Research
An Insight into the petroleum system and hydrocarbon potential of Miano and Kadanwari blocks, Central Indus Basin, Pakistan

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Abstract: The main purpose of this paper is to evaluate the hydrocarbon potential of Miano and Kadanwari blocks, located in the Central Indus Basin (CIB), Sindh province, Pakistan. Kadanwari and Miano fields located in between two extensive NW-SE oriented regional highs i.e. Jacobabad-Khairpur and Mari-Kandhkot High were discovered in 1989 and 1993 respectively. The CIB is an extensional basin exhibiting normal faulting. Borehole data from 5 wells was used to assess the petroleum system of the two fields. Well logs of Miano-02 and Kadanwari-10 were analysed to calculate the petro-physical parameters such as the volume of shale, porosity, water saturation, and hydrocarbon saturation. These fields are interpreted to have significant recoverable reserves of 1662 (BCF) equivalents to 280 (MMBOE).

Keywords: Hydrocarbon Potential, Central Indus Basin, Extensional Basin, Normal Faulting, Petrophysical Parameters, Recoverable Reserves

INTRODUCTION

The present study focuses on the Miano and Kadanwari blocks, that lie between latitude 27° 10' 0" - 27° 24' 42" N and longitude 69° 19' 0" - 69° 19' 16" E, in the Sukkur and Khairpur districts of Sindh Province, Pakistan (Fig. 1). Tectonically, the area is located in the Central Indus Basin (CIB) along the western margin of the Indian Plate, bounded between two regional highs i.e. the Mari-Kandhkot High to the northeast and the Jacobabad-Khairpur High to the southwest. The CIB is a gas prone province containing 70% of Pakistan’s known gas reserves. Proven reserves are trapped dominantly in the Upper Cretaceous and Tertiary reservoirs. The discoveries of Kadanwari, Miano, Mari Deep and Sawan fields have
confirmed the potential Lower Cretaceous sandstone play in CIB. These fields mainly produce from Lower Goru sands. The reservoirs of the Miano and Kadanwari Fields are charged by the Early Cretaceous Sembar Formation, which is a proven hydrocarbon source rock in Pakistan. The principal qualities of the good source rocks are; organic richness, gas prone kerogen, and thermal maturity. Sembar Formation has all these qualities which is the main reason for discoveries in the Indus Basin (Viqar-un-nisa Quadri, 1986; Kadri, 1995).

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

Beginning of Cretaceous marks the worldwide rising of the sea level which made the organic life flourish. Furthermore, basin wide anoxia caused the preservation of organic matter. Time and temperature were favorable to turn this preserved organic matter into hydrocarbons. CIB was an area of extensional tectonics during Lower to Middle Cretaceous associated with slightly restricted circulation of the sea waters at the north western margin of Indian plate. Lower Cretaceous source rocks (Sembar Formation) were deposited while the basin was opening up and anoxia was prevailing. Similarly Middle to Upper Cretaceous clastics were deposited in a setting favorable for preservation of organic matter.
Geochemical analyses of the rock samples from the Indus Basin have shown that the bulk of the hydrocarbons produced are derived from the Lower Cretaceous Sembar Formation and equivalent rocks. Sembar Formation is composed of shale’s of mixed type-II and type-III kerogen with total organic carbon (TOC) content ranging from <0.5 percent to >3.5 percent. In addition, the average TOC of the Sembar Formation is ~1.4 percent with vitrinite reflectance ($R_0$) values range from immature (<0.6 percent $R_0$) to over mature (>1.35 percent $R_0$) (Wandrey et al., 2004). Thermal generation of hydrocarbons in the Sembar Formation began during Paleocene to Oligocene (65-40Ma). Hydrocarbon expulsion, migration and entrapment are interpreted to have occurred mainly during Eocene to Miocene (50 to 15 Ma), prior to and contemporaneously with the development of structural traps in Upper Cretaceous and Tertiary reservoirs (Wandrey et al., 2004). The intra-shales of Lower Goru Formation combined with marl, and shale sequence of the Upper Goru Formation of Early to Middle Cretaceous act as the cap rock to the Lower Goru sands (Viqar-un-nisa Quadri, 1986).

**REGIONAL GEOLOGY AND TECTONIC SETTINGS**

Miano and Kadanwari are located in the CIB between two regional extensive highs i.e. the Mari-Kandhkot High to the northeast and Jacobabad-Khairpur High to the southwest (Fig. 2). The development of structural highs i.e Jacobabad-Khairpur and Mari-Kandhkot may be attributed with the development of a Cretaceous and Cenozoic passive margin along southwestern part of the Indian plate during its northwards drift from Africa. Miano and Kadanwari fields have been subject to intense episodic deformation since the beginning of Indian Plate drift towards north with the presence of numerous normal faults perpendicular to the drift plane. The anti-clock wise motion of the Indian plate around 55-50 Ma (Powell, 1979; Ding et al., 2005; Ding et al., 2016; Baral et al., 2018; Qasim et al., 2018) may have led to the development of strike-slip faults with complex structures in the present study area. As a result of the Early Cretaceous uplift, Early Eocene wrenching, and Late Tertiary compression the area has developed structural/stratigraphic traps exhibiting negative flowers structures, sand bed pinchout, and vertical to sub-vertical normal fault (Ahmad et al., 2011).
The CIB can be 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 northwest-southeast oriented Jacobabad-Khairpur High acts as a barrier between two foredeep basins, (Kaachhu and Sulaiman Foredeep) and is interpreted as a basement induced structure that interrupts the westward dipping of the Sindh platform (Krois et al., 1998). Jacobabad-Khairpur High was most likely active between Mesozoic and Lower Tertiary period, evidenced by the base Tertiary unconformity (Fig. 3).

From Jurassic to Late Cretaceous, the area of present Khairpur High has occupied a basinal position. The depo-center during the Lower Cretaceous is situated to the east of the high. During Early Tertiary, either extensional or wrench tectonics induced uplift leading to the development of structural highs, and erosion of Upper Cretaceous Mughal Kot and Pab Formations. Normal faulting with a dominant NW-SE trend has taken place (Ahmed et al., 2013; Jadoon et al., 2016). The final development Khairpur High started in the Oligocene along the western and northern margins, and continued into the Late Cenozoic time. The reservoir in the Miano-02 well is configured with a structural trap developed as a result of...
Fig. 3 Generalized tectono-stratigraphy and distribution of the source and reservoir rocks along an EW cross-section in the region.

Fig. 4 Interpreted seismic line P2092-113 showing the presence of high angle planar normal faults in Cretaceous section. Marker horizons from top to bottom are: Top Habib Rahi Limestone (dark blue), top Ghazij shale’s (Orange), top Sui Main Limestone (light blue), top Ranikot (aqua blue), top Upper Goru (light green), top Lower Goru (pink), top Chiltan (purple), and base Chiltan (mint).
extension with the presence of horst and graben, half graben, and roll-over anticlinal structures. The well Miano-02 was drilled in a horst which is bounded by two normal faults (Jadoon et al., 2016) (Fig. 4).

WELL DATA SET

Data of five wells (Miano-02, Miano-03, Miano-09, Kadanwari-05, Kadawanri-10) was acquired from Landmark Resources (LMKR), Pakistan with prior permission from Directorate General of Petroleum Concession (DGPC).

POST, SYN AND PRE-RIFT SEQUENCES

The Indian Plate has experienced episodic rifting throughout the Mesozoic, as a result of its separation from Africa, and other micro continents. The rapid (~15 cm/year) northwards drift of the Indian plate decreased to ~5 cm/yr after docking with the Eurasian Plate in the Eocene at ~ 55 to 47 Ma, leading to the development of the spectacular Himalayan orogeny (Powell, 1979; Ding et al., 2005; Ding et al., 2016; Baral et al., 2018; Qasim et al., 2018).

A fence diagram was constructed for understanding the rift related sequences (Figs. 5 and 6). It shows that the post-rift sequence of the post-Eocene strata is uniformly distributed in all the wells with minor changes towards the west (Miano-03), the Siwaliks thin out but increase gradually towards the south noticed in Kadanwari-10 and 05 These results can be attributed to the fact that Siwaliks are recent deposits, deposited from the movement of the clasts towards the basin, located south of the Himalayan orogeny, and east of Sulaiman fold-and-thrust belt. All the four members (Drazinda, Pirkoh, Sirki, Habib Rahi Limestone) of the Eocene Kirthar Formation are uniformly distributed, and are getting shallower towards the west (Miano-03) possibly due to the presence of the Jacobabad-Khairpur High. The thickness of the Laki Formation (Ghazij shale and Sui Main Limestone) is uniform throughout the section while the great thickness of the Ghazij shale points to the fact that during the Early Eocene deep marine conditions prevailed for a long period of time giving Ghazij shale an ample time to deposit. Such a thick sequence of shale can act as a good source rock for the formations above and can also serve as a seal rock for the formations beneath, especially for Sui Main Limestone which is a proven reservoir to the west in the Sulaiman fold-and-thrust belt. Ranikot Formation is deposited on top of the Tertiary unconformity showing a gradual increase in thickness towards the west with an exponential increase in its thickness towards the south, the thick sequence to the south can also be related to the accommodation space created due to the uplift and erosion during Late Cretaceous.
Cretaceous to Early Eocene syn-rift sequence is characterized by thick sequences, and growth strata as a result of accommodation space created due to normal faulting. The Late Cretaceous Parh Formation was only encountered in two wells (Miano-09 and Miano-03). The thickness of Parh Limestone decreases to the west from 69 m encountered in Miano-09 to 6 m in Miano-03 before pinching out against an unconformity. The uplift of the Jacobabad-Khairpur High during Late Cretaceous to Early Tertiary may have led to the erosion of the Late Cretaceous sequence, which is evidenced by the base Tertiary unconformity (Krois et al., 1998). The thickness of Upper Goru Formation is constant in the east-west cross-section (Miano-02, Miano-09 and Miano-03) with an abrupt increase to the south (Kadanwari-10) before decreasing farther south (Kadanwari-05). The thickness of Lower Goru Formation varies from well to well; it is increasing towards the west due to the westward transportation of the sediments during the Cretaceous as a result of rifting. Due to the absence of well data of Chiltan Limestone and older formations, we did not incorporate it in the fence diagram.

**INTERPRETATION OF WELL LOGS OF MIANO-02 AND KADANWARI-10**

To evaluate the potential of each formation for producing hydrocarbons, we carried out the petrophysical analysis of two wells (Miano-02 and Kadanwari-10) by using the common log curves (caliper, GR, SP, resistivity, density, neutron and sonic) to analyze formation characteristics, and fluid presence (Fig. 7a–7b). The horizon of interest i.e. Lower Goru Formation in Miano-02 having thickness of 1324 m was divided into two zones (zone-1 & zone-2) due to data variations which were difficult to track or interpret as a single zone. On the basis of the above mentioned zones

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**Fig. 5 Map view of the wells used for constructing the fence diagram.**
petrophysical parameters were calculated, which include volume of shale, sonic porosity, effective porosity, water saturation, and hydrocarbon saturation (Fig. 8). Zone-1 (Fig. 8a) ranges from 3000 m to 3250 m, having a thickness of ~250 m. Two potential hydrocarbon zones (1A and 1B) can be identified. Zone-1A has all the characteristics required of a good reservoir, the volume of shale fluctuates between 0 and 45% from 3000 m to 3076 m with a thickness of 76 m. Sonic and effective porosity show positive results ranging from 12% to 30%, and 9% to 18% indicating interconnected pore spaces in this zone. It is worth mentioning that water saturation (8% to 28%) is on the lower side, most of the pore spaces are filled with hydrocarbons confirmed by the low P-wave values in the zone (Fig. 7a). After crossing the 3076 m mark a spike in GR log is noticed (Fig. 7a) indicating an increase in the volume of shale, which is also confirmed by the decrease in the values of sonic and effective porosity. This zone from 3076 m to 3135 m marks an increase in water saturation which ultimately leads to a decrease in the presence of hydrocarbons. Zone-1B yielded a thickness of 114 m, volume of shale fluctuates between 0 and 60%. The values of effective porosity range from 10% to 24% before decreasing significantly at a depth of 3180 m with an increase in the volume of shale, indicating that the formation has changed from dominant sand to dominant shale and vice versa. The hydrocarbon percentage in this interval is good but the
cross-over of neutron and density log is very less, on the basis of this finding we draw the conclusion that zone-1A probably has a much better hydrocarbon potential than zone-1B. The change in the lithology from sand to shale and vice versa also gives an insight into constant fluctuations in sea level and environment of deposition of the Lower Goru Formation.

The zone-2 (Fig. 8b) yielded a thickness of 300 m, the volume of shale varies from 0 > 60% at some points with an average of 37.62%. Negligible crossovers of neutron and density log of minimal thickness 20 m and 5 m in the upper portion can be noticed. The values of effective porosity, sonic porosity, hydrocarbon saturation encountered are encouraging but the drawback is the thickness of the crossover. The only favorable zone encountered with an appropriate thickness starts from 3436 m to 3498 m having a thickness of 62 m; the volume of shale is on a higher side above 45%. The values of sonic and effective porosity observed are also good which range from 5% to 24%, and 4% to 12% respectively. The hydrocarbon saturation starts on the lower side but gradually increases at a depth of 3456 m to about above 75%. Below the depth of 3498 m the pore spaces are largely saturated with water.

In the Kadanwari-10 well the horizon of interest i.e. Lower Goru Formation was divided into two potential zones based on the response of the well logs, and the calculated petrophysical parameters: zone 1 (3140 m – 3328 m), and zone 2 (3384 m- 3496 m) (Fig. 9). Zone-1 (3140 m- 3328 m) has a thickness of 188 m, volume of shale calculated in this zone ranges between
Fig. 7b Basic log curves of Kadanwari-10.

Fig. 8a Petrophysical parameter curves for zone-1, Miano-02.
Fig. 8b Petrophysical parameter curves for zone-2, Miano-02.

25% - 50% with an average of about 35%. Volume of shale calculated shows that the formation is mostly clean and can be classified as predominantly argillaceous sand deposit. High sonic (2% - 60%) and effective porosity (2% - 60%) values are encountered to a depth of 3184 m, which then slightly decrease as the volume of shale increases slightly. The pore spaces are well connected with a very good overall porosity. Hydrocarbon saturation encountered is excellent (65% - 80%) with slight fluctuation at some levels. Neutron and density log cross-over can be noticed in the whole column which is a good indication of the presence of gas in the region.

Zone-2 (3384 m - 3496 m) has a thickness of 112 m, a clear cross-over of the neutron and density log can be noticed. Volume of shale is constant throughout with an average of 32%. Sonic and effective porosity values also lie in a good range of 12% - 28%, and 8% - 20% respectively. The only problem is that the pores are mostly water saturated, values of sonic log vary from 25% to >75% with a decrease in the concentration of hydrocarbon potential (Fig.7b).
HYDROCARBON POTENTIAL AND PROSPECTS

CIB is a potential hydrocarbon province in the Indus Basin. In the region between the Jacobabad-Khairpur and Mari-Kandhkot High a number of prolific gas fields have been discovered by OMV such as: Miano, Sawan, Latif, and Tajjal. Eni Pakistan is producing from the Kadanwari block, and Mari Petroleum Company Limited (MPCL) from Mari and Mari deep fields located at 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 displayed in the form of a bar chart (Fig.10). Miano and Kadanwari fields show a significant amount of original recoverable gas reserves of 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/Kadanwari fields. The balance recoverable gas reserves as of June 30, 2011 were 114 bcf and 690 bcf equivalent to 19 mmboe and 110 mmboe for the Miano/Kadanwari fields. 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 is 280 mmboe which is minutely less to the 300 mmboe calculated in Salt Range/Potwar Plateau (Jadoon et al., 2015).

<table>
<thead>
<tr>
<th>Fields</th>
<th>Original Recoverable</th>
<th>Cumulative Production</th>
<th>Balance Recoverable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kadanwari Field</td>
<td>1110 BCF</td>
<td>420 BCF</td>
<td>690 BCF</td>
</tr>
<tr>
<td>Miano Field</td>
<td>552 BCF</td>
<td>438 BCF</td>
<td>114 BCF</td>
</tr>
</tbody>
</table>

Figure 10a Gas reserves of Kadanwari and Miano Fields as of June 30, 2011.

Fig. 10b Bar graph representation of gas reserves in the Kadanwari and Miano Fields as of June 30, 2011.

CONCLUSIONS

1. The petroleum system sedimentary strata are divided into three (03) tectono-stratigraphic units: post-rift (Jurassic and older), syn-rift (Cretaceous and Paleocene), and post-rift (Eocene and younger) sequence.

2. The cross-correlation between wells shows a thick syn-rift sequence consisting of Lower Goru Formation (reservoir) and the Upper Goru Formation providing seal for the thick sequence of Lower Goru Formation. The post rift sequence is uniformly distributed throughout the area, an increase in its thickness is noticed towards the west.

3. Petrophysical analysis of Miano area shows that both the zones (1 and 2) have a good hydrocarbon potential. Two Potential zones (1A-1B) were identified in the zone 1 ranging in depth from 3000 m – 3250 m, having a thickness of 76 m and 114 m respectively. In the zone-2, a few small crossovers of neutron and density logs could be seen but on the basis of thickness only one potential zone was identified having a thickness of 62 m.
4. Petrophysical analysis of Kadanwari-10 shows two favorable zones having a good a hydrocarbon potential. The depth of the reservoir zone ranges between 3080 m - 3480 m. The zone-1 has a greater thickness of 188 m as compared to the zone-2 having a thickness of 112 m. The hydrocarbon potential in the zone-1 is greater than that of zone-2.

5. Collective original recoverable reserves of 280 (mmboe) of the Miano and Kadanwari fields are now limited to 129 (mmboe). Thus significant amount of hydrocarbon reserves are present in Miano and Kadanwari Fields.

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