



Structural styles, hydrocarbon prospects, and potential of Miano and Kadanwari fields, Central Indus Basin, Pakistan

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Abstract

The main purpose of this paper is to evaluate the structural styles of Miano and Kadanwari Fields, located in the Central Indus Basin, Sindh province, Pakistan. Discovered in 1989 and 1993, Kadanwari and Miano Fields are located on the Pano Aqil graben and Kadanwari High, in between two extensive NW-SE-oriented regional highs, i.e., Jacobabad-Khairpur and Mari-Kandhkot High. The Central Indus Basin is an extensional basin exhibiting normal faulting. Fourteen seismic lines were interpreted to understand the presence, trend, and development of the fault system in the Central Indus Basin along with the assessment of the Petroleum system based on the analysis of seismic reflection data and well logs across the Cretaceous clastic reservoirs. The tectonics of Miano and Kadanwari Fields has been interpreted with the presence of normal faults, strike-slip faults, and inverted structures leading to ambiguities about the structural framework of the area. However, with this detailed study, an extensional fault system has been interpreted in the Cretaceous and lower Tertiary sections over a detachment in the incompetent Sembar Formation. In Miano Field, the faults are dominantly recognized to have NNW-SSE trend due to NW-SE-oriented extension related to northward drift of Indian Plate from Madagascar. Resultantly tilted fault blocks of half grabens geometry have developed in the area depicting bookshelf geometry of an extensional system Wrench fault system is found to be absent with exception of a probable strike-slip fault in the Kadanwari Field. The fields are interpreted to have significant recoverable reserves of 1662 (bcf) equivalents to 280 (mmboc) in tilted fault blocks having an average displacement of about 50 m.

Keywords Extensional system · Bookshelf geometry · Half grabens

Introduction

The study area of Miano and Kadanwari Fields lies between latitude 27° 10' 0"–27° 24' 42" N and longitude 69° 19' 0"–69° 19' 16" E (Fig. 1). Tectonically the area lies in the Central Indus Basin along the western margin of the Indian Plate,

between two regional highs, i.e., the Mari-Kandhkot High to the northeast and the Jacobabad-Khairpur High to the southwest. The Thar Desert lies in its south, and the Delhi Aravalli range is in its east (Jadoon et al. 2016).

Kadanwari Field is operated by a joint venture between ENI Pakistan as the operator (18.42%), KUFPEC and Premier (15.79%), and Oil and Gas Development Company (50%). The drilling activities started in 1989 with the discovery of gas from Kadanwari-01.

Miano Field (Block-20) is operated by a joint venture between OMV Exploration Pakistan as the operator (17.68%), ENI Pakistan (15%), Pakistan Petroleum Limited (15.16%), and Oil and Gas Development Company (52%), respectively. Drilling activities in the Miano area started in 1993, and so far, 20 wells have been drilled out of which 9 of these were gas discoveries (Ahmed et al. 2013).

The study area is gas prone and has structural as well as stratigraphic traps. The seismic and well data were analyzed for subsurface structural analysis to delineate the (i) orientation, (ii) geometry, and (iii) development of the fault system.

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Regional geology and tectonic settings

The study area of Miano and Kadanwari is located in the Central Indus Basin in between two regional extensive highs, i.e., the Mari-Kandhkot High to the northeast and Jacobabad-Khairpur High to the southwest (Fig. 1). Central Indus Basin can be further classified into three broad tectonic units: (1) Sulaiman Fold Belt, (2) Sulaiman Foredeep, and (3) Punjab Platform (Figs. 1–2). It is bounded by Indian shield to the east and highly folded mountain belts to the west.

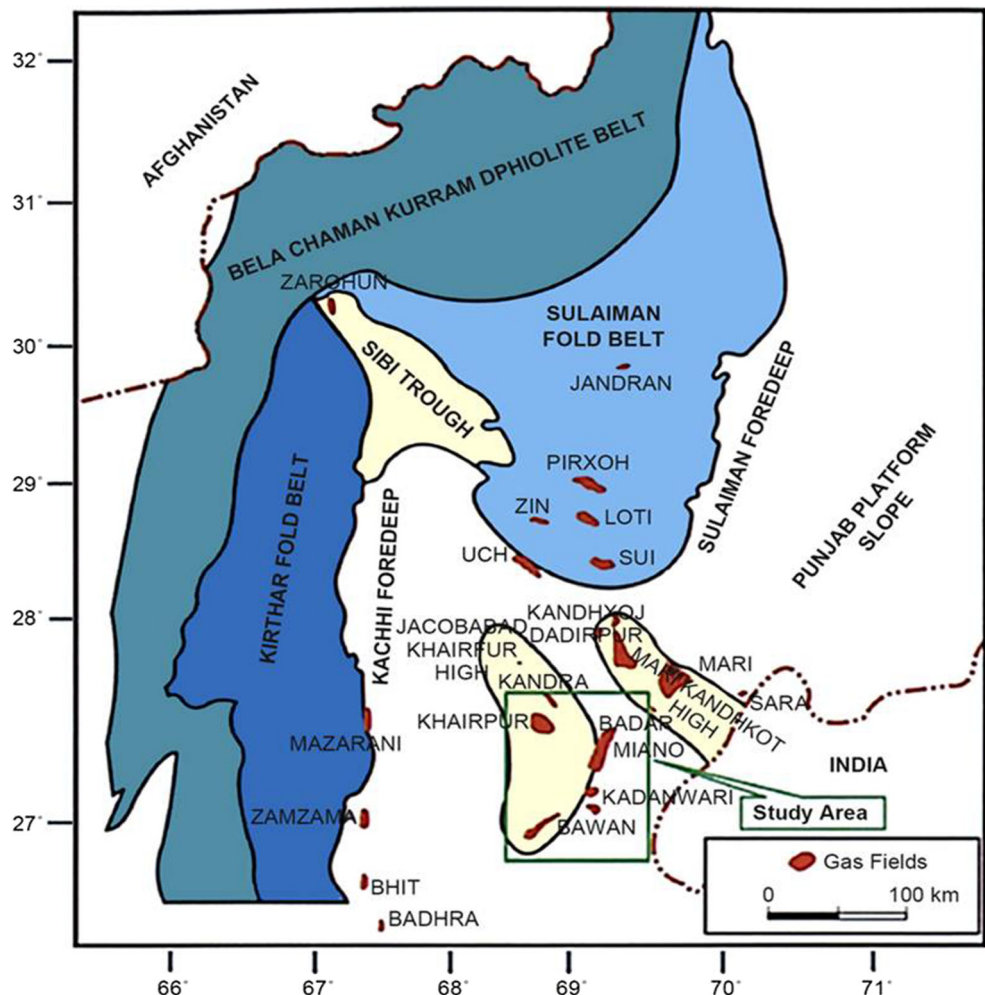
A gentle arc of north-south-oriented Jacobabad-Khairpur High is interpreted as a basement-induced structure that interrupts the westward-directed dip of the Sindh Platform (Krois et al. 1998). West of the Jacobabad-Khairpur High, the Sindh Platform resumes its westward dip. The Jacobabad-Khairpur High forms a barrier separating the Kachhi Foredeep from the Sulaiman Foredeep. It was most likely active from the Mesozoic to early Tertiary, evidenced by the base Tertiary unconformity (Fig. 3).

The Kirthar Fold Belt has large NNW- to SSE-oriented anticlines composed of sediments of Mesozoic to Neogene

period. Sulaiman lobe is interpreted as an active fold belt over transitional crust related to the northwestern oblique passive margin of the Indian Plate (Jadoon et al. 1994; Jadoon and Khurshid 1996), whereas the development of structural highs, i.e., Jacobabad-Khairpur and Mari-Kandhkot Highs, may be attributed to the development of a Cretaceous and Cenozoic passive margin along the southwestern part of the Indian plate due to its northwards drift from Africa.

From Jurassic to late Cretaceous, the area of present Khairpur High has occupied a basinal position. The depocenter during early Cretaceous caused by rapid subsidence was situated to the east of the high. During the early Tertiary, either extensional or wrench tectonics induced uplift lead to the development of structural highs and erosion of late Cretaceous Mughal Kot and Pab Formations. Normal faulting with a dominant NW-SE trend has taken place. Clastics sediments of Ranikot on lap the base Tertiary unconformity. The area of present-day Khairpur High occupies a basinal position from early to middle Eocene. The final development of Khairpur High started in the Oligocene along the western

Fig. 1 Generalized regional tectonic map with the location of major oil and gas fields in the study area (modified after Ahmed et al. 2013)



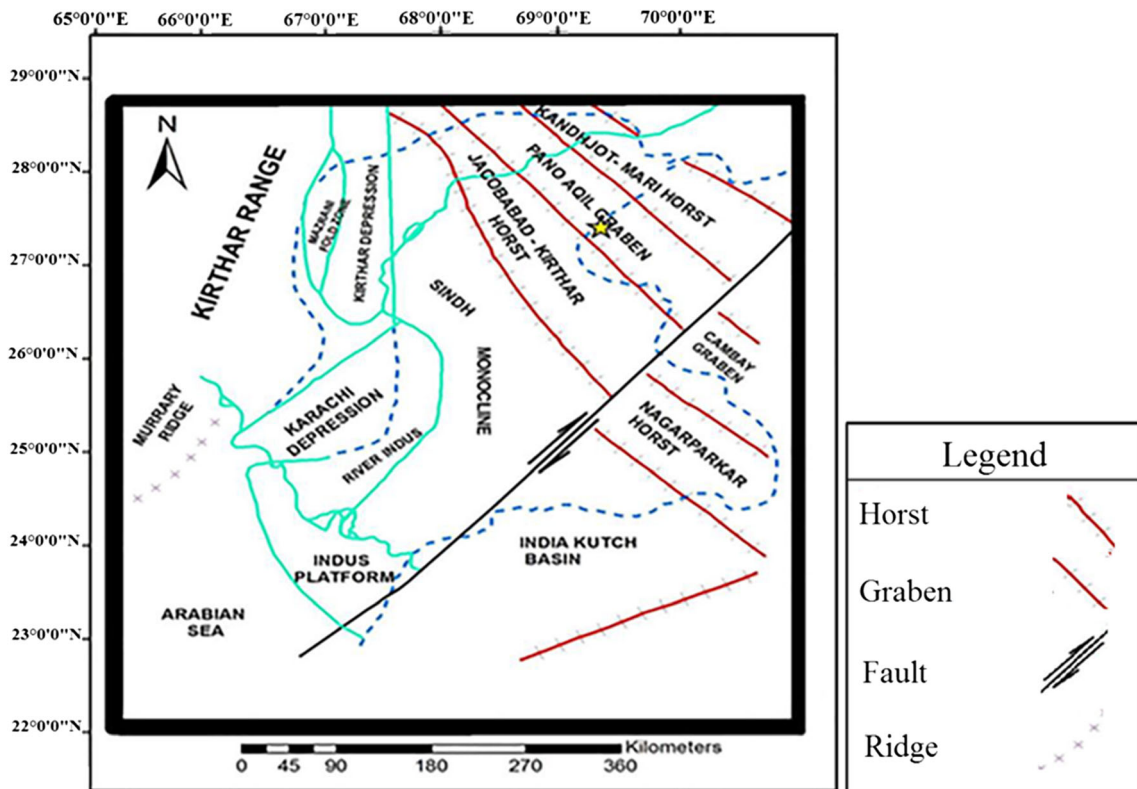


Fig. 2 Generalized tectonic map of the study area adjoining regions in the Central Indus Basin. The study area is located on Pano-Aqil Graben and Kadanwari High in between Mari-Kandhkot Horst and Jacobabad-Khairpur Horst (Raza et al. 1990)

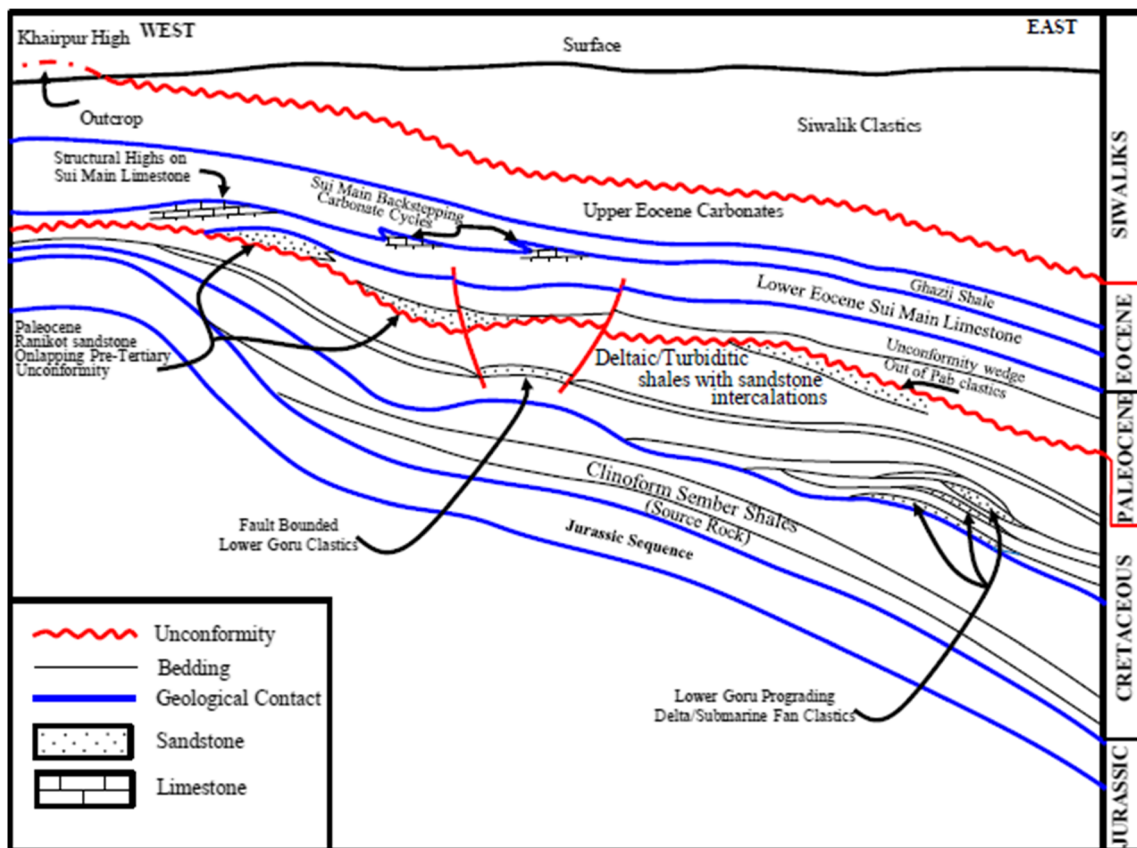
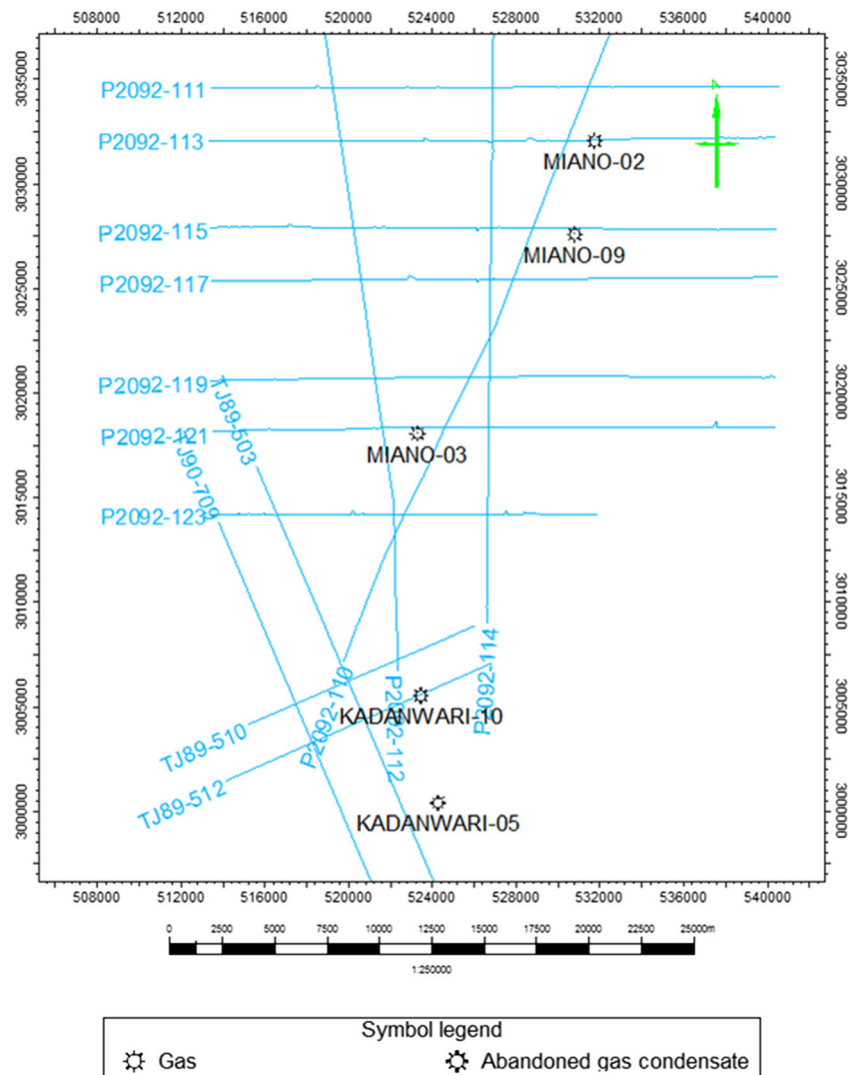


Fig. 3 Generalized tectonostratigraphic and distribution of the source and reservoir rocks along an EW cross-section in the region. (Krois et al. 1998)

Fig. 4 Seismic layout map of the study region



and northern margins of the basin which continued to late Cenozoic time.

Seismic reflection profiles

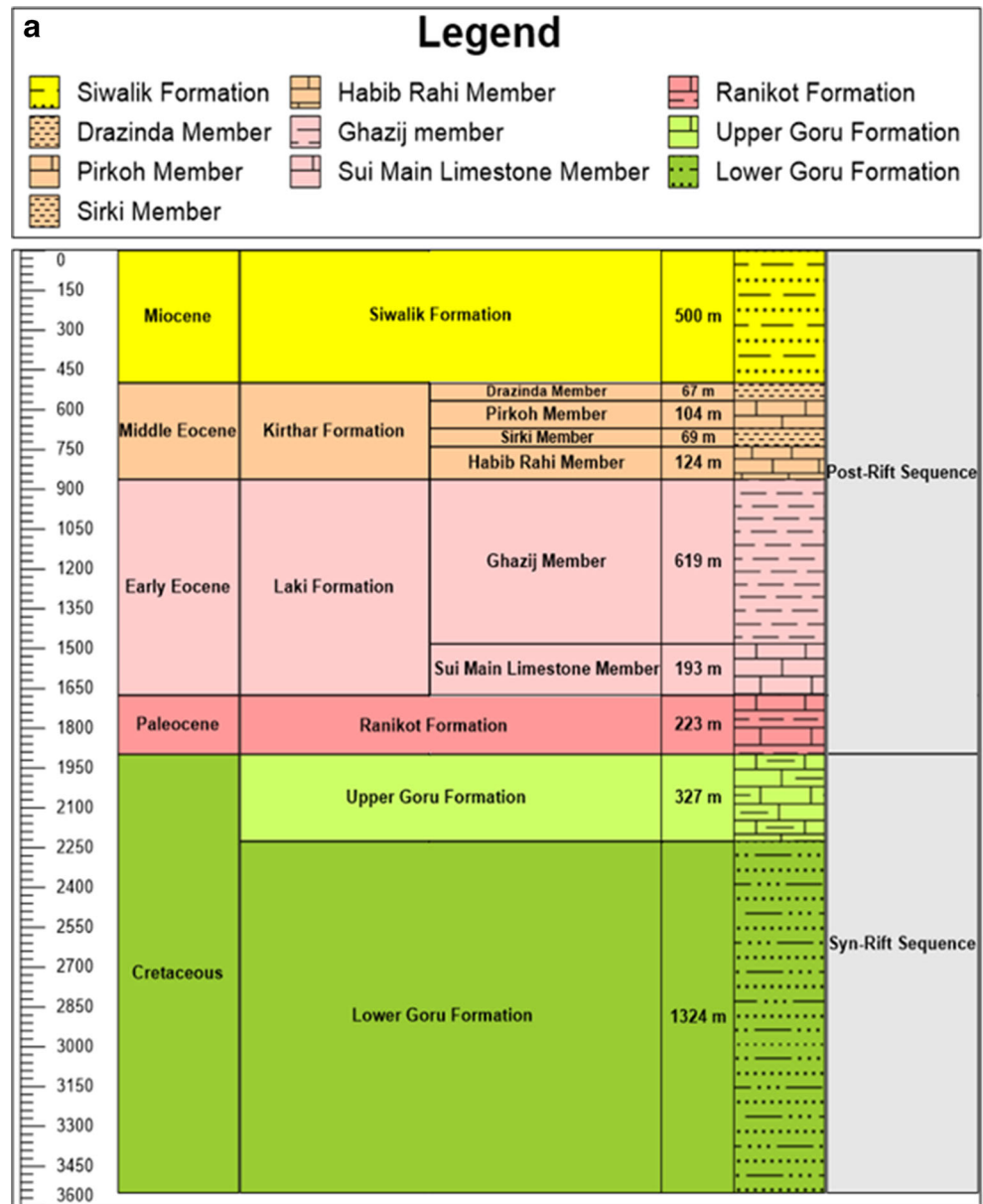
Industry seismic reflection profiles from the Central Indus Basin were made available for this project by Landmark Resources (LMKR), Pakistan with prior permission from Directorate General of Petroleum Concession (DGPC). The interpretation of the reflection data involves its expressions in geological terms. When completely carried out, it requires the fitting together of all pertinent geological and geophysical information into an integrated geological picture that is more complete and more reliable than either source is likely to give alone.

The seismic reflection interpretation usually consists of calculating the position of/and identifying geologically

concealed interfaces or sharp transition zones from which seismic pulses return to the ground surface by reflection. The influence of varying geological conditions is eliminated along the profiles to transform the irregular recorded travel times into acceptable subsurface models. This is very important for a confident estimation of the depth and geometry of the bedrock or target horizons. The main purpose of a seismic reflection survey is to reveal as clearly as possible, the structures and stratigraphy of the subsurface. The geological meanings of seismic reflection are simply an indication of different boundaries where there is a change in acoustic impedance. These observed contrasts are associated with different geological structures and stratigraphic contacts.

For structural interpretation, fourteen seismic lines were used out of which nine were dip lines oriented in an E-W direction, four NW-SE/N-S striking strike lines, and an NE-SW oblique line which was acquired on the Pano Aqil graben

Fig. 5 Stratigraphic column (a) Miano-02, (b) Kadanwari-10



and Kadanwari High (Fig. 4). In the given data, the total depth of the sections is 5 sec (TWT). Each reflector has been picked according to the time and interpreted in terms of velocity and depth. Eight reflectors (Habib Rahi Limestone, Ghazij Shale, Sui Main Limestone, Ranikot Formation, upper Goru Formation, lower Goru Formation, top Chitan Limestone, and base Chiltan Limestone) were picked representing Cenozoic and Mesozoic strata (Fig. 3). Data from Miano-02 and Kadanwari-10 was used for the identification of the horizons on the seismic sections (Fig. 5a and b created using starter). The reflectors were strong enough to be picked due to variation in acoustic impedance that is eventually caused by changes in lithology.

The area was tectonically stable until the Jurassic and probably early Cretaceous. The rifting started to occur during the early to middle Cretaceous, the effects of which can be seen on the seismic section in the form of faults of dip-slip displacement, where the post-Eocene strata are either not or very less affected. Information about the description and deposition of rock units is available in the literature (Kadri 1995).

Seismic data and structural interpretation

The local tectonics of Miano and Kadanwari has led to many uncertainties in understanding the structural

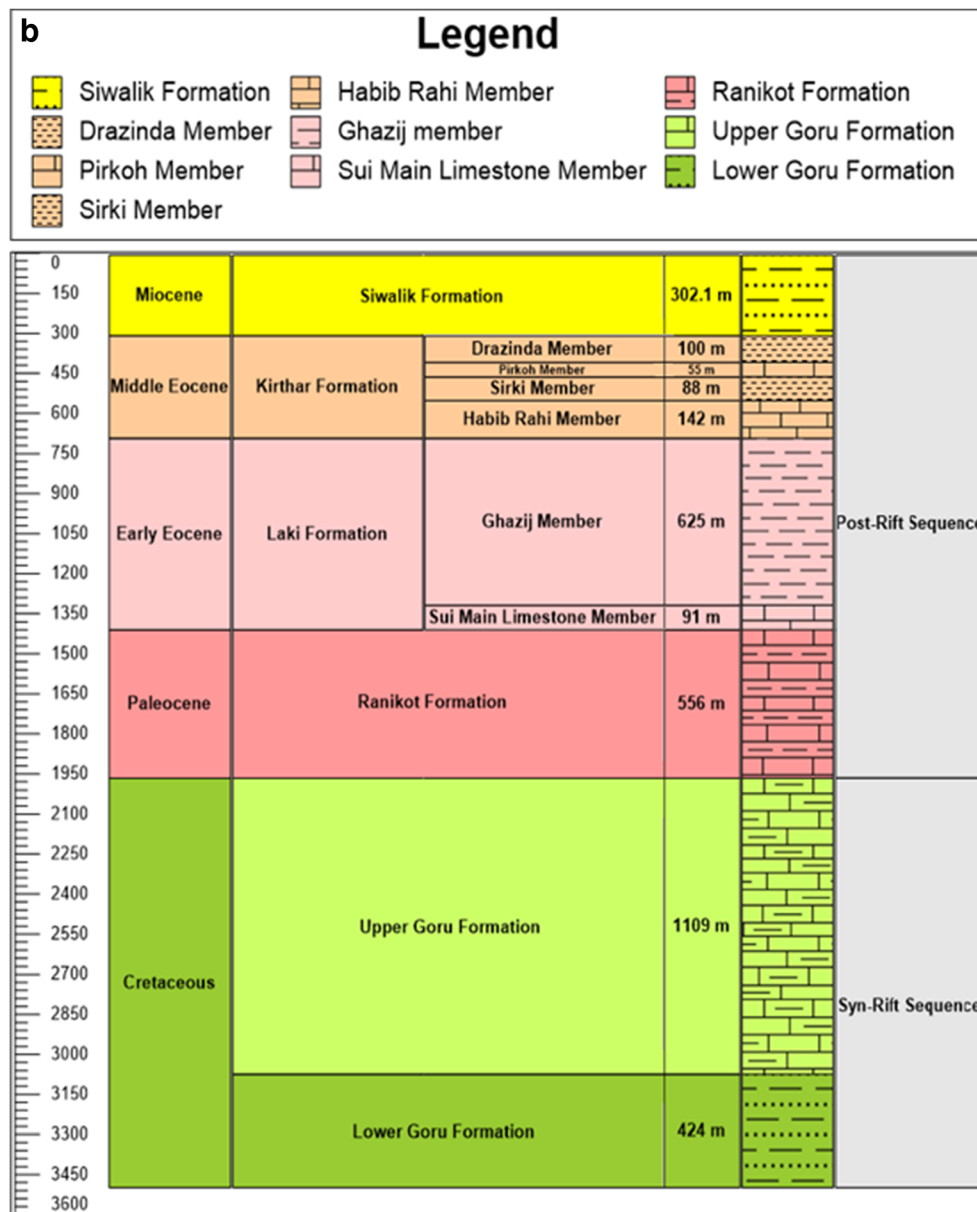


Fig. 5 continued.

framework of the study area. With this detailed study based on well data and seismic interpretation, an extensional fault system has been interpreted as a dominant structural style in the Cretaceous section in the Central Indus Basin (Figs. 6–7). Petrel was used for the interpretation of the seismic data.

In Kadanwari Field, the quality of the seismic lines is of poor to fair quality. The presence of normal faults to the level of Chiltan Limestone have been observed, except one fault which seems to be penetrating across the base Chiltan Limestone of Jurassic age and may likely be of strike-slip origin (Fig. 8). However, the dominance of normal faults in the Cretaceous strata is interpreted throughout the study area (Figs. 6–7).

In Miano Field based on their orientation, faults are dominantly recognized to have an NNW-SSE trend except for subordinate N-S trend (Fig. 9). The majority of the faults are dipping towards the SW. The NNW-SSE trending planar normal faults probably formed as a result of the NE-SW-oriented extension due to the development of the Indian Ocean and NE drift of the Indian plate. Biswas (1999) has observed the change of spreading center to E-W before continuing into the Kutch region in India. The rifting in the Kutch region has taken place along this E-W trend which was active till the late Cretaceous, as a result of which N-S-oriented lineaments may have been interpreted based on gravity interpretation. Therefore, the possibility of N-S faults related to the E-W extension in the Kutch region is minimal.

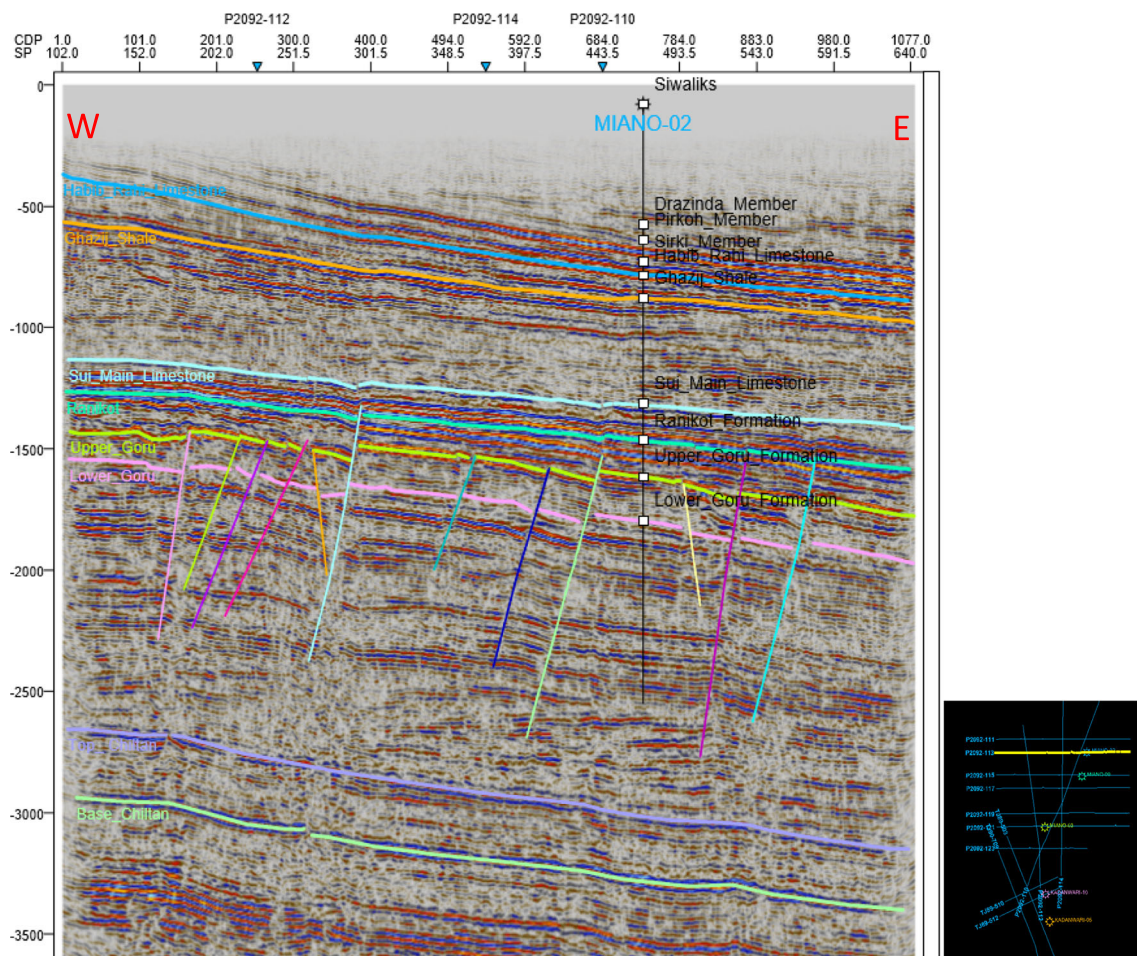


Fig. 6 Interpreted seismic line P2092–113 showing the presence of high-angle planar normal faults

The faults observed in the Miano Field are mostly of high angle, restricted within the Cretaceous sequence that rarely cut the Sui Main Limestone of Eocene age. Thus, indicating that rifting had ceased or slowed down significantly at the beginning of the early Eocene. As a result of normal faulting in the region, tilted fault blocks have developed in the study area depicting bookshelf geometry with the presence of half grabens (Fig. 6).

An extensional system dominantly prevailed in the region during the Cretaceous which is evident by the high density of normal faults in the area (Figs. 6–7). Since faults are generally restricted to the Cretaceous strata, therefore, the possibility of a detachment in the early Cretaceous incompetent Sembar Formation is interpreted at the base of the tilted fault block. The average throw observed was to the order of about 50 m, whereas the maximum throw observed was to the order of about 189 m on the seismic line P2092–123 (Fig. 7).

Wrench or strike-slip faults are found to be absent except for a probable wrench fault to the south of the study area in the Kadanwari Field (Fig. 8). Based on this, the possibility of strike-slip deformation may be interpreted in

the Kadanwari Field. However, the evidence is very weak as the one observed dies out towards the north with no presence at all in the Miano Field. The fault seems to be emanating from somewhere below Chiltan Limestone where a clear disruption can be seen at that level. As the fault propagates upward in the section, it bifurcates with a splay dipping towards the main fault with the development of a graben structures. The set is interpreted as a negative flower structure, related to trans-tensional stresses due to rotation and/or trans-tension along the western margin of the Indian plate. The throw along these faults is less in Kadanwari Field due to probable small magnitude of vertical displacement which is characteristic of strike-slip faults; the maximum throw that was observed was to the order of about 113 m.

Orientation, geometry, and development of the faults

The Indian Plate has experienced episodic rifting throughout the Mesozoic era, which is related to its separation

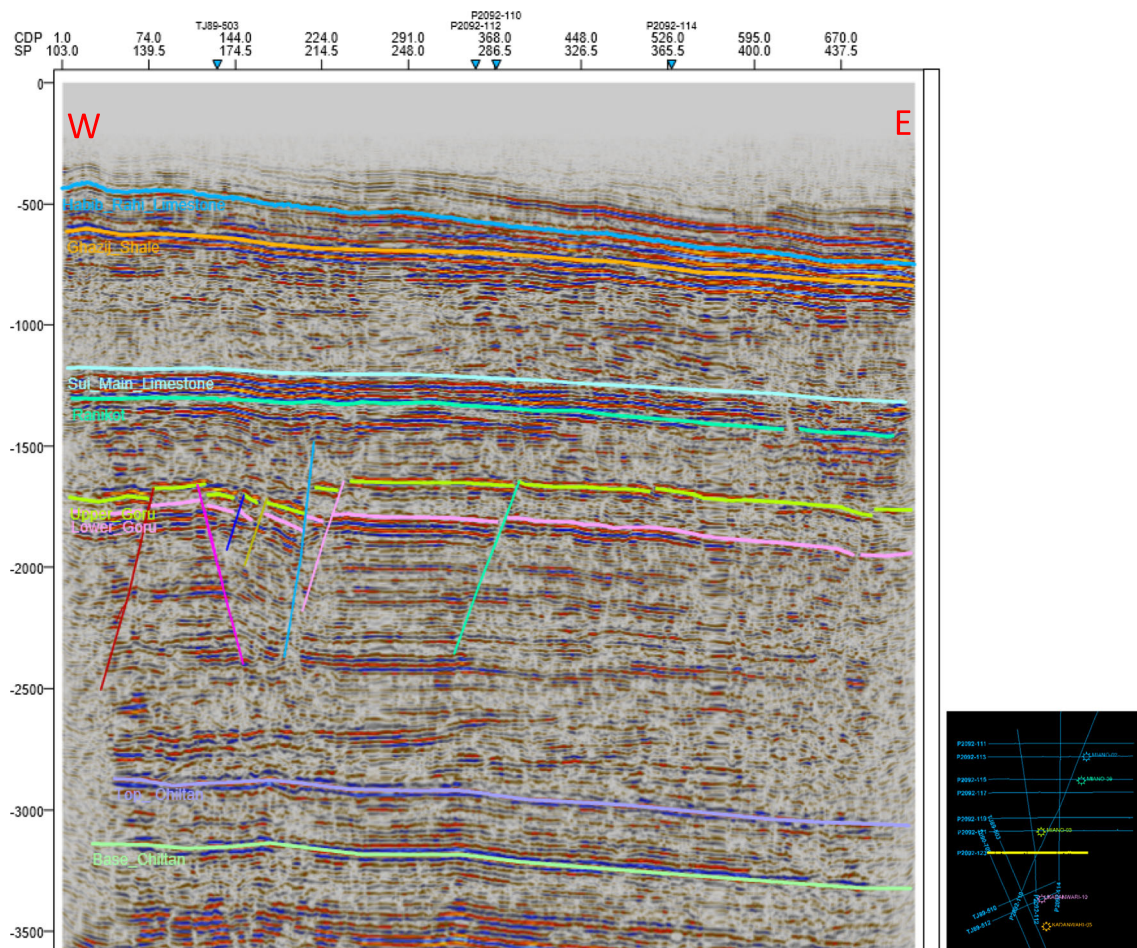


Fig. 7 Interpreted seismic line P2092–123 depicting the greater amount of throw in the upper Goru Formation

from Africa and micro-continents. The rapid 15 cm/yr northwards drift of the Indian plate has decreased to about 5 cm/yr with its collision with the Eurasian Plate in the Eocene about 55–47 Ma which has led to the development of the spectacular Himalayan orogeny.

The initiation of rifting of the Indian Plate ~130 Ma has led to the development of an extensional fault system in the Southern and Central Indus Basin. These faults are mostly restricted to the Cretaceous sequence with a couple of them extending till Paleocene Ranikot Formation. To understand the development of faults, seismic data were critically analyzed to identify pre-rift, syn-rift, and post-rift sequences in the basin. Eight horizons were picked for this purpose, namely, Habib Rahi Limestone, Ghazij Shale, Sui Main Limestone, Ranikot Formation, upper Goru Formation, lower Goru Formation, top and base Chiltan Limestone (Figs. 6–7). The top and base of the Chiltan Limestone were picked based on a bright reflector which depicts the seismic character of Chiltan. Chiltan limestone was interpreted as a continuous strong reflector with no disruptions in the Miano Field portraying that it is

a part of the pre-rift sequence. In the Kadanwari Field, a strike-slip fault seems to be cutting the Chiltan Limestone which may be a deep-rooted fault with a possible link with the anticlockwise motion of the Indian Plate as a result of its collision with the Eurasian Plate (Fig. 8). Syn-rift sequence (Cretaceous) is dominated by intense extension-related normal faulting with the presence of a thicker sequence in the hanging wall of the faults formed as a result of the accommodation space created due to displacement along the faults (Fig. 6). The presence of the normal faults in the Cretaceous sequence serves as evidence that they were developed as a result of the rifting of the Indian Plate. Seismic data depicts a uniformly distributed sequence of Paleocene and younger strata with the interpretation of a post-rift sequence. The post-rift sequence is observed to thicken towards the west, showing an influx of sediments towards the basin with the development of the passive margin of the Indian Plate.

Two sets of faults (Fig. 9) have been interpreted in the study area, i.e., dominant NNW-SSE trending fault which were formed as a result of the NW-SE oriented extension

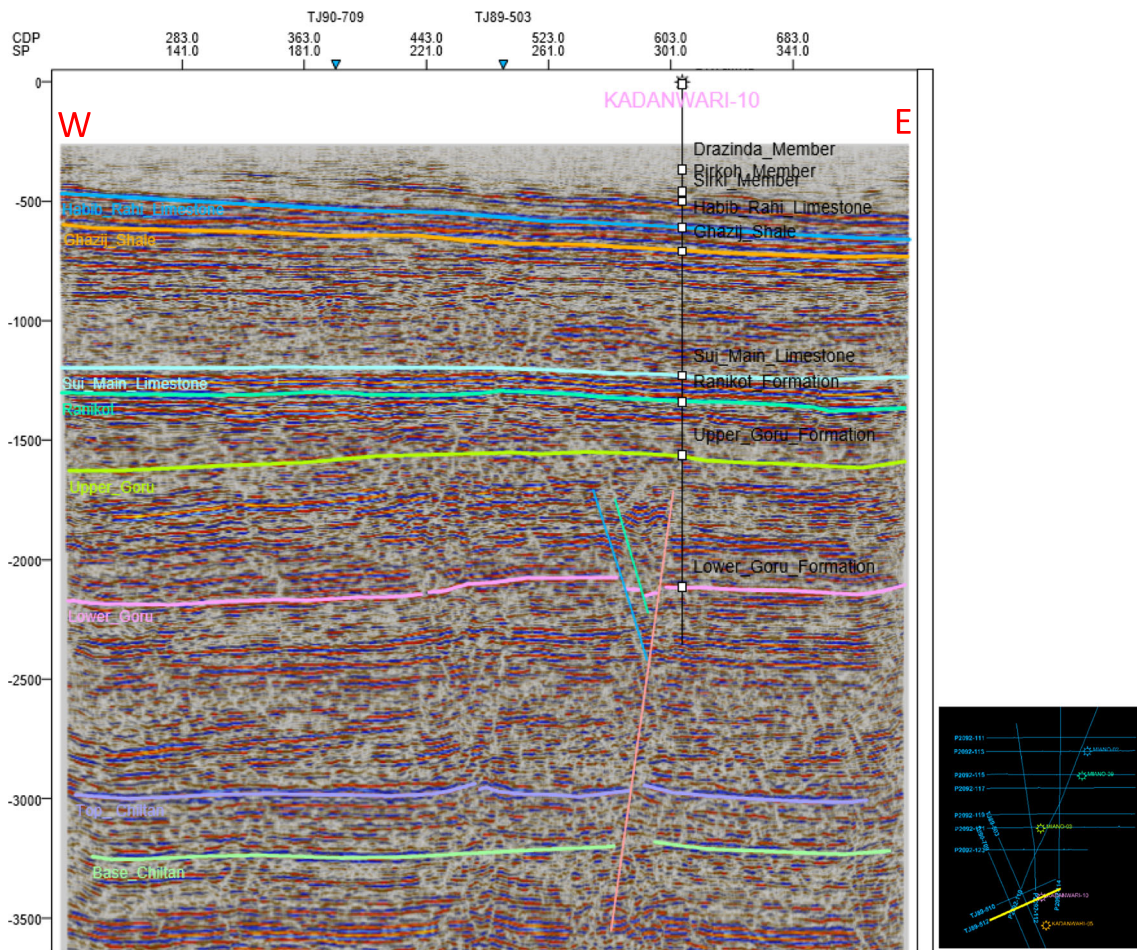


Fig. 8 Interpreted seismic line TJ89-512 showing the presence of a probable strike-slip fault

during the Cretaceous. A few N-S trending faults are also identified which may be associated with minor changes in the trend of fault system and/or E-W extension in the Kutch region. Kutch rifting took place along the E-W extension as a result of which the NNW-SSE trend may have experienced a shift to the N-S trend with the interpretation of a prominent lineament on the residual gravity data (Biswas 1999). Noteworthy is the fact that Biswas (1982) has documented three types of fault trends, underlying the sedimentary cover from across the border on the Indian side, i.e., NNW-SSE (Dharwar trend), NE-SW (Arvalli-Dehli trend), and ENE-WSW (Satpura trend). The concentration and dominance of extension-related normal faults are more towards the northwestern side of the study area; here the faults are closely spaced. The majority of the faults are dipping towards the southwest with an average throw to the order of about 50 m, and the maximum throw of 189 m, and 113 m in the Miano and Kadanwari Fields, respectively. A greater amount of displacement along the faults was seen in the upper Goru Formation as compared to the lower Goru Formation which may be due to the fact

that upper Goru Formation was deposited around 99–65 Ma, which coincides with the timing of the split of the Indian Plate from Madagascar at about 94–90 Ma and Seychelles at about 65 Ma (Raval and Veeraswamy 2003) (Figs. 7–10).

The study area lies on the NW-SE oriented Pano Aqil graben, Biswas (1999) has interpreted the Cambay region an extension of the Pano Aqil graben as a half-graben, with the presence of tilted fault blocks in the Kutch Basin. Tilted fault blocks of planar geometry and half grabens are observed as dominant structures in the study area (Figs. 6–7). Here it is also to be noted that the faults are observed to depict bookshelf geometry over the incompetent Sembar Formation implying the presence of a possible detachment in it (Figs. 6–7).

The pre-rift sequence of uniform thickness is observed to gently dip towards east. A thick syn-rift sequence of variable thickness was encountered in the seismic and well data as a result of growth strata along normal faults in the Cretaceous section. The syn-rift sequence is gently tilted with a thick accumulation of upper Goru sediments

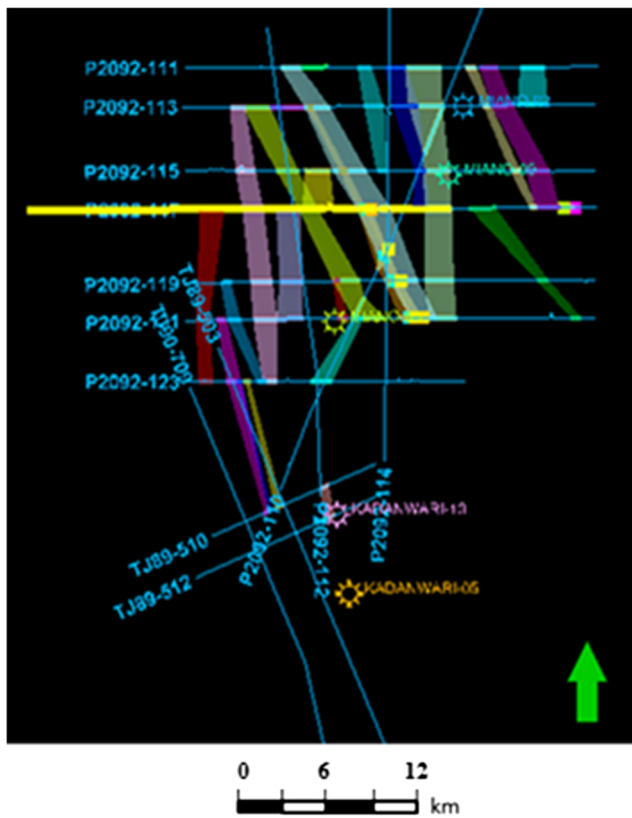


Fig. 9 Distributed trend of the faults in the study area based on seismic interpretation

in Kadanwari-10 (Fig. 5b). The post-rift sequence is mostly gently dipping towards the east with increased thickness towards the west showing that the direction of the sediment influx was from east to west at the time of its deposition. Subsequently, it is tilted towards west due to the development of the Jacobabad-Khairpur High; the strata resume its westward dip after crossing the Jacobabad-Khairpur High (Fig. 6).

Fault model

A lot of work has been done in the southern part of the Central Indus Basin regarding the importance of stratigraphic traps in the region. Structurally only a single model is present that too of the Kadanwari Field proposed by Ahmad et al. (2011) in which he has stressed the presence of deep-rooted strike-slip tectonics in the region with the presence of flower structures formed during the Paleogene as a consequence of the anticlockwise rotation of Indian Plate on its initial collision with the Eurasian Plate. Structurally, the Miano and Kadanwari Fields are important as Ahmad and Chaudhary (2002) have also

stressed the presence of fault-bounded structures in the Kadanwari Field which may be considered as future potential prospects.

In the Miano Field, no apparent evidence of strike-slip tectonics was observed. The structural style in the Miano region mostly involves planar-tilted fault blocks with the dominance of half grabens, the concentration of which increases towards the west (Jacobabad-Khairpur High) as compared to the eastern side. These tilted fault blocks can be good prospects for future exploration because most of the wells in the Miano region have been drilled towards the eastern and southern sides. If the faults are non-sealing in nature, the importance of these tilted blocks towards the Jacobabad-Khairpur High increases exponentially as we know that the hydrocarbons move in an up-dip direction which in this case is towards the Jacobabad-Khairpur High, which is also evident from the dip of the strata which are dipping in the easterly direction. Even if the faults are sealing in nature than also the tilted fault blocks can provide a good prospect in the region, here it is to be noted that the spacing between the faults concentrated towards the west is small and are closely spaced as compared to the spacing of the faults towards the east. Thus, the tilted fault blocks are recognized as a potential prospect for future hydrocarbon exploration in the region (Fig. 11).

Hydrocarbon potential and prospects

Central Indus Basin is a potential hydrocarbon province in the Indus Basin. Many local and multinational oil and gas companies are involved in active exploration and production in the region. It is a prolific gas province with several gas discoveries being made each year. In the region between the Jacobabad-Khairpur and Mari-Kandhkot High, several prolific gas fields have been discovered by OMV, which is actively exploring for gas in several fields such as Miano, Sawan, Latif, and Tajjal. Eni Pakistan is working in the Kadanwari field and Mari Petroleum Company Limited (MPCL) in Mari and Mari deep fields located on the Mari-Kandhkot High. The reserves of Miano and Kadanwari Fields as of June 30, 2011 (Petroleum exploration and production activities in Pakistan, annual report (2010–2011)), are analyzed in the form of a bar chart to get an idea of the reserves in these fields (Fig. 12) (Table 1). Miano and Kadanwari Fields show a significant amount of original recoverable gas reserves, i.e., 552 (bcf) and 1110 (bcf) equivalent to 90 (mmboe) and 190 (mmboe), respectively. Out of these original recoverable gas reserves, 438 (bcf) and 420 (bcf) have been extracted from the Miano and Kadanwari Fields, respectively. The balance recoverable gas reserves as of June 30, 2011,

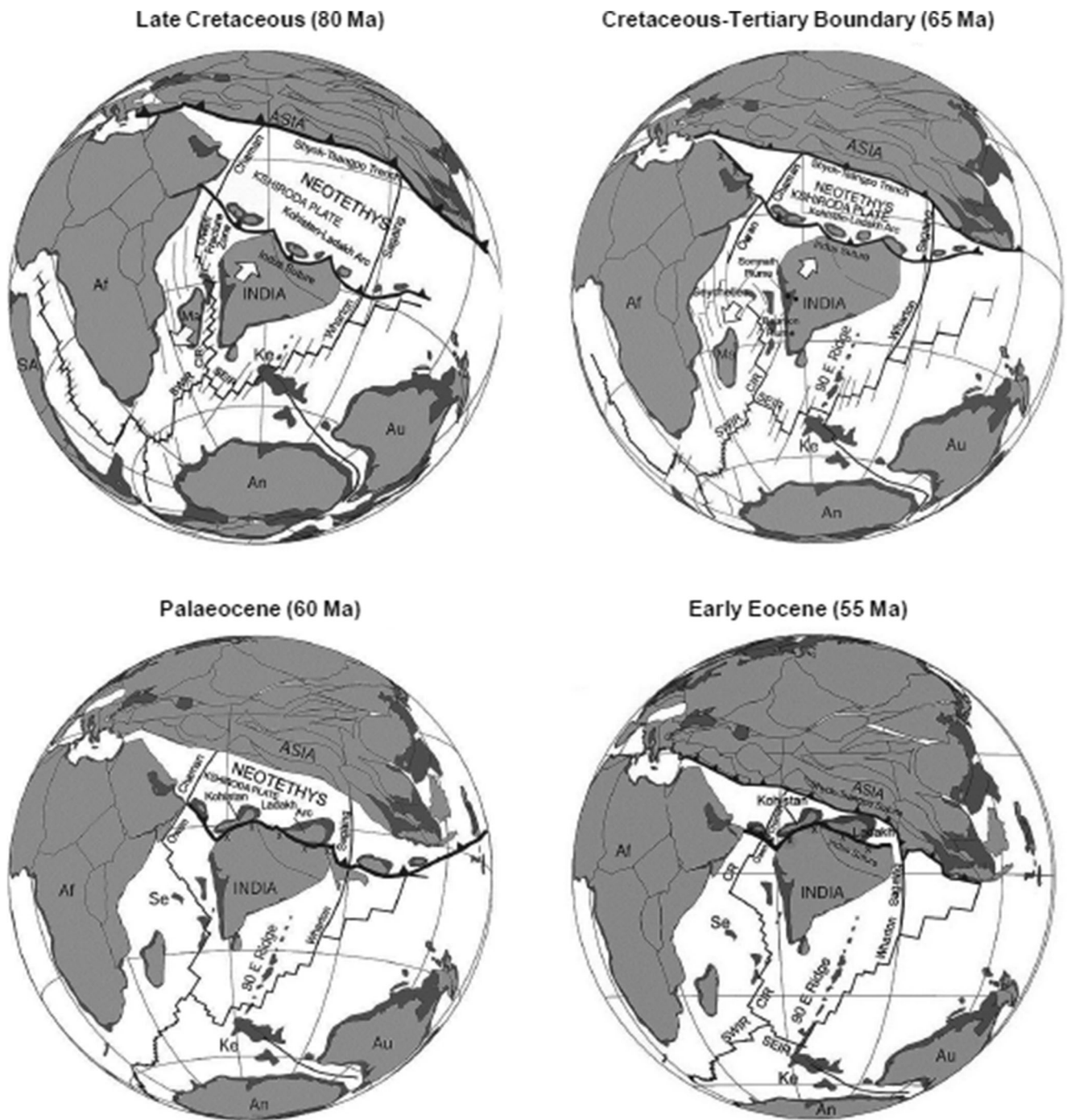


Fig. 10 Rift and drift of the Indian Plate leading to its split from Madagascar at about 90 Ma ago (Chatterjee and Bajpai 2016)

were 114 (bcf) and 690 (bcf) equivalent to 19 (mmboe) and 110 (mmboe) for the Miano and Kadanwari Fields, respectively. The increased amount of gas reserves in the Kadanwari Field as compared to the Miano Field may be attributed to the up-dip migration of the hydrocarbons as the Kadanwari Field lies on a structural high known as the

Kadanwari High. Cumulative reserves of these two fields are 280 (mmboe) which is minutely less to the 300 (mmboe) in Salt Range/Potwar Plateau.

Due to the dominant extensional regime, planar normal faults have developed in the region with the presence of tilted fault blocks that are dominantly dipping in the

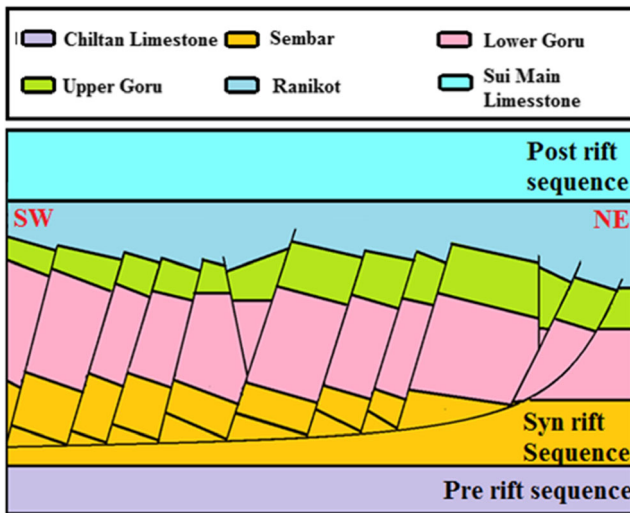


Fig. 11 Planar geometric fault model for the Miano Field with the presence of tilted fault blocks

southwest direction. Half grabens are the dominant structures formed in response to the extensional-related normal faulting. The tilted fault blocks with the southwest dip along with the strata getting shallower towards the west are recognized as potential prospects in the region due to the up-dip migration of hydrocarbons.

Conclusions

1. The seismic data interpretation of the Miano and Kadanwari Fields shows that the area is mostly dominated by extension-related normal faulting with a probable strike-slip fault to the south of the study area, i.e., in Kadanwari Field.
2. The faults are interpreted to occur as a set of dominant NNW-SSE and less dominant N-S trending normal faults with dips either towards northeast or southwest,

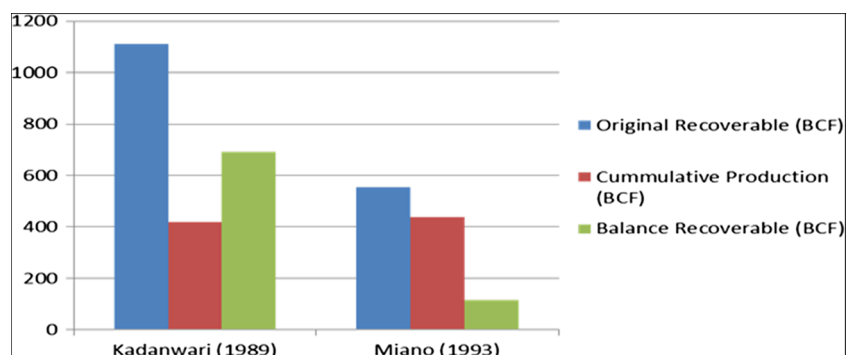
Table. 1 Gas reserves of Kadanwari and Miano Fields as of June 30, 2011

Field	Original recoverable	Cumulative production	Balance recoverable
Kadanwari field	1110 BCF	420 BCF	690 BCF
Miano field	552 BCF	438 BCF	114 BCF

with the majority of the faults dipping towards the southwest.

3. The average displacement observed is to the order of ~50 m with the maximum throw of ~189 m, and ~113 m observed in the Miano and Kadanwari Fields, respectively. The greater amount of displacement observed in the upper Goru Formation may be attributed to the drift of the Indian Plate from Madagascar at about 94–90 Ma and Seychelles at about 65 Ma.
4. Tilted fault blocks of planar geometry were interpreted in the Miano Field with the dominance of half grabens in the Cretaceous strata. The graben structures are observed to sole out/merge in a detachment in the incompetent Sembar Formation above Jurassic Chiltan Limestone which is generally not disturbed by the fault system.
5. Sedimentary strata are divided into three tectonostratigraphic units as pre-rift (Jurassic and older), syn-rift (Cretaceous and Paleocene), and post-rift (Eocene and younger) sequence. 3D structural analysis of the picked horizons shows a moderate structural dip of strata towards the east in the post-rift sequence, the syn-rift, and pre-rift sequences are gently dipping towards the east.
6. Tilted fault blocks with westward dip are identified as prospects for drilling.
7. Collective original recoverable reserves of 280 (mmboc) of the Miano and Kadanwari Fields are now

Fig. 12 Bar graph representation of gas reserves in the Kadanwari and Miano Fields as of June 30, 2011



limited to 129 (mmboc). Thus, a significant amount of hydrocarbon reserves are present in Miano and Kadanwari Fields.

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