Volume 17, Issue 4, 172526 (1-11)

Iranian Journal of Earth Science (IJES)

https://doi.org/10.57647/j.ijes.2025.16848

Impact of structural style variation on hydrocarbon entrapment in Kirthar Foldbelt, and Kirthar Foredeep, of Southern Indus Basin, Pakistan

Muhammad Kashif Shahzad Baig[1,2,*], Shahid Ghazi[1]

[1] *Institute of Geology, University of Punjab, Lahore, Pakistan.*
[2] *Pakistan Oil Fields Limited, Rawalpindi, Pakistan.*

*Corresponding author: kashifgeophysicist@gmail.com

Original Research

Received:
2024-01-15
Revised:
2024-08-19
Accepted:
2024-09-24
Published online:
2025-05-25
Published in issue:
2025-10-30

Abstract:

The style of structural deformation plays a crucial role in the trapping of hydrocarbons within the Kirthar Foldbelt and Foredeep. This investigation explores the factors contributing to the success and challenges of hydrocarbon exploration in these regions of the Southern Indus Basin of Pakistan. Despite the drilling of numerous wells in both geological zones, the success rate persists at approximately 20%. A common reason for unsuccessful drilling is often linked to trap integrity. Many wells have targeted surface structures bounded by major faults. It has been observed that most of these faults, extending to the surface, fail to provide effective sealing, leading to trap breaches. Nevertheless, there are instances within the study area where faults reaching the surface have successfully sealed traps. The current study aims to identify the distinguishing factors between sealing and non-sealing bounding faults in this region. The seismic data from producing and nonproducing fields within the Kirthar Foldbelt and Foredeep has been utilized in the analysis. However, only 3D seismic data of Zamzama Field was available, so it is interpreted while for analyzing the structural style of other fields the published 2D seismic data from available sources have been utilized.

Keywords: Kirthar Foldbelt; Kirthar Foredeep; Hydrocarbon entrapment

1. Introduction

The integration of seismic data with well and geological information offers a consistent tool for depicting subsurface geology (Qureshi et al., 2021). An integrated approach is crucial for petroleum exploration and subsurface interpretations. It assists in tracing the subsurface geological structures and establishing reliable correlations. Sub-surface structural analysis to comprehend an area's geology and tectonics is consistently beneficial for locating Hydrocarbon resources (Hussain et al., 2019). A precise identification of the subsurface geological perspectives and structures is vital for Hydrocarbon probe, and it delivers a perception about the framework and structural styles of a basin. Furthermore, interplay between shortening and shear has imperative implications for location of traps and their preservation. These seismic and surface data along with site of Hydrocarbon fields portray substantial clue that might be valuable for upcoming exploration in Kirthar Foredeep and adjoining areas.

Lower Indus Basin is an oil and gas prone basin (Ehsan et al., 2021; Jehangir Khan et al., 2021; Ahmad and Ghazi, 2022). Kirthar Foldbelt and Kirthar Foredeep has long been the subject of exploration, but it wasn't until the Bhit-2 well made its first significant finding in 1997 as a consequence of exploration operations between 1994 and 1997 by Eni-Lasmo Pakistan and partners after securing an exploration license in the southern section of Kirthar Foldbelt (Smewing et al., 2002). This discovery was made without the use of seismic technology and was instead supported by extensive field geological research, geological modelling, and knowledge of the region's tectonic history. Later, however, 2D and 3D seismic data was gathered, which aided in a better understanding of the area.

A number of local and international Exploration and Production companies are working for exploring Hydrocarbons in Kirthar Foldbelt and Kirthar Foredeep. The several wells were drilled in this region and results were achieved from the wells Zamzama and Bhit but failed the wells Bhan-1, Chung-1, Taj Mohammad-1 and Mol-1. The discovery of Bhit gas field highlighted the potential for exploration in Kirthar Foldbelt while Zamzama is the fourth largest gas field of Pakistan in Kirthar Foredeep. Although Hydrocarbon accumulation is proven in Kirthar Foldbelt and Kirthar Foredeep but complex structural regime with a range of tectonic episodes as well as complex Transpressional deformation regime remain a challenges of trapping mechanism that requires comprehensive assessment. The Kirthar Foldbelt differs from the rest of the western shear zone because it is primarily deformed by compressional tectonics (Khalid et al., 2023). This paper is aimed to decipher the understanding of impact of structural deformation style on Hydrocarbon entrapment potential in Kirthar Foldbelt and Kirthar Foredeep. The faulted anticline's hanging wall offers ideal locations for optimal gas entrapment (Lisa et al., 2023). Furthermore, this paper provides a comprehensive knowledge of the crucial element i.e. trap integrity that needs to be examined prudently for Hydrocarbon exploration in Kirthar Foldbelt and Kirthar Foredeep region in future.

2. Geological settings of Kirthar Foldbelt & Foredeep

Indus Basin of Pakistan is divided into three parts i.e., Upper Indus Basin, Central Indus Basin and Southern Indus Basin (Wandrey et al., 2004). Kirthar Foldbelt and Foredeep are the part of Southern Indus Basin of Pakistan. The Southern Indus Basin is defined by an array of structural highs, including those at Sibi, Jacobabad, Khairpur, Mari-Khandkot, and Hyderabad (Zaigham and Mallick, 2000). The Kirthar Foldbelt and Foredeep are positioned adjacent to the current strike-slip western boundary of the Indian Plate, delineated by the Chaman Fault (Bannert et al., 1992) make up the south western portion of the Southern Indus Basin of Pakistan (Fig. 1).

The North-South oriented Kirthar Foredeep, subducted as a result of the evolving Kirthar Foldbelt (Kazmi and Jan, 1997; Kazmi and Rana, 1982), which developed because Indian and Eurasian plates collided during the Mio-Pliocene to the present day (Powell, 1979). It has a combined sediments thickness of more than 15,000 meters (Kadri, 1995). Its eastern border with Thar Platform is faulted. It is assumed that the sedimentation in this depression had been ongoing. However, it appears that the Upper Cretaceous would not be present in the region based on the correlation of the Mari, Khairpur, and Mazarani wells. The depression appears to have a relatively well-developed Paleocene, although the Khairpur-Jacobabad High area does not. This depression has a lot of potential for the source rocks to mature.

The carbonates of the Chiltan Formation were formed in a stable shelf platform during the Middle Jurassic (Bathonian/Callovian), and then extension and subsequent fault block rotation occurred in the Late Jurassic (gentle), leading to the development of a suitable reservoir within shoals and karstified areas (Kemal et al., 1991; Kadri, 1995).

The interior of the Indian Plate was gradually uplifted as

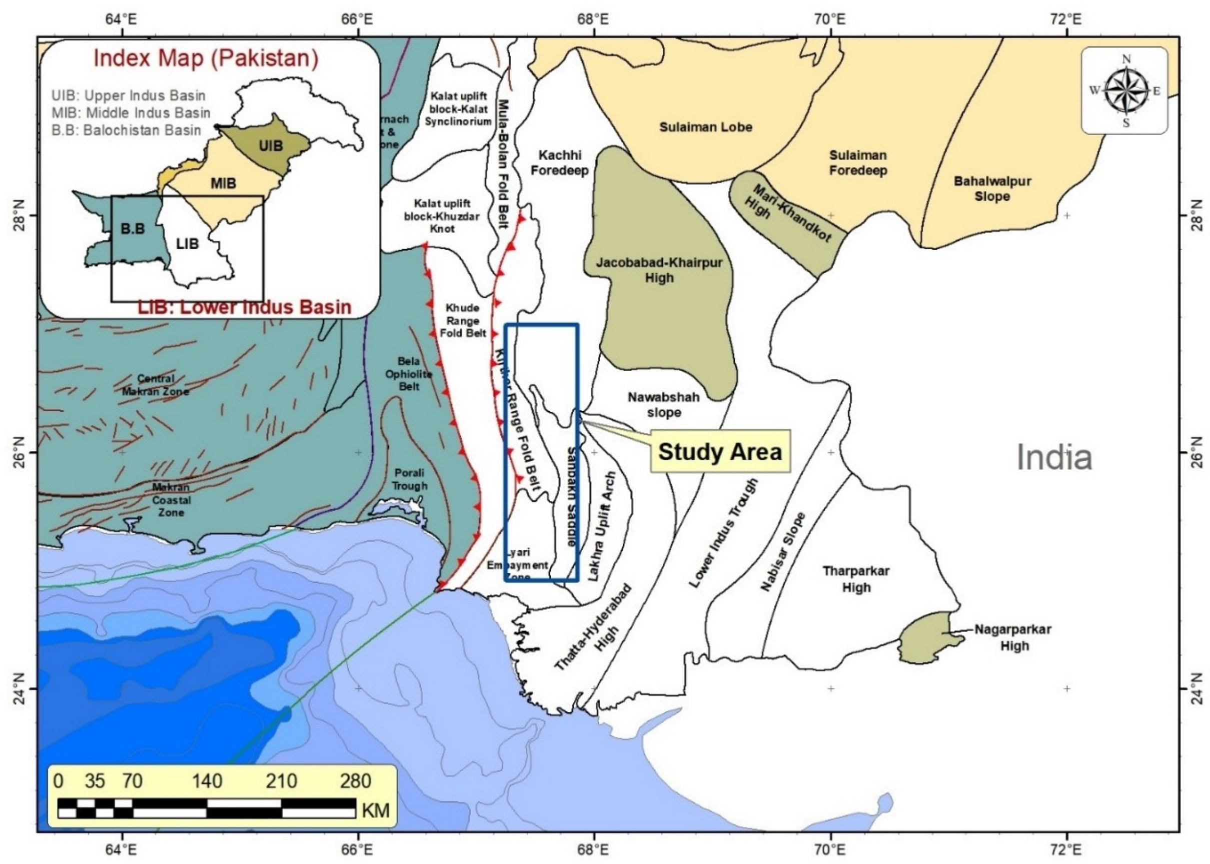

Figure 1. Location of study area on tectonic map.

a result of the Late Jurassic to Early Cretaceous Gondwana's continuing splitting (Powell, 1979), and eventually the Middle Jurassic carbonate platform was replaced by Shales and Sandstones from shallow marine to deltaic environments (Sembar and Goru formations). The Deccan Trap (Khadro Formation) was formed as a result of the Indo-Pakistan plate's separation from Madagascar during the Late Cretaceous, when a portion of the Indian plate from the North-West passed over the Reunion hot spot (Powell, 1979). The aforementioned occurrences are once more responsible for the elevation of the Indian plate border and the subsequent replacement of the carbonate platform by Clastic deposits (Kazmi and Abbasi, 2008; Shah, 1977, 2009). By the Paleocene, sinistral transpression had progressed over the western edge of the Indus Basin to the point where the previously deposited sequences were inverted (Meissner and Rahman, 1973; Kadri, 1995). On the passive margin settings in the North, carbonates were deposited due to relatively quiet conditions (Meissner and Rahman, 1973; Shah, 1977, 2009). The majority of the Oligocene layers have disappeared, but the Eocene strata are clearly visible. Due to the lesser impact of the Himalayan Orogeny, a thick mass of Miocene to Recent age molasses sediments developed (Kazmi and Jan, 1997; Kazmi and Rana, 1982; Shah, 1977, 2009).

Kirthar Foldbelt having North-South orientation is structurally and stratigraphically equivalent to the Sulaiman Foldbelt. In this area, rocks dating from the Triassic to the Recent age were deposited. The Oligocene-Miocene seas' dosage is also shown by the Kirthar Foldbelt structure. The western portion of the Kirthar Foldbelt, which forms the western boundary of the Indus Basin and is next to the Baluchistan Basin, is badly damaged. Hydrothermal activity on this western border is linked to the production of commercial mineral resources of baryte, fluorite, lead, zinc, and manganese (Kadri, 1995).

Following the Indo-Pakistan Plate's separated from the East African border in the Late Jurassic, sediments of the Kirthar Foldbelt were deposited on the plate's Northwestern margin as it drifted first south-eastward and subsequently Northward over the Indian Ocean (Besse and Courtillot, 1988). In the Early Eocene (55 Ma), the Northern boundary of the plate first collided with the Eurasian plate, ending this rift-drift phase (Patriat and Achache, 1984; Besse and Courtillot, 1988; Searle et al., 1997). In the Late Middle Eocene (40 Ma), the first Himalayan-sourced Clastics arrived, and late Paleogene flysch (Kohan Jhal Formation) was deposited in a thinning seaway between the Indo-Pakistan Plate and the Afghan Plate (J. and Searle, 1993). The mountain belt's first uplift can be traced to the Miocene, when the depocenter of Clastics from the Himalayas shifted from west of the mountain front to an emerging Foredeep to the east. In this Foredeep (Gaj, Manchar, and Dada formations), Clastic sediments were primarily deposited between Miocene and Pleistocene periods. However, the majority of the uplift and deformation occurred during the Plio-Pleistocene and was caused by the final docking of the Kirthar edge with the Afghan Plate along the proto-Chaman Fault (J. and Searle, 1993).

In the Middle Indus Basin to the east of the Foldbelt, this event represents the first time when large westerly-derived Clastics have replaced the previous Northerly-sourced Clastics. The Laki Fault, the easternmost emergent fault, and the Bela Ophiolite form the western and eastern boundaries of the southern Kirthar Foldbelt, respectively. The Bela Ophiolite was created in the Maastrichtian at about 70 Ma and deposited onto the continental margin in the Middle/Late Paleocene during the Indo-Pakistan Plate's final phases of Northward drift (Gnos et al., 1998). The Porali Trough, an alluvial-covered embayment between the Kirthar and Makran Ranges, is to the west of the Foldbelt. Gravity studies show that the Bela Ophiolite continues into the subsurface beneath the alluvial cover and reaches southward into the Oman Sea on its eastern side, next to the Kirthar Foldbelt (Nayyer and Mallick, 1994). The locations of the previous extensional faults have an influence on the structures in the KFB, which are not scattered randomly. Most of these faults are thought to have come from Jurassic rifting inheritance. During the Plio-Pleistocene impact event, the primary inversion of the Jurassic faults occurred. The Bela Ophiolite's positioning on the plate's leading edge, however, is tied to an earlier inversion that occurred in the late Paleocene (Smewing et al., 2002).

2.1 Petroleum system

The Kirthar Foredeep is identified as possessing an established petroleum system subsequent to the commercial gas discovery in the Upper Cretaceous Sandstone of the Pab Formation (Kadri, 1993, 1995). The Zamzama field is thought to have its primary source rock in the Cretaceous Shales of the Sembar and Goru formations. A large portion of the Southern Indus Basin's Sembar Formation was formed in marine settings (Kazmi and Abbasi, 2008; Shah, 2009). The Sandstone of Pab Formation from the upper Cretaceous that serves as a reservoir majorly (Lisa et al., 2023). Lower Paleocene Khadro Sandstone is producing in Zamzama Field. In the Kirthar Foldbelt, the Pab Formation is well-developed; nonetheless, it truncates to the east of the Zamzama gas field. In the west of the Kirthar region, it serves as a significant reservoir unit (Jackson et al., 2004). Seals are present within the Pab Formation. The Lower Ranikot, which is thought to be the best seal, covers both the Pab and Khadro formations.

A proven petroleum system is available from Kirthar Foldbelt. The primary source intervals are the Sembar Shales. The majority of the Kirthar Basin is covered by the Sembar Formation, whose source quality ranges from Fair to Good based on the amount of organic carbon present. Shales from the Ranikot and Mughalkot formations might also act as the source rock. In the Kirthar Foldbelt, numerous confirmed Cretaceous to Eocene reservoirs have been identified as gas producers. Gas is being produced in the Bhit and Badhra fields from the Upper Cretaceous Pab and Mughal Kot formations, respectively. A generalized stratigraphic column of Kirthar Foldbelt and Foredeep along with elements of Petroleum System is shown in Fig. 2.

In the Mazarani, Hundi, and Sari fields, gas is produced by the Ranikot Formation (Upper Paleocene). The Sui Main

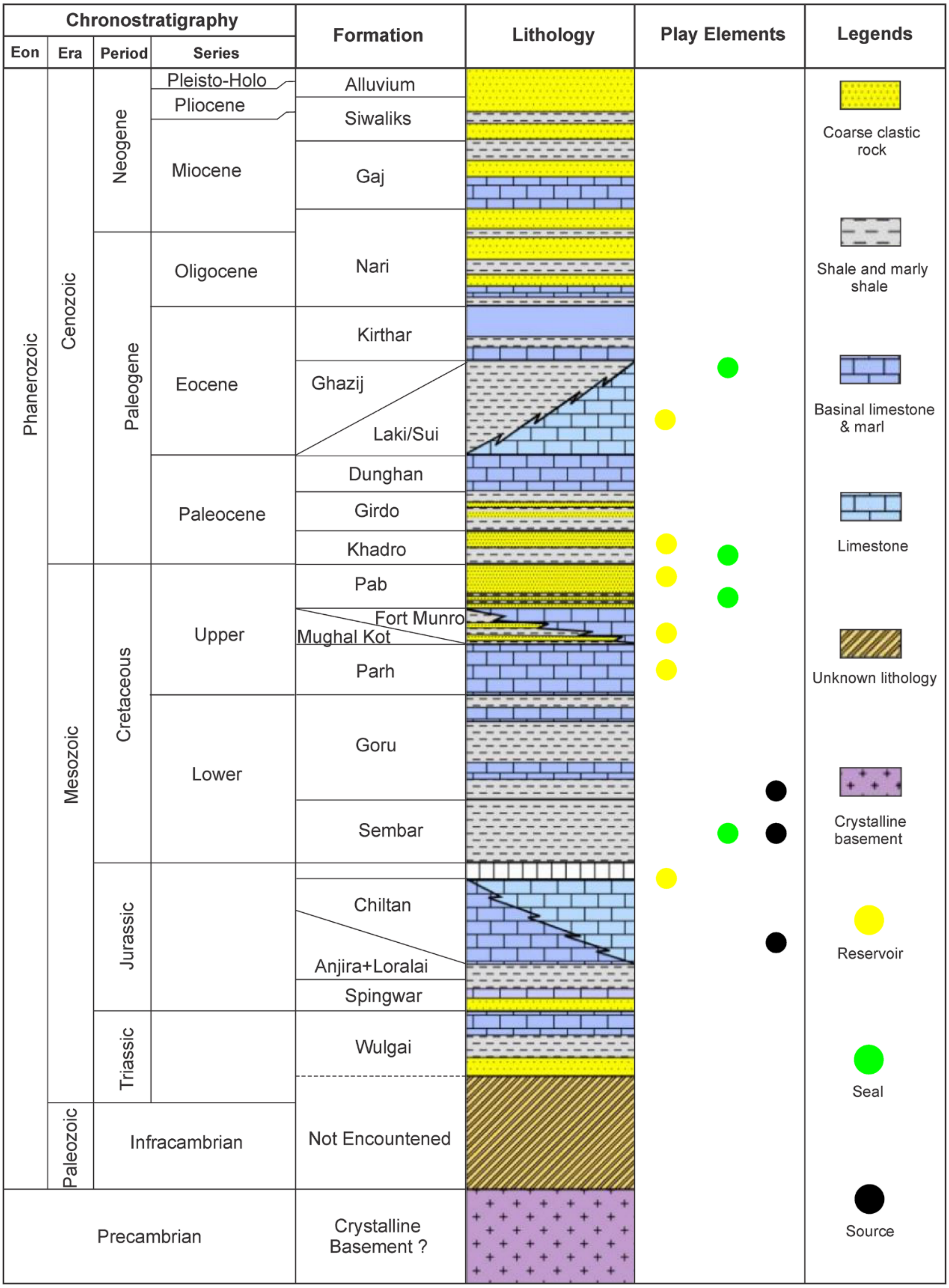

Figure 2. Stratigraphic Column of Kirthar Foldbelt and Foredeep, Southern Indus Basin, Pakistan (modified after Abbasi et al. (2016) and Zafar et al. (2018).

Limestone, the Laki Formation's counterpart, is a significant reservoir in the Kirthar/Sulaiman Basins and is producing gas in the Sui, Mari, and Jhal Magsi fields. However, it has not yet been shown to be a reservoir in this basin. The Ranikot Formation's thick interbedded clay sequence can serve as a great seal for the Ranikot Formation. Pab Formation top seal is provided by Mudstone, Volcanics, and Clays of the Khadro Formation, while the top seal for the lower portion of the turbiditic Sandstone in the Mughalkot Formation is provided by a thick shaly sequence.

3. Material and methods

Subsurface seismic and well data were used to analyze the Zamzama field structure. The data was provided by Landmark Resources (LMKR) after approval from the Directorate General of Petroleum Concessions (DGPC), Ministry of Energy, Petroleum Division, Islamabad, Pakistan. The data included Zamzama 3D seismic data and well log data of Zamzama-04 well. Additionally, representative 2D seismic lines from the wells Bhan-1, Mol-1, Taj Mohammad-1, and Chung-1 were taken from published data. The base map showing the location of seismic lines and wells is shown in Fig. 3.

Zamzama 3D seismic data was interpreted using Landmark's Halliburton Decision Space Geoscience (DSG) software. The data was structurally interpretated. Seven reflectors (top of the Gaj, Nari, Kirthar, Laki, Girdo, Khadro, Pab and Fort Munro formations) were marked on the seismic data on the basis of logs data from well.

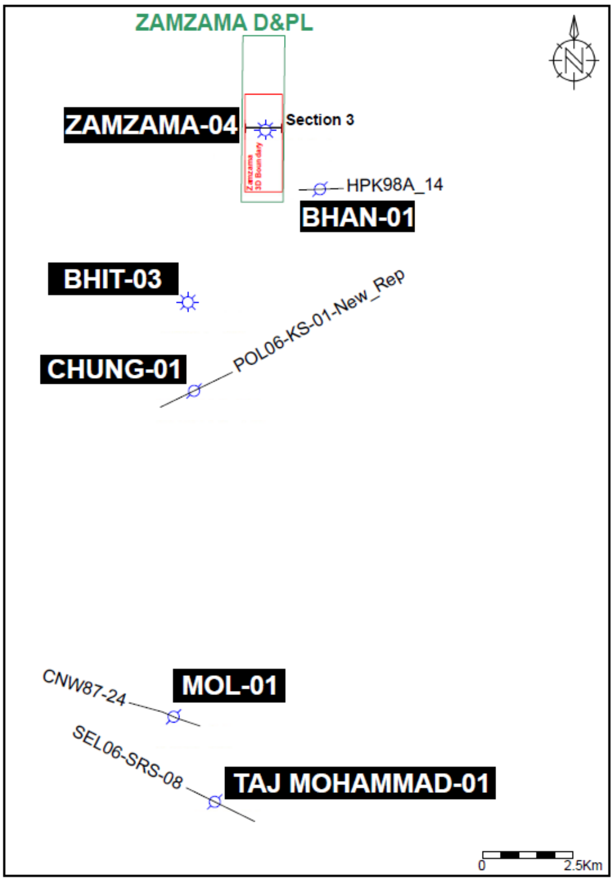

Figure 3. Base map base map showing the location of seismic lines and wells in the study area.

4. Results and discussion

The integrity of structural traps in Kirthar Foredeep and Kirthar Foldbelt is an important factor for Hydrocarbon discoveries. The 3D seismic data of the Zamzama gas field were interpreted, and the outcomes of wells drilled in the structures of the Kirthar Foredeep and Kirthar Foldbelt were assessed. This analysis aimed to develop a strategy for understanding the impact of structural style on hydrocarbon entrapment and guiding future hydrocarbon exploration

4.1 Structural interpretation of Zamzama 3D seismic data

Seismic data interpretation of Zamzama 3D seismic data was conducted to identify the subsurface structure style of Zamzama field. Zamzama 3D Seg-Y data and Zamzama-4 well logs data was loaded on the workstation for interpretation. Stepwise interpretation is discussed below:

4.1.1 Synthetic seismogram generation

Sonic and density logs of Zamzama-4 well were used for the generation of synthetic seismogram (Fig. 4). Sonic log gives information about velocity and density is derived from density log. Horizon picking on seismic data was conducted on the basis of synthetic seismogram.

4.1.2 Fault marking and interpretation

Faults were marked on the basis of break in continuity, on 3D Inline 630 in Fig. 5. Zamzama Field is situated in the Kirthar Foredeep immediately east of the Kirthar Foldbelt area, on strike with other fields like Mazarani, Sofiya and Mehar. The area also has a number of minor faults, the structural significance of which is unclear, in addition to the major and minor faults that are clearly charted.

4.1.3 Horizon marking and interpretation

After identifying the reflectors, target horizons were marked along seismic lines where reflectors transitioned from high to low amplitude. Interpretation was done based on the changes in acoustic impedance or the thickening or thinning of the different formations. The horizons along each seismic gird were determined by correlating the seismic occurrences.

The inline-630 in Fig. 5 (a) are oriented in an east-west orientation, parallel to the major fault's dip, and perpendicular to the axis of the Zamzama structure. The eight reflectors (top of the Gaj, Nari, Kirthar, Laki, Girdo, Khadro, Pab, and Fort Munro formations) make up the packages found in the Zamzam-4 well on the inline-630 and Zamzama 3D Geological Model (Fig. 5 (a) & 5 (b)). The anticlinal structure is bordered to the East by a Westward dipping major thrust that separates the footwall structure from the hanging wall structure.

4.1.4 Time structure map of Pab formation

The contour lines with the same time values are shown on the time contour maps. They stand in for the round-trip

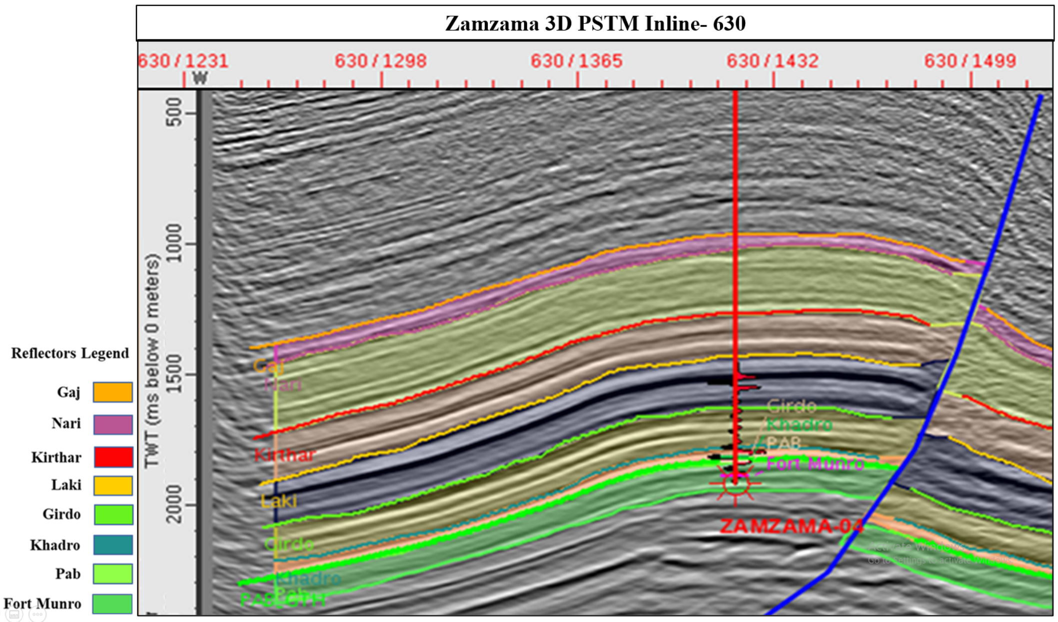

Figure 4. Synthetic seismogram of Zamzama-4 well in red displayed on Inline- 630.

time. Time Contour Maps are created based on the horizons that have been selected. For the same area, more than one slice of seismic data is needed for interpretation. While they are higher along the flanks, the time values are lower in the anticlines along the center. As the time values rise, the color will become lighter; as the time values fall, the color will get darker. All of this information was interpreted using contextual mapping. The time contour map is generated for Pab Formation (Fig. 6).

4.1.5 Depth structure map of Pab formation

Depth contour structural maps primarily illustrate the depth of the reservoir and typically used to show faults, anticlines, and folds. In order to produce structural maps of the subsurface, the transformed depth data is used. These maps depict where geological elements including faults, folds, and stratigraphic layers are distributed. Their interpretation is comparable to that of time-contour maps. This makes it possible to gather accurate information about the underlying structure's design. With a 25 m contour interval, the top Pab Formation's depth contour map was generated (Fig. 7). The structure becomes shallower as the color changes from green to red, showing that the structure is changing from syncline to anticline.

Time and depth structure maps reveal that there is no significant change in the structural configuration of Zamzama Structure on time & depth map. The general orientation of faults in Southern Indus Basin is North-South. The main fault in Zamzama field is dipping towards west as shown on the map (Fig. 7). Zamzama Field has westward four-way dipping strata and snake-head folds of low structural relief and axes.

4.2 Traping mechanism of hydrocarbon discoveries

Trap integrity is the key beyond successful Hydrocarbon discoveries in the Kirthar Foldbelt and Kirthar Foredeep. Trap

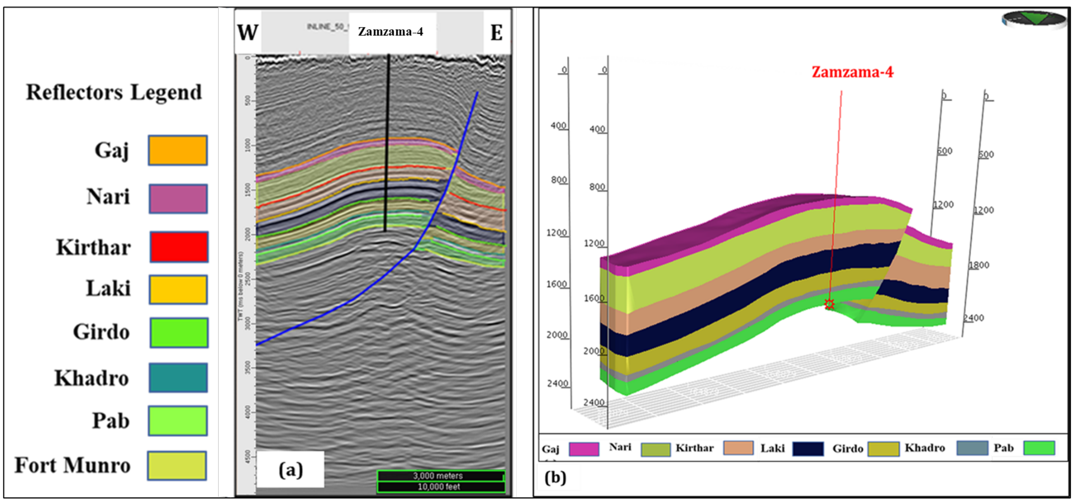

Figure 5. Zamzama 3D Seismic showing Zamzama Field roll over (a) Inline-630 over Zamzama-4 well (b) Zamzama 3D Geological Model.

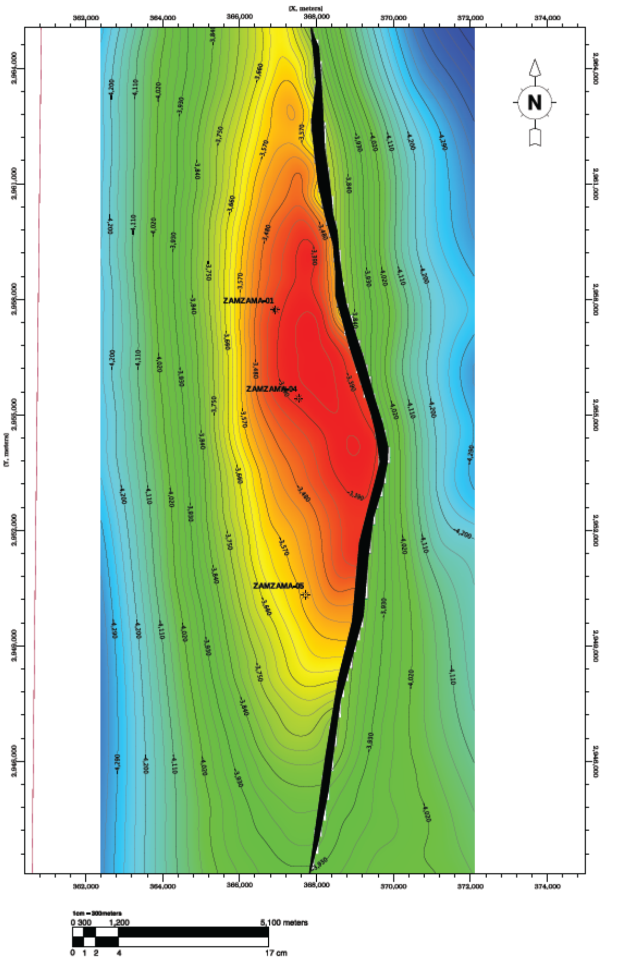

Figure 6. Time Structure Map at the Top Pab Formation of Zamzama field.

failure is the primary cause of well failure in the Kirthar Foldbelt and Kirthar Foredeep. The majority of traps are fault-bounded structures, with the thrust/reverse fault serving as the primary boundary fault and frequently reaching the surface or very close it. If there is a role-over above the intersection of the fault and reservoir, which creates a four-way dip closure independent of the fault, then it becomes a legitimate trap, similar to the Zamzama (Fig. 8), Bhit and Lundali structure (Fig. 9 (a) and 9 (b)).

In Bhit field, the trap is formed at the intersection of fault, only above the Gas-Water Contact (GWC), although the faults are leaking at the surface, therefore, Hydrocarbons are only trapped above the fault contact. However, there are certain instances where fault is not leaking to the surface despite a significant bounding thrust. The best example is of Zamzama structure, where the bounding fault is quite obvious, and the Gas-Water Contact (GWC) is deeper than the fault-reservoir intersection. This leads to the conclusion that the fault may become sealing vertically if it does not reach the surface and has sufficient depth. Similar to Zamzama structure, the thickness of the top seal may be crucial for sealing the fault. Moreover, wells were drilled on both sides of Zamzama structure and gas was discovered in the wells on both sides of the fault (Fig. 9 (c)). However, production from the wells on the hanging wall depleted the smaller portion of the footwall side. This demonstrated that there is cross-fault leakage rather than vertical leakage through the fault. This suggests that the risk will be higher if there is no structure on the footwall.

4.3 Traping mechanism of hydrocarbon failures

As it has been mentioned that the structures in the Kirthar Foldbelt and Kirthar Foredeep are fault-bounded in general, with the thrust/reverse fault acting as primary bounding fault that typically reaches to the surface or near to surface, causing the structures to breach. In general, it is believed that the structures have been breached by the bounding reverse/thrusts faults. The seismic data of dry wells like Bhan-1, Taj Mohammad-1, Mol-1 and Chung-1 (Fig. 10 (a), 10 (b), 10 (c) & 10 (d) respectively) indicates that the structure was breached and there is no role-over above the fault-reservoir intersection. This makes a fault bounded trap with three-way dipping closure instead of four-way dip closure independent of fault, hence leading to an invalid trap and subsequently well failures.

Bhan-1 well (Fig. 10 (a)) was drilled on a fault bounded structure, but it was unsuccessful and the failure is considered to be due to the leaking bounding fault. The analysis of wireline logs from Taj Mohammad-1 well (Fig. 10 (b)) indicated excellent reservoir quality, yet it revealed a fail-

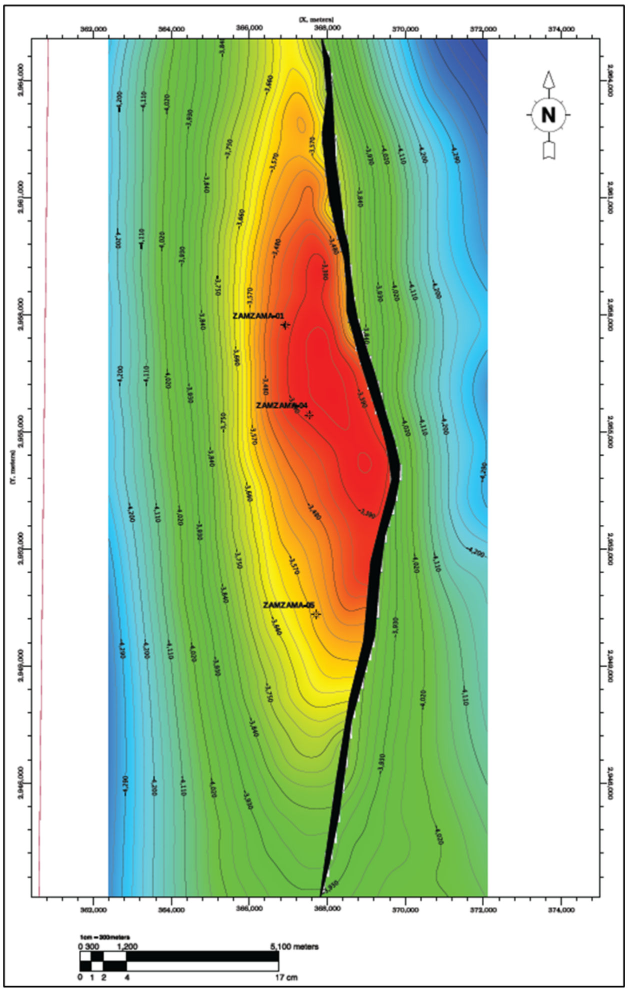

Figure 7. Depth Structure Map at The Top Pab Formation of Zamzama field.

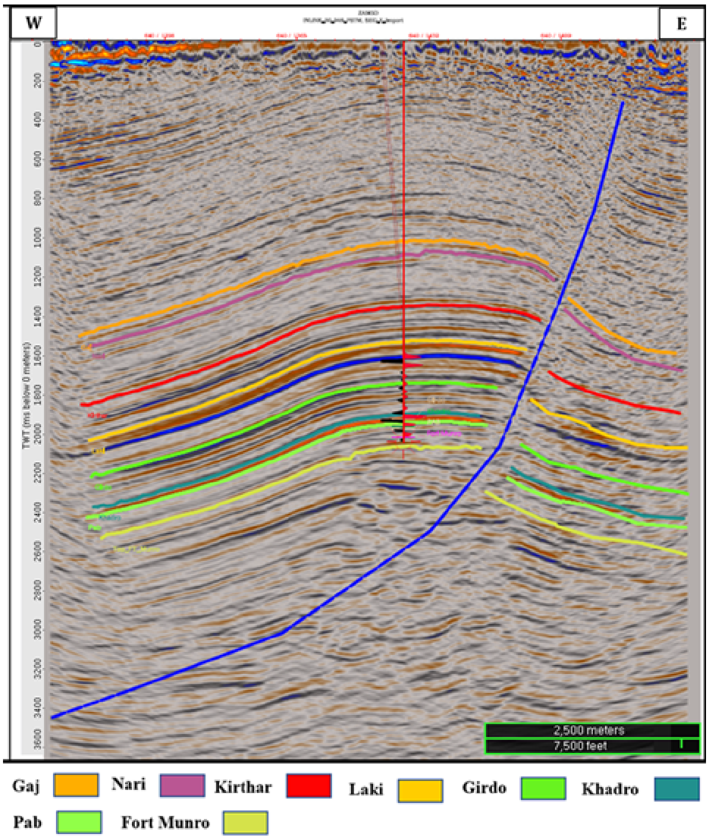

Figure 8. Geo- Seismic Model at Pab level of Zamzama Structure.

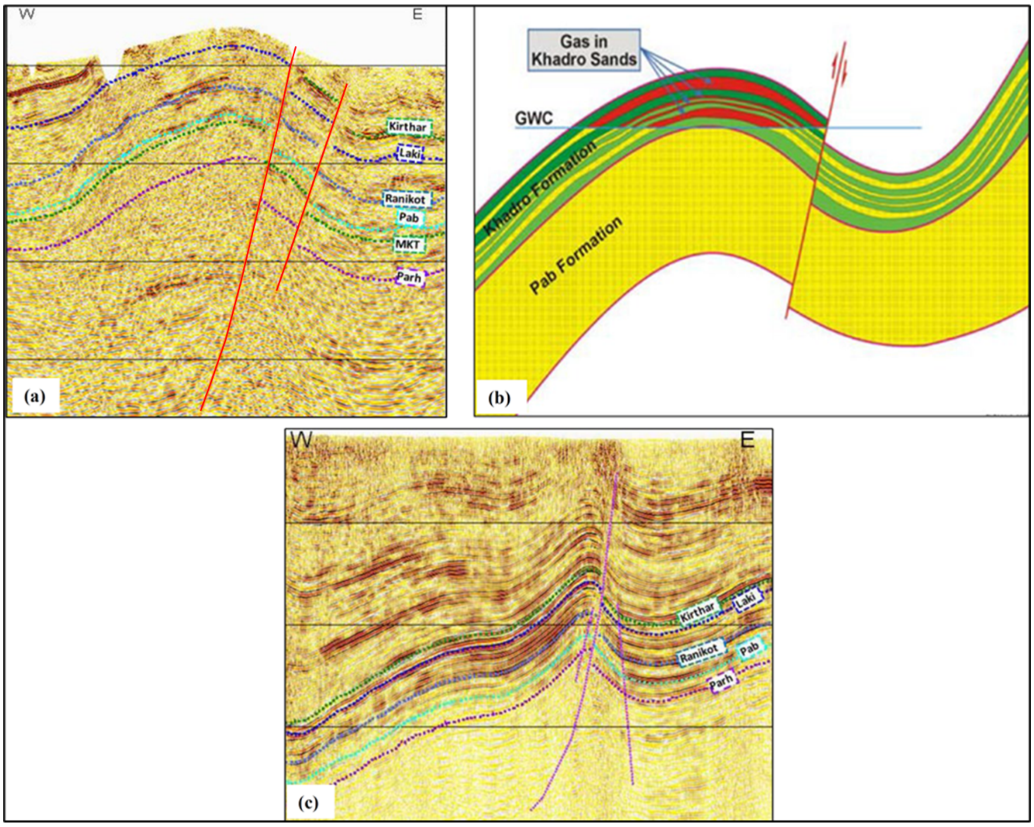

Figure 9. (a) Seismic section of Bhit area showing fault bounded structure with fourway dip structure above the fault contact making valid trap (b) Lundali area cross section showing fault bounded structure with fourway dip structure (c) 2D Seismic section of Zamzama area showing fault bounded structure. Although the fault is leaking laterally but vertically it is sealing.

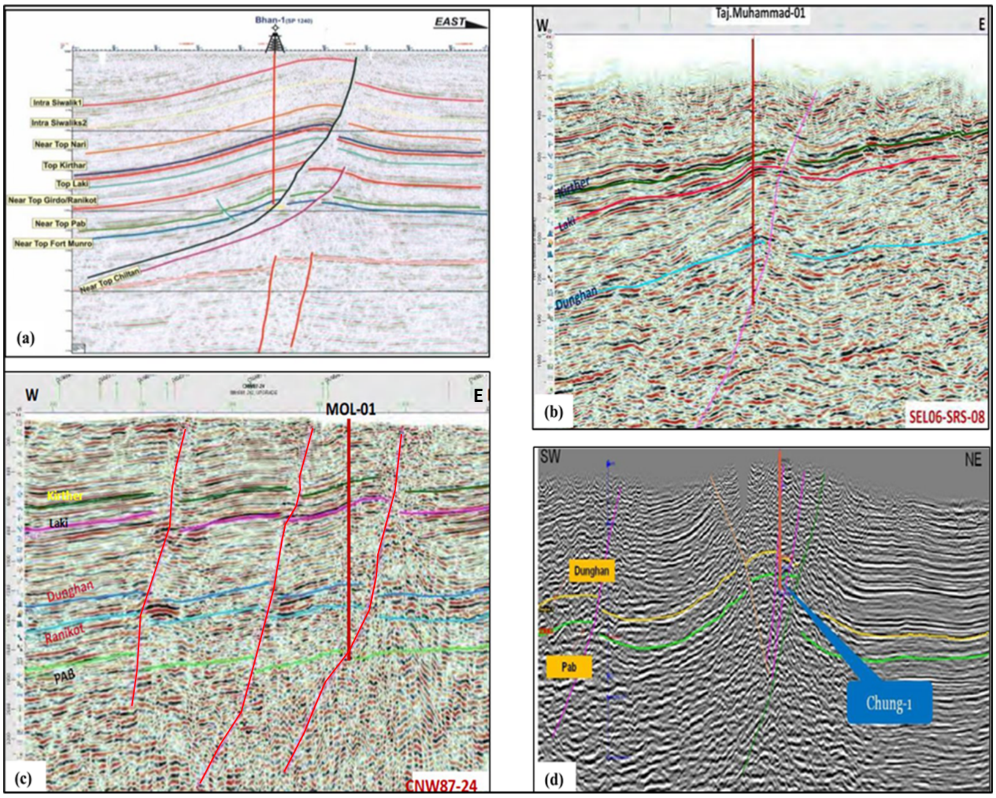

Figure 10. Seismic lines over dry wells in which trap was breached due to leaking of bounding fault. (a) Seismic line passing through Bhan- 1 well. (b) Seismic line passing through Taj Mohammad-1, a dry well (c) Seismic line passing through Mol-1 well (d) Seismic section of Chung-1 well area showing leaking fault bounded structure.

ure due to leaking fault. Similarly, in Mol-1 well, the Pab Sandstone exhibited favorable porous reservoir attributes. However, a significant issue arose where the main fault, which formed the trap at the top of the Pab Formation, was leaking at the surface (Fig. 10 (c)). Moreover, in Chung-1 well (Fig. 10 (d)) the wireline logs of primary reservoir Pab Formation reveals excellent reservoir quality but as the trap forming bounded fault is breaching the structure so it resulted in failure of the well and ultimately abandonment of the well.

5. Conclusion

The subsurface structure of the Zamzama field was analyzed through the interpretation of seismic data, leading to the creation of time and depth structure maps at the top of the Pab Formation. This assessment reveals a well-developed structural configuration that is conducive to hydrocarbon trapping. Furthermore, all essential conditions for hydrocarbon accumulation are confirmed to be present within the study area. Pab Formation serves as a reservoir rock, while the Sembar and Goru formations from the Cretaceous age are established as the proven source rocks. Additionally, the shales of the Pab, Khadro, and Ranikot formations act effectively as seal rocks in the Zamzama field.

A comparative analysis was performed to compare the subsurface structural configuration of the Zamzama field with the structural styles observed in nearby hydrocarbon discoveries and failed ventures. This comparison is crucial as the style of structural deformation directly influences trap integrity in the Kirthar Foldbelt and Foredeep. Despite numerous wells drilled in Kirthar Foldbelt and Foredeep, the success rate remains around 20%. A good understanding has been developed regarding the aspects which are necessary to be analyzed prior to placing well in both the zones. Following aspects needs to be analyzed in order to establish the trap integrity and assessment of Hydrocarbon potential of any prospect in Kirthar Foldbelt and Foredeep:

1. The bounding faults needs to be examined whether they are emergent thrusts or blind thrusts because if the bounding fault is blind fault then there is no issue of Hydrocarbons trapping.
2. If the bounding fault is an emergent thrust i.e. it is approaching to the surface then it may be a non-sealing fault and may lead to breach of the structure. The integrity of the trap is the most crucial in this case; so, structures with four-way dip closure will be a low risk trap and safe to drill in such type of structural settings.
3. The structure which are fault-bounded are safe if they have four-way dip closure, but in the case of fault bounded structure there is a high risk that it will be breached through the main thrust. Such traps should be examined on the following basis. (a) The risk is greater if the fault reaches the surface, although it has been demonstrated in some locations that faults that do not reach the surface are sealing (b) The chance of fault leakage is decreased if the structure is deep. (c) If top seal sediments are quite thick then it will reduce the risk of fault breaching.

Acknowledgement

The authors are grateful to the Director General, Petroleum Concessions (DGPC), Pakistan, for the provision of data for this research work.

Authors contributions

Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abbasi S. A., Asim S., Solangi S. H., Khan F. (2016) Study of fault configuration related mysteries through multi seismic attribute analysis technique in Zamzama gas field area, Southern Indus Basin Pakistan. *Geodesy and Geodynamics* 7 (2): 32–142. DOI: https://doi.org/10.1016/j.geog.2016.04.002.

Ahmad S., Ghazi S. (2022) Depositional trends & Reservoir geometries of the Early Cretaceous Lower Goru Formation in Lower Indus Basin, Pakistan: Evidence from Sequence Stratigraphy (Manuscript Number: PEPT-D-20-00545R2). *Journal of Petroleum Exploration and Production Technology* 12 (3): 1–13. DOI: https://doi.org/10.1007/s13202-022-01489-y.

Bannert D. A., Cheema A., Schaffer A. (1992) The structural development of the Western Foldbelt Pakistan. *Geologisches Jahrbuch* B80:3–60.

Besse J., Courtillot V. (1988) Paleogeographic maps of the continents bordering the Indian Ocean since the Early Jurassic. *Journal of Geophysical Research* 92 (B10): 11791–11808. DOI: https://doi.org/10.1029/JB093iB10p11791.

Ehsan M., Gu H., Ali A., Akhtar M. M., Abbasi S. S., Miraj M. A. F., Shah M. (2021) An integrated approach to evaluate the unconventional Hydrocarbon generation potential of the Lower Goru Formation (Cretaceous) in southern Lower Indus Basin, Pakistan. *Journal of Earth System Science* 130 (2): 80–90. DOI: https://doi.org/10.1007/s12040-021-01584-4.

Gnos E., Khan M., Mahmood K., Khan A. S., Shafique N. A., Villa I. M. (1998) Bela oceanic lithosphere assemblage and its relationship to the Reunion hot spot. *Terra Nova* 10:90–95.

Hussain H., Shuangxi Z., Abid M. (2019) Understanding the Hydrocarbon prospect of Buzdar block, Southern Indus Basin, Pakistan, by using 2-D seismic data: A case study. *Contributions to Geophysics and Geodesy* 49 (3): 249–263. DOI: https://doi.org/10.2478/congeo-2019-0013.

J. Treloar P., Searle M. P. (1993) Himalayan tectonics. Geological Society, London:1–7. DOI: https://doi.org/10.1144/GSL.SP.1993.074.01.01.

Jackson M. A., Jellis R. G., Hill R., Roberson P., Woodall M. A., Wormald G., Jafri N. (2004) Zamzama gas field-balancing risk and value. SPE Asia Pacific Oil and Gas Conference, Perth, Australia DOI: https://doi.org/10.2118/88577-MS.

Jehangir Khan M., Ghazi S., Mehmood M., Yazdi A., Naseem A. A., Serwar U., Zaheer A., Ullah H. (2021) Sedimentological and provenance analysis of the Cretaceous Moro formation Rakhi Gorge, Eastern Sulaiman Range, Pakistan. *Iranian Journal of Earth Sciences* 13 (4): 252–266. DOI: https://doi.org/10.30495/ijes.2021.1917721.1564.

Kadri I. B. (1993) Cretaceous source rocks in Pakistan. *AAPG/SVG International Conference and Exhibitions, Venezuela,* 11–35.

——— (1995) Petroleum Geology of Pakistan. Pakistan Petroleum Ltd, Karachi:1–275.

Kazmi A. H., Abbasi A. I. (2008) Stratigraphy and historical geology of and historical geology Pakistan. Peshawar Publication, Peshawar:181–185.

Kazmi A. H., Jan M. Q. (1997) Geology and tectonic of Pakistan. Graphic Publishers, Karachi:528.

Kazmi A. H., Rana R. A. (1982) Tectonic map of Pakistan. *Geological Survey of Pakistan* 39:283–300.

Kemal A., Ahmed G., Kemal A., Zaman A. S. H. (1991) Geology and new trends for petroleum exploration in Pakistan.

Khalid A., Ahmad S., Ali A., Rehman G., Yaseen M. (2023) Structural Analysis of Kirthar Foldbelt, Lower Indus Basin, Balochistan, Pakistan; Implications from Compression and Inversion Tectonics. *Sains Malaysiana* 52 (2): 417–430. DOI: https://doi.org/10.17576/jsm-2023-5202-08.

Lisa M., Ullah Khan Z., Hussain M., Adnan Ahmed S. (2023) Evaluation of seismic responses from well-associated gas producing Sands using integrated approaches for optimal field production in Zamzama gas field, Pakistan. *Journal of Asian Earth Sciences* 10:100–163. DOI: https://doi.org/10.1016/j.jaesx.2023.100163.

Meissner Jr. C., Rahman H. (1973) Distribution, thickness, and Lithology of Paleocene Rocks in Pakistan. USGS Professional, US Government Office, Washington.716–E.

Nayyer Z. A., Mallick K. A. (1994) Sub-surface continuation of the Ophiolites in the Bela plain of Baluchistan, Pakistan. Ofioliti:269–278.

Patriat P., Achache J. (1984) India-Eurasia collision chronology and its implications for crustal shortening and driving mechanisms of plates. *Nature* 311:615–621. DOI: https://doi.org/10.1038/311615a0.

Powell C. M. (1979) A speculative tectonic history of Pakistan and surroundings: Some constraints from the Indian Ocean *Geodynamics of Pakistan* 13:5–24.

Qureshi M. A., Ghazi S., Riaz M., Ahmad S. (2021) Geo-seismic model for petroleum plays an assessment of the Zamzama area, Southern Indus Basin, Pakistan. *Journal of Petroleum Exploration and Production Technology* 11 (1): 33–44. DOI: https://doi.org/10.1007/s13202-020-01044-7.

Searle M. P., Corfield R. I., Stephenson B., McCarron J. (1997) Structure of the North Indian continental margin in the Ladakh-Zanskar Himalayas: Implications for the timing and Obduction of The Spontang Ophiolite, India-Asia collision and deformation events in the Himalaya. *Geological Magazine* 134 (3): 297–316. DOI: https://doi.org/10.1017/S0016756897006857.

Shah S. M. I. (1977) Stratigraphy of Pakistan. *Geological survey of Pakistan* 12:138.

——— (2009) Stratigraphy of Pakistan. *Geological survey of Pakistan,* 1–400.

Smewing J. D., Warburton J., Cernuschi A. (2002) Structural Inheritance in the southern Kirthar Foldbelt *Annual Technical Conference (ATC) of PAPG & SPE Islamabad,* 26–35.

Wandrey C. J., Law B. E., Shah H. A. (2004) Sembar Goru/Ghazij Composite Total Petroleum System, Indus and Sulaiman-Kirthar Geologic Provinces, Pakistan and India. U.S. Geological Survey Bulletin, 2208-C:1–21.

Zafar Z. A., Shoaib K., Afsar F., Raja Z. A., Tanveer A., Burley S. D. (2018) A radical seismic interpretation re-think resolves the structural complexities of the Zamzama Field, Kirthar Foredeep, Pakistan. PAPG/SPE Annual Technical Conference. Islamabad, Pakistan:1–11.

Zaigham N. A., Mallick K. A. (2000) Prospect of Hydrocarbon associated with fossil-rift structures of the Southern Indus Basin, Pakistan. *Am. Assoc. Pet. Geol. Bull* 84 (11): 1833–1848. DOI: https://doi.org/10.1306/8626C3A7-173B-11D7-8645000102C1865D.