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Structural Analysis of Kirthar Fold Belt, Lower Indus Basin, Balochistan, Pakistan; Implications from Compression and Inversion Tectonics

(Analisis Struktur Jalur Lipatan Kirthar, Lembangan Indus Awal, Balochistan, Pakistan; Implikasi daripada Tektonik Mampatan dan Penyongsangan)

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ABSTRACT

The current research work mainly focuses on tectonic evolution of the Central Kirthar Fold Belt. It also deals with the structural impact of the Late Cretaceous/Paleocene, Indian-Eurasian collision on the Central Kirthar Fold Belt which is situated in the western shear zone of Indian Plate. The Kirthar Fold Belt is different from the rest of western shear zone because it is mainly deformed by compressional tectonics which has created wide anticlines, narrow synclines and overturned folds as shown by geological mapping. It has been observed that thin-skinned deformation has played a major role in structural disharmony which is mainly seen in the Early Eocene Ghazij and Oligocene Nari formations. Seismic data shows thick-skinned deformation because the faults seem to penetrate deeper stratigraphic levels. Involvement of the basal decollement and the penetration of the interpreted faults to the level of basement rocks is also evident from the exposure of Jurassic/Cretaceous rocks at surface on the western part of the mapped area. Cross sections data shows that Kirthar Thrust Fault has a structural throw around 3-4 km in the Kirthar Folded Zone featuring deformational front while the seismic data and well data shows that this intensity decreases in the Kirthar Foredeep Zone towards east where the structural throw is about 2-3 km. Restoration of cross sections show an overall 17.3% shortening which shows that the area is under influence of compressional stresses.

Keywords: Inversion; Kirthar Fold Belt; thick-skinned deformation; thin-skinned deformation; thrust kinematics

ABSTRAK

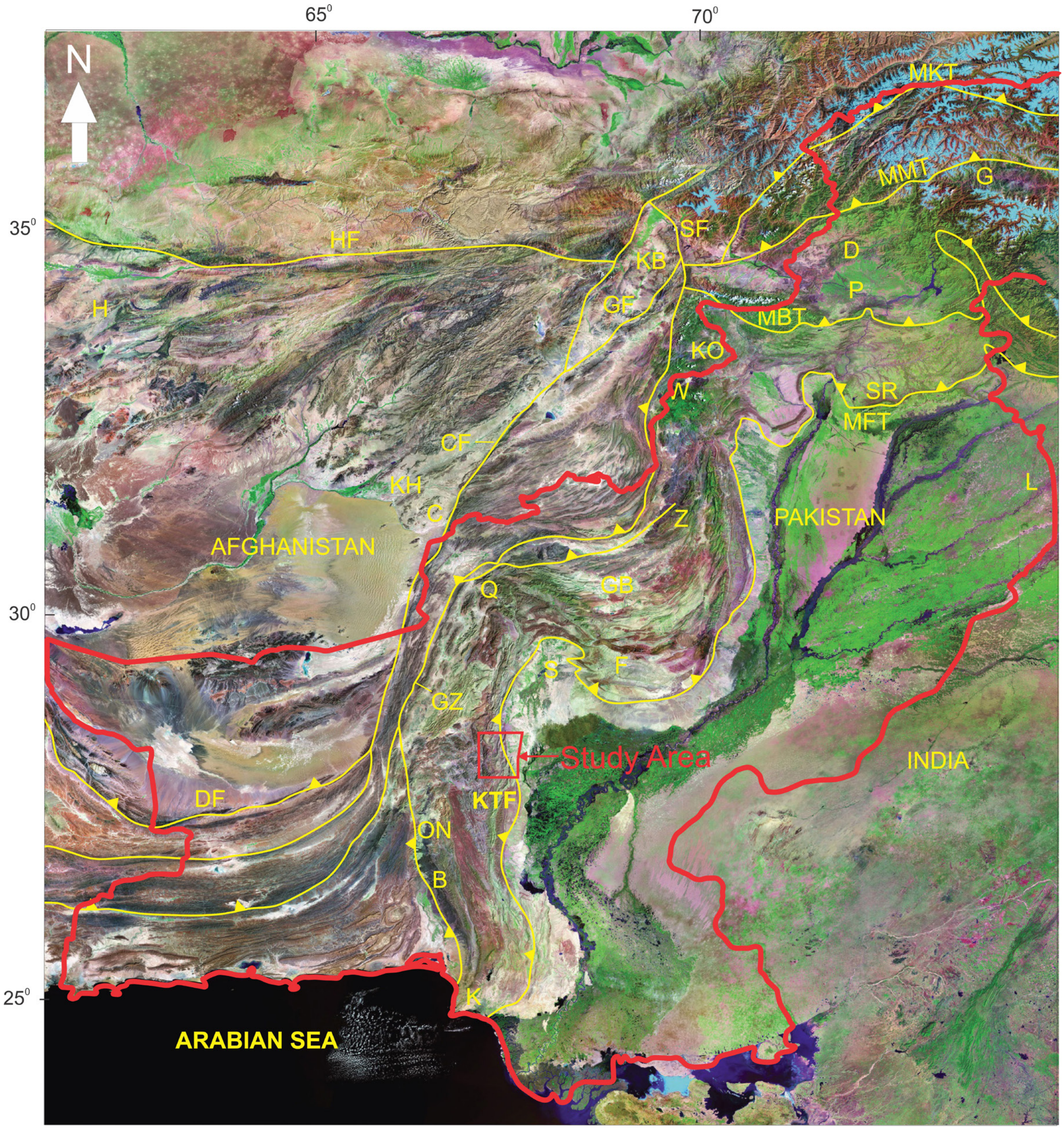
Penyelidikan ini tertumpu terutamanya pada evolusi tektonik Jalur Lipatan Kirthar Tengah. Ia juga berkaitan dengan kesan struktur perlanggaran Akhir Kapur/Paleosen, India-Eurasia pada Jalur Lipatan Kirthar Tengah yang terletak di zon ricih barat Plat India. Jalur Lipatan Kirthar berbeza daripada zon ricih barat yang lain kerana ia dicangga terutamanya oleh tektonik mampatan yang telah mencipta antiklin lebar, sinklin sempit dan lipatan terbalik seperti yang ditunjukkan oleh pemetaan geologi. Telah diperhatikan bahawa canggaan kulit nipis telah memainkan peranan utama dalam ketidakharmonian struktur terutamanya yang dilihat dalam pembentukan Ghazij Eosen Awal dan Nari Oligosen. Data seismik menunjukkan canggaan kulit tebal kerana sesar kelihatan menembusi tahap stratigrafi yang lebih dalam. Penglibatan dekolemen basal dan penembusan sesar yang ditafsirkan ke tahap batuan bawah tanah juga jelas daripada pendedahan batuan usia Jura/Kapur pada permukaan di bahagian barat kawasan yang dipetakan. Data keratan rentas menunjukkan bahawa sesar sungkup Kirthar mempunyai lontaran struktur sekitar 3-4 km di Zon Lipatan Kirthar yang menunjukkan canggaan hadapan manakala data seismik dan data telaga menunjukkan bahawa keamatan ini berkurangan di Zon Lembangan Depan Kirthar ke arah timur dengan lontaran struktur adalah kira-kira 2-3 km. Pemulihan keratan rentas menunjukkan keseluruhan 17.3% pemendekan yang menunjukkan bahawa kawasan itu berada di bawah pengaruh tegasan mampatan.

Kata kunci: Canggaan kulit nipis; canggaan kulit tebal; jalur lipatan Kirthar; kinematik tujahan; penyongsangan

INTRODUCTION

The study area is situated in the Central Kirthar Fold Belt of the Lower Indus Basin (Balochistan, Pakistan) situated between longitude 65°33’07’’ to 67°01’04’’ E and latitude 27°51’11’’ to 28°25’ 42’’ N covering an area of 3150 km^2 (Figure 1). The rugged hilly terrain of the study area is accessible by a network of roads (N-25, N-85 & M-8) from major cities of Pakistan; Quetta, Karachi and Khuzdar.

This area is located adjacent to western collisional boundary of the Indian plate. The study area is bound to the west by Khuzdar Knot, east by Kirthar Foredeep which is joined by Kalat Block towards north while the Karachi arc is situated towards south (Figure 1). The aim of the current study was to understand structural architecture of the Central Kirthar Fold Belt through following objectives: 1. To determine the structural geometries produced due to E-W compression related to the oblique convergence along the western plate boundary of the Indian Plate, 2. To develop a structural model that will lead to understanding the tectonic evolution of the Central Kirthar Fold Belt, 3. To understand the structural impact of the Late Cretaceous/Paleocene, Indian-Eurasian collision on the Central Kirthar Fold Belt; and 4. To understand subsurface geometries and behavior of Kirthar Thrust Fault from seismic data.



C, Chaman; G, Gilgit; H, Herat; I, Islamabad; K, Karachi; KB, Kabul; KD, Kandahar; L, Lahore; P, Peshawar; Q, Quetta; S, Sibi; SR, Salt Range; B, Bela Ophiolite Complex; D, Dargai Ophiolite complex; KO, Khost Ophiolite Complex; MB, Muslim Bagh-Bagh Ophiolite Complex; WO, Waziristan Ophiolite Complex; Z, Zhob Ophiolite Complex; CF, Chaman fault; DF, Dalbandin fault; GF, Gardez fault; GB, Gwal-Bagh fault; GZ, Ghazaband-Zhob fault; F, Frontal fault; HF, Herat fault; MBT, Main boundary thrust; MFT, Main frontal thrust; MKT, Main Karakoram thrust; MMT, Main mantle thrust; ON, Ornach-Nal fault; SF, Sarobi fault

FIGURE 1. Landsat imagery showing major tectonic elements of the region. Study area is marked as red box. Geology modified from Farah et al. (1984) and Maldonado and others (1998)

MATERIALS AND METHODS

To understand the structural style of the study area, previously published literature in the form of research articles, books and old maps was studied. Google Earth Imagery was used as a base map to identify different lithological units and structures. Field visits were made to the study area to witness geological features. Three traverses were constructed which covers most of the geological features. The proposed geological transects were explored in detail to mark the lithological units, structural and tectonic features. Dip and strike data was recorded using Silva Ranger Compass and GPS. All recordings were properly documented. The nature of various faults was also studied by observing and recording key features i.e., stratigraphic juxtaposition and kinematics. All the data was plotted in Google Earth and then exported to ArcGIS ® to prepare a geological map at a scale of 1:100000. Three cross sections; AA', BB', CC' having 50, 46.1, 45.4 kilometers length were prepared in the Midland Valley Move Suite. These cross sections were restored and balanced to study the regional kinematics and amount of shortening. 3D models of the cross sections were prepared in Midland Valley Move software to show continuity and general behavior of different structures. A 2D seismic line was acquired from OGDCL Pakistan and time/depth graph was generated from velocity header which helped to convert time data into depth. The seismic line was imported in Move software and a nearby well J-1 was projected on it to identify formation tops. All horizons and faults were drawn in Move software to interpret the seismic line.

TECTONIC HISTORY OF THE REGION

Numerous models have been proposed for Indian and Eurasian Plate collision but the widely accepted models are Powell (1979) and Tapponnier et al. (1981). These models show Indo-Eurasian Plate collision started in Late Cretaceous (70 Ma) as a result of intra oceanic subduction within Neo-Tethys. According to Powell (1979), this collisional process has been divided into three phases; a fast northward flight of Indian Plate towards Eurasian Plate from Cretaceous to Early Eocene, a slower drift and anticlockwise rotation of Indian Plate during Eocene and slower northward drift accompanied by oblique collision from Oligocene till present. During the Paleocene this oblique collision caused obduction of ophiolites along western margin of the Indian Plate known as Bela-Waziristan ophiolites (Gnos et al. 1998). The anticlockwise rotation caused collision of Indian Plate and Afghan block (amalgamated part of Eurasian Plate) which caused a reduction in drift velocity and initiated oblique collision. The Oligocene-Miocene is the phase of intense oblique collision (Sarwar & De Jong 1979). The Plio-Pleistocene is the final phase of amalgamation of the Indian Plate with the Afghan block (Treloar & Izatt 1993). This oblique collision and counterclockwise rotation created the Chaman transform Zone at the western margin of Indian Plate. This zone signifies three regional faults which are Chaman Fault, Ghazaband Fault and Ornach-Nal sinistral faults (Figure 1; Farah et al. 1984; Lawrence & Yeats 1979). This collisional process developed complex fold and thrust belts (Kirthar and Sulaiman fold belts) and transpressional structures.

TECTONIC HISTORY OF THE STUDY AREA

The detailed mapping of this area was carried out by Hunting Survey Corporation (1960) and gave comprehensive formational descriptions of various rock assemblages. According to Sarwar and Dejong (1979), thrust kinematics has affected the study area. The deformation in Kirthar Fold Belt is extended up to the Bolan Pass in the north and is signified by development of three basement faults namely Kirthar Basement Fault, Sulaiman Basement Fault and Jhelum Basement Fault (Bannert et al. 1992). The Indian-Eurasian collision caused two-way deformation in the region. The first phase was towards north in the direction of Indo-Pakistan plate motion during the Paleocene and the Eocene. The second Phase was the dissection of the region by large mostly left lateral fault system which caused individual block motions during the progress of further collision. The central Kirthar Fold belt has been severely affected by thin to thick skinned deformation and the older detachment zone is possibly within the Cretaceous Sembar shales while the younger detachment zone is in the Eocene Ghazij shales (Bannert & Raza 1992; Smewing et al. 2002). Although the Plio-Pleistocene marks the final phase of collision yet model of basement inversion is evident by emplacement of Ophiolites during Late-Paleocene (Fowler et al. 2004). The frontal part of the Central Kirthar Fold Belt is affected by inversion tectonics that is linked with thin–skinned tectonic deformation (Hinsch et al. 2019). The evidence of inversion is understood by seismic data or well data but in case of Kirthar Fold belt limited subsurface data is available and to overcome this problem regional understanding of tectonic evolution and basin architecture is crucial (Tari et al. 2020).

STRATIGRAPHY OF THE STUDY AREA

The sharp contrast in stratigraphy of Pakistan is highly attributed to tectonic events related to Indian-Eurasian

Plates collision which affected the Indo-Pakistani Basin since Cretaceous. Stratigraphy of Lower Indus Basin is highly variable. Maximum development of Mesozoic rocks has been recorded from the Lower Indus Basin with several thousand meters of calcareous and argillaceous sediments (Quadri & Shuaib 1986). In this paper, stratigraphy of the study area has been adapted from nomenclature proposed by Hunting Survey Corporation (1960) and Shah (2009). Following stratigraphic packages are present in the study area (Figure 2).

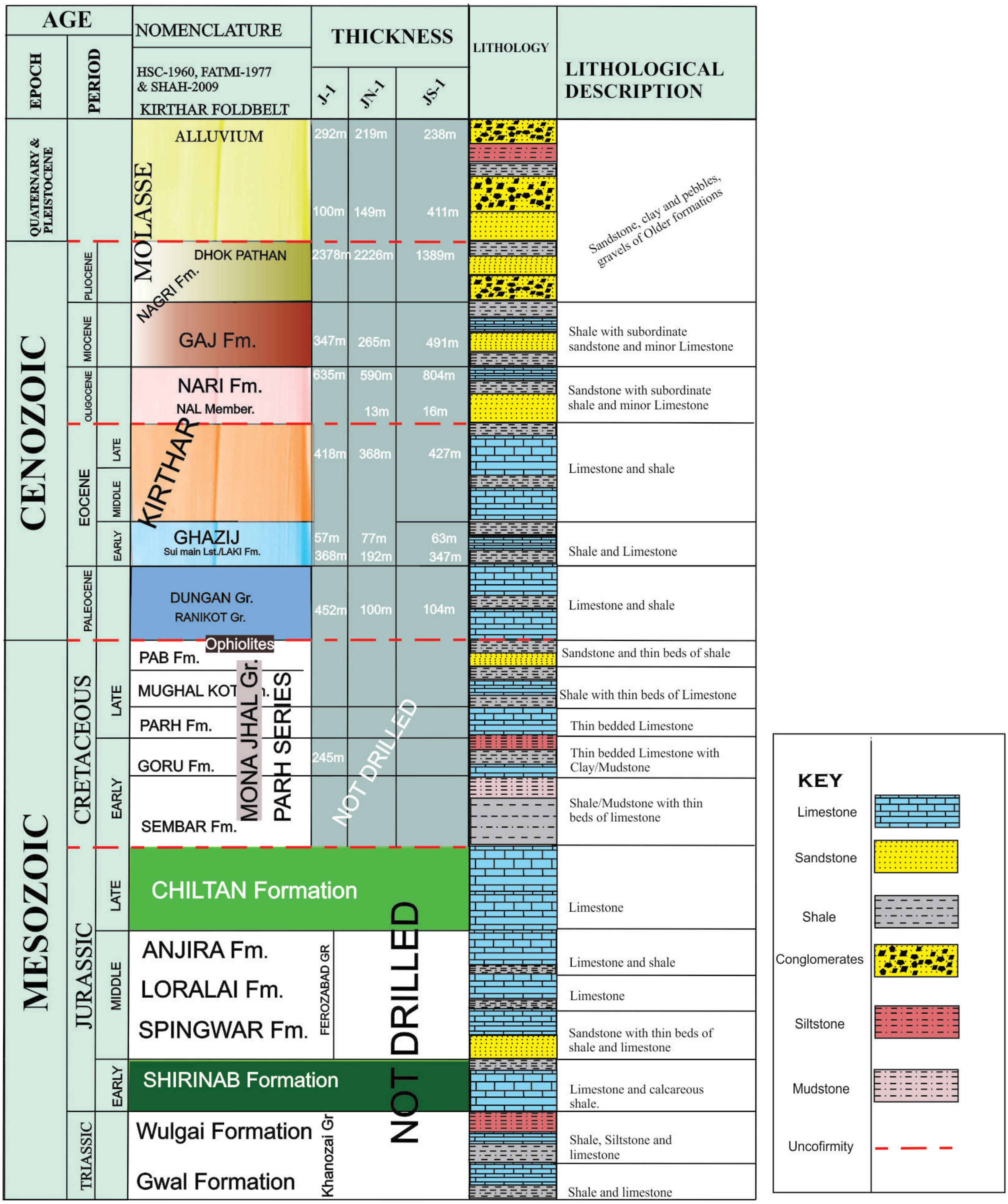


FIGURE 2. Generalized stratigraphic chart of the Kirthar Fold Belt. Well data (JN-1, J-1 and JS-1) shows formation tops and their thicknesses

MESOZOIC ROCKS

Jurassic Chiltan and Cretaceous Parh Series have occupied the western part of the study area. Early Jurassic Chiltan Formation mainly consists of different varieties of thick bedded limestone; coarse grained, oolitic and lumpy. Its colour is light gray to dark gray and the exposed thickness of limestone is ±760 m. It is overlain by the Cretaceous Parh Series of Hunting Survey Corporation (1960). The Parh Series was first used by the Hunting Survey Corporation (1960). According to Fatmi et al. (1986), some members of Cretaceous rocks are not fully developed in the Central Kirthar Fold Belt so it is called as the Parh Series Undifferentiated. Parh Series include Sembar, Goru, Parh Limestone, Mughal-Kot, Fort Munro, Pab and Moro formations. This group consists of limestone, marl, and shale which is calcareous in nature. The weathered color of limestone is yellowish and greenish maroon whereas the fresh color of limestone is light gray and white. Shale is green and flaky, splintery and hard. Occasionally its lower contact with Chiltan formation is transitional while it is sharp at some places. The thickness of this formation is ±500 m in the study area.

CENOZOIC ROCKS

Paleocene Dungan Formation predominantly consists of brownish gray thick bedded nodular limestone. This formation also contains some shale, marl and conglomerate. The marl is varicoloured while shale is calcareous which is bluish gray, brown and olive. The conglomerates consist of pebbles, cobbles of grey and brownish limestone and marl. In the study area its thickness is ±243 m. Its upper contact with Early Eocene Ghazij Formation is conformable (Figure 3(E)). The Ghazij Formation mainly consists of greenish grey, olive green shale with some claystone. The upper contact is transitional with the Mid-Late Eocene Kirthar Formation. The thickness of Ghazij Formation is variable and its thickness in the Kirthar Folded Zone is ±450 m while in the Kirthar Foredeep it is ±60 m. The reason for this difference is a shelf break controlled by the development of Kirthar Basement Fault which was active during deposition of Ghazij Formation (Khan et al. 2011). Kirthar Formation is predominantly limestone with some shale and marl. The colour of limestone is yellowish gray, creamy white, light gray which is thick-bedded (massive) and makes most of the ridges. Its lower contact with Ghazij Formation is transitional while the upper contact with Oligocene Nari Formation is conformable. The thickness of this formation is ±350 m. Oligocene Nari Formation consists of greenish gray sandstone, brown shale and some gray limestone. Its upper contact with Gaj Formation is transitional. The thickness of this formation is ±650 m. Miocene Gaj Formation mainly consists of soft, reddish brown and purple shale with some sandstone and limestone. Sandstone is yellowish brown to dark brown and is calcareous and gritty. The contact of Gaj Formation with Nari Formation is transitional. At a few places, it is very hard to distinguish between two formations. Its exposed thickness is ±350 m. Nari and Gaj formations have been included in the Momani Group (Shah 2009).

SIWALIK GROUP

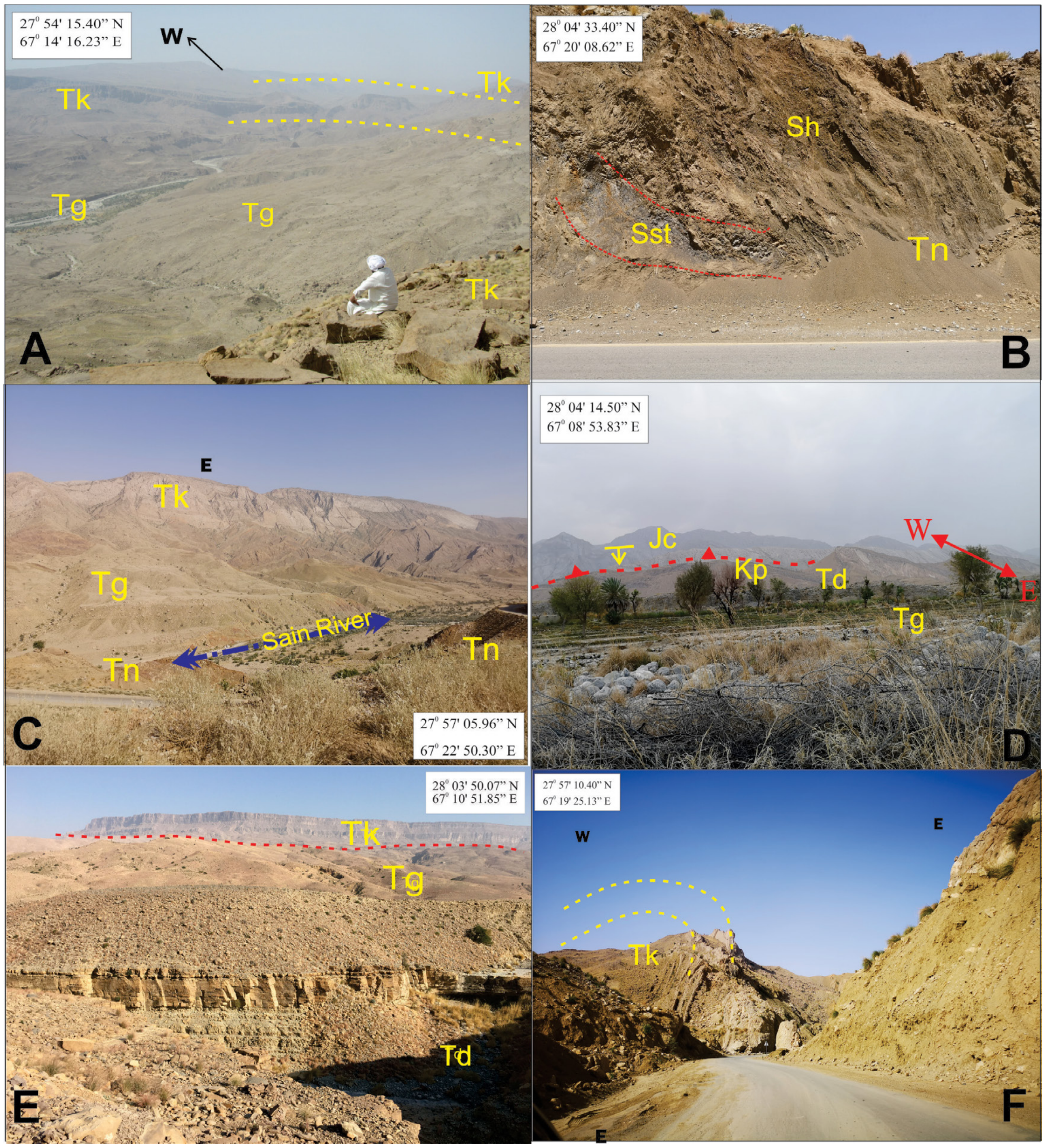
Siwalik Group includes Soan, Dhok Pathan, Nagri and Chingi formations. The study area contains Late Miocene to Early Pliocene Nagri Formation only which is exposed in Kirthar Folded Zone whereas Kirthar Foredeep part contains ±2400 m of Siwalik sediments and the stratigraphy has been known from three drilled wells (J-1, JN-1, JS-1; Figure 2). Nagri Formation mostly consists of alternating beds of greenish gray sandstones, olive green shales, reddish brown siltstone and light to dark gray conglomerates. It is underlain by Gaj Formation and the contact is transitional.

STRUCTURAL GEOLOGY OF THE AREA

The study area has been divided into two zones; Kirthar Folded Zone and Kirthar Foredeep Zone and has a very complicated surface and subsurface geology. Limited research work has been carried out in this area due to partial accessibility. The study area is located adjacent to the western margin of Indian Plate. The oblique collision between Indian-Eurasian Plate resulted in a compression-transpression zone which is evident by thrust and strike slip faults in the region. The tectonic uplift has caused rocks to expose and erode due to which unique patterns of lithology are witnessed. A detailed geological map of the study area was prepared at a scale of 1: 100,000 in ArcGIS ® (Figure 4).

THE KIRTHAR FOLDED ZONE

The eastern part the study area has been occupied by the Kirthar Fold Belt which is a major tectonic feature clearly visible on satellite imagery (Figure 1). It extends in a North-South direction and marks the eastern boundary of the Lower Indus Basin. Kirthar Fold Belt can be divided into three parts. The northern part of Kirthar Fold Belt joins Kalat Plateau, central part is covered by



(Tn= Tertiary Nari, Tk=Tertiary Kirthar, Tg=Tertiary Ghazij, Td=Tertiary Dungan, Kp=Cretaceous Parh Series, Jc=Jurassic Chiltan)

FIGURE 3. Field pictures showing different formations and their structure style. (A) showing an eroded anticline where Eocene Kirthar Formation is eroded to expose Early Eocene Ghazij Formation. (B) Field Photograph showing distortion within soft shale of Oligocene Nari Formation (C) Facing east Kirthar Formation making ridge along Kirthar Thrust Fault showing E-W compression. Ghazij Formation is exposed on the flank whereas Oligocene Nari Formation is present in the core of syncline. (D) The western limit of study area which shows Jurassic Chiltan making a ridge along Kharzan Fault. The eastern flank of the Kharzan Fault shows Cretaceous Parh Series, Paleocene Dungan whereas Early Eocene Ghazij Formation is in the core of syncline. (E) Facing east field photograph showing contact of Eocene Kirthar Formation, Early Eocene Ghazij Formation and Paleocene Dungan Formation. (F) Overturned and eroded limb of Karkh anticline

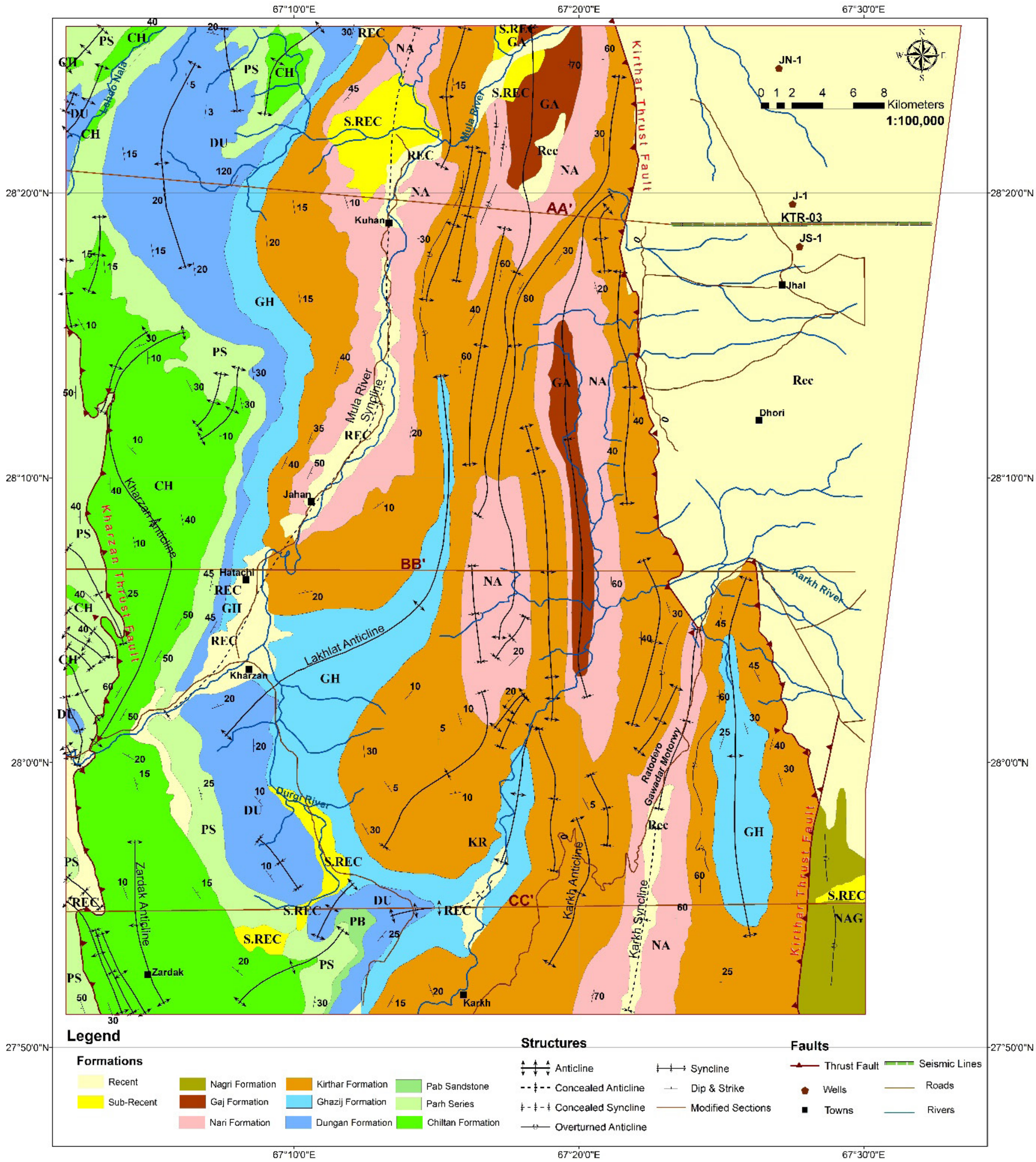


FIGURE 4. Geological Map of the study area drawn at a scale of 1:100000 in Arc GIS ®. KTR-03 seismic line is shown in the Kirthar Foredeep Zone with three drilled wells JN-1, J-1, JS1.Three cross section AA', BB', CC' are also shown

the study area and the southern part extends towards Karachi Arc. It is a north-south trending folded zone which hosts different stratigraphic packages ranging from Jurassic to Recent. This folded zone dominantly hosts Eocene Kirthar Formation in anticlinal cores whereas Oligocene-Miocene Momani Group (Nari and Gaj Formations) is present in the core of synclines. At a few places, the Momani Group rocks are overlain by

Recent/Sub-recent deposits Eocene Kirthar Formation is eroded to expose Early Eocene Ghazij Formation (Figure 3(A)). The western part of the study area is occupied by mostly Mesozoic rocks. Cretaceous Parh Series is present in synclines whereas Jurassic Chiltan Formation is present on anticlinal cores. Kirthar Folded Zone makes prominent ridges of the region where the average height ranges between 800-1500 m.

KIRTHAR FOREDEEP ZONE

Kirthar Foredeep is situated to the east of the Kirthar Folded Zone which hosts a thick stratigraphic package of molasses and joins Sibi Trough to the north (Figure 1). This part is covered with alluvium and the subsurface geology is known by Seismic data and three drilled wells (J-1, JN-1, JS-1; Figure 2). It is evident from the well data that the upper +/- 2400 m are covered by Siwaliks followed by +/-1000 m Oligocene-Miocene Momani Group (Figure 7(A) & 7(B)).

ANTICLINES & SYNCLINES

The study area is dominantly a compression zone which highlights N-S trending anticlines. Zardak Anticline is a large anticline which is located on the western part of the study area and hosts Chiltan Formation in the core. The eastern limb is steep whereas its western limb has a faulted contact with Cretaceous Parh Series in a synclinal position. This fault is known as Kharzan Fault. This anticline in trending in NNW-SSE direction and its northern end is connected with NNE-SSW trending Kharzan Anticline which is also hosting Chiltan Formation in the core and Kharzan Fault is continued along its western limb as well. Lakhlat Anticline is present to the east of Kharzan Anticline and hosting Ghazij Formation in the core. This anticline is trending in the NE-SW direction. Karkh Anticline is present to the east of Lakhlat Anticline and is trending in NNE-SSW direction towards the southern end of the study area and changes its orientation to NNW-SSE in the north. Karkh Anticline hosts Kirthar Formation in the core and the eastern and western limbs are gently dipping. Mula River Syncline is a 48 km long syncline which is present to the east of Kharzan Anticline. It hosts Oligocene Nari formation in the core which is covered by Alluvium at many places. Its southern end is trending in the NE-SW direction which changes its orientation to N-S in the north. NNE-SSW trending Karkh Syncline is located to the east of the Karkh Anticline and hosts Oligocene Nari Formation.

SEISMIC INTERPRETATION & STRATIGRAPHIC CORRELATION CHART

The sub-surface geometries of Kirthar Foredeep Zone have been interpreted by a 15 km long east- west oriented 2D seismic line (Figure 7(A)). The seismic line was imported in Midland Valley Move software and drilled well J-1 was projected on the seismic line which helped to interpret stratigraphic horizons. The interpretation of the seismic line shows the continuity of Kirthar Thrust fault from Kirthar Folded Zone to Kirthar Foredeep Zone in such a way that it becomes a low angle fault and has many splays which are continued in Kirthar Foredeep Zone as well. A stratigraphic correlation chart has been created from three drilled wells (JN-1, J-1, JS-1) which are located in Kirthar Foredeep Zone and explains subsurface geology (Figure 7(B)). The chart shows that Siwaliks have occupied the top +/-2500 m whereas Oligocene-Miocene Momani Group (Nari & Gaj Formation) has covered +/- 1000 m below Siwaliks. This is a very thick sequence which is a characteristic feature of Kirthar Foredeep. The formation tops from well J-1 show that normal stratigraphic succession is present below Momani Group until Cretaceous Goru Formation is thrusted upon Nari Formation (Nal Member). The throw of this fault is about 2500 m. It is observed that thickness of the Early Eocene Ghazij Formation is ~60 m Kirthar Foredeep whereas it is ~400 m in Kirthar Folded Zone. Middle Eocene Sui Main limestone has also been encountered in the well data but it is not developed in the Kirthar Folded Zone. Primary Target of these wells was to drill Paleocene Dungan and Jurassic Chiltan Formation, however due to poor drilling conditions the drilling was abandoned.

FAULTS

KIRTHAR THRUST FAULT

Kirthar Fold Belt is recognized by a regional thrust Fault known as Kirthar Thrust Fault. The Kirthar Fault is a 225 km long regional structural feature and the formational contacts along this fault are transitional and show synclinal occurrences as there is a very narrow space in between them. The straight alignment and shortage of synclinal closures suggests fault (Bannert et al. 1992). These synclines occur in thrust fault footwall blocks. In the study area the length of the Kirthar Thrust Fault exposed on the surface is ~ 65 km (Figure 3(C)). The northern limit of this fault is not known as it is covered by alluvial cover whereas the southern limit extends up to Karachi Arc. It represents the site of thrusting which mostly dips to the west in the central Kirthar fold belt. In the study area the Eocene Kirthar Formation has been thrusted over the Miocene-Pliocene Nagri Formation along this fault. Kirthar Thrust Fault shows west facing and east facing anticlines and contains numerous subsurface fault splays which dies out in Kirthar Foredeep Zone.

KHARZAN FAULT

This fault is present on the western part of the study area and is continued along western limb of Kharzan and Zardak anticlines. This ~46 km fault is trending in NS direction and is a back-thrust (west verging). It is present in the form of a narrow syncline where Jurassic Chiltan Formation is thrusted upon Cretaceous Parh Series (Figure 3(D)). This fault coincides with one of the Spector's anomaly (Bannert et al. 1992; Spector & Associates Ltd 1981).

GEOLOGICAL CROSS SECTIONS

The structural geology of the study area is very unique and complex. Data acquired by field reconnaissance was examined thoroughly and used to draw three (AA', BB', CC') balanced cross sections using Midland Valley Move software. Cross section AA' covers the northern part of the study area from east to west and its length is 50 km (Figure 5(a)). As we travel along this cross section from east, it is covered with alluvium which represents Kirthar Foredeep. Drilled wells and seismic data shows Siwaliks, Oligocene Nari and Miocene Gaj Formations below this segment. If we move towards west, it is followed by eastern terminus of Kirthar Thrust Fault showing an anticline cored by Kirthar Formation. This anticline is trending in the NE, NNE direction. Further towards west there is a major syncline cored by Nari and Gaj Formation. This syncline is followed by another anticline cored by Eocene Kirthar Formation. Further towards west Mula River Syncline is present which hosts Oligocene Nari Formation in the core. It is followed by another anticline hosting Eocene Kirthar Formation on its eastern flank whereas the western flank is eroded to expose Ghazij Formation. Further towards west an anticline is present which is cored by Paleocene Dungan Formation and shows signs of uplifting. The western flank of this anticline has a faulted contact with the Cretaceous Parh Series. This fault is known as Kharzan Fault. The Cross sections BB' occupies the central part of the study area and its length is 46.1 km (Figure 5(b)). The eastern part is covered by Kirthar Foredeep. A small anticline is present which is separated from Kirthar Foredeep by Kirthar Thrust Fault. As we move along this cross section towards west three anticlines are present which are hosting Kirthar Formation. The first two anticlines are separated from each other by a syncline covered with Alluvium. The second and third anticline is separated by a syncline which hosts Momani Group (Nari and Gaj formations) in the core. Further towards west a major anticline is present which hosts Kirthar Formation on the eastern and western flank while the core is eroded to expose Early Eocene Ghazij Formation. The western part after this anticline shows signs of uplifting as Paleocene Dungan Formation and Cretaceous Parh Series rocks are present. Further towards west is a major anticline which hosts Jurassic Chiltan Formation. This anticline is known as Kharzan Anticline. The eastern flank of this anticline is eroded away to expose Cretaceous Parh Series and Paleocene Dungan Formation. The left flank of this anticline has a faulted contact with Cretaceous Parh Series. This fault is known as Kharzan Fault. The cross section CC' has occupied the southern part of the study area in east-west direction and its length is 45.4 km (Figure 5(c)). Kirthar Thrust Fault is present on the eastern side where the Eocene Kirthar Formation is thrusted on the Miocene-Pliocene Nagri Formation. As we move towards west along this cross section a major anticline is present which is eroded at the center to expose Early Eocene Ghazij Formation. The eastern and western flanks of this anticline are cored with gently dipping Eocene Kirthar Formation. It is followed by a syncline which hosts Oligocene Nari formation in the core. Further towards west a major anticline is present which is known as Karkh Anticline which is hosting Kirthar Formation in the core. It is followed by a syncline where Early Eocene Ghazij Formation is present in such a way that the middle part is covered with alluvium. Further towards west a small anticline is present which hosts Paleocene Dungan Formation in the core. It is eroded at top to expose Cretaceous Pab Sandstone. This small anticline is followed by a small syncline which hosts Cretaceous Parh Series in the core. This syncline is followed by a major anticline known as Zardak anticline which is covered with Jurassic Chiltan Formation and its western flank has a faulted contact with Cretaceous Parh Series. This fault is known as Kharzan Fault.

RESTORATION AND SHORTENING

Four geological cross-sections were restored using the Move 3D suite (Figure 6). This restoration is done in two detailed phases as followed by Khalid et al. (2020) and Yaseen et al. (2021). The restoration process uses two modules; move on fault and 2D unfolding. In first phase, faults are restored and the movement along all the formational horizons is eliminated by assigning different values to faults. In the second phase a pin is inserted to the deepest part of the cross section which contains most of the stratigraphic packages and the beds are unfolded and compared with original stratigraphic thickness. The main purpose of cross section restoration is to understand

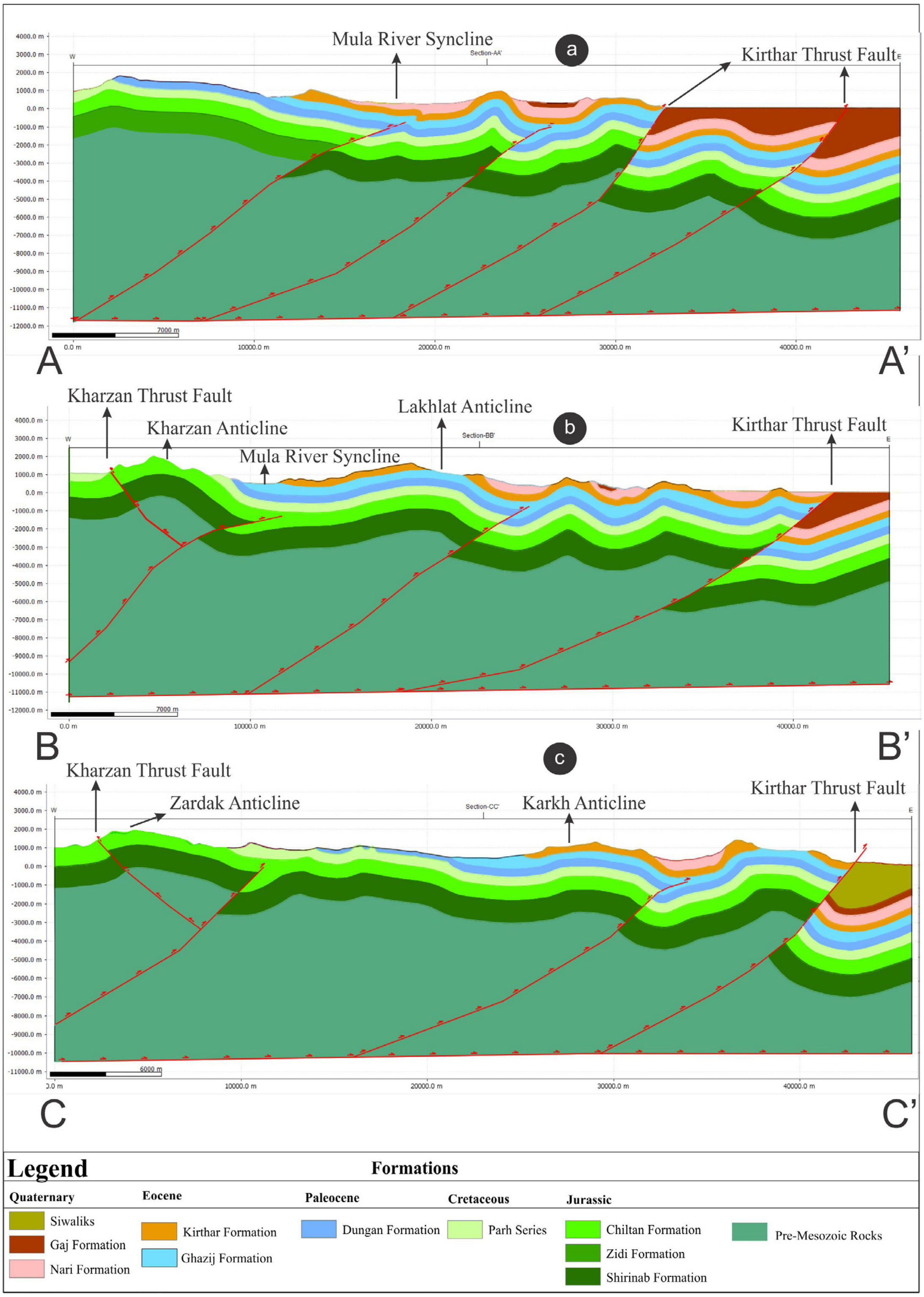


FIGURE 5. Showing three cross sections AA', BB', CC' which were drawn using Midland Valley Move software

the changes occurred due to tectonic events. When cross sections are restored back to its original state, they represent the depositional settings of the rock packages. The cross section restoration of three cross sections shows an overall shortening of 17.3%.

Shortening in Percentage = (Change in length/ Restored length) × 100

Cross sections name	Deformed length (km)	Restored length (km)	Change in length (km)	Shortening percentage
AA’	45.8	60.5	14.7	24.3
BB’	45.4	52.2	6.8	13.1
CC’	46.1	53.9	7.8	14.5
		Average shortening		17.3

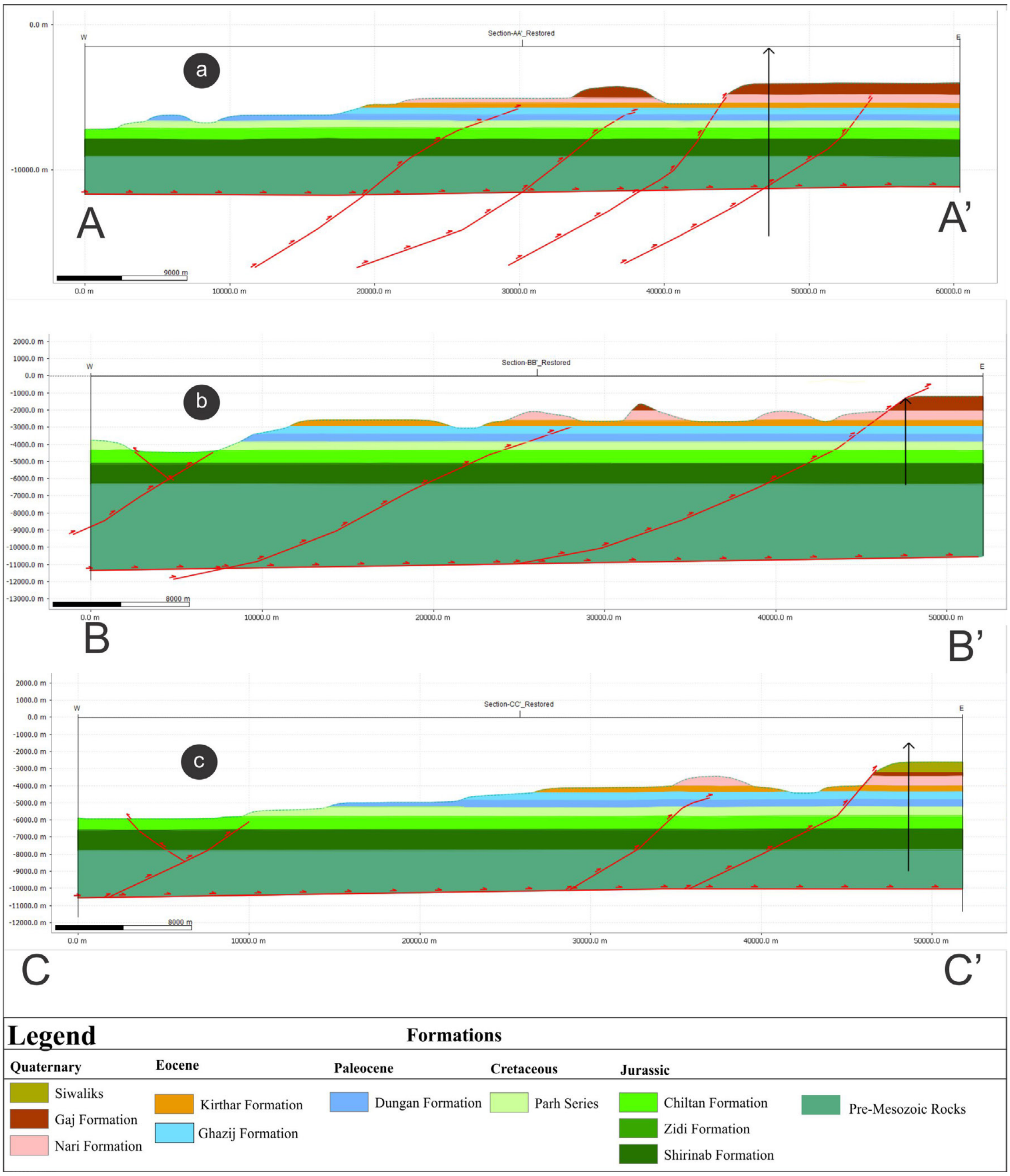


FIGURE 6. Restored cross sections AA’, BB’, CC’

3D MODELLING

The 3D model has been generated by Midland Valley Move suite which helps to visualize the structural geometries produced across Kirthar Thrust Fault which is a regional fault and controls the main structural architecture of the Kirthar Fold Belt (Figure 7(C)). 3D surfaces are generated from different rock packages from east to west which shows local distribution of stratigraphy and the position of different anticlines and synclines (Figure 7(C)). These structures are dissected by various basement faults which are shown by the 3D model. This disharmony within structures is a result of compression and thick-skinned deformation.

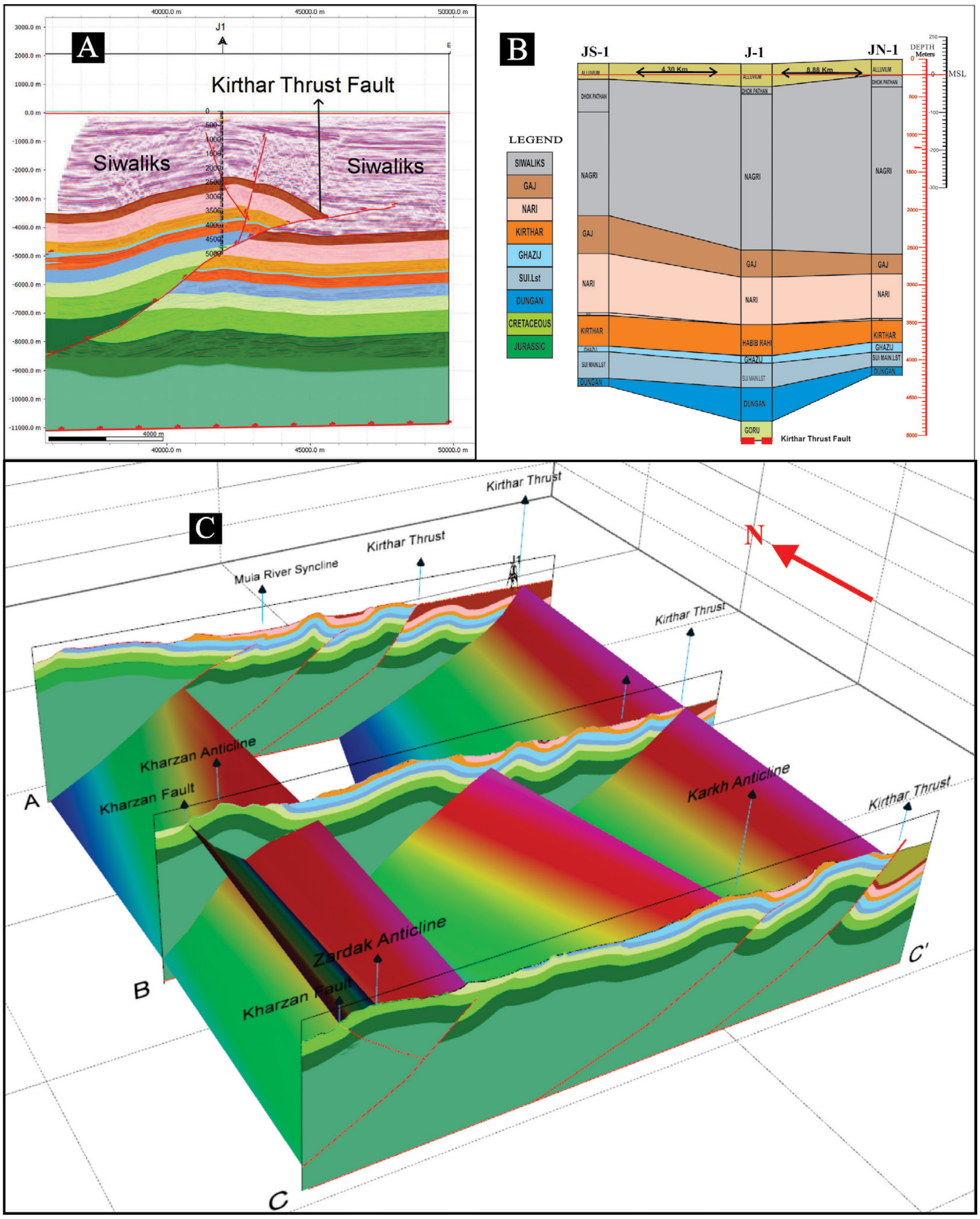


FIGURE 7. (A) Interpretation of seismic line KTR-03 which is present in Kirthar Foredeep Zone of the study area. The upper ± 2500 m are occupied with Siwaliks. Kirthar Fault seems to be an imbricate from the basement. (B) Stratigraphic correlation Chart of three drilled wells in the Kirthar Foredeep Zone. Kirthar Thrust Fault is marked at the base of Well J-1. The black scale shows mean sea level whereas red scale shows depth in meters. (C) 3D view of three cross sections along which 3D models for Kharzan and Zardak anticline are generated. These anticlines host Jurassic Chiltan Formation. 3D models of different faults are also drawn showing Kirthar Thrust Fault on the eastern limit whereas Kharzan Fault on the western limit of the study area

DISCUSSIONS

Surface and subsurface data shows that the study area has been affected primarily by three deformational events; compression, thin-skinned deformation and thick-skinned deformation. Fold geometries show that this area is under strong influence of east-west compression due to ongoing Indian-Eurasian plates collision. The strong compressive forces have not only oriented various folds in NNE-SSW & N-S direction but also developed thrust faults and overturned folds (Figure 3(C) & 3(F)). Second major element is thick-skinned deformation or basement driven inversion and is observed in the eastern and western part of the study area. The eastern part of the study area is deformed by thick skinned deformation where the Kirthar Thrust Fault is linked to the basement as shown by seismic data (Figure 7(A)). The Kirthar Thrust Fault is the regional frontal thrust which has occupied the eastern margin of the study area. Cross sections show that it has a vertical throw of ~3-4 km. The seismic data shows that Kirthar Thrust Fault is an imbricate thrust from basement with a number of splays which exemplifies thick-skinned deformation. This basement driven inversion is shown on surface and subsurface. The intensity of compression decreases in the Kirthar Foredeep Zone where Kirthar Thrust Fault has a vertical throw of ~2.5 km. The western part of the study area also shows basement driven inversion where Mesozoic rocks are uplifted and exposed on the surface. Two major anticlines Zardak and Kharzan anticlines featuring Jurassic Chiltan Formation are oriented NNE and NNW which shows that the western part is not only under influence of compression but also thick-skinned deformation. The western margin of these anticlines is bounded by a back-thrust known as Kharzan Fault which seems to be a splay from west verging deep seated faults. Third major factor is thin-skinned deformation within shales which facilitate the deformation by providing a plastic medium. Three deformational zones; Cretaceous shales, Early Eocene Ghazij and Oligocene Nari formations play an important role in the structural disharmony. The deformation shown by Ghazij and Nari formations is observed on the surface in the eastern part of the study area where the rocks are disintegrated and distorted (Figure 3(B) & 3(F)). The seismic and well data shows that Cretaceous shales (Sembar and Goru formations) act as a detachment zone in sub-surface along Kirthar Thrust Fault where Cretaceous sequence is thrusted upon Oligocene Nari Formation. The development of deep seated faults due to thick-skinned deformation have triggered the structural disharmony on the surface which is evident in the form of thin-skinned deformation. The linkage between thick-skinned deformation and thin-skinned deformation has been proven in many fold and thrust belt systems of the world (Butler et al. 2018; Hinsch et al. 2019).

CONCLUSIONS

The structural architecture of major anticlines and synclines present in the Kirthar Folded Zone shows NNE-SSW and NS orientation which indicates that this zone is under strong East-West compression from Indian-Eurasian plates collision featuring a regional Kirthar Thrust Fault. Seismic data shows that the east verging Kirthar Thrust fault is not only the result of compression but has a number of splays from the basement which extends from folded zone to Foredeep zone. Cross sections data illustrates a vertical displacement of 3-4 km on the surface. The intensity of the Kirthar Thrust Fault is decreasing in the Kirthar Foredeep zone where it has a vertical throw of ~2.5 km. Oligocene Nari and Eocene Ghazij shales have played a major role in distortion of surface outcrops due to thin skinned deformation which is influenced by deep seated faults. The western part of the study area is under the influence of compression and thick-skinned deformation where Mesozoic rocks are exposed on the surface in N-S oriented anticlines and synclines. Kharzan Fault is a back-thrust where Jurassic Chiltan Formation is thrusted upon Cretaceous rocks in a synclinal position. The exposure of Mesozoic rocks to the surface is attributed to on-going oblique collision between Indian Plate and Eurasian Plate. Siwalik group from Kirthar Foredeep signifies folding which indicates that compression due to on-going collision between Indian and Eurasian plates was significant post Oligocene as well. The Late Cretaceous-Paleocene, Indian-Eurasian collision has multiple impacts on the Central Kirthar Fold Belt. Eocene rocks are exposed in the eastern part whereas Jurassic rocks are exposed in the west indicating an uplift. Compression is the dominant force which is governing the structural geometries of the study area through basement driven faults.

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