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AN INTEGRATED OVERVIEW OF PAKISTAN'S PETROLEUM BASINS WITH EMPHASIS ON THEIR CORRELATION TO ADJOINING IRANIAN BASINS

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A B S T R A C T

The Pakistan-Iran border region remains underexplored despite its strategic location within the hydrocarbon-rich Middle East. The Middle East holds 50% of proven oil reserves and 40% of world's natural gas reserves in the world. There have been several myths of shared petroleum system between the two countries, without proper geological evidence. However, there has never been a comprehensive discussion of the geological setting and framework. Recently, there has been interest of several oil and gas companies in Pakistan to explore the Makran-Kharan area. This review investigates the geological characteristics and petroleum systems of the transboundary basins between Pakistan and Iran. The study synthesizes existing geological, geophysical, and geochemical data to assess hydrocarbon potential, highlighting key elements such as sedimentary basins, source rocks, reservoir formations, and trapping mechanisms. Although significant petroleum reserves are concentrated in western Iran, the southeastern region near the Pakistan border exhibits minimal exploration and discoveries. Key basins, include the Makran Offshore Basin, Kharan Forearc Basin, and Jaz Murian-Mashkel Forearc Basin. Furthermore, these basins show promising indicators such as oil seeps, structural traps, and seismic anomalies. This paper calls for increased collaboration between Pakistan and Iran, enhanced exploration efforts, and further geophysical surveys to unlock potential reserves. This will not only boast exploration efforts in Eastern Iran and Western Pakistan but also bring a positive changes in their economies. This study will be a landmark in understanding the sedimentary basins of the Middle East, South Asia, Southwest Asia, and the Caspian Sea region.

Keywords: proven oil reserves; gas reserves; geophysical and geochemical data; Makran-Kharan area; sedimentary basin.

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1. Introduction

The occurrence and distribution of hydrocarbons across the Pakistan-Iran frontier are primarily controlled by shared geological structures, basin evolution, and stratigraphic continuity rather than by political or national boundaries (fig. 1). Iran and Pakistan, countries in the Middle East, have varied geological environments, some endowed with active petroleum systems [1]. The petroleum potential along the Pakistan–Iran frontier represents a microcosm of the Middle East's geological diversity, where the heterogeneous distribution of hydrocarbons is controlled by basin evolution, tectonic deformation, and variable source rock maturity. In this trans-

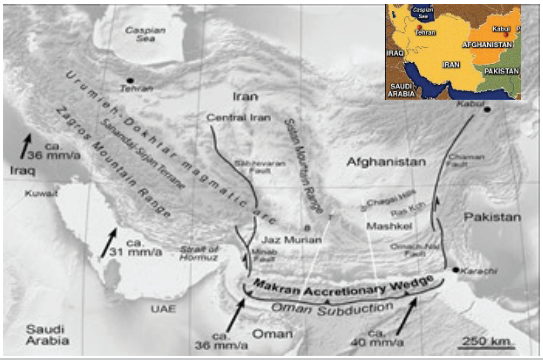

Fig. 1. Regional geographic map of Iran and Pakistan [6]; the Caspian Sea and Arabian Gulf basins are also shown in this tectonic map

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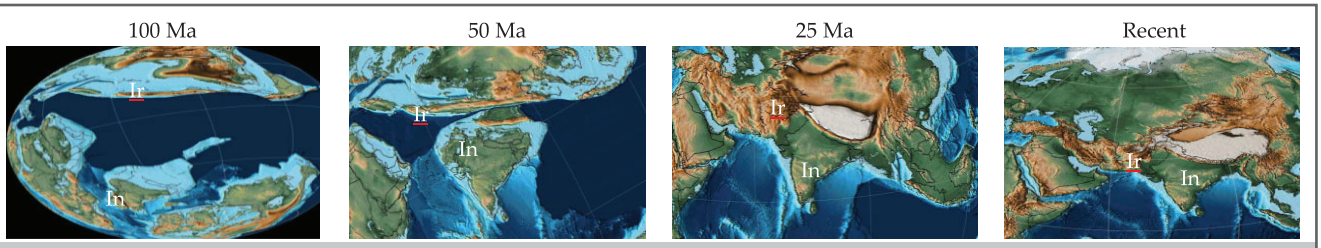

Fig. 2. Paleo-tectonic Reconstruction of Iran territory (Courtesy: GPLATES)

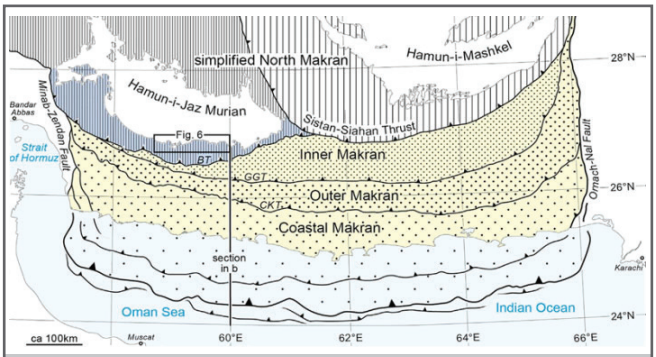

Fig. 3. Basins Across Border map (the position of this [6])

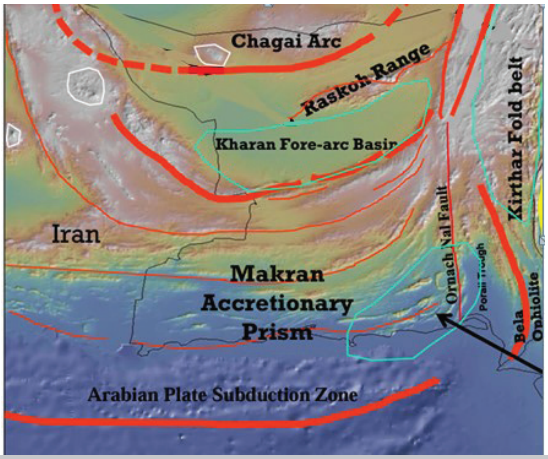

Fig. 4. Tectonic map showing major tectonic zones in Pakistan near the Iranian Border [30]

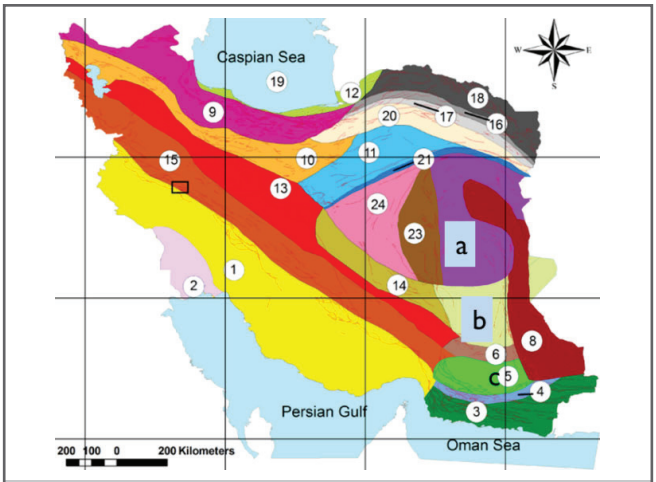

Fig. 5. Map showing basins in Iran near Pakistan Border: a) Jaz Murian-Mashkel Forearc Basin; b) South Lut-Helmand Backarc Basin; c) Lut Plain Gonabad Backarc Basin) [17]

boundary region, basins such as Makran, Kharan, Jaz Murian, and South Lut-Helmand have developed under complex subduction and forearc–backarc settings, leading to diverse stratigraphic architectures and reservoir characteristics. The interplay of active tectonics, thermally mature organic-rich source rocks, and structurally intricate traps collectively controls the occurrence and variability of hydrocarbons, underscoring the need for integrated geological and geophysical studies to delineate the petroleum systems shared between Pakistan and Iran [2]. Due to sparsely performed geological and geophysical investigations [3], the Pakistan-Iran border area has been little explored despite its strategic location [4, 5]. A lack of systematic studies has created a knowledge gap on the functional petroleum system within the region. This review seeks to integrate existing geological information, evaluate the prospectivity of transboundary basins, and highlight the need for further exploration. Improved insight into the geological background, basin construction, and hydrocarbon system evolution is needed to lay the basis for hydrocarbon prospectivity within the area.

2. Geological framework

The collision between the Arabian, Eurasian, and Indian plates controls the tectonic history of the Pakistan-Iran border zone [5] (fig. 2).

The area includes several sedimentary basins of diverse hydrocarbon potential. The key geological aspects are:

- *Makran Accretionary Wedge:* A tectonically active zone formed by the subduction of the Arabian Plate beneath the Eurasian Plate, with mud volcanoes and cold seeps are indication of fluid migration. [6, 4, 7-11]. The wedge is made up of strongly deformed sediments stripped from the subducting plate and, in a complicated structure, may have trapped hydrocarbons (fig. 3).
- *Kharan Forearc Basin:* Situated in western Pakistan, between the Ras Koh volcanic arc at the north and the Makran Accretionary Prism in the south, the basin consists of thick sequences of sedimentary rocks, marine and deltaic sediments, which are potentially rich in hydrocarbon accumulation (fig. 4) [12-15].
- *Jaz Murian-Mashkel Forearc Basin:* A transboundary basin with east-west trending structures has formed in the southern margin of East-Central Iran. The basin consists mainly of Paleogene turbidites supplemented by other Neogene-Quaternary terrestrial sediments, which provide a promising environment for hydrocarbon reservoirs [16].

The stratigraphy in this area is composed of Paleogene to Neogene turbidites, volcaniclastics, and siliciclastic deposits with known petroleum system analogues in similar

tectonic domains [17]. The Jaz Murian Basin, in particular, exhibits E-W trending structural patterns filled with deep-water marine sediments interbedded with fine-grained organic-rich units that potentially serve as both source and seal rocks [16]. These sediments were deposited in a forearc setting adjacent to an active convergent margin and exhibited geologic continuity across the Pakistan border into the Mashkel Basin.

2.1. Petroleum basins in Iran's territory:

- *Jaz Murian-Mashkel Forearc Basin:* The basin extends into Iran, where the sedimentary deposits are conducive to hydrocarbon accumulation (fig. 5). The thick Paleogene turbidities suggest a history of high sedimentation rates, which may have resulted in organic-rich source rocks [17].
- *South Lut-Helmand Backarc Basin:* Located in southeast Iran, it has a thick succession of Tertiary volcanic rocks with hydrocarbon prospectivity (fig. 5). Alternating marine sediments and volcaniclastics sequences constitute the basin, containing potential reservoir and seal sequences [16].
- *Lut Plain Gonabad Backarc Basin:* An extensional tectonic setting located over a subduction zone (fig. 5), where sediments have been deposited over a long time, suggesting possible petroleum reserves. Deep-seated faults and graben structures suggest active hydrocarbon migration [18, 10].

3. Possible petroleum potential in Iran near the Pakistan Border

The southeastern frontier of Iran, bordering Pakistan, encompasses several underexplored sedimentary basins, including the Jaz Murian Forearc Basin, South Lut-Helmand Backarc Basin, and the Lut Plain-Gonabad Backarc Basin. This region, characterized by complex subduction-driven tectonics, offers promising structural and stratigraphic settings for hydrocarbon generation and entrapment but remains significantly understudied relative to Iran's prolific western basins, such as the Zagros Fold Belt [11, 19-24].

Source rock assessment based on regional geochemical surveys and satellite interpretations suggests that Cretaceous to Paleogene shales within the Lut and Helmand zones have TOC values between 1.5 and 3.5 %, with Type II kerogen dominance, and maturity levels ranging from early to peak oil generation window (Tmax 430–455 °C) [25]. Limited exploration data indicate possible expulsion of hydrocarbons from mature source intervals, particularly where heat flow is elevated due to volcanic activity in the Lut Block.

With thermogenic and biogenic gas from mature Eocene–Oligocene shales, the Makran offshore basin exhibits the highest hydrocarbon potential. Because of its complex tectonics and appropriate reservoir-seal pairs, the Kharan Basin has moderate potential. In localized depocenters, the Sistan and Zahedan sub-basins show gas-prone conditions despite having less developed systems with shallow burial.

The tectono-structural framework of the region is defined by syn- and post-orogenic features such as thrust systems, strike-slip faults, and back-thrusting, which together create multiple trapping geometries including fault-propagation folds, duplexes, and inversion structures (table 1) [6, 26, 27]. Additionally, regional unconformities and lateral facies changes present opportunities for stratigraphic traps, although their extent and connectivity require further investigation.

Reservoir units comprise sand-rich turbiditic sequences and Tertiary volcanic–volcaniclastic rocks exhibiting secondary porosity through fracturing and alteration. In the South Lut–Helmand Basin, up to 2 km of Tertiary volcanics contain porous interbeds and clastic horizons with demonstrated storage potential [16]. Despite their unconventional nature, fractured volcanic reservoirs are increasingly recognized as viable hydrocarbon hosts in frontier basins worldwide.

In Pakistani Basins, the Kharan Limestone is massively bedded, vuggy, and cavernous, with favorable reservoir characteristics. Oligocene sequence is made up of shelf-marginal marine sandstones and Deep-water turbidites. In outcrops these sands have good reservoirs characterstics (table 2).

Table 1

Major folds and faults present in the adjacent basins of Pakistan and Iran

Structural element	Location / extent	Type and orientation	Associated tectonic setting	Remarks / significance
Makran Accretionary Fold Belt	Along the coastal belt of SW Pakistan and SE Iran	NW–SE trending thrusts and imbricate folds	Formed by subduction of the Arabian Plate beneath the Eurasian Plate	Active accretionary wedge; offshore continuation contains anticlines and mud diapirs; important for gas hydrates and traps
Chagai Magmatic Arc	Western Balochistan (Pakistan–Iran border region)	Normal and strikeslip faults, with local folding	Magmatic arc overlying the subduction zone (Cretaceous–Tertiary)	Hosts porphyry copper–gold systems (Saindak, Reko Diq)
Kharan Foreland Basin Structures	Between Chagai Arc and Makran Belt	NW–SE thrust faults, gentle open folds	Flexural response to Makran compression	Structurally complex; possible hydrocarbon traps in Neogene strata
Siahan Range and Coastal Fault Zone	Parallel to the Makran coast	N–S to NW–SE thrusts, local wrench faults	Active deformation due to subduction and plate coupling	Fault-related folding forms potential structural traps offshore
Ornach–Nal Fault System	Central Balochistan, continuing into Iran	Major right-lateral (dextral) strike-slip fault	Transform link between Makran subduction and Sulaiman fold belt	Key structure accommodating oblique convergence
Kuh-e-Mond and Bashagard Faults (Iran)	SE Iran continuation of Makran and Lut block boundaries	Thrust and strikeslip systems, NW–SE	Compressional regime linked to Makran accretionary processes	Represents structural continuity from Pakistan's Makran zone into Iran

Table 2

Facies changes across the sedimentary basins

Basin / region	Main stratigraphic intervals	Observed or inferred facies	Lateral facies changes (claimed)	Unclear / missing details	Recommendation
Offshore and Onshore Makran Basin	Paleocene–Miocene	Marine shales, turbiditic sandstones, marls, and pelagic limestones	Transition from deep marine turbidites (south) to shelf–deltaic clastics (north)	No consistent mapping of Eocene–Oligocene transitions; uncertain boundaries between slope and basin facies	Develop facies maps for Paleocene, Eocene, Oligocene, and Miocene units showing bathymetric gradients and depocenters
Kharan Basin (Pakistan)	Cretaceous–Neogene	Continental red beds, deltaic sandstones, shallow marine limestones	Claimed shift from marine to continental facies northward	No details on which members (e.g., Neogene vs Paleogene) record the transition	Construct paleogeographic cross-sections and correlate with Chagai volcanic arc stratigraphy
Sistan Basin (Iran–Pakistan border)	Oligocene–Pleistocene	Fluvio-lacustrine clays, deltaic sands, evaporites	Gradual change from fluvial (east) to lacustrine–evaporitic (west)	Lacks interval-specific facies markers; age control weak	Use sedimentological logs and microfacies analysis to delineate depositional shifts
Bashagard / Jask Basin (SE Iran)	Eocene–Miocene	Deep marine turbidites, hemipelagic shales, carbonates	Suggested equivalents of Makran deep-marine facies	Facies boundaries poorly constrained; need regional seismic tie	Generate correlative facies maps linking Iranian and Pakistani sectors across the Makran subduction system

Paleocene sandstone of Rakhshani Formation, Eocene limestone of Kharan Formation and sandstone of Nauroze/ Amalaf Formation of Oligocene age are the potential reservoirs in the basin. The Rakhshani Formation sandstones have favourable reservoir quality in outcrops. The turbidities of Middle to Upper Miocene of Panjgur and Parkini Formations are considered as reservoir rocks. Lithologically, turbidites are mainly fine to coarse grained sandstones with shale intercalations. Samples from Panjgur display porosities reaching17.34% in sandstones.

Exploration in this region has historically been minimal due to limited infrastructure, remoteness, and the perception of low prospectivity. Seismic coverage is sparse, and industrial priorities have favoured the western and central Iranian petroleum provinces. However, satellite and surface geochemical data have revealed methane anomalies and thermogenic gas indicators near the Jaz Murian Basin, suggesting active petroleum migration systems [17].

Considering the foregoing, southeastern Iran near the border with Pakistan represents an underappreciated petroleum potential. Modern techniques such as full-tensor gradiometry, remote spectral mapping, and high-resolution magnetotellurics could facilitate subsurface imaging in this complex terrain. Investment in early-phase exploration, such as reconnaissance seismic surveys and shallow coring programs, is warranted to validate the geologic models.

In summary, southeastern Iran represents a frontier exploration domain with potentially viable petroleum systems. Coordinated bilateral geoscientific action would realize that potential, enhancing regional economic diversification and energy cooperation.

Enhanced scientific and diplomatic collaboration between Pakistan and Iran, especially in joint ventures and regional data sharing, would significantly improve understanding and exploration of this transboundary petroleum frontier.

5. Petroleum basins in Pakistan's territory:

- *The Kharan Forearc Basin:* This significant geological structure has immense sedimentary deposits between the Ras Koh volcanic arc and the Makran Accretionary Prism (fig. 4), indicating potential for hydrocarbon reservoirs. The Basin is characterised by Late Cretaceous and Tertiary successions composed of limestone, mudstone, sandstone, and volcanics. The volcanic successions are overlain by Late Cretaceous limestone and thick succession of Paleogene turbiditic shale, sandstone and conglomerate of the Rakhshani Formation. These followed a period of uplift and relative tectonic stability, recorded in the Eocene by platform carbonates and basinal muds. The sediments are overlain by deep marine muds and distal prodeltaic turbidites of the Oligocene, which shallow upwards in the east to delta front sands and muds of the Oligocene Nauroze Formation. Terrestrial to shallow marine clastic and carbonate sediments of the Amalaf Formation. The basin has complex structural environments, including thrust faults and anticlines, contributing to its hydrocarbon accumulation [28].
- *The Makran Accretionary Wedge* is characterised by intricate structural deformations due to subduction, and mud volcanoes and hydrocarbon seeps (fig. 4). The area exhibits extensive detachment faults and melange units, reflecting an active geological environment that may facilitate hydrocarbon migration [29].
- *Makran Offshore Basin:* Situated off the southwest coast, the basin has high potential for offshore hydrocarbon exploration based on tectonic activity and sedimentary processes (fig. 4). The Makran Offshore Basin contains numerous anticlinal traps and fault-bounded structures that are favorable for hydrocarbon accumulation due to the intense tectonic compression and folding associated with subduction. Ongoing tectonic uplift and deformation enhance fracturing and secondary porosity, thus improving reservoir potential, though excessive faulting may locally disrupt the seal integrity.

Table 3

Basins with probable petroleum content

Basin name	Country	Source rocks	Reservoir rocks	Trap types	Seal rocks	Status
Kharan Forearc Basin	Pakistan	Oligocene (Hoshab Formation), Miocene (Panjgur and Parkini Formation) and Pliocene (Talar Formations) 0.48 wt. % to 5.62 wt. %	Eocene rocks (Carbonates)	Anticlines, Faults	Shale, Marl	Underexplored (Moderate oil and gas potential)
Makran Offshore Basin	Pakistan	Miocene (Parkini Formation) 1.5 wt. %	Turbidite Sandstones	Submarine Fans	Deep Marine Shales	Frontier High gas potential (biogenic and thermogenic))
Jaz Murian-Mashkel Basin	Iran	Paleogene Shales	Fluvial-Turbiditic Sands and carbonates	Folds, Strat. Traps	Marl, Shale	Poorly studied
South Lut-Helmand Basin	Iran	Tertiary Organics, Cretaceous shales	Volcaniclastics, Sandstones, carbonates	Horst/ Graben	Interbeds, Shales	Untapped
Lut Plain-Gonabad Basin	Iran	Mesozoic Organics / limestones	Fractured Carbonates	Basement Faults	Evaporites, Shales	Potential

- The basin contains deepwater turbidite deposits, which may locally exhibit good reservoir quality, where coarse-grained, well-sorted, sand-rich intervals are dominant. Not all turbidites, however, form effective reservoirs since their quality depends upon grain size, sediment supply, and post-depositional compaction or cementation [25].

6. Possible petroleum potential in Pakistan near the Iran Border:

The southwestern margin of Pakistan, particularly the Kharan Forearc Basin, Makran Accretionary Wedge, and Makran Offshore Basin, presents a unique geological configuration conducive to hydrocarbon accumulation. These basins, formed under complex tectonic regimes dominated by the oblique convergence of the Arabian and Eurasian plates, display critical petroleum system elements such as thick sedimentary infill, active deformation structures, and observed seepage phenomena [6].

The stratigraphic architecture in these basins is dominated by Mesozoic to Cenozoic siliciclastic sequences interbedded with organic-rich marine shales, particularly within the Siahan and Rakhshani formations [25]. These shales, buried under sufficient overburden thickness, exhibit Type II and III kerogens and have reached late oil to wet gas window maturity in multiple basin modelling studies. Thermal maturity of source rocks, supported by vitrinite reflectance data (Ro>0.9%) and Tmax values exceeding 435 °C, confirms that hydrocarbon generation is active or recently ceased [17].

Structurally, the region is dissected by a network of compressional features, including fold-and-thrust belts, imbricate fans, and pop-up structures. These features form robust traps often associated with subsurface bright spots and amplitude anomalies observed in 2D seismic profiles [30]. Trap integrity is further supported by the widespread occurrence of Neogene marls and Eocene shales, which act as regional seals, capping both stratigraphic and structural reservoirs.

Reservoir characterization indicates significant potential within the Panjgur and Kharan sandstone members, which possess average porosities of 15–22 % and permeability values ranging from 100 to 600 mD in outcrop analogues. Fractured carbonates in the Kharan Limestone Play also demonstrate secondary porosity enhancement due to tectonic fracturing and dissolution processes, which are crucial in tight reservoir settings [31].

Despite the promising geology, the region remains underexplored due to challenging terrain, limited access to high-resolution seismic data, and geopolitical constraints. Historical drilling campaigns have been sparse, and most wells in Baluchistan were either dry or poorly logged (table 3). However, advances in seismic imaging, remote sensing, and offshore drilling technologies now provide an opportunity to re-evaluate this region with integrated petroleum system modelling methods.

Comparative analysis with analogue basins, i.e., Indonesia's forearc basins and the Nile Delta, indicates that analogous tectonostratigraphic settings can contain significant hydrocarbon reservoirs. Evidence of active mud volcanoes, hydrocarbon-seeping vents, and gas chimneys also makes the case for active petroleum systems in this yet-to-be-explored area [16].

In summary, southwest Pakistan near the Iran frontier has robust geological prospectivity that remains underexplored. An integrated exploration approach using innovative geological, geophysical, and geochemical techniques is required to delineate prospective areas and reduce the risk of exploratory investments.

7. Pakistan petroleum plays

Several petroleum plays have been identified in the region, including (table 4 and 5):

- *Kharan Limestone Play:* Composed of fractured limestone formations that serve as potential reservoirs.
- *Rakhshani Sand Play:* Contains porous sandstones with moderate permeability, supporting hydrocarbon accumulation.
- *Siahan Sand Play:* High porosity sandstone formations, suitable for hydrocarbon reservoirs.
- *Panjgur Sand Play:* Consists of a mixture of clastic and carbonate sequences, with structural and stratigraphic traps [12].

Table 4

Properties of petroleum plays

Petroleum Play	Age	Lithology / Reservoir	Source / Charge	Seal	Trap / Entrapment
Rakhshani Sandstone Play	Paleocene	Sandstone bodies	Rakhshani shales	Inter-bedded shales	Potential for joint testing via one well, similar to Kharan Play
Kharan Limestone Play	Eocene	Limestone	Indigenous charge or from the Rakhshani source	Nauroz Formation (mud-dominated basal part)	Three-way fault closures and large four-way dips
Panjgur Sand Play	Miocene	Sandstone (dominant in the Panjgur Formation)	Similar to Siahan Sand Play	Thick shale interbeds	Similar mechanism as Siahan; expected in the southern Kharan Forearc Basin
Siahan Sand Play	Late Miocene to Early Pliocene	Sandstone lenses (30–50 m thick, laterally extensive)	Good quality source rock within the Siahan Formation (?)	Shale encasement in channel sands	Stratigraphic traps and faulted anticlines

Table 5

Petroleum system elements and risk assessment

Element	Pakistan Basins (Avg. Rating)	Iran Basins (Avg. Rating)	Risk level (H/M/L)
Source rock	Moderate	Moderate	M
Reservoir quality	Moderate	Variable	M
Seal integrity	Good	Moderate	M
Trap integrity	Good	Variable	M
Exploration data	Poor	Poor	H

Conclusions

The transboundary basins of Iran and Pakistan, particularly the Makran Offshore, Kharan Forearc, and Jaz Murian-Mashkel basins, represent underexplored frontier regions with significant geological potential for hydrocarbon generation and accumulation. The Kharan Basin features Late Cretaceous and Tertiary formations of limestone, mudstone, sandstone, and volcanics, with significant stratigraphy including the Rakhshani Formation and Oligocene Nauroze Formation, reflecting varied depositional environments.

Makran Offshore Basin's tectonic activity enhances hydrocarbon traps, however excessive faulting poses a risk to seal integrity. The turbidite deposits in this basin vary in quality based on grain size and sediment history.

The Offshore Makran Basin contains Paleocene–Miocene sediments and Eocene–Oligocene shales as key sources, while Kharan, Sistan, and North Makran–Zahedan basins feature older continental–marine successions, reflecting a progressive shift from deep marine to continental depositional settings toward the north and east.

However, the absence of detailed 3D seismic, geochemical, and basin modeling studies has limited a comprehensive understanding of hydrocarbon migration pathways and trap integrity in these basins. Future research should emphasize petroleum system modeling, high-resolution seismic interpretation, and geochemical fingerprinting. Targeted exploration, supported by regional modeling and facies maps, will enhance understanding of petroleum systems and identify drilling prospects along the Pakistan–Iran border, emphasizing collaborative research.

The following are the future recommendations for conducting high-resolution seismic surveys and geochemical analyses to confirm the presence of hydrocarbon systems: Implement deep exploratory drilling programs in underexplored basins to confirm reservoir potential, foster collaboration between research institutions and the petroleum industry for integrated geological studies. Establish transboundary hydrocarbon development agreements between Pakistan and Iran for joint exploration initiatives.

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