Tectono-Stratigraphic Model for Ghazij Formation in Kirthar Foldbelt, Pakistan*

Abrar Ahmad[1], Mohsin Ali[1], Abid H. Baitu[1], and Naeem Sardar[1]

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[1]Pakistan Petroleum Limited, Karachi (a_abrar@ppl.com.pk)

Abstract

An abrupt change in lithology and thickness of the Ghazij Formation of Late Paleocene - Early Eocene and its isochronological units, from east to west within a short distance along depositional strike, has been observed in the Kirthar Foldbelt, Lower Indus Basin Pakistan. These changes are attributed to a shelf break controlled by the Kirthar Basement Fault (KBF) that was active during the deposition of the Ghazij Formation. Surface and subsurface data provides an excellent opportunity for understanding the influence of this tectonic event on sedimentation and paleogeography of this rock unit. Gross lithofacies distribution maps also support the deposition of Ghazij Formation in a tectonically active basin. In the present study, seismic, stratigraphic transects and gross depositional environment (GDE) mapping are used to explain the lithofacies variation of Ghazij Formation in the area.

The Kirthar Basement Fault is a normal fault created by the breakdown of Gondwana and reactivated during Late Paleocene-Early Eocene time due to collision of the North Western Indian Plate with the Kabul block. KBF is possibly present between the Tangna Pusht Nala section and Tangna Pusht X-1 well and played a critical role in controlling the physiography of the basin and consequently on the thickness and lithofacies of the Ghazij Formation across the basin. Similar variations are also observed across depositional strike along three other sections and on seismic lines. The Ghazij Formation has its time equivalent lithofacies of dominantly limestone to the east of KBF, where carbonate production was able to keep pace with the rate of sea level rise with limited clastic supply whereas thick basinal shales were deposited to the west of KBF. The presence of Marap Conglomerates and marginal marine facies in the upper part of the Ghazij Formation, towards the western side of KBF, suggest some uplifted areas within basinal settings.

A Common Risk Segment (CRS) map of the Ghazij Formation as a seal based on regional lithofacies model helped in explaining the possibilities of failure and working of Dunghan/Sui Main Limestone (SML) Play in the Kirthar Foldbelt. The absence/thinning and presence of effective regional seal over Dunghan carbonates decrease the prospectivity in the eastern and increase in the western part of Kirthar Foldbelt respectively.

Introduction

The Kirthar Foldbelt provides an excellent opportunity for understanding tectonic and its influence on sedimentation during Palaeogene time (Figure 1). Late Paleocene-Early Eocene shelf sequence is represented by the SML/Dunghan carbonates and back stepping marine shales of Ghazij Formation. In a petroleum prospectivity viewpoint, the Late Paleocene-Early Eocene SML play hosts the most prolific gas producing reservoirs in the Middle Indus Basin. More than 15TCF of gas has been discovered from these carbonates, which still constitute primary targets for petroleum exploration in the Middle Indus Basin (Shah and Malik, 1995). The Northern Kirthar Foldbelt is a relatively less explored area of the Indus Basin. Several attempts made by exploration companies to target the Late Paleocene-Early Eocene Play in the past were not as successful as in the nearby Sulaiman Lobe area due to the limited G&G data and poor understanding of complex geology and structural behavior of depositional sequences of the area.

There are only three commercial discoveries in the SML/Dunghan Play in the entire Kirthar Fold Belt, whereas large reserves are confined to the Cretaceous sandstone play (Pab Sandstone) which based on available borehole and outcrop information is interpreted to be missing or significantly thinned out in the northern part of the Kirthar Foldbelt. Discoveries in SML/Dunghan in the north (Zarghun South-1) and in the south (Jhal Magsi South and Mazarani) make the area attractive for further exploration.

The Ghazij Formation, exposed in the Tangna Pusht Nala, is 700 m thick and comprises mainly shale. It was found to be 600 m thick in the Tangna Pusht X-1 well and is dominantly limestone. Anomalous increase in its thickness is evident, west and northwest of Tangna Pusht Nala in Johan (1,800 m) and Bibi Nani (1,740 m) sections (Figure 2) where it is mainly comprised of shale with thin layers of limestone, marl and sandstone. Sparse seismic data covering the Kirthar Fold belt also indicates the abrupt change of thickness of this sequence from east to west. Dunghan/SML carbonates are overlain by the calcareous shales and interbedded limestones of the Ghazij Formation, which provides a regional upper seal. Abrupt changes in the facies architecture of the Ghazij Formation have been observed in the east-west direction in the Kirthar Fold Belt. These changes are suggestive of fault-controlled sedimentation of the Ghazij Formation in a tectonically active basin. In this study, we attempt to delineate the abrupt change of lithofacies and thickness of the Ghazij Formation and associated seal risk with the SML/Dunghan play in the northern part of the Kirthar Foldbelt.

Tectonic Framework

The Kirthar Foldbelt area remained tectonically active and recorded several phases of synrift and post-rift sedimentation since the Jurassic. The rift-drift-collision history of this plate is well documented (Patriat and Achache, 1984; Besse and Courtillot, 1988; Searle, et. al., 1997). The oldest established stratigraphic unit is the shallow marine clastics and limestones of the Shirinab Group (Spingwar, Loralai, Anjira Formations), which may be regarded as the syn-rift deposition in the study area (Figure 3). During Middle-Late Jurassic, the Chiltan Limestone was deposited on a wide carbonate shelf of Indian Sub-continent (Dolan, 1990). During the Early Cretaceous, sediments were deposited in a passive margin setting with the uplifting of the emergent Indian Continent to the southeast. Large prograding delta systems resulted in the deposition of thick sediments of the Goru and Sembar Formations along the edge of passive margin (Richard, et. al., 2001; Bender, 1995). Restricted marine, anoxic, environments prevailed in the Early Cretaceous during deposition of the Sembar Formation, which is the most prolific source rock in the Lower and Middle Indus basins and the Kirthar Foldbelt.

The transgressive-regressive cycles continued throughout Middle Cretaceous, depositing shoreface sand of the Lower Goru Formation in the eastern part of the Indus Basin. Kirthar foredeep and foldbelt area only received thin turbidites through channels delivering the sediments to the basin floor. The study area remained too far from the input feeders and only marine shales and carbonates of the Goru Formation were deposited. During the Turonian, there was a major marine transgression over the area, which further reduced clastic sediment supply to the basin and thus led to sediment starvation and condensation in deeper areas. Deeper water carbonates (Parh Limestone) were deposited in the Kirthar Foldbelt area throughout the Coniacian-Companian (Richard and Johan, 2001). During the Late Cretaceous, the Kirthar Foredeep and frontal part of the foldbelt areas received thick succession of sand rich turbidities (Mughalkot) that are well exposed in the Southern Kirthar Foldbelt due to uplifting of the Indian Shield when the Indian Plate passed over the Reunion Hotspot (Gnos et. al., 1998). Uplifting of the Shield until Early Paleocene created shallow marine environments in many parts of the Kirthar Foldbelt, which caused the preferential deposition of shallow marine and fluvio-deltaic sands of the Pab and the Lower Ranikot formations. This was followed by a drop in the rate of sea level during the Late Paleocene-Early Eocene, which facilitated the deposition of Dunghan/SML carbonates in the study area. During the Late Early Eocene, regional transgressive and back stepping events are observed throughout the basin. Thin shales with alternating limestone units of the Ghazij Formation were deposited in the eastern part of the Kirthar Foldbelt, while in the western part of the Kirthar Foldbelt area, the Ghazij Formation was deposited as thick shales in deep to shallow marine environments.

During the Late Eocene, calm marine conditions prevailed enabling the deposition of the Kirthar Limestone throughout the basin. During the Oligocene, the Western Kirthar part of the basin was restricted for sedimentation due to plate collision resulting in the development of small, isolated basins where sedimentation continued until Quaternary times.

Stratigraphy of Ghazij Formation

The term Ghazij Formation was introduced by Oldham (1890) for a shale formation between the Dunghan and Spintangi/Kirthar Limestones in the region southeast of Harnai near Quetta. It is well exposed along the western margin of the Indo-Pakistan plate. The term Ghazij is sometimes used for a formation or group representing all sediments deposited during Early Eocene time (Shah, 1991; Kazmi and Jan, 1997). In this study, we use the term “Ghazij Formation” (like Oldham, 1890) for the genetic sequence between the Late Paleocene Dunghan Limestone and Late Eocene Kirthar Limestone. This genetic sequence includes the lithostratigraphic units of SML/Laki and Ghazij shale.

The SML/Laki Limestone is exposed in the southern Kirthar Foldbelt but not in the northern part (Figure 4). This unit is encountered in the Tangna Pusht X-1, Jhal Magsi South-1, Mazarani-1 and Bhan-1 wells. It is composed of mainly platform limestone deposits. The limestone is medium hard to hard, crystalline, argillaceous and fossiliferous which shale out in the Tangna Pusht Nala section, Johan section, South Karkh section and Hallel-1 well and is mapped as the Ghazij Formation.

The Ghazij Formation is divided into three parts by (Jones et. al., 1960) in the Sulaiman and Northwest Kirthar Foldbelts where it is exposed: (1) a lower green shale unit with marine fossils and minor lenticular sandstones indicating that it was deposited offshore in Tethys beyond the transport of coarse clastics; (2) a middle green shale unit with thin coals and tabular sandstones interpreted as having been deposited in a paludal environment in a lagoonal setting; and (3) an upper variegated green, brown, red, purple, and yellow mudstone and shale unit, with cross-bedded lenticular sandstones, and conglomerate in places. The conglomeratic unit on top of the Ghazij shale and sandstone is also observed in the western part of Kalat Plateau. This unit is described as the Marap Conglomerates (Jones et. al., 1960). In the eastern part of the Kirthar Foldbelt, the Ghazij Formation is a thin unit predominantly comprised of limestone with thin alternations of calcareous shales encountered in the Tangna Pusht X-1, Jhal Magsi South-1, Mazarani-1 and Bhan-1 wells. Shale is indurated, fissile, laminated, splintery and highly calcareous. This limestone within the Ghazij Formation is the same as that of SML/Laki.

Tectono-Stratigraphic Model

Data Set and Methodology

The data set used for building the model is comprised of measured stratigraphic sections, well data (mud logs, wireline logs) and seismic transects. It includes two east-west and one north-south stratigraphic correlation panels and two east-west seismic transects. For complete understanding of shelf break setting controlled by Kirthar Basement Fault (KBF) and lithological characteristics, a schematic depositional model was also prepared using the above data. The description of each section is given in the following paragraphs.

Section A: An east-west stratigraphic correlation panel from Tangna Pusht X-1 well and measured sections of Tangna Pusht Nala and Johan is prepared (Figure 5). This panel shows an abrupt change in lithology and thickness from Tangna Pusht X-1 well to Tangna Pusht Nala within a distance of a few kilometers. In Tangna Pusht X-1, the genetic sequence of the Ghazij Formation is comprised of thick limestone and thin calcareous shales with alternating layers of limestones while at Tangna Pusht Nala section this sequence changes into predominantly thick marine shales and further in the west at Johan section, the thickness of the shale unit increases up to 1,800 m. This change in facies from predominantly carbonate sequence to thick marine shales is interpreted to be controlled by a faulted (KBF) shelf margin that caused the deepening of the basin and sediment supply from the west/northwest.

Section B and C: The east-west stratigraphic correlation panel (Section B) is transecting the middle part of Kirthar Ranges from the Mazarani-1 well to the measured section at South Karkh (Figure 6). It also represents a change in lithology, which again may be attributed to the fault controlled shelf margin. At Mazarani-1 well, a thick carbonate sequence was encountered between Dunghan and Kirthar Formations with subordinate thin shales and mudstones in the upper part. Moving to the west, at the South Karkh section, the Ghazij sequence is comprised of thick marine shales (about 1,000 m). Similarly an east-west seismic transect (Section C) flattened on top of the Ghazij from Mehar-1 well to the Karkh area, in the depositional strike of Mazarani-1, also shows transition from carbonate to shale dominated lithofacies and an increase in thickness from east to west (Figure 7).

Section D: Further in the south, another east-west seismic transect from Bhan-1 to Hallel-1 well, flattened on top of the Ghazij, classically represents the Late Paleocene-Early Eocene depositional setting as discussed above (Figure 8). KBF provided the tectonic hinge that changed the shelfal setting in the east to deep marine basinal setting in the west. This deepening of the basin caused the change in facies and thickness.

Section E: This north-south correlation panel from Tangna Pusht X-1 to Bhan-1 shows the distribution of thick carbonate sequence and thin calcareous shale sequence at the top. Well developed carbonates of the Ghazij Formation deposited along the strike where carbonate production was able to keep pace with the rate of sea level rise with limited clastic supply. This correlation panel represents the sequence in the east of KBF.

Discussion

The Ghazij Formation was deposited in a tectonically active basin where regional tectonics and paleogeography played a very important role in the distribution of facies and thickness. The Kirthar Basement Fault was activated during Late Paleocene-Early Eocene, which enabled the Indian plate east of it to continue its travel northwards, where as the Kalat-Khuzdar block slowed down and passed through different tectonic history (Bannert, et. al., 1992). This fault (KBF) controlled the shelf break resulted in deepening the basin toward west and distribution of lithofacies along the depositional dip. The Kirthar Basement Fault runs roughly in the north-south direction and is present between the Tangna Pusht Nala, South Karkh sections and Hallel-1 well in the west and Tangna Pusht X-1, Mazarani-1, Mehar-1 and Bhan-1 wells in the east (Figure 4).

The Ghazij Formation has its time equivalent lithofacies of dominantly limestone to the east of the KBF, where carbonate production was able to keep pace with the rate of sea level rise with limited clastic supply whereas thick basinal shales were deposited to the west of KBF. The basin deepens to the west due to KBF and tectonic loading of Bela Ophiolites on to the Kalat-Khuzdar block during Late Paleocene to Early Eocene (Allemann, 1979) which provided accommodation space for the deposition of thick Ghazij shales (over 1,800 m in the Johan area). The presence of Marap conglomerates at the upper part of the Ghazij Formation and paleocurrent directions measured in western part of the Kirthar Foldbelt indicate transportation of clastic sediments from the west and north-west (Jones, et. al., 1960; Waheed and Wells, 1990; Pivnik and Wells, 1996; Warwick et. al., 1998). This also indicates some uplifted areas at the W/NW margin of basin. The basin was leveled off before the deposition of Kirthar Limestone and equally thick (400-500 m) shallow marine limestone was deposited on both side of KBF.

Implication for Exploration

The results of this study have implications for the hydrocarbon potential of Paleogene play/s in the study area.

Gross lithofacies and subsequently Gross Depositional Environment (GDE) maps have been prepared using the stratigraphy encountered in wells and outcrop sections from different locations/areas of Kirthar Foldbelt (Figure 9 and Figure 10). A Common Risk

Segment (CRS) Map for regional top seal for SML/Dunghan carbonates has been generated by using the GDE map of Ghazij considering the uncertainties related to the existence and effectiveness of seal (Figure 11). The area east of KBF is comprised of predominantly limestone with relatively thin interbedded shale. These shale facies are thinner, but where buried under the thick overburden sequence of Siwaliks, will provide a better seal (orange polygon in Figure 11) for the underlying SML/Dunghan reservoirs, as evident by the discovery of gas at Jhal Magsi South-1 and Mazarani-1. In the area where the Kirthar Limestone is exposed on the surface, there will be higher seal risk (red polygon in Figure 11). As a result, shale as a seal is more erratic and ineffective in this part of depositional setting reflected by the failure of Tangna Pusht X-1. In the western side of KBF, predominantly basinal shale facies developed an exceptionally good regional top seal for Dunghan Limestone and increases the petroleum prospectivity of Kalat Plateau (green polygon in Figure 11).

Conclusions

We conclude the following:

- Diversity of lithofacies of Late Paleocene to Early Eocene carbonates to clastics along depositional dip has been observed in Kirthar Foldbelt.
- The platform carbonates facies of SML/Laki and the clastics sediments, mainly shale, are represented by the Ghazij Formation in the area.
- The variation of carbonate to clastic facies and their thickness are attributed to shelf break controlled by KBF, which is running north-south parallel to the strike of the Kirthar Foldbelt.
- Gross Lithofacies and GDE maps help to understand the distribution of the Ghazij Formation and its role as a regional seal.
- Common Risk Segment (CRS) map of the Ghazij Formation as a seal based on regional lithofacies model is helping in explaining the failure of the Dunghan/Sui Main Limestone Play in the northern part of the Kirthar Fold belt.
- Thick shale facies of the Ghazij Formation in the Kalat Plateau will provide an effective top seal for the underlying Dunghan play and regional seal for whole of the area.

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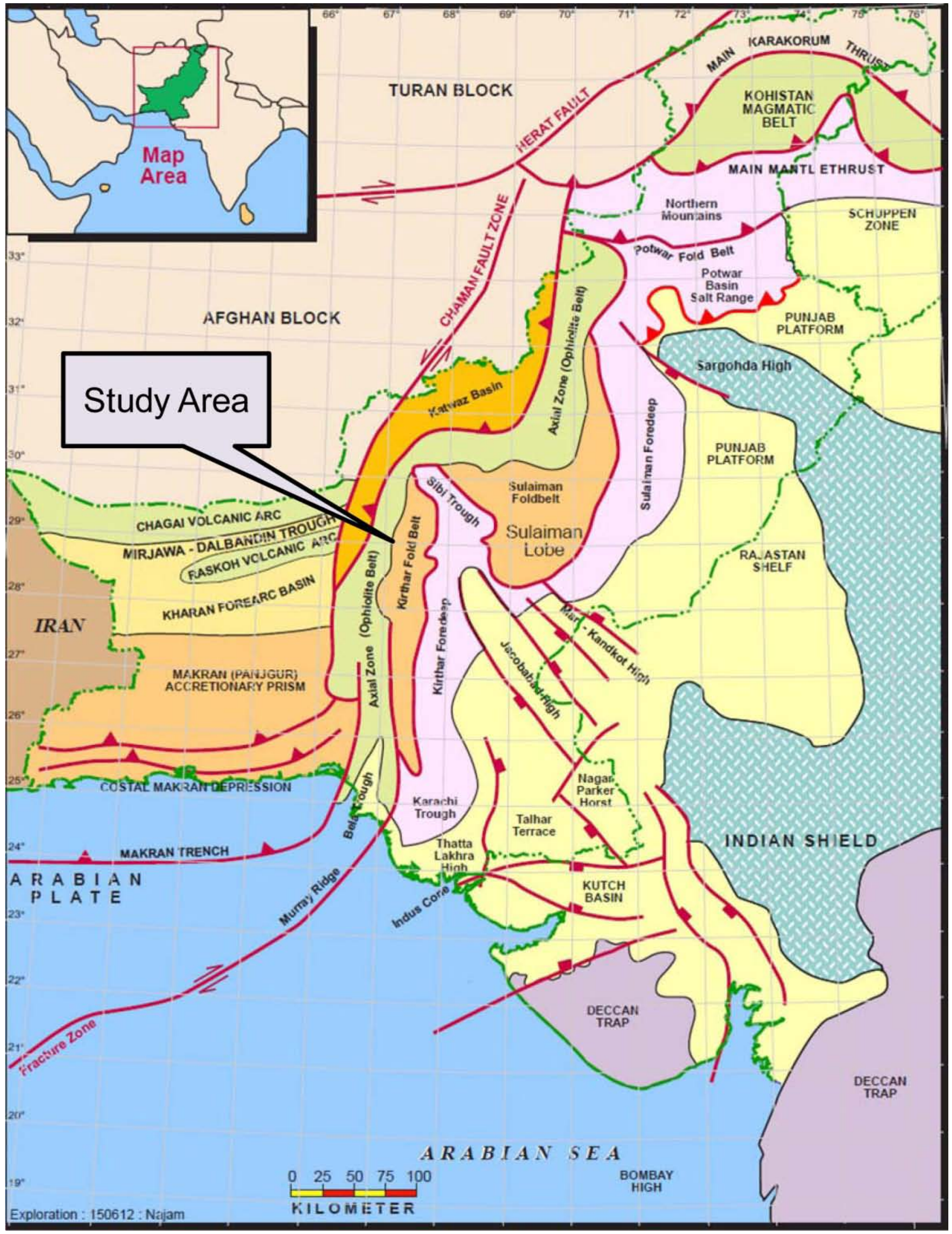

Figure 1. Generalized tectonic map of Pakistan showing location of the study area.

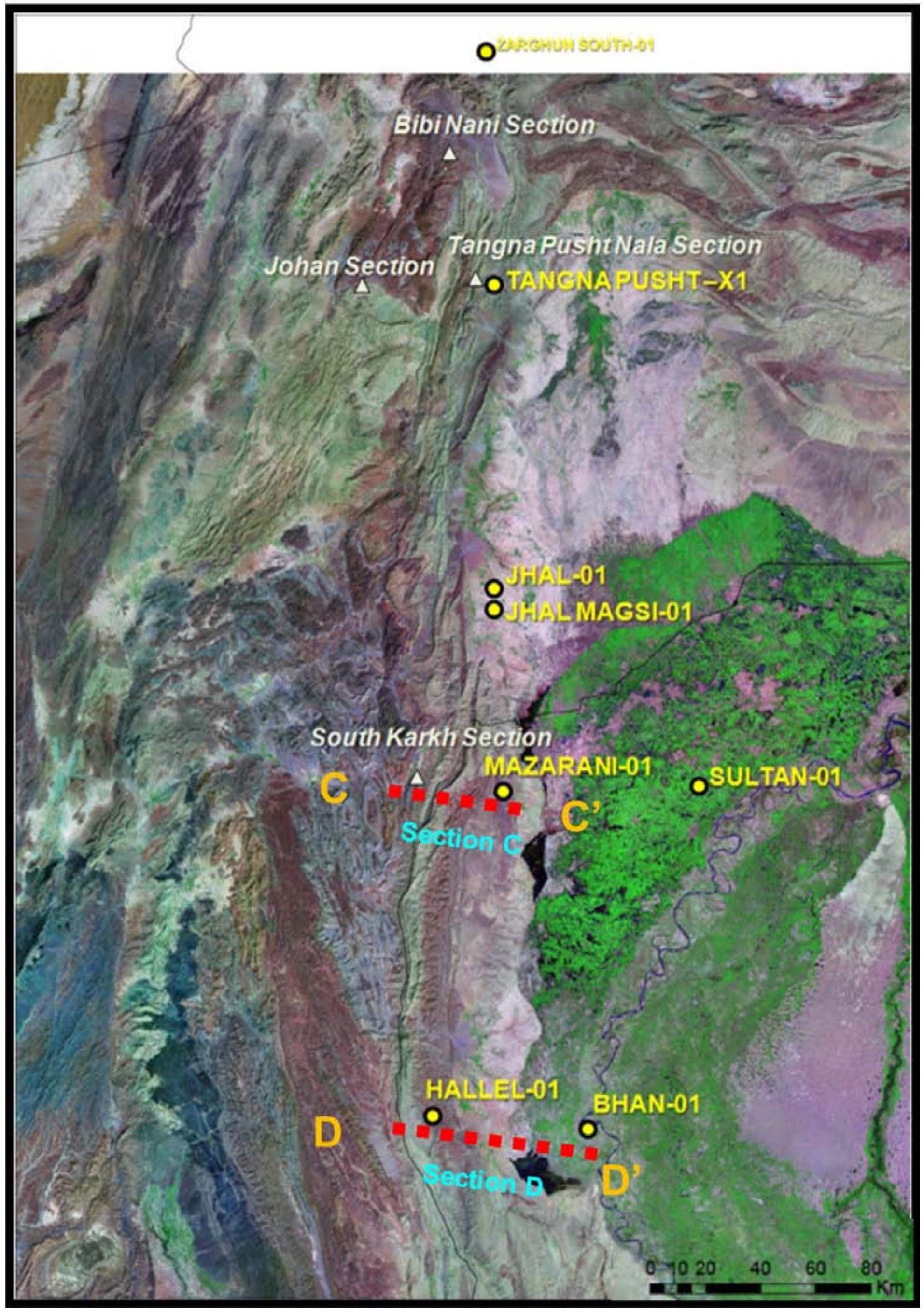

Figure 2. Location map of study area.

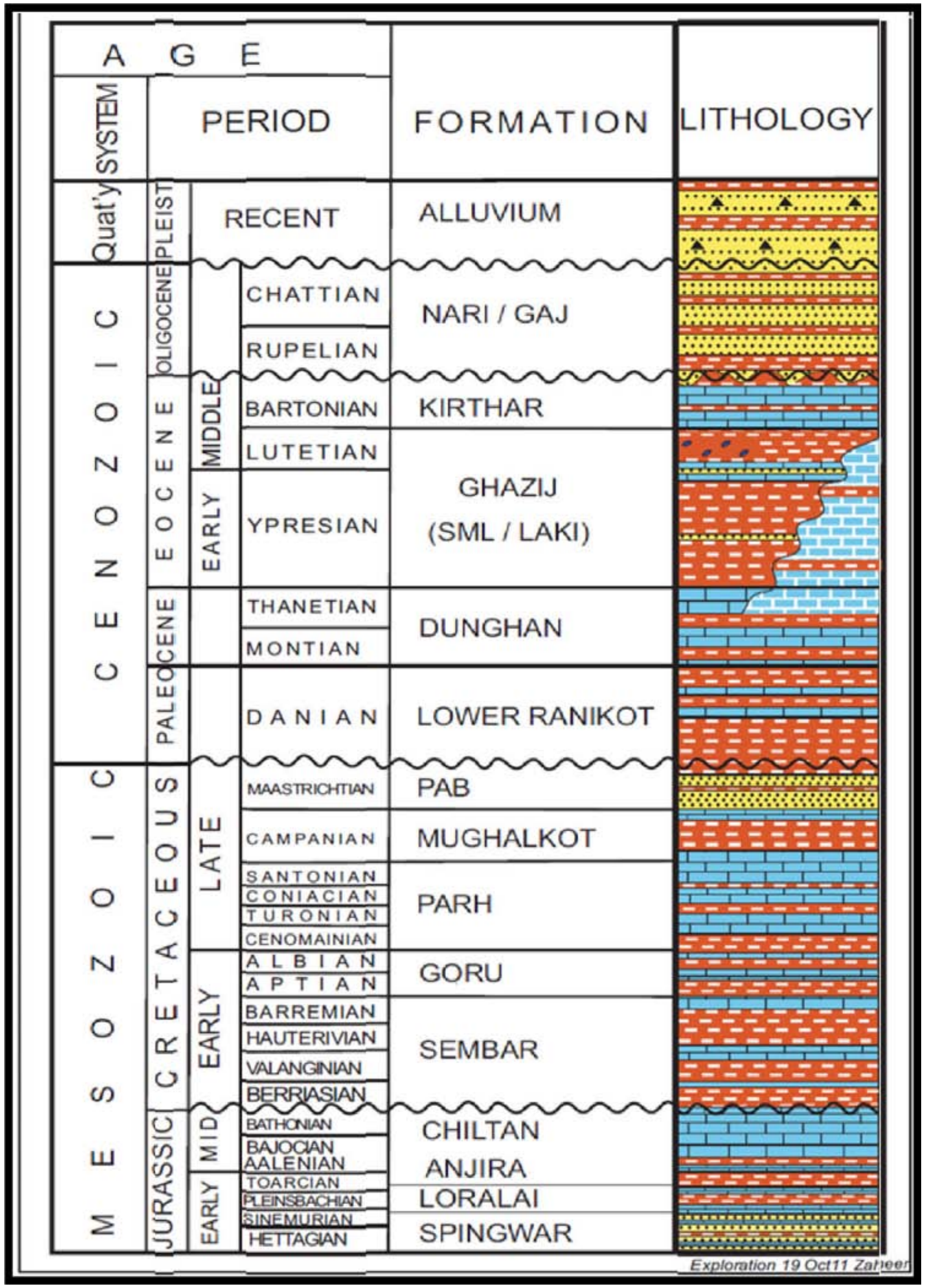

Figure 3. Generalized stratigraphic column of Kirthar Foldbelt area.

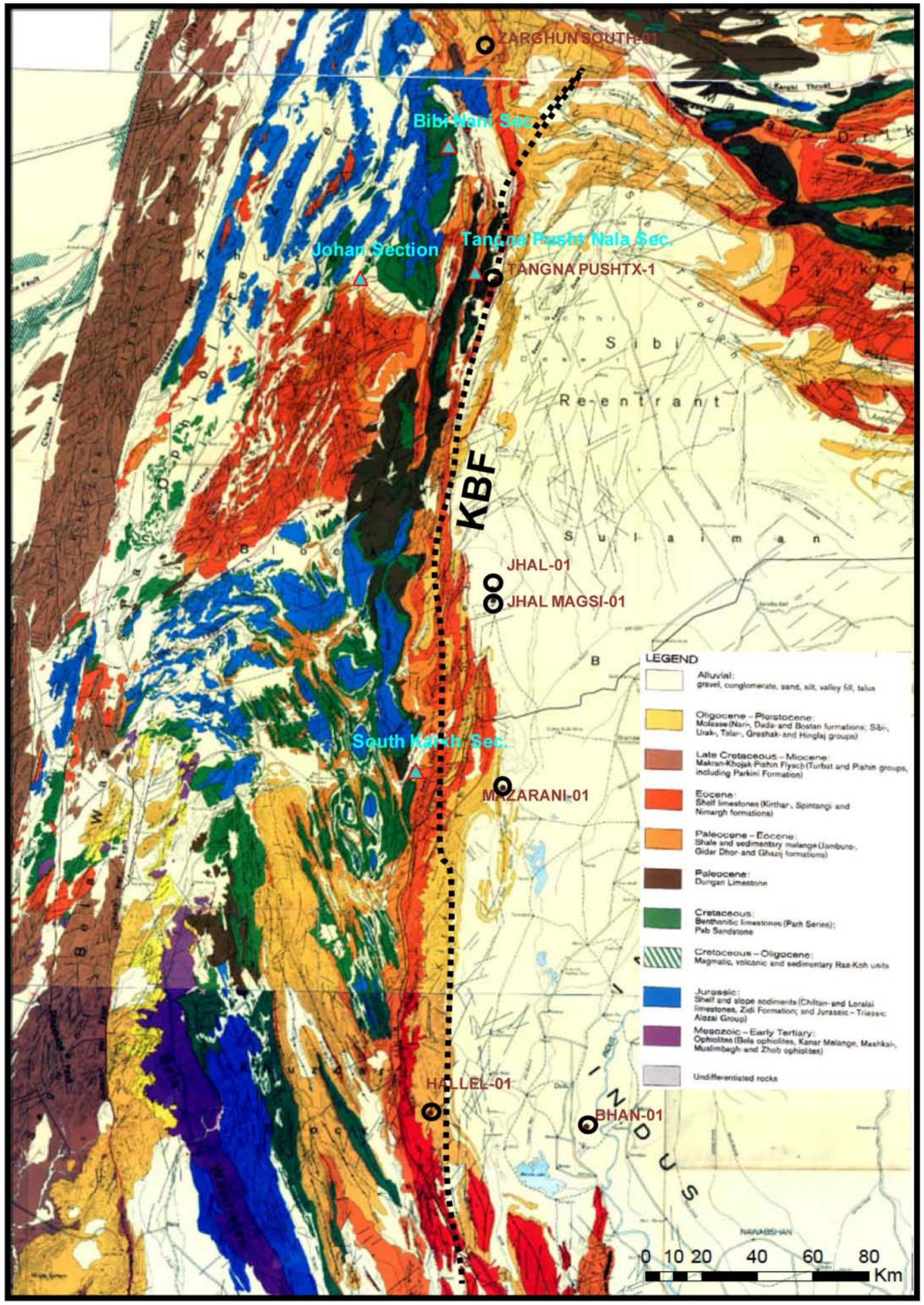

Figure 4. Geological map of study area, showing the position of KBF (Dotted line) (after Bannert et al., 1992).

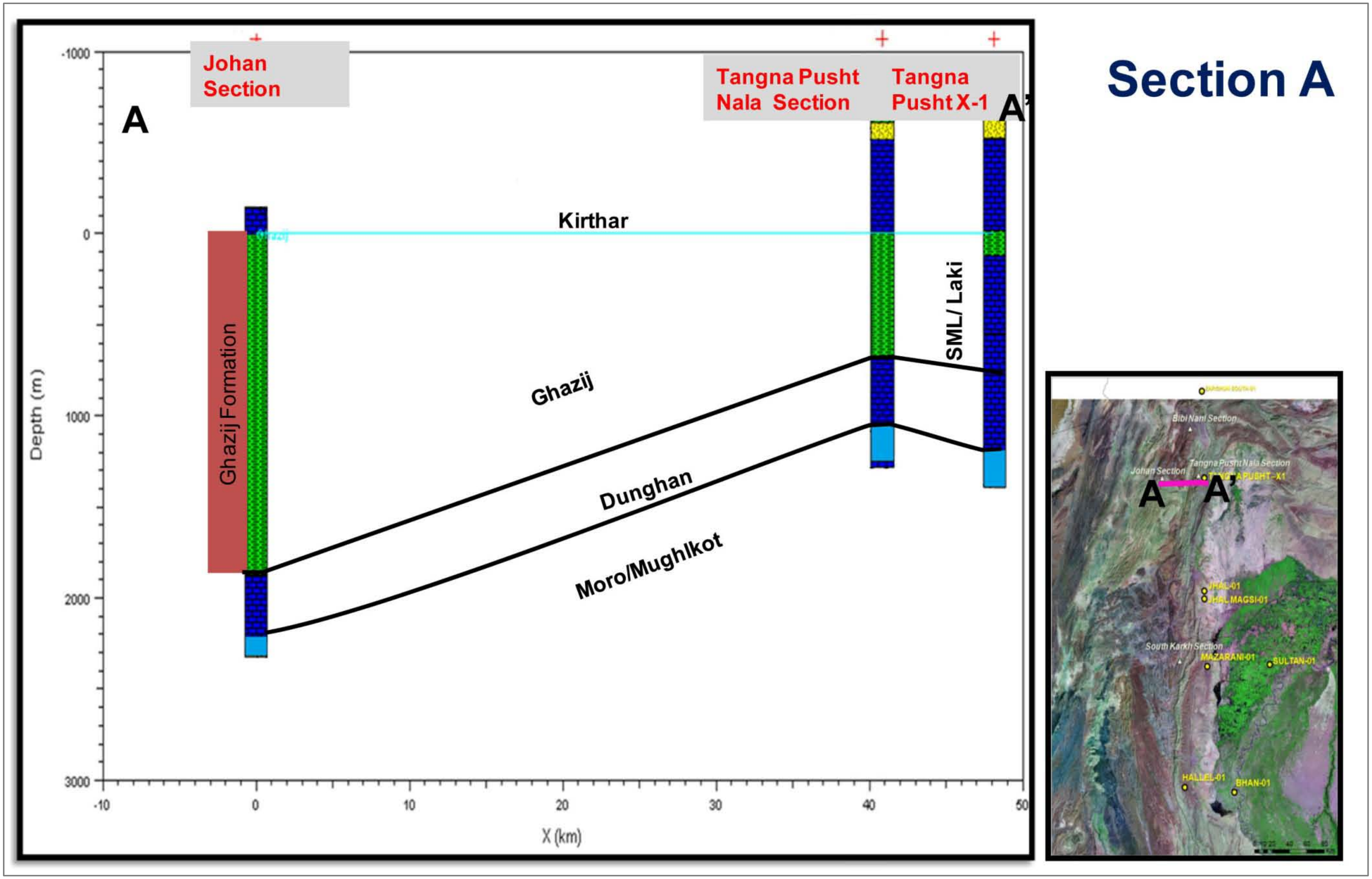

Figure 5. East-West correlation of stratigraphic units from Tangna Pusht Well to Johan section in the north of Kalat plateau, showing the facies change of Ghazij Formation.

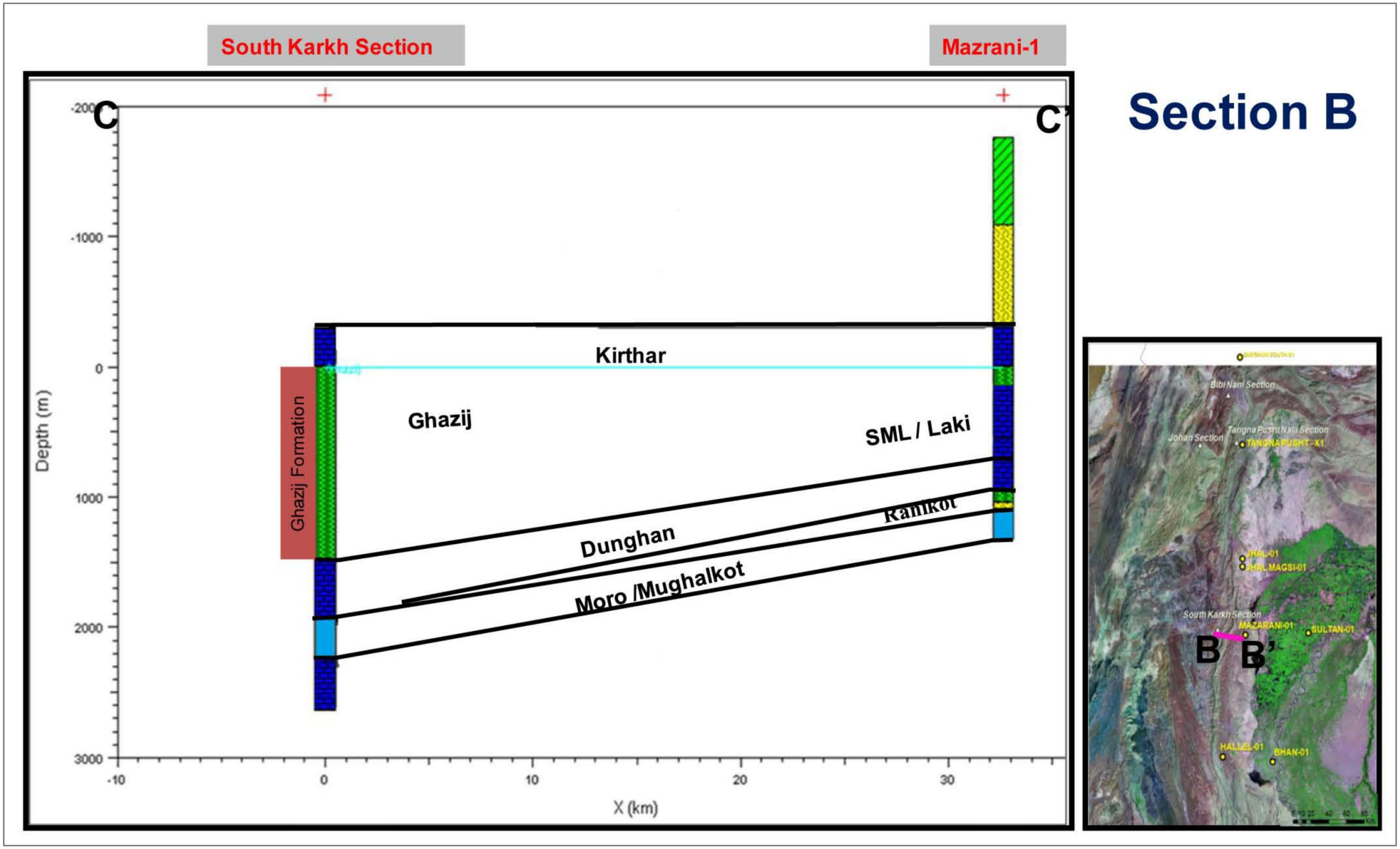

Figure 6. Correlation of stratigraphic units show change in facies and thickness from Mazarani-1 to South Karkh section.

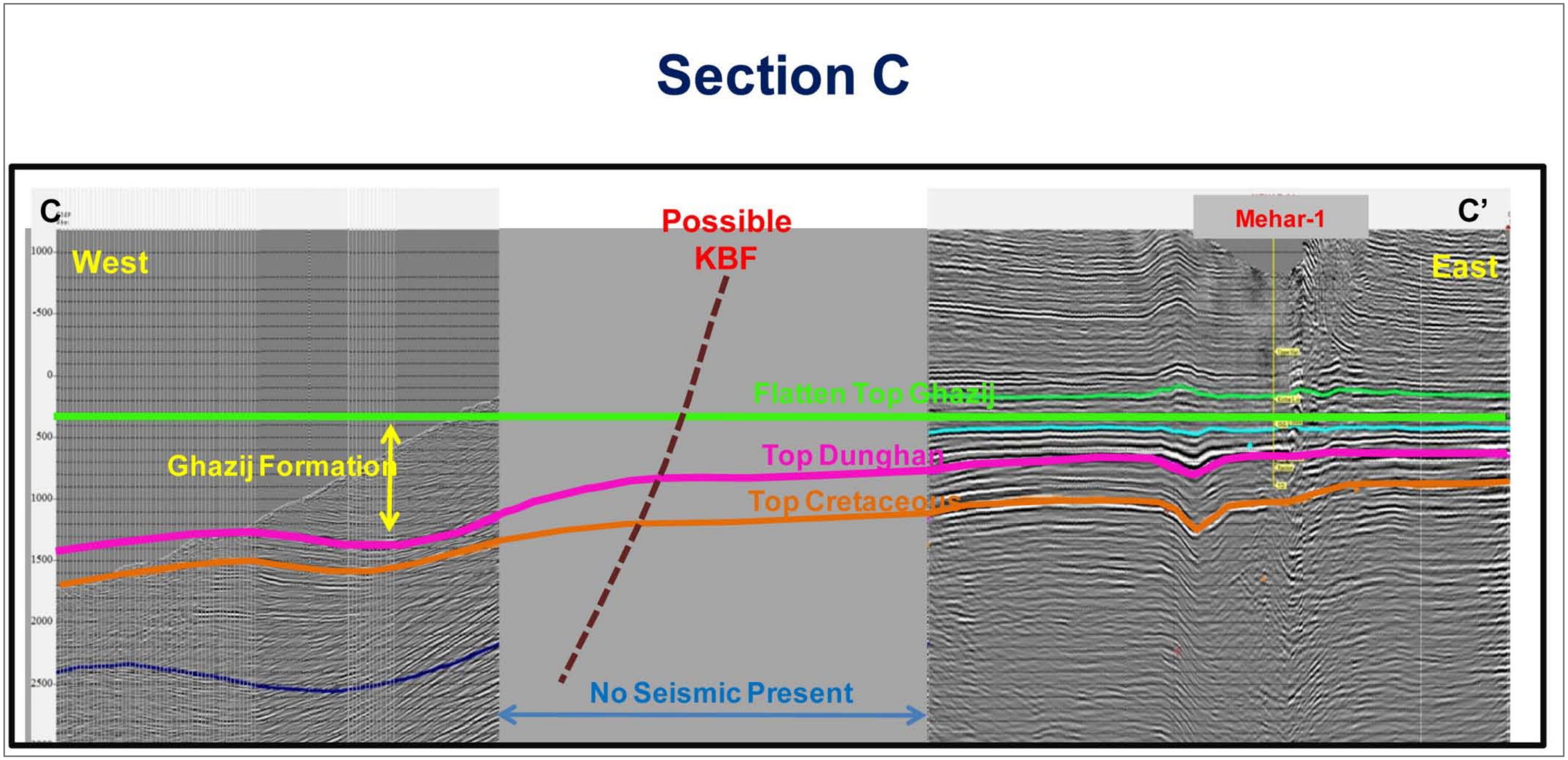

Figure 7. East-west seismic transect showing significant increase in thickness, position of shelf margin and KBF between the Mehar-1 and South Karkh section. Location of transect is shown in Figure 2.

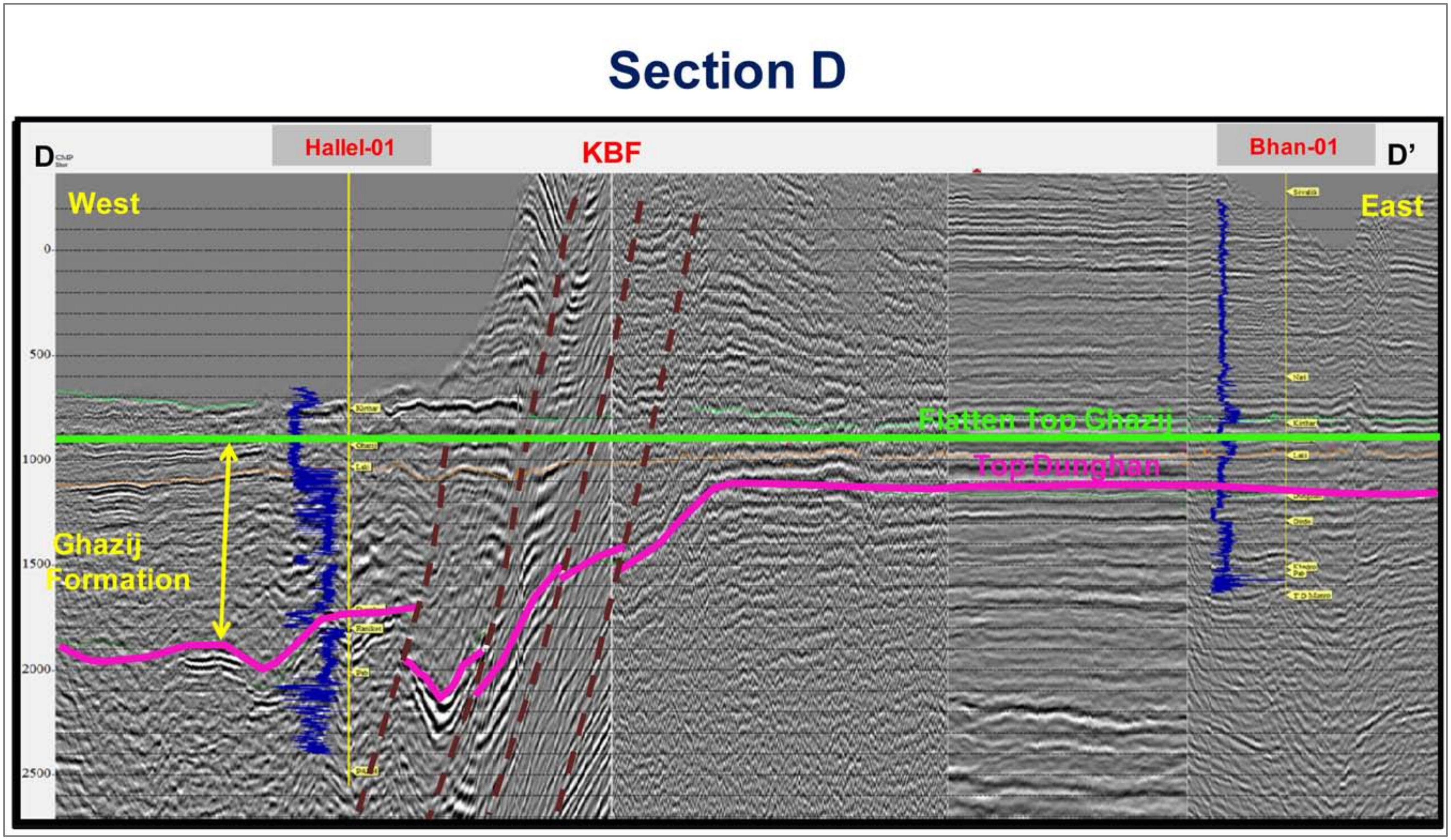

Figure 8. East-West Seismic transact from Bhan-1 to Hallel-1 well shows the fault controlled shelf margin during the Late Paleocene–Early Eocene (KBF) causing the significant change in facies and thickness from east to west. Location of transect is shown in Figure 2.

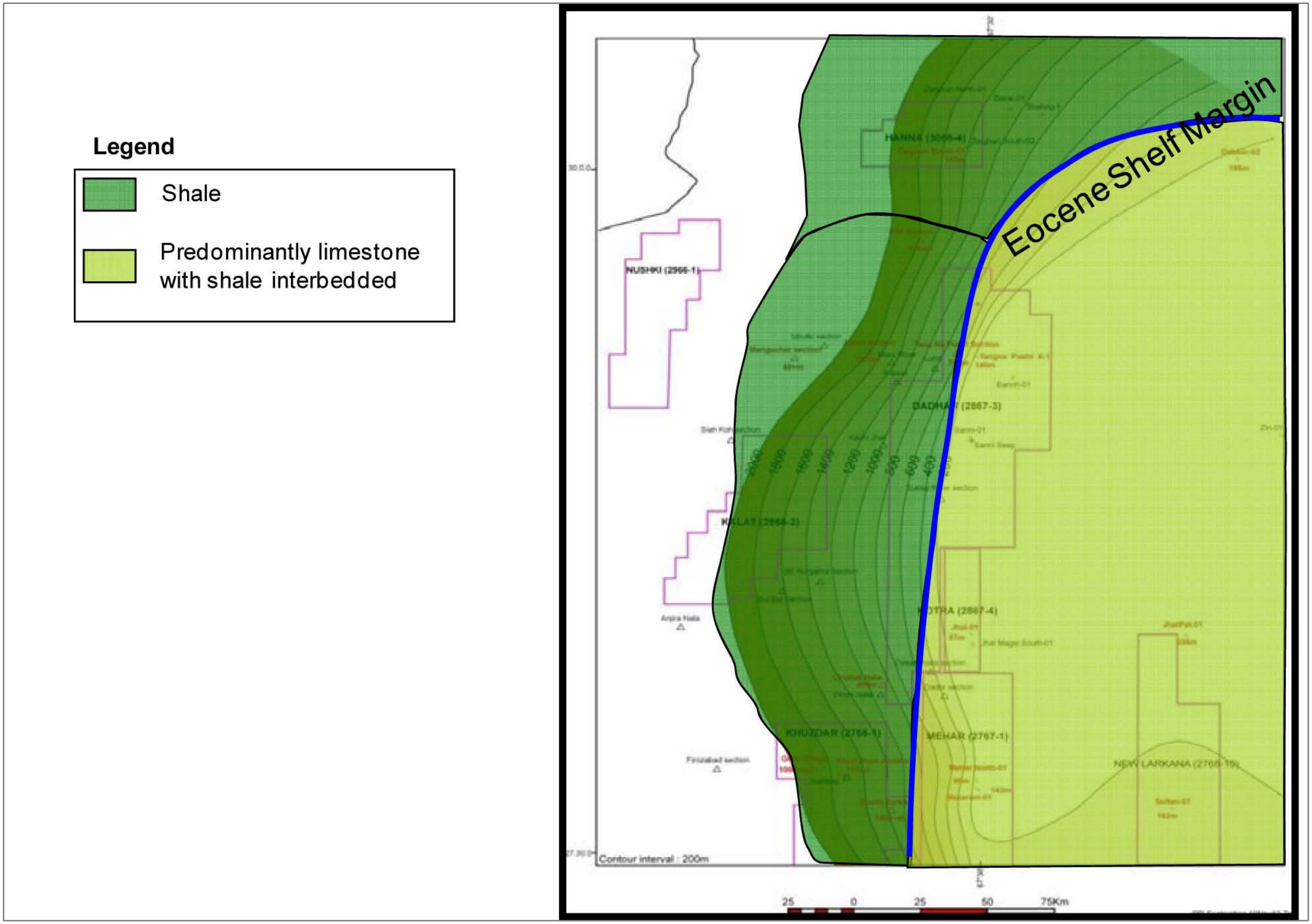

Figure 9. Gross Lithofacies Map of Ghazij Formation and showing the fault controlled shelf margin.

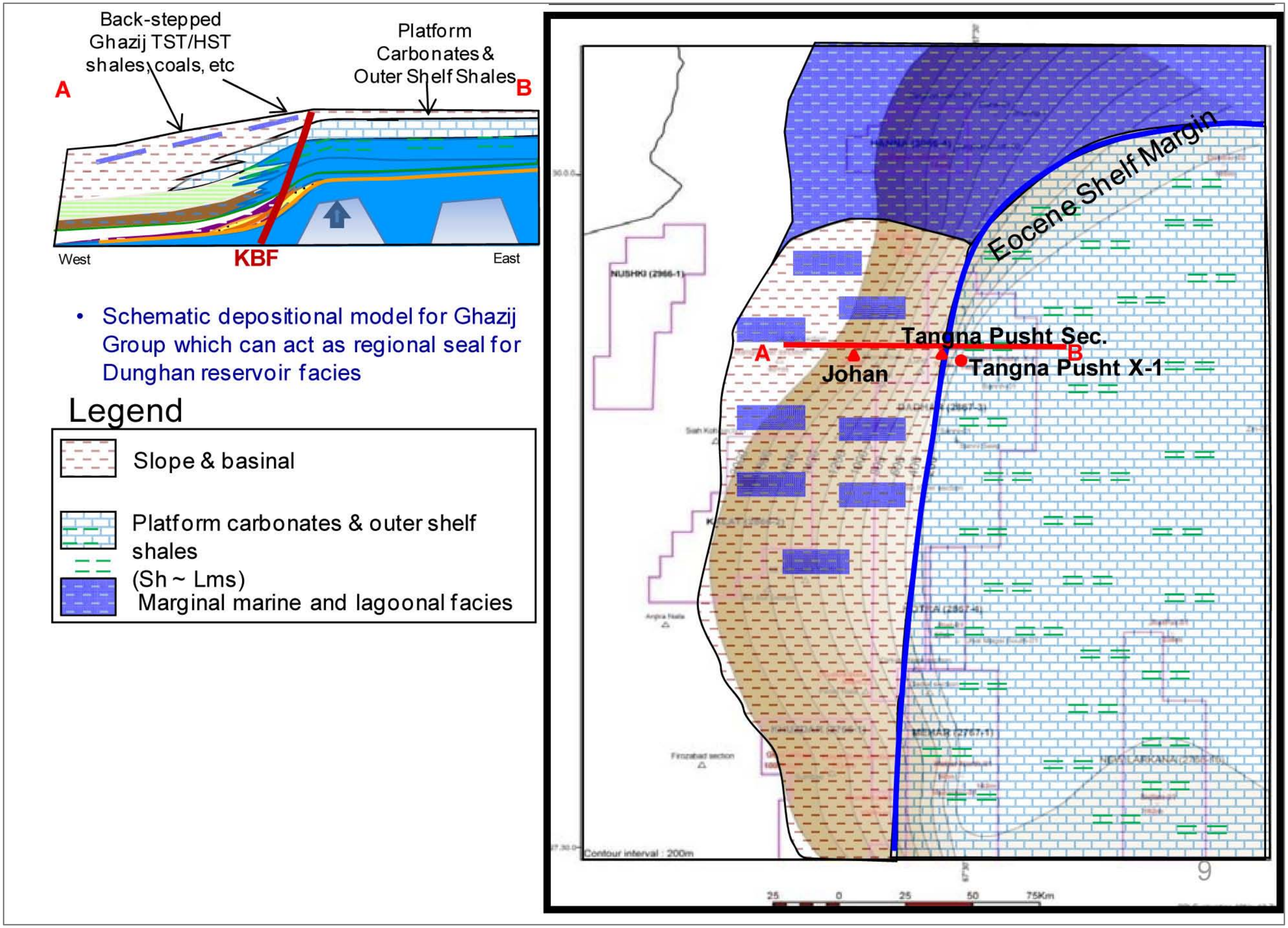

Figure 10. GDE map and schematic depositional model of Ghazij Formation.

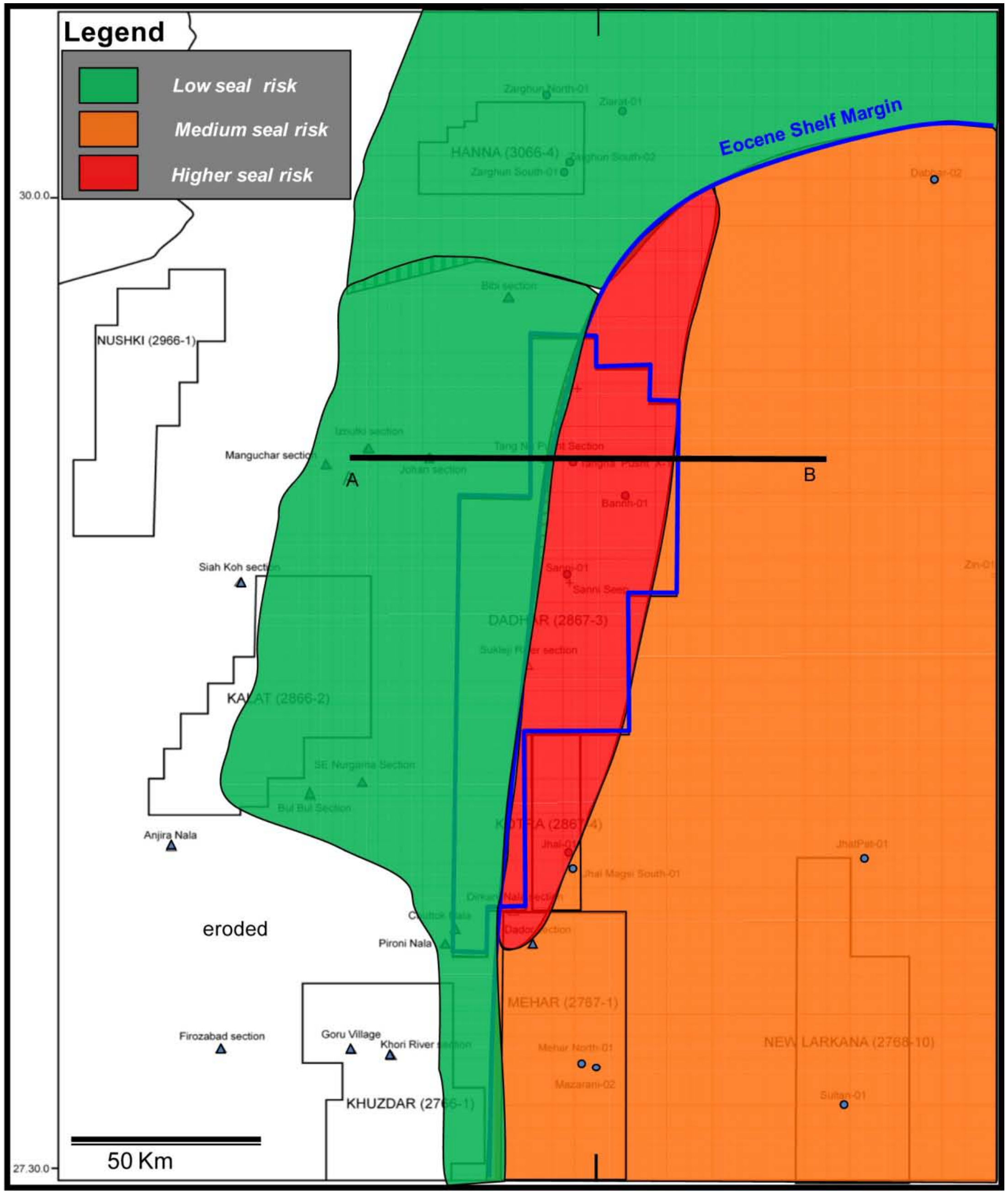

Figure 11. Seal Common Risk Segment Map for Ghazij Formation.