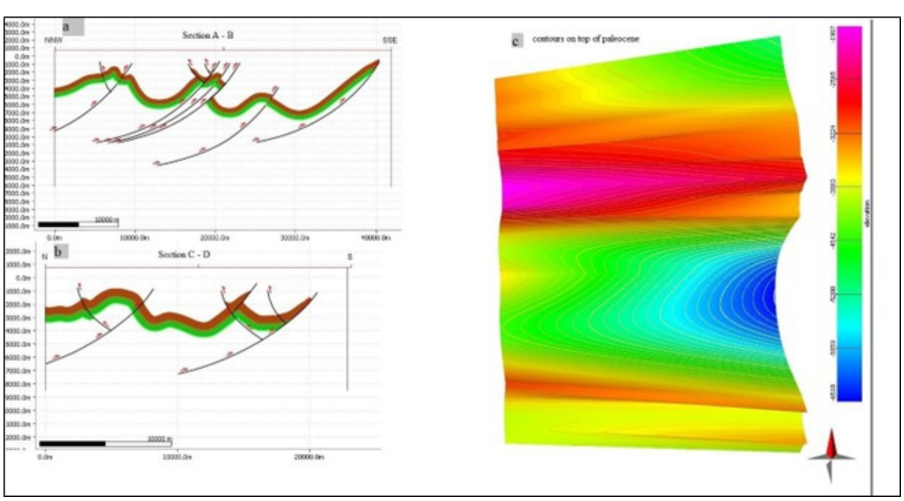


Fig. 7. (a) Reservoir horizons along section A-B (b) reservoir Horizons along section C-D (c) Contour map on top of Paleocene.

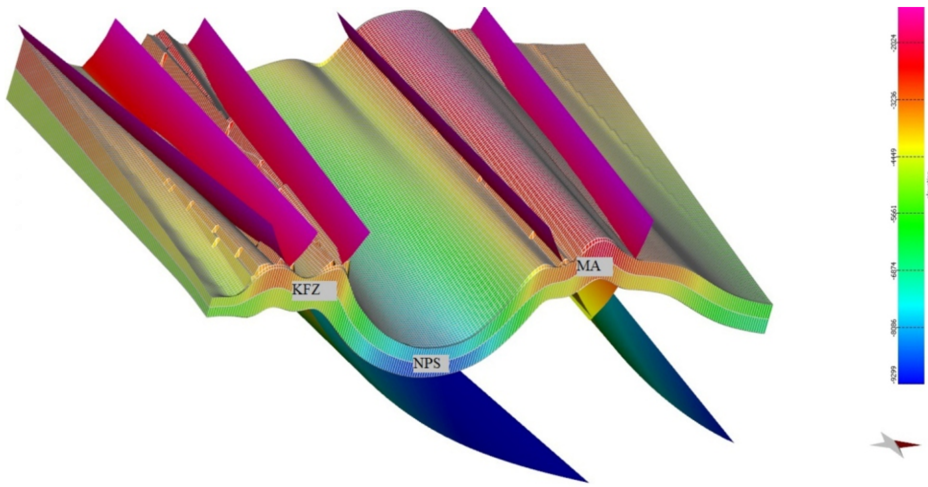


Fig. 8. 3-D block diagram of reservoir rocks and faults interactions. KFZ=Karak fault zone, NPS=Nari Panos syncline. MA=Manzalai anticline

Conclusion

The research has effectively provided a comprehensive understanding of the structural setup of the study area using sub-surface 2-D modelling, which can benefit future hydrocarbon exploration. The study has identified several structural domains in the region, including Manzalai anticlinorium, Nari Panos syncline, Karak fault zone, Karak anticline, and Surghar Thrust. The Eocene salt has played a minor role in the formation of basin structures, contributing to syncline broadening and anticline sharpening due to isostatic flow in response to unequal post-Eocene stratigraphic overburden. The current deformed state of the study area can infer to initial state of deformation compared to the deformation in the northern part of the basin where it is explained by Ghani et al. (2018) and Ahmed (2003) as the ramp stack due to over thrusting. The deformation is concentrated in the structural highs of the study area like Manzalai anticlinorium, Karak fault zone and Karak anticline.

Thrust tectonics have played a crucial role in the structural development of the study area, with most structures in the region verging south due to the north-south oriented tectonic stress vector of Himalayan collision. The western margins of the study area exhibit en-echelon folding at an intra-formational scale, indicating hybrid trending structures influenced by both northern tectonics of Himalayan collision and western tectonics of the Indian plate collision with Afghan block. Further detailed studies are needed to examine the wrench tectonics in the area due to the hybrid tectonic regime. Medium to low stratigraphic throw faults truncate the southern common limbs of the most folded structures. The calculated shortening is higher on the structural transect A-B compared to C-D, which suggests that the compressive stress vector is more dominantly acting or that the thrust sheet is easily moving over the decollement in the central parts of the basin compared to the basin margins, resulting in a differential movement in the thrust sheets.

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Authors' Contribution

Nasim Javid, the First Author, collected field data, completed laboratory work, conducted formal analysis, and drafted the manuscript. Dr. Norasiah Sulaiman provided comprehensive supervision throughout the research, assisted in software configuration, and contributed significantly to critically reviewing the work. Sadaf Nayab played a role in finalizing the Geologic map using ArcGIS. Hikmat Salam aided in manuscript composition and addressing review comments. Muhammad Ishfaq contributed to fieldwork and also assisted in addressing review comments.

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