Tectono-Stratigraphic Controls on Source-Rock Preservation and Petroleum-System Architecture in Pakistan: Geochemical Synthesis from Infracambrian to Paleogene

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Abstract

Pakistan preserves a highly partitioned petroleum-system architecture in which source-rock occurrence and effectiveness reflect not only depositional age and organic facies, but also inherited crustal architecture, episodic accommodation, non-deposition and erosion, rifting, burial, inversion, exhumation, and later structural connectivity. This synthesis integrates regional tectono-stratigraphic evolution with harmonized total organic carbon, Rock-Eval, biomarker, stable-isotope, maturity, and burial-history evidence to evaluate four interrelated petroleum-system questions within a broader nine-hypothesis framework.

The Ordovician-Silurian-Devonian gap is shown to be regional rather than Pakistan-wide. Much of the Indus-Punjab-western fold-belt succession lacks a preserved Middle Paleozoic section, whereas Silurian-Devonian rocks survived in northern tectonostratigraphic belts; three Khyber-Peshawar samples contain 8.47-12.47 wt.% TOC, demonstrating substantial preserved organic richness although their original generative potential and thermal maturity remain unresolved. This preservation contrast is interpreted as the product of spatially variable accommodation, emergence, erosion, and later tectonic overprint rather than a single country-wide erosional event.

Ediacaran-Infracambrian source systems provide a credible older-source hypothesis for the Punjab Platform, supported by regional source-quality data and the distinctive Karampur-Baghewala-Huqf biomarker family. Their petroleum significance, however, depends critically on reconstructed maximum paleoburial and thermal history; present-day depth and low geothermal gradient cannot be assumed to represent peak source maturity following major erosional episodes. Jurassic Chiltan, Shinawari, and Datta intervals similarly establish a viable deeper-source family beneath and adjacent to proven Mesozoic reservoirs, but available evidence supports prospect-scale Jurassic contribution or mixed charge rather than regional replacement of the Lower Cretaceous Sembar-Lower Goru system. Paleogene comparisons further show that Patala effectiveness reflects the conjunction of source quality, preservation, burial, kitchen development, migration connectivity, and trap timing rather than Paleogene age alone.

The resulting model is a multi-source, multi-stage petroleum system superimposed on a tectonically partitioned stratigraphic framework, in which inherited basin architecture governs deposition, tectonic events govern preservation and burial, and subsequent inversion and exhumation may decouple present structural and thermal conditions from the conditions under which hydrocarbons were generated. Direct source-to-fluid geochemistry integrated with restored paleogeography, burial-maturity history, and migration timing therefore provides the decisive test of competing source hypotheses.

Keywords

Pakistan; Indus Basin; Punjab Platform; Mesozoic source rocks; Qusaiba; Infracambrian; Sembar Formation; Chiltan; Patala; Paleogene source rocks; biomarkers; petroleum systems

1. Introduction

Pakistan is commonly discussed as a set of petroleum provinces, yet its present basins and fold belts are the products of several superimposed tectonic systems. The eastern and southeastern sedimentary cover belongs to the Indian Plate interior and rifted western margin; the north records Himalayan-Karakoram collision and foreland loading; the Sulaiman-Kirthar region records contraction, inversion, and oblique strain; and the southwest passes

into the Makran subduction-accretion system. Consequently, a source rock that is rich at deposition may later be eroded, thermally exhausted, structurally isolated, or reconnected to a reservoir by younger deformation. Conversely, a reservoir may receive hydrocarbons from a source much older or younger than the reservoir itself. Petroleum-system interpretation in Pakistan therefore requires a time-dependent framework rather than a single national stratigraphic column (Wandrey et al., 2004a; Ghani et al., 2021; Hinsch et al., 2019).

A country-wide analysis is in progress, to establish nine working hypotheses that separate observations from published interpretation, competing explanation, and integrated synthesis. However, for a journal-length petroleum paper, the most consequential questions are confined to four source-rock problems. The first is the regional Middle Paleozoic preservation gap. Productive Cambrian and Permian intervals occur in parts of the Indus and northern foreland systems, but a regionally demonstrated Lower Silurian source interval comparable in petroleum-system function to the basal Qusaiba of Arabia is absent from the recognized Indus and western fold-belt succession. At the same time, Silurian-Devonian strata are preserved in Peshawar-Nowshera, Khyber-Spinghar, Chitral, and western Karakoram domains, demonstrating that the interval was not absent from Pakistan as a whole (Hasany & Khan, 2012; Stauffer, 1968, 1975).

The second question concerns whether older Ediacaran-Infracambrian systems can compensate locally for the missing Middle Paleozoic source function. This question is particularly important on the Punjab Platform and its geological continuation toward the Bikaner-Nagaur Basin, where Neoproterozoic-Cambrian rift architecture, evaporites, carbonates, and organic-bearing intervals are better constrained than in many deep Pakistani wells (Raza et al., 2008; Mandal et al., 2022; Yasin et al., 2022). Biomarker evidence from the Baghewala-Karampur-Huqf family provides a regional genetic template that is difficult to explain by age coincidence alone, but it does not by itself demonstrate a laterally continuous Infracambrian kitchen beneath the Punjab Platform (Peters et al., 1995). The thermal part of this hypothesis is equally important: a presently cool Punjab Platform section may have experienced greater pre-erosional burial and peak thermal exposure than its modern depth and geothermal gradient imply, so maturity must be reconstructed through time rather than inferred from present conditions.

The third question is whether Jurassic source kitchens make a material contribution to hydrocarbons reservoired in Jurassic Chiltan carbonates and other Mesozoic reservoirs of the Sulaiman-Kirthar and Indus systems. The established regional baseline is the Lower Cretaceous Sembar-Lower Goru petroleum system (Wandrey et al., 2004a). Nevertheless, source-capable Jurassic Chiltan, Shinawari, and Datta intervals, proven Jurassic reservoirs, Jurassic rift depocentres, and compositionally variable hydrocarbons require a test of Sembar-only, Jurassic-dominant, and mixed-charge models rather than an assumption that reservoir age identifies source age (Ahmad et al., 2019; Khan et al., 2026; Nazeer et al., 2012).

The fourth question is source selectivity in the Paleogene. The Paleocene Patala-Nammal petroleum system is established in Kohat-Potwar, where younger source rocks charge reservoirs that include much older stratigraphic levels (Wandrey et al., 2004b). Yet source rocks of Paleocene-Eocene age elsewhere in Pakistan and adjacent basins are not uniformly demonstrated as comparably effective regional kitchens. The appropriate question is therefore not whether Paleogene shale exists outside Kohat-Potwar, but why a Patala-type combination of source quality, preservation, maturation, kitchen volume, and migration connectivity is demonstrably effective in one province and not yet demonstrated in others (Fazeelat et al., 2010; Ishaq et al., 2026).

Question	Working interpretation	Most useful evidence	Decisive test
Middle Paleozoic preservation	Regional hiatus/non-preservation in the Indus-Punjab-western fold-belt record; preserved northern domains demonstrate that the gap is not Pakistan-wide.	Time-space preservation, TOC, maturity, stratigraphic and thermal constraints.	Subcrop mapping plus Rock-Eval, maturity, biomarker/isotope testing of northern preserved intervals.
Infracambrian alternative charge	Ediacaran-Infracambrian sources are credible local alternatives but not a proven basin-wide substitute for a Qusaiba-style source; their maturity must be tested against maximum pre-erosional burial rather than present thermal conditions.	Salt Range/Fort Abbas source quality; Karampur-Baghewala-Huqf biomarker family; rift architecture.	Source-to-fluid biomarkers/isotopes integrated with reconstructed maximum paleoburial, erosion, heat flow, maturity and migration history.

Question	Working interpretation	Most useful evidence	Decisive test
Jurassic deeper-source contribution	Jurassic sources may contribute locally or in mixtures; Sembar remains the regional Cretaceous baseline.	Chiltan, Shinawari, Datta source quality; Jurassic biomarker fingerprints; Sembar controls.	Matched produced-fluid/source correlation and restoration of mature Jurassic kitchens.
Paleogene source selectivity	Patala effectiveness reflects a favorable petroleum-system conjunction, not Paleogene age alone.	Patala subsurface/outcrop, Sakesar, Cambay and Jaddala comparisons; maturity and biomarker evidence.	Region-wide source/fluid comparison with common maturity, burial, and connectivity controls.

Table 1: *Four petroleum-system questions used to organize the publication synthesis (Note. These are geological working hypotheses, not formal statistical null hypotheses. A preferred interpretation is retained only where it is consistent with the evidence and is stated together with a discriminating or falsifying test)*

This study transforms these four questions into an evidence-ranked, geochemically testable framework. The purpose is not to declare age-equivalent rocks genetically equivalent, nor to replace proven petroleum systems with speculative deeper sources. Instead, regional analogues are used to define falsifiable fingerprints. Source quality establishes whether a candidate could generate hydrocarbons; maturity establishes whether it could have generated at the relevant time; biomarkers and stable isotopes test molecular affinity; and restored burial and migration geometry determine whether the inferred source could have charged the observed accumulation.

The central proposition is that Pakistan is best interpreted as a multi-source, multi-stage petroleum province in which tectonic preservation and later structural reactivation determine which potential source intervals become effective petroleum systems.

These four objectives of the current article are nested within the (in-progress) hypothesis-spine of the country-wide synthesis, rather than replacing it. H2-H6 carry the direct petroleum-system tests; H1 and H7-H9 provide the tectonic and thermal boundary conditions that determine whether those source rocks were deposited, preserved, matured, connected to traps, or later breached.

ID	Working hypothesis	Role in this publication	Decisive / falsifying test
H1	Inherited lithospheric and basement architecture exerted a first-order control on later rifting, inversion, fold-thrust geometry and migration pathways.	Cross-cutting tectonic mechanism linking all four source-rock questions.	Restoration, seismic/well ties and age control must demonstrate real continuity or reactivation rather than geometric coincidence.
H2	The Middle Paleozoic gap reflects preservation partitioning: prolonged low accommodation/emergence combined with variable later exhumation and erosion.	Central objective 1: explains why the main Indus-Punjab-western fold-belt succession lacks a regional Silurian system while northern Pakistan preserves it.	Subcrop mapping, provenance and thermochronology; a widespread concealed Silurian-Devonian section beneath the Indus system would weaken the model.
H3	Ediacaran/Infracambrian source systems may compensate locally for the missing Silurian source function. Their maturity may record greater pre-erosional burial rather than present-day depth and geothermal gradient, but they are not a proven basin-wide substitute.	Central objective 3: tests Punjab Platform charge, paleothermal inheritance and regional Bikaner-Nagaur-Huqf functional analogues.	Direct source-to-fluid biomarkers/isotopes plus prospect-specific maximum paleoburial, erosion, heat-flow, maturity and migration modelling.
H4	Patala effectiveness is selective and depends on organofacies, preservation, burial/maturity and structural connectivity, not Paleogene age alone.	Central objective 4: asks why a Patala-type effective source system is not comparably demonstrated across Middle, Lower and Offshore Indus.	Common-workflow Paleogene source-rock and produced-fluid comparison with burial/maturity control.
H5	Jurassic sources contribute locally or in mixed systems rather than replacing Sembar regionally.	Central objective 2: tests Chiltan-Anjira and Datta-Shinawari source contributions to Jurassic reservoirs and younger accumulations.	Matched oil/condensate/gas-source correlation plus restoration of mature Jurassic kitchens.
H6	Sembar-Lower Goru remains the regional Cretaceous baseline; mixed charge should be invoked only where fluids and migration history require it.	Null/baseline model against which Jurassic and Paleogene additions are tested.	Multi-parameter fluid fingerprinting and prospect-scale generation-migration modelling must discriminate Sembar-only from mixtures.
H7	India-Eurasia collision and basin response were diachronous and process-specific, not one synchronous country-wide event.	Controls burial, trap formation, uplift and exhumation timing.	Independent ages for suturing, metamorphism, foreland loading and outward migration of shortening.
H8	Western Pakistan is a distributed Chaman-Ghazaband-Ornach-Nal-fold-belt transpressional system rather than a single-fault boundary.	Controls later structural segmentation, leakage and remigration in the western petroleum provinces.	Regional motion budget from GNSS/InSAR, paleoseismology and balanced structures.
H9	The first-order plate model is India-Eurasia collision plus Arabian subduction beneath Makran; P-IMM remains a falsifiable alternative or transient block.	Provides the southwest boundary condition but is secondary to the source-rock tests.	Independent paleomagnetism, Euler rotations, restored boundaries, deep structure and subduction polarity.

Table 2: The hypothesis framework of the on-going country-wide synthesis (Note: The petroleum-centered objectives of this paper are H2-H6; H1 and H7-H9 remain cross-cutting tectonic controls. Each hypothesis is treated as falsifiable and is not presented as established fact where direct evidence is incomplete)

2. Data and Analytical Framework

The evidence base combines the avaiable literature assembled for the coutry-wide synthesis with a harmonized geochemical workbook developed specifically for cross-province comparison. Individual analytical rows are separated from published formation-level averages and ranges so that aggregate literature statistics are never treated as pseudo-samples. Each usable row retains, where available, country, basin or tectonic domain, formation, age, well or outcrop, sample type, depth, TOC, S1, S2, S3, Tmax, hydrogen index (HI), oxygen index, production index, vitrinite reflectance, extract composition, isoprenoid ratios, sterane and hopane parameters, stable-carbon isotopes, mineralogy, and source citation. This distinction is essential because a regional benchmark based on hundreds of measurements has a different statistical meaning from a small set of individual rock samples.

Quality control was designed around petroleum-system interpretation rather than around maximizing the number of plotted points. Core, cuttings, outcrop, oil, condensate, and source-rock extract data are not pooled without flags. Weathered outcrops are separated from fresh subsurface samples because oxidation and leaching can reduce preserved TOC, S2, and HI; this is directly demonstrated by recent work on exposed Qusaiba shale and is relevant to northern Pakistani outcrops as well (Lashin et al., 2025). Thermal maturity is also retained wherever possible because residual source potential decreases as generation proceeds. Thus, low HI in a mature sample cannot automatically be interpreted as poor original kerogen quality (Cole et al., 1994a).

The analytical sequence follows an evidence ladder. Age and depositional association define plausible candidates; TOC and Rock-Eval establish present source quality; Tmax and reflectance constrain maturity; biomarker patterns compare organic-matter input and depositional environment; stable isotopes provide an independent compositional test; and source-to-fluid correlation is considered convincing only when molecular similarity is compatible with burial, generation timing, and migration geometry. Multivariate statistics can be useful for pattern recognition, but they are subordinate to these independent petroleum-system tests. This approach explicitly prevents a rich nearby shale from being promoted to the effective source of an accumulation without genetic and temporal support.

The main paper now uses a deliberately expanded but still selective figure set. The geochemical crossplots and figures presented here are retained because each contributes to one of the four petroleum-system questions or to the tectonic boundary conditions needed to interpret them. The geochemical figures test source richness, kerogen quality, maturity compatibility, redox and organic-matter character, sterane family relationships, stable-carbon-isotope separation and source selectivity. Regional maps, stratigraphic panels and event-response diagrams are included only where they explain preservation, burial, exhumation, structural inheritance or migration timing.

The study has four deliberate limitations. First, the Khyber-Peshawar Silurian-Devonian samples used in Figure 6 are TOC-only observations (Hasany and Khan, 2012); no Rock-Eval or maturity values are available for those specific samples in the cited source. Second, the Infracambrian biomarker comparison uses selected high-value molecular parameters and does not replace full GC-MS and compound-specific isotope correlation. Third, several Arabian benchmarks are published aggregates rather than row-level data. Fourth, present-day depth or geothermal gradient is not used as a surrogate for maximum paleotemperature in structurally exhumed provinces. A quantitative burial-exhumation-temperature model for the Punjab Platform Infracambrian system remains a priority rather than an assumed result.

3. Regional Tectono-Stratigraphic Context

The four source questions are linked by one regional observation: stratigraphic preservation across Pakistan is strongly partitioned. Across the Salt Range, Punjab Platform, and much of the recognized Indus and western fold-belt succession, Cambrian rocks are followed by a large Paleozoic gap before Permian restoration. The missing interval commonly encompasses Ordovician, Silurian, Devonian, and much of the Carboniferous. This geometry is inconsistent with a model in which a continuous Qusaiba-like Lower Silurian marine source was simply deposited everywhere and preserved everywhere until later burial. Instead, the present evidence favors a combination of low

accommodation or emergence, sediment starvation, later exhumation and erosion, and local structural relief, with the relative contribution of those processes varying across the plate (Ghani et al., 2021).

Source population	n	Mean TOC (wt.%)	Mean S2 (mg HC/g rock)	Mean HI (mg HC/g TOC)	Interpretive role
Basal Qusaiba, all (published aggregate)	Values are kept hidden, but used inside Brill-Viz for visualization				Regional Silurian primary-source benchmark (Cole et al., 1994a).
Salt Range Fm., Bijnot-1					Pakistan Ediacaran-Infracambrian candidate (Yasin et al., 2022).
Fort Abbas-1 selected Infracambrian					Punjab Platform older-source test; small selected subset.
Chiltan, Sann-1					Direct southern Pakistan Jurassic source-capable control (Ahmad et al., 2019).
Shinawari, Kohat					Jurassic marine-to-marginal-marine source candidate (Khan et al., 2026).
Datta, Kohat					Highly heterogeneous Jurassic terrestrial/mixed system; coal-rich outliers affect means (Khan et al., 2026).
Sembar, Sann-1					Same-well Cretaceous competing-source control (Ahmad et al., 2019).
Sembar, Zindapir-1					Mature/gas-prone Cretaceous control (Ahmed et al., 2026).
Patala subsurface, Manzalai-1					Hydrogen-rich Paleocene source subset (Ishaq et al., 2026).
Patala outcrop, Panoba					Weathering/exposure-affected Paleocene comparison (Ishaq et al., 2026).

Table 3: Selected geochemical populations used as representative source-rock controls (Note: The values have been used in analyytics inside Brill-Viz aplicaton, but data are kept heidden; Sample-level means are calculated from the harmonized project workbook. The Qusaiba row is a published aggregate and is not mixed with individual-sample statistics. Means summarize heterogeneous populations and should not substitute for point-level interpretation).

Northern Pakistan provides the critical control because it preserves Middle Paleozoic rocks in tectonostratigraphic belts outside the standard Indus petroleum column. The Peshawar-Nowshera succession contains fossiliferous latest Silurian to Devonian carbonates and associated dark lithologies; Khyber and Spinghar contain correlated packages of variable age confidence; and Chitral-western Karakoram contains a substantially more complete Paleozoic record (Stauffer, 1968, 1975). These occurrences demonstrate that Middle Paleozoic marine environments existed along parts of the northern Indian margin while the more southerly platform experienced a different accommodation and preservation history.

The Mesozoic record represents a second shift in petroleum architecture. Rifting and passive-margin development created thick Jurassic-Cretaceous depocentres across the western Indian margin, while later Cenozoic compression inverted or shortened parts of that architecture. In Kirthar, positive inversion of older normal faults means that present fold crests can be spatially displaced from original hanging-wall source depocentres (Hinsch et al., 2019). In the Sulaiman region, deep synclines and foredeep burial can mature source rocks that are leaner or shallower on present anticlines. The petroleum question is therefore not simply which formation occurs beneath a reservoir, but where the source-rich facies originally accumulated and whether later burial and faulting connected them to the trap.

Paleogene foreland development then introduced younger source opportunities and changed the maturity of older systems. In Kohat-Potwar, flexural loading and younger molasse burial matured Paleocene and older source rocks while thrusting created migration pathways and structural closures. This enables a younger source such as Patala to charge Paleozoic reservoirs, illustrating why source age and reservoir age must be decoupled in genetic interpretation (Wandrey et al., 2004b). The same principle is relevant to the Sulaiman-Kirthar system, where Cenozoic deformation can both improve vertical migration from deep kitchens and damage earlier traps through uplift, faulting, or leakage.

3.1 Plate-Boundary Architecture and Province Framework

Pakistan occupies the junction of the Indian, Eurasian and Arabian plate systems, so the source-rock problem cannot be separated from the spatially variable tectonic framework in which those source intervals were deposited and later modified. Northern Pakistan records India-Eurasia collision through the Himalaya-Karakoram-Kohistan system; western Pakistan transfers oblique convergence through the Sulaiman fold-thrust belt and the Chaman-Ghazaband-Ornach-Nal family of structures; and the southwest passes into the Makran subduction system, where Arabian lithosphere is consumed beneath the Eurasian-affinity margin. Large parts of the Indus region, by contrast, preserve the sedimentary record of the western and northwestern Indian continental margin. These domains therefore experienced different accommodation, burial and exhumation histories even when they were influenced by the same plate-scale event (Jenkins et al., 2013; Turner et al., 2013; Maldonado et al., 2011). This regional framework is summarized in Figure 1.

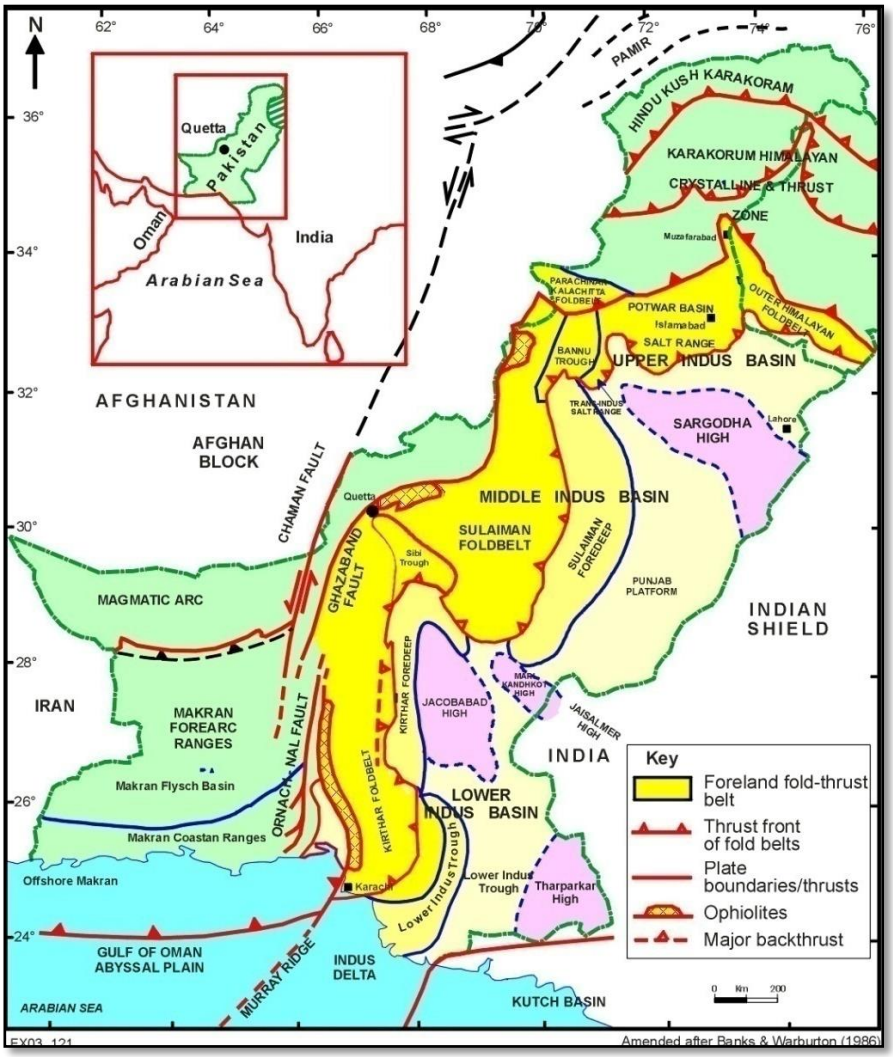


Figure 1: Regional tectonic setting of Pakistan within the India-Arabia-Eurasia convergence system (Note: Modified after Banks and Warburton, 1986. The map is used as a tectonic-province and structural-boundary framework; it does not imply that all modern province boundaries existed through geological time)

The distinction between a sedimentary-basin map and a tectonic-province map is important for this synthesis. The Punjab Platform is a platformal part of the Indian Plate sedimentary domain; Potwar-Kohat-Bannu is a deformed foreland family; Sulaiman and Kirthar are fold-thrust and inversion belts superimposed on older Indian-margin architecture; Makran is an accretionary prism; and Chaman is a distributed transform/transpressional system. A source-rock comparison that ignores those differences risks comparing units that share an age but not the accommodation, redox, burial or migration conditions required for the same petroleum-system function. The modern sedimentary-basin classification is retained as a geographic reference, but the analytical comparisons in this paper follow tectonic function and age-specific paleogeography rather than modern basin names alone (Kazmi & Abbas, 2001; Wandrey et al., 2004a). The alternative exploration-basin classification used as a geographic reference is shown in Figure 2.

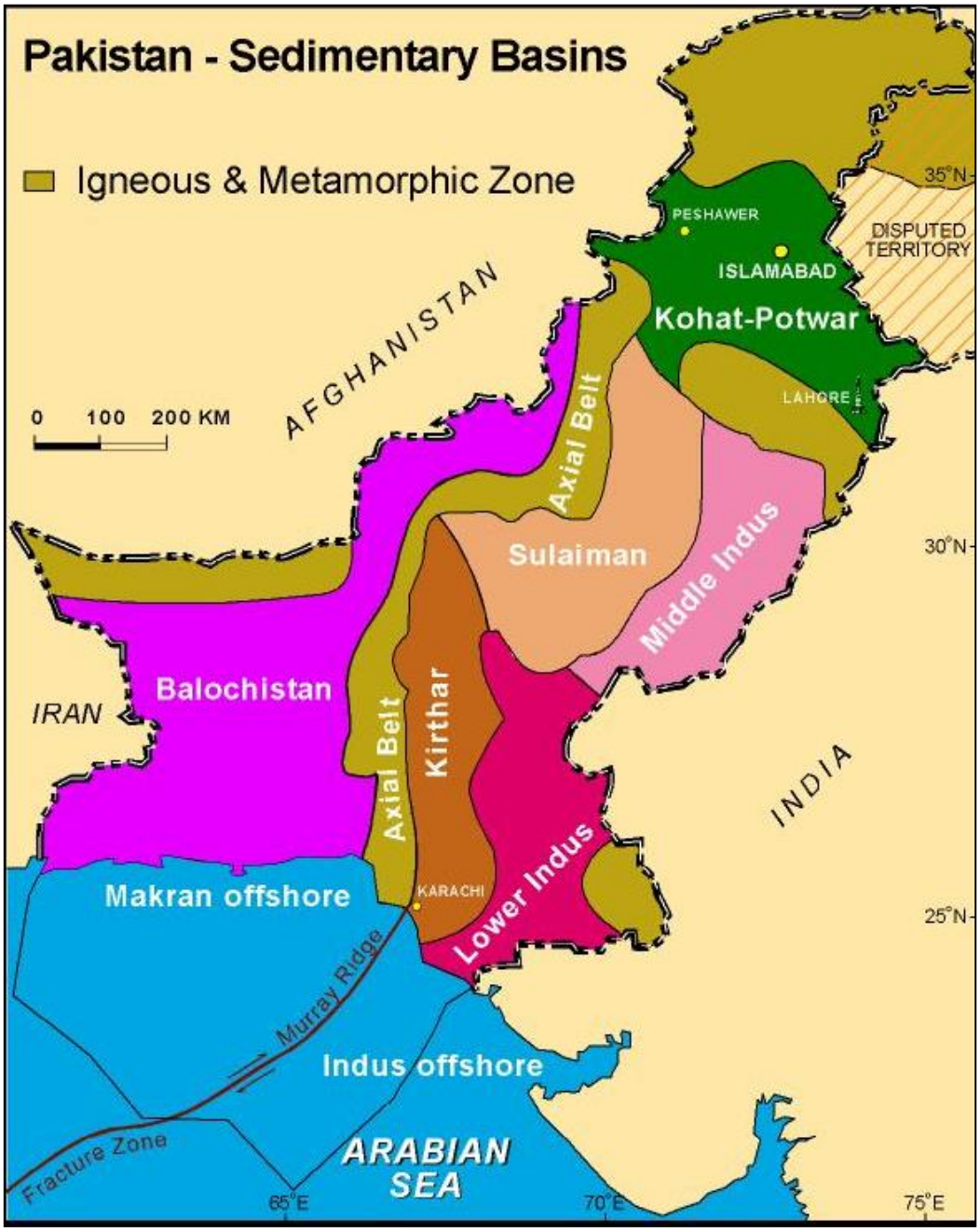


Figure 2: Simplified sedimentary-basin division of Pakistan (Note: Regional compilation based on Banks and Warburton, 1986. The figure is included to show how exploration-basin nomenclature differs from the tectonic classification used in Figure 1)

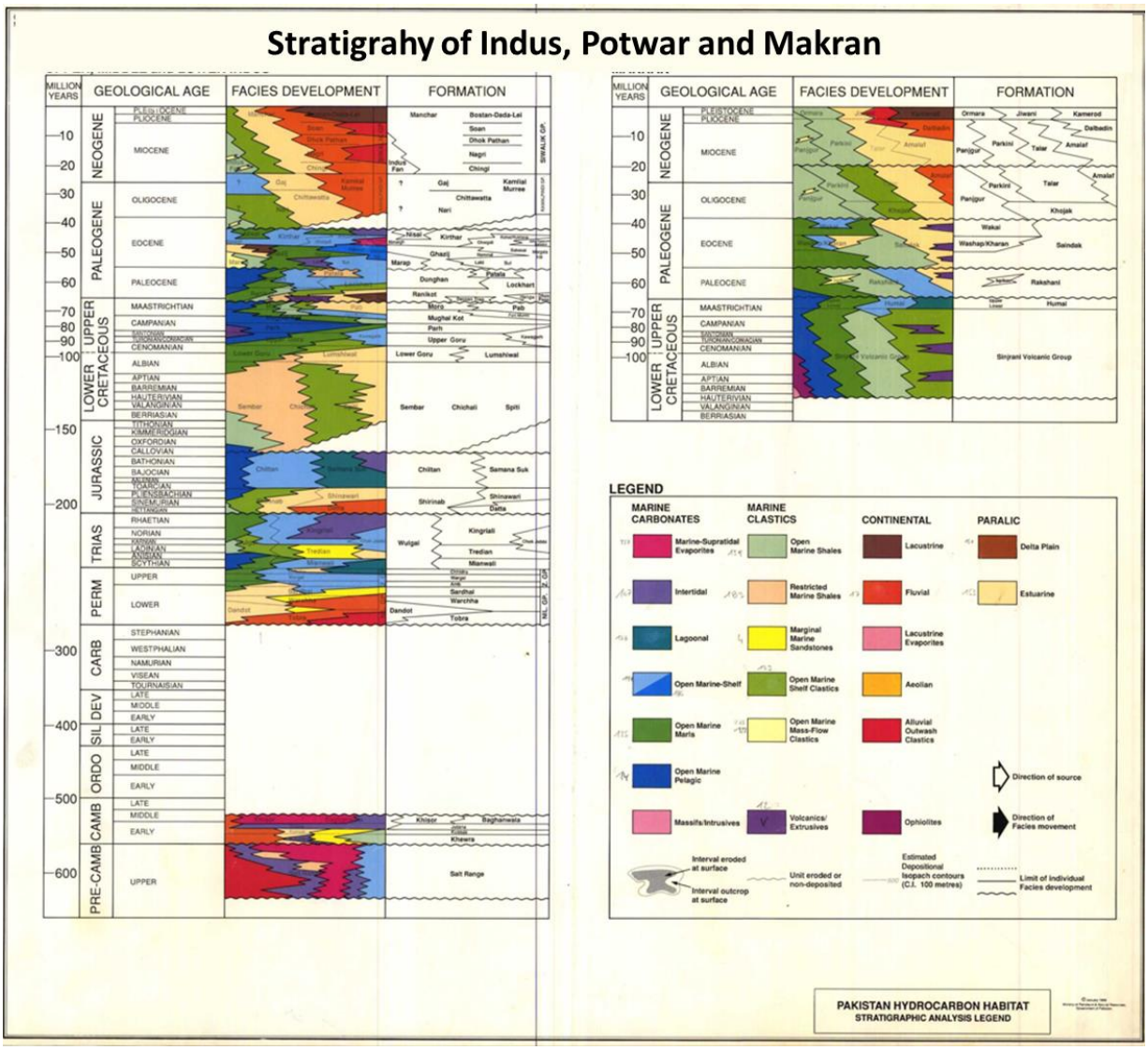


Figure 3: Country-wide stratigraphic guide for the Indus, Potwar, and Makran domains (Note: Regional stratigraphic chart reproduced from Hydrocarbon Habitat of Pakistan and included here as a broad country-wide guide. It is used for general comparison only and should not be interpreted as a single uniform stratigraphic column for all tectonic provinces)

3.2 Stratigraphic Architecture of the Middle-Lower Indus and Sulaiman-Kirthar System

The Mesozoic petroleum question is best understood in a vertical stratigraphic framework. Across the Middle-Lower Indus and Sulaiman-Kirthar system, the Jurassic Chiltan-Shinawari-Datta-Samana Suk family lies beneath the Lower Cretaceous Sembar-Goru petroleum system and is overlain by Paleogene and younger packages. This arrangement creates a fundamental ambiguity: a Jurassic reservoir does not identify a Jurassic source. Hydrocarbons in Chiltan or Samana Suk can be charged from Jurassic source-prone facies, vertically or laterally migrating Sembar fluids, younger sources, or mixtures, depending on local paleogeography and structural connectivity. The generalized column therefore serves as a source-reservoir-seal architecture, not as evidence of genetic linkage by stratigraphic proximity. Figure 3 provides the broad country-wide stratigraphic guide, while Figure 4 focuses on the Middle-Lower Indus and Sulaiman-Kirthar source-reservoir-seal architecture.

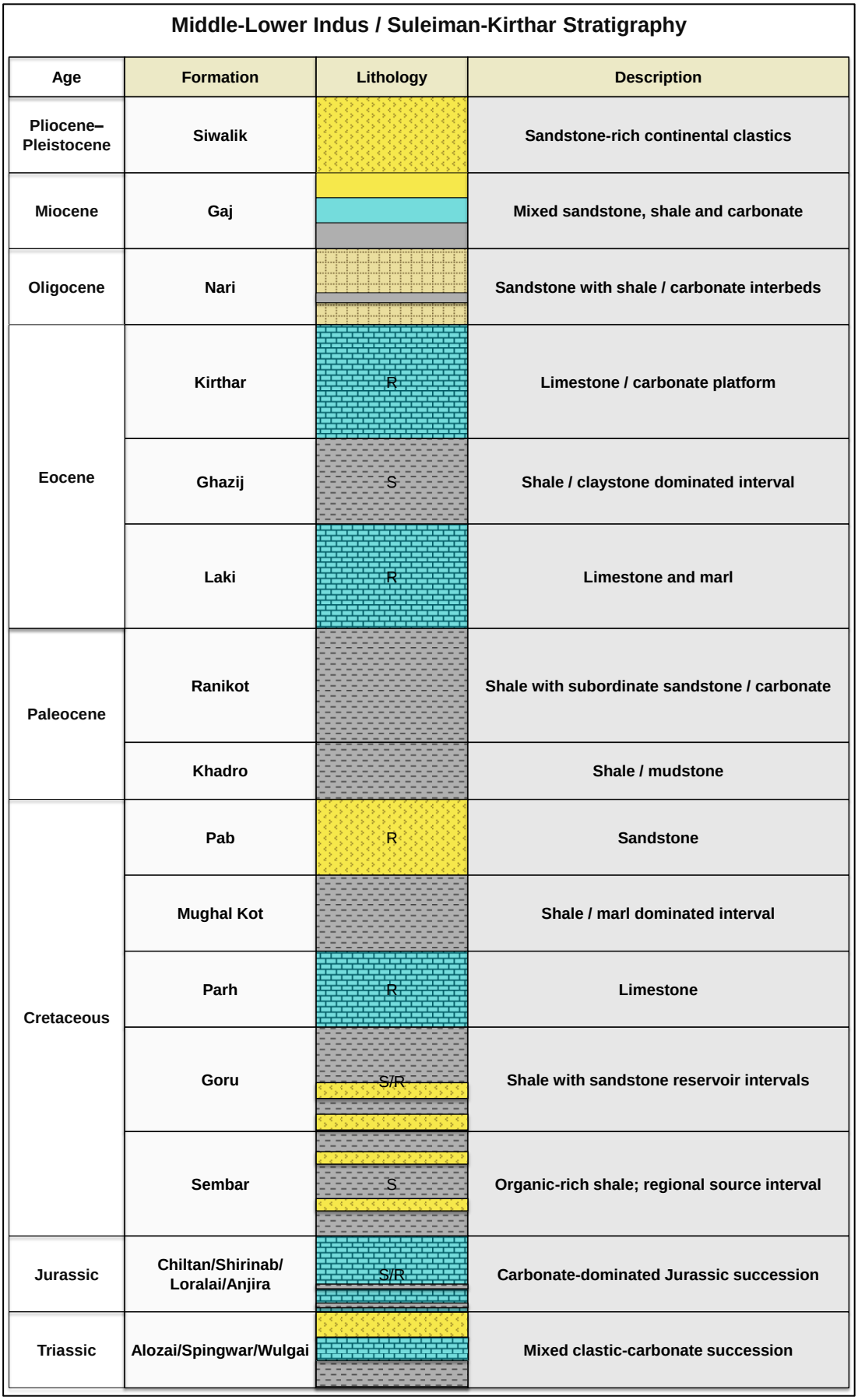


Figure 4: Generalized stratigraphic framework of the Middle-Lower Indus and Sulaiman-Kirthar fold belt (Note: The column emphasizes the vertical position of Jurassic carbonate/source candidates below Sembar-Goru and Paleogene packages; formation thicknesses and local presence vary between provinces and wells).

3.3 Country-Wide Preservation and Hiatus Framework

The most important stratigraphic asymmetry in the paper is the regional Middle Paleozoic preservation gap. Pakistan does not have one uniform stratigraphic column. Cambrian and Permian packages are widely recognized in the main Indus-Potwar system, whereas Ordovician, Silurian, Devonian and much of the Carboniferous are absent or unproven across broad parts of that province. Northern Pakistan preserves the critical counterexample: Peshawar-Nowshera-Khyber and Chitral-western Karakoram retain Middle Paleozoic successions. Apparent absence may represent non-deposition, emergence, erosion, structural truncation, limited subsurface control, or combinations of these processes rather than one Pakistan-wide event (Talent et al., 1999; Gaetani et al., 2008; Ghani et al., 2021). The country-wide time-space expression of this contrast is summarized in Figure 5.

Time / Stratigraphic interval	Tectonic Province / Basin							
	Punjab Platform	Potwar-Kohat / Bannu†	Middle Indus	Lower Indus / Offshore Indus	Northern Pakistan*	Sulaiman-Kirthar	Pishin-Balochistan	Makran
Pliocene-Recent	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread
Oligocene-Miocene	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread
Paleocene-Eocene	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread
Cretaceous	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Local / uncertain	Preserved / widespread
Jurassic	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Local / uncertain	Preserved / widespread
Triassic	Local / uncertain	Local / uncertain	Local / uncertain	Local / uncertain	Preserved / widespread	Local / uncertain	Local / uncertain	Not comparable / different story
Permian	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Preserved / widespread	Local / uncertain	Not comparable / different story
Carboniferous	Major hiatus / absent	Local / uncertain	Major hiatus / absent	Major hiatus / absent	Preserved / widespread	Local / uncertain	Not comparable / different story	Not comparable / different story
Devonian	Major hiatus / absent	Major hiatus / absent	Major hiatus / absent	Major hiatus / absent	Preserved / locally widespread	Major hiatus / absent	Not comparable / different story	Not comparable / different story
Silurian	Major hiatus / absent	Major hiatus / absent	Major hiatus / absent	Major hiatus / absent	Preserved / locally widespread	Major hiatus / absent	Not comparable / different story	Not comparable / different story
Ordovician	Major hiatus / absent	Major hiatus / absent	Major hiatus / absent	Major hiatus / absent	Preserved / widespread	Major hiatus / absent	Not comparable / different story	Not comparable / different story
Cambrian	Preserved / widespread	Preserved / widespread	Local / uncertain	Local / uncertain	Preserved / widespread	Local / uncertain	Not comparable / different story	Not comparable / different story
Precambrian / Ediacaran-Infracambrian	Local / uncertain	Local / uncertain	Local / uncertain	Local / uncertain	Preserved / widespread	Local / uncertain	Not comparable / different story	Not comparable / different story

† Potwar-Kohat / Bannu includes the Bannu Basin and Trans-Indus foreland domain; preservation is composite and locally variable, particularly near the Carboniferous-Permian transition.

** Northern Pakistan is a composite category including Hazara, Peshawar-Nowshera-Khyber, Chitral-Hindu Kush, Karakoram and Himalayan domains; preservation is not continuous or uniform across all constituent domains or stratigraphic intervals.*

Preserved / widespread | Local / uncertain | Major hiatus / absent | Not comparable / different story

Core message:

Pakistan does not have one uniform stratigraphic column. Apparent absence may reflect non-deposition, erosion, or limited subsurface control. The strongest national contrast is the preservation of Middle Paleozoic strata in northern Pakistan versus their widespread absence across the main Indus–Punjab–western fold-belt system.

Petroleum significance:

The Middle Paleozoic preservation gap helps explain the absence of a regionally preserved Qusaiba-style source system across most of Pakistan and increases reliance on older alternative sources and younger Jurassic–Cretaceous–Paleogene systems.

Figure 5: Pakistan-wide stratigraphic preservation and hiatus framework from the Precambrian to Recent (Note: The matrix distinguishes preserved, local/uncertain, major hiatus/absent, and non-comparable tectonic domains; it is a time-space synthesis rather than a single national stratigraphic column).

4. Results

4.1 Middle Paleozoic Preservation and the Northern Silurian-Devonian Test

The Middle Paleozoic problem is best expressed as a preservation-partitioning problem rather than as a Pakistan-wide absence. In the recognized Indus, Punjab Platform, Salt Range, and much of the western fold-belt stratigraphic record, no regionally established Lower Silurian source interval occupies the petroleum-system position of the basal Qusaiba. In contrast, Peshawar-Nowshera, Khyber, and more northerly Tethyan-margin domains preserve Silurian-Devonian rocks. This contrast shifts the exploration question from 'Did Silurian rocks exist in Pakistan?' to 'Where were they deposited, where were they preserved, and did any preserved organic-rich facies remain sufficiently mature and connected to function as a source?'

Hasany and Khan (2012) reported three broadly Silurian-Devonian samples from the northwestern Pakistan belt with unusually high TOC: Yakha Cheena shale, 8.57 wt.%; Ali Masjid carbonaceous shale-silt-limestone, 12.47 wt.%; and Lowara Mena shale-limestone, 8.47 wt.%. Figure 6 compares these individual values with the large basal Qusaiba dataset summarized by Cole et al. (1994a). The Pakistani values lie above the Qusaiba mean and within the broad range of the Saudi source interval. This is geologically significant because it demonstrates local preservation of abundant organic carbon in a stratigraphic interval that is missing from the principal Indus petroleum column.

The comparison must nevertheless be interpreted conservatively. The three Pakistan samples have no reported Rock-Eval, HI, S2, vitrinite-equivalent maturity, biomarker, or oil-source correlation in the source used here. High TOC cannot distinguish oil-prone marine kerogen from thermally altered or inert organic matter. It also cannot

reconstruct how much generative potential may have been lost during orogenic heating, deformation, weathering, or metamorphic overprint. The Qusaiba benchmark itself demonstrates the maturity problem: the less mature subset has a mean TOC of 4.67 wt.%, mean S2 of 22.04 mg HC/g rock, and mean HI of 434, whereas the more mature subset has lower mean TOC, S2, and HI as generation proceeds (Cole et al., 1994a).

Accordingly, the petroleum significance of the Khyber-Peshawar occurrences is potentially large but presently unproven. Their strongest value is as a paleogeographic and geochemical control. If targeted Rock-Eval, petrography, reflectance, biomarker, and stable-isotope analyses demonstrate that organic-rich Silurian facies originally contained marine oil-prone kerogen, then the northern belt would prove that high-quality Middle Paleozoic source facies were present on at least part of the northwestern Indian margin. If those rocks are now overmature, they may still record a formerly effective source system. Conversely, if the organic matter is dominantly inert, heavily oxidized, or metamorphically transformed without reconstructable generative potential, the high TOC values would not support a viable petroleum-source analogue.

This result has another implication for Indus basins. A missing source interval represents loss or non-development of a potential future kitchen, not necessarily erosion of an already generated petroleum accumulation. Where Silurian-Devonian strata were never deposited or were removed before deep Mesozoic-Cenozoic burial, they could not have entered a later oil or gas window comparable to Qusaiba kitchens in Arabia. This helps explain why productive Cambrian and Permian reservoirs in Pakistan commonly require composite charge models involving older Ediacaran, younger Mesozoic, or Paleogene sources rather than a vertically integrated Middle Paleozoic source-reservoir system.

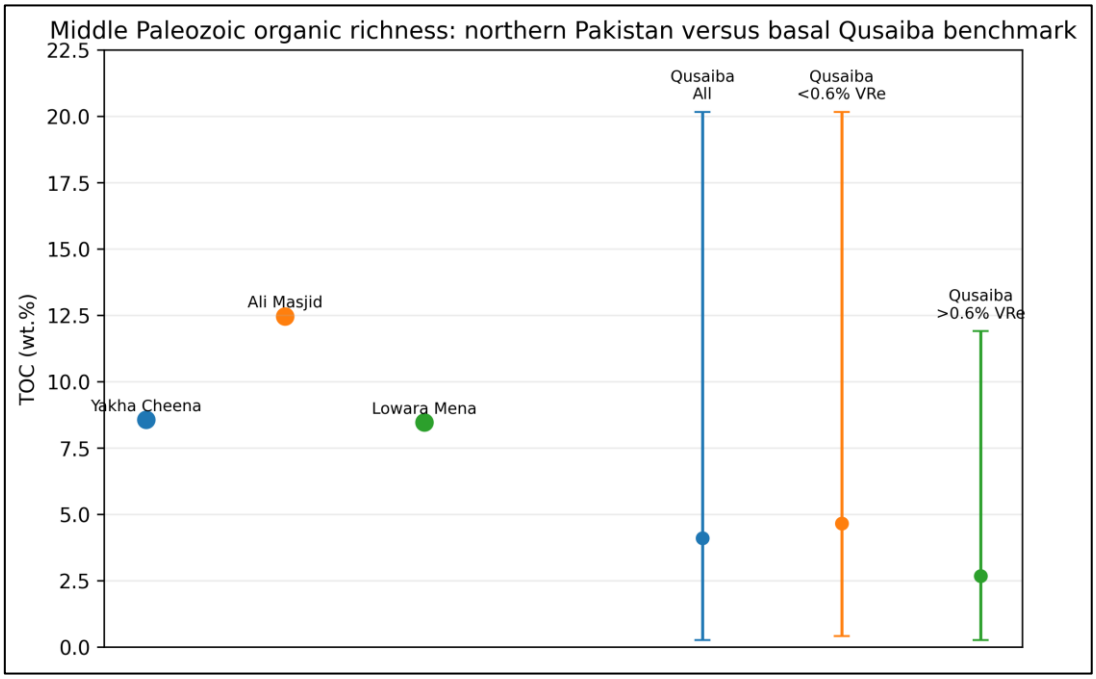


Figure 6: Middle Paleozoic organic richness in northern Pakistan compared with the basal Qusaiba benchmark (Note. Northern Pakistan values are three individual TOC measurements reported by Hasany and Khan (2012). Qusaiba points are published aggregate means from Cole et al. (1994a); vertical bars show the reported minimum-to-maximum TOC range, not standard deviation. The figure tests organic richness only. The northern Pakistan samples lack equivalent Rock-Eval and maturity measurements and therefore are not shown as proven Qusaiba-equivalent source rocks).

The preservation pattern becomes clearer when domains are compared directly. The Salt Range-Punjab Platform records the strongest documented Ordovician-Silurian-Devonian-Carboniferous hiatus, whereas Peshawar-Nowshera-Khyber preserves confirmed Silurian and Devonian rocks and Chitral-western Karakoram preserves a still more extensive Middle Paleozoic archive. Kurram-Spinghar contains more uncertain or locally correlated intervals, and the western Balochistan-Makran domains are dominated by younger oceanic, arc, flysch and accretionary histories. This pattern is the core support for H2: preservation partitioning is more plausible than a model in which one later erosional event removed a once-uniform Middle Paleozoic section everywhere. Figure 7 summarizes this preservation partitioning across the selected tectonostratigraphic domains.

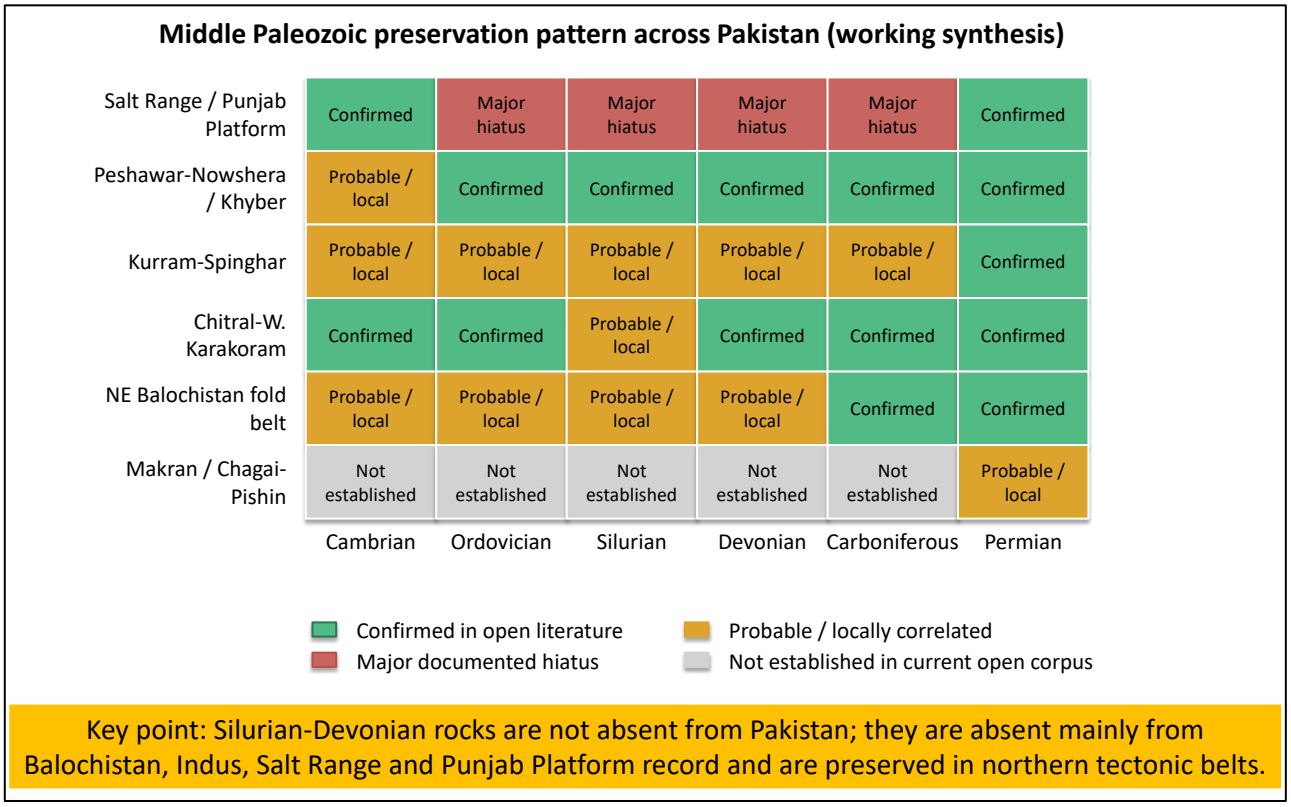


Figure 7: Middle Paleozoic preservation pattern across selected Pakistan tectonostratigraphic domains (Note: Confidence categories reflect the openly-accessible published evidence corpus, which should be updated as new well, fossil and seismic constraints become available)

The Arabian comparison sharpens the petroleum consequence rather than providing a claim of lithostratigraphic equivalence. In Saudi Arabia, the basal Qusaiba is a regionally persistent Lower Silurian source with a published mean TOC of about 4.11 wt.% and values to about 20.17 wt.%; localized Devonian Jauf source beds provide an additional, more heterogeneous contribution. Hercynian erosion removed substantial section locally, yet Qusaiba survived in regional kitchens and generated much of its petroleum during later Mesozoic-Cenozoic burial. The recognized Indus and western fold-belt succession instead lacks the corresponding regional Silurian-Devonian source-carrier interval between Cambrian and Permian packages. Thus, the missing interval represents loss or non-development of a potential future source-kitchen function, not evidence that pre-existing Paleozoic oil fields were physically eroded away (Cole et al., 1994a; Ahlbrandt et al., 2002). The resulting Saudi Arabia-Pakistan preservation contrast is summarized in Figure 8.

The overlying Carboniferous-Permian transition provides an independent stratigraphic constraint on the termination of the hiatus. In the Salt Range, Permian strata locally overlie Cambrian or even older rocks, and thermochronologic evidence supports significant Late Paleozoic cooling and exhumation. The spatial variability of the subcrop implies that erosion and non-deposition were not uniform in magnitude. This is why the paper separates three questions that are often conflated: whether Middle Paleozoic strata were deposited, whether they were preserved, and whether any preserved organic-rich facies retained petroleum-generative capacity after later burial, deformation and thermal overprint (Ghani et al., 2021; Ali et al., 2021). The schematic relationship is shown in Figure 9.

4.2 Infracambrian Alternative Charge and the Punjab Platform

The Infracambrian hypothesis addresses a different petroleum-system function: whether older source rocks can locally compensate for the missing Middle Paleozoic source interval. The Punjab Platform is the most direct test because its early sedimentary architecture is related to the Bikaner-Nagaur system across the Pakistan-India border. Seismic and stratigraphic studies describe Neoproterozoic-Cambrian fault-bounded depocentres, clastic-carbonate-evaporite packages, and later structural reactivation, while geochemical work demonstrates source-capable organic matter in the regional Salt Range Formation and correlated intervals (Raza et al., 2008; Mandal et al., 2022; Yasin et al., 2022).

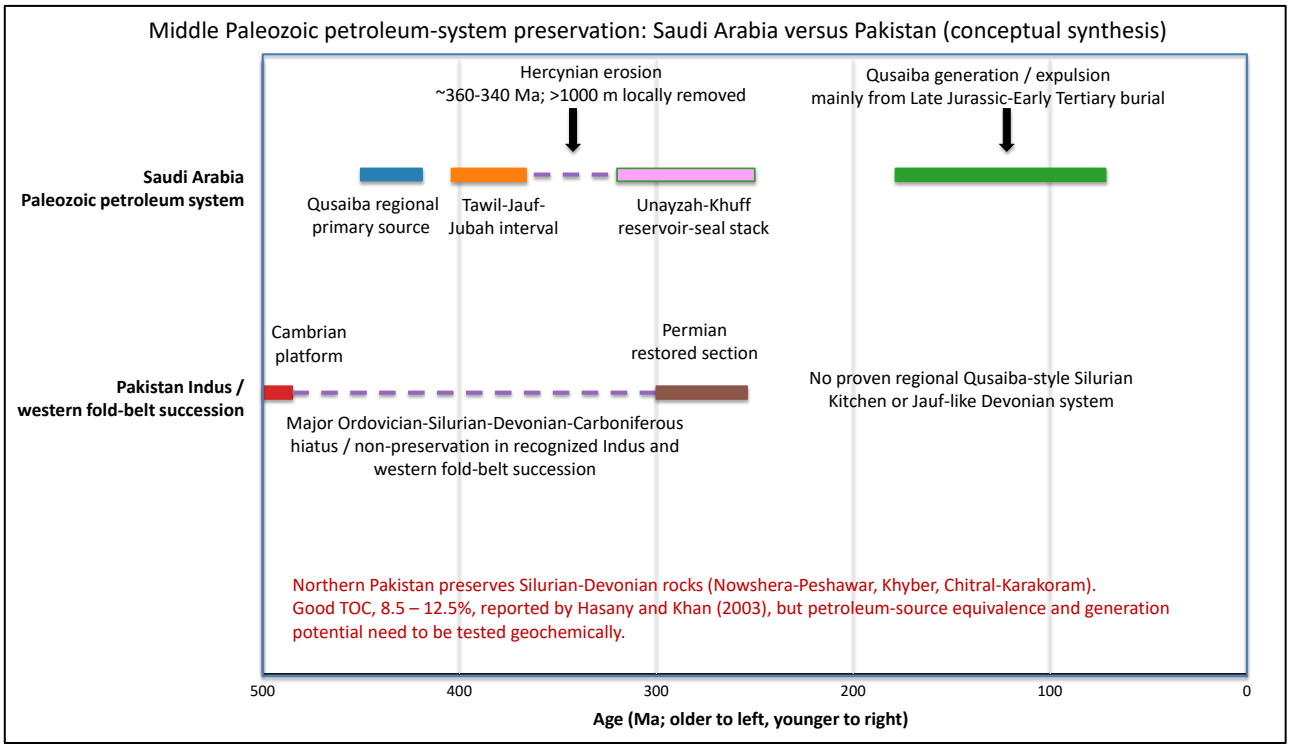


Figure 8: Middle Paleozoic petroleum-system preservation: Saudi Arabia versus Pakistan (Note: Bar positions are schematic and illustrate source/reservoir preservation and later generation relationships; they are not intended as precise formation-boundary chronostratigraphy)

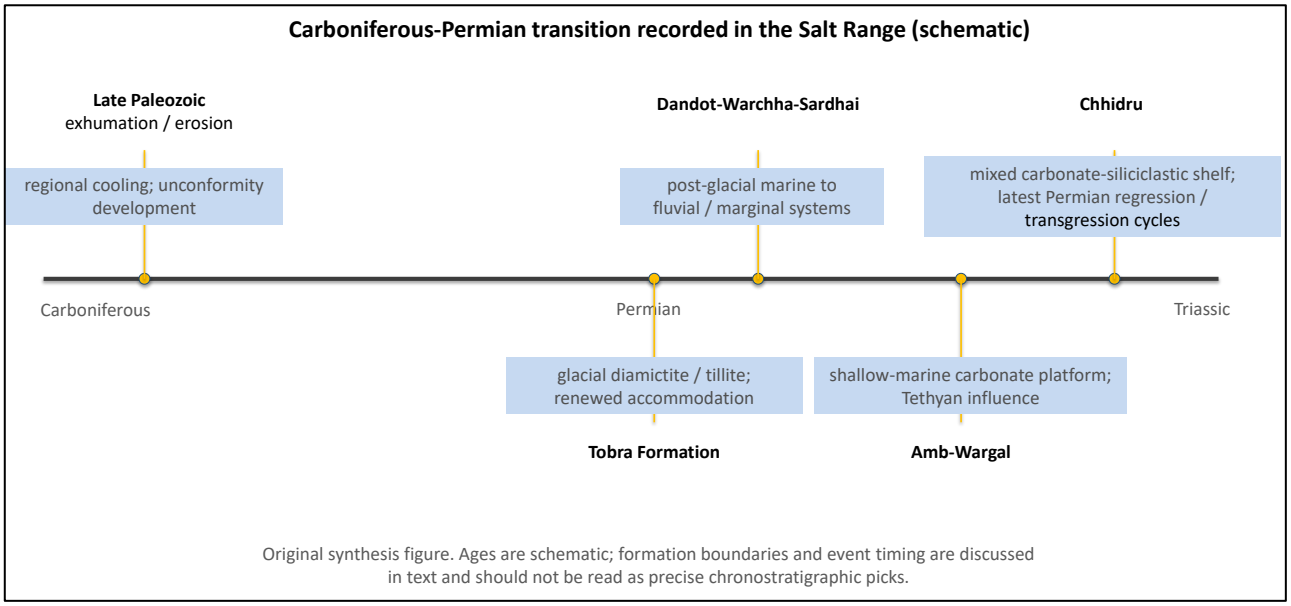


Figure 9: Schematic Carboniferous-Permian transition recorded in the Salt Range (Note: The schematic emphasizes the regional unconformity between older Paleozoic to post-glacial/glaciogenic intervals and the overlying Permian carbonate platform)

The sample-level project compilation contains nine Bijnot-1 Salt Range Formation samples with mean TOC of 0.96 wt.%, mean S2 of 2.27 mg HC/g rock, and mean HI of 202. A selected three-sample Fort Abbas-1 Infracambrian subset has mean TOC of 0.85 wt.%, mean S2 of 3.64, and mean HI of 404. The small Fort Abbas population should not be generalized, but it demonstrates that hydrogen-rich organic matter can occur in the deep older section. Published Bijnot values span a wider range, including TOC up to approximately 2.4 wt.% and HI up to approximately 451, consistent with mixed Type II-III source potential in at least some intervals (Yasin et al., 2022).

The regional biomarker evidence is more distinctive than source richness alone. Peters et al. (1995) used carbon-isotope and biomarker evidence to identify an Infracambrian source family in Baghewala-1 and relate it to Huqf petroleum systems of Oman. In the harmonized compilation, the Pakistan Karampur-1 heavy oil/tar has a bulk carbon-isotope composition near -37 per mil, low Pr/Ph, and a high C29 sterane proportion near 72%. Baghewala-1 and several Oman Huqf oils and source-rock extracts occupy the same broad isotopically light, C29-rich field, whereas the contrasting Oman Q-oil family is substantially heavier isotopically and contains much lower C29 sterane percentages. Figure 11 visualizes that first-order separation.

The significance is not that Karampur, Baghewala, and Oman's Huqf are one continuous reservoir or one directly connected kitchen. Rather, the molecular family demonstrates that distinctive Ediacaran petroleum systems developed around the western and northwestern Indian-Arabian region and provides a testable fingerprint for Pakistan. A produced oil or bitumen that repeatedly matches the full Infracambrian biomarker-isotope suite, has compatible maturity, and can be connected by a restored migration pathway would materially strengthen an older-source charge model. A mismatch would weaken it even if an organic-rich Ediacaran rock occurs nearby.

Present-day cool conditions on the Punjab Platform do not by themselves falsify the hypothesis. Thermal maturity integrates maximum burial, heat flow, duration, uplift, and erosion rather than present geothermal gradient alone. This creates a specific Pakistan-India exploration prediction. If equivalent Punjab Platform Infracambrian organofacies experienced greater maximum paleoburial than the Bikaner-Nagaur/Baghewala system before erosion, they may have reached higher maturity and could have expelled less viscous, higher-API petroleum than Baghewala. This is a testable prediction, not an inference from present depth alone; source facies, biodegradation, migration fractionation, mixing and reservoir alteration must be constrained independently. The current dataset does not yet contain a publication-grade burial-exhumation-temperature reconstruction for the Punjab Platform deep Infracambrian section, so a numerical maximum paleotemperature should not be invented. The importance of this missing step is illustrated by Zindapir-1 in the Suleiman Foldbelt: present Sembar depth is only about 1.4-2.2 km, yet basin modeling indicates substantially greater former burial, temperatures near 160 degrees C, and approximately 4 km of erosion before exhumation (Ahmed et al., 2026). Zindapir is not a direct thermal analogue for the Punjab Platform; it demonstrates the methodological point that present depth can be a poor proxy for maximum thermal exposure in an exhumed basin.

The Infracambrian hypothesis is, therefore, best classified as credible and testable, not demonstrated basin-wide. The next decisive figure for a later paper revision should be a one-dimensional burial and maturity history for one or more Punjab Platform wells tied to erosion estimates, measured maturity indicators, and heat-flow scenarios. Until then, molecular affinity and source quality establish possibility, while generation timing and volumetric kitchen effectiveness remain open. Figure 10 summarizes the Punjab Platform petroleum-system event relationships used to frame this timing problem.

A broader sterane comparison strengthens the regional relevance of this result. Baghewala, Karampur and the selected Huqf oils and source-rock extracts are dominantly C29-rich, whereas the contrasting Oman 'Q' oil family is strongly C27-rich and C29-poor. The Jurassic Shinawari extracts occupy a more C27-rich intermediate field, Datta is distinctly C29-enriched, and Patala extends farther toward C29 dominance while retaining considerable C27 variability. The separation demonstrates why a single ratio cannot be used to assign source age: similar C29 enrichment can arise in source families of very different age, and interpretation must combine sterane distribution with isotopes, depositional environment, maturity and migration history. At the same time, the close Baghewala-Karampur-Huqf relationship in regular-sterane space supports the use of Huqf as a functional restricted-marine source-facies benchmark rather than a claim of continuous source bed or transregional migration. The multi-family regular-sterane comparison is shown in Figure 12.

4.3 Jurassic Deeper Sources Versus the Sembar Baseline

The Jurassic source question is the strongest direct test of a deeper source beneath the proven Mesozoic petroleum architecture. It is also the question most vulnerable to a common interpretive error: equating a Jurassic reservoir with a Jurassic source. Chiltan carbonate is a proven reservoir in the Sulaiman-Safed Koh trend, but hydrocarbons in that reservoir could have been generated by adjacent Jurassic source facies, by younger Sembar-Goru kitchens migrating downward or laterally through faults and carrier beds, or by mixtures generated at different times (Nazeer et al., 2012; Asim et al., 2014). The appropriate model is Sembar-dominant charge, with Jurassic contribution introduced only where independent geochemical and basin-model evidence requires it.

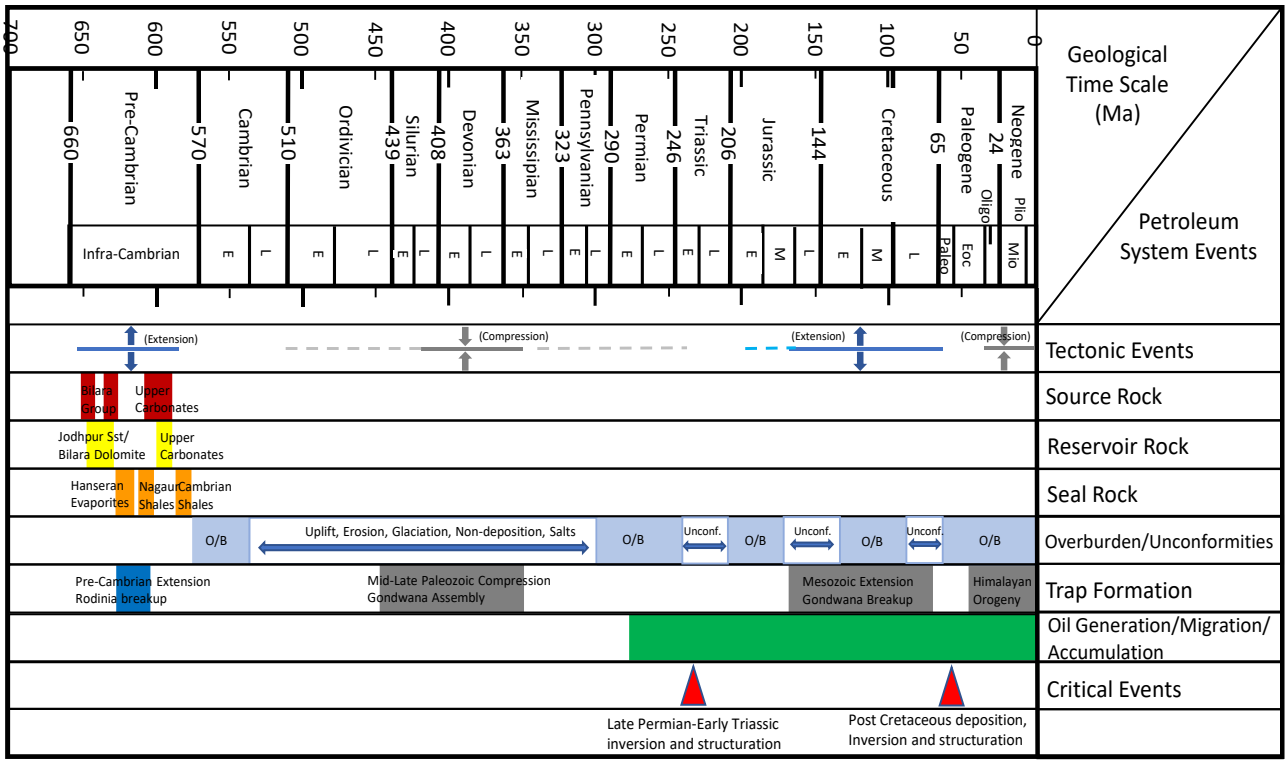


Figure 10: Punjab Platform petroleum-system events (Note: The chart summarizes the temporal relationship between stratigraphy, tectonic events, source, reservoir and seal elements, major unconformities, and inferred generation-migration-accumulation history on the Punjab Platform. Importantly, source maturity reflects cumulative burial and thermal history before uplift and erosion and should not be inferred from present-day burial depth or geothermal gradient alone. Age boundaries and event windows are schematic)

The available source-rock data justify testing that alternative. Eight Sann-1 Chiltan samples have mean TOC of 2.18 wt.%, mean S2 of 8.75 mg HC/g rock, and mean HI of 329, establishing source-capable Jurassic facies in the southern Pakistan system (Ahmad et al., 2019). Kohat provides an independent northern Jurassic control. Shinawari samples have mean TOC near 1.48 wt.% and include locally hydrogen-rich intervals; Datta is much more heterogeneous, with a sample-level mean TOC above 5 wt.% because coal and coaly shale end members are present, while its biomarker signal is more terrestrially influenced (Khan et al., 2026). These data demonstrate source potential but do not establish the source of every Jurassic-reservoired accumulation.

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The same-well Sann-1 comparison is particularly informative. Ten Sembar samples average approximately 3.25 wt.% TOC, 10.77 mg HC/g rock S2, and HI of 275, while the eight Chiltan samples average 2.18 wt.% TOC, 8.75 S2, and HI of 329. Both intervals are source-capable, making a purely stratigraphic choice between them unjustified. In contrast, the 28-sample Zindapir-1 Sembar population is more mature and gas-prone, with mean TOC near 0.99 wt.%, mean S2 near 0.54, mean HI near 49, and mean Tmax near 456 degrees C (Ahmed et al., 2026). Sembar therefore should not be represented by a single basin-wide average: source quality, organic facies, and maturity vary markedly between localities.

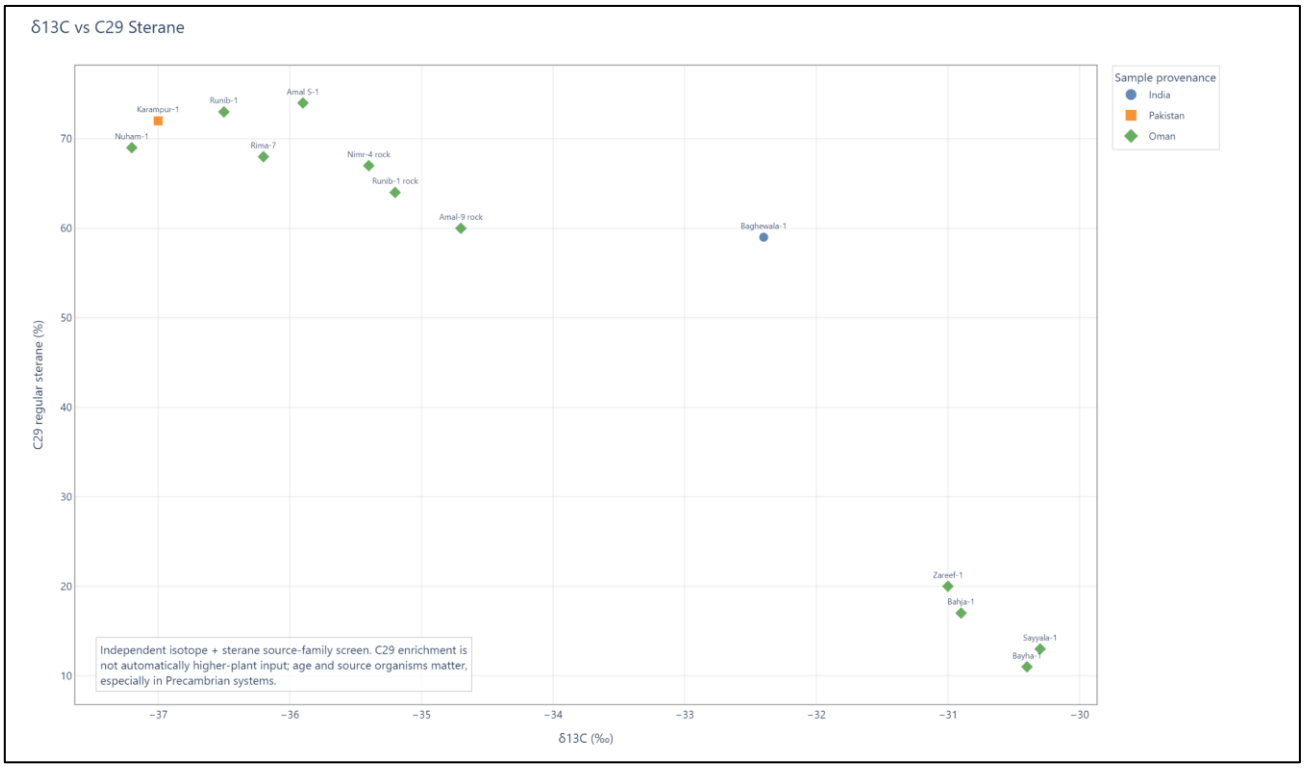


Figure 11: Infracambrian biomarkers: Karampur-Baghewala-Huqf relationship (Note: Crossplot of bulk stable-carbon isotope composition and C29 sterane percentage for selected Pakistan-India-Oman Infracambrian petroleum-system samples compiled from Peters et al. (1995). Karampur and Baghewala plot with the isotopically light, C29-rich Oman Huqf family and away from the contrasting Q-oil family. This two-parameter separation is a regional fingerprint, not a complete genetic correlation; full biomarker suites, maturity compatibility, and migration history are required for source attribution). *Click here for Brill-Viz Interpretive Summary*

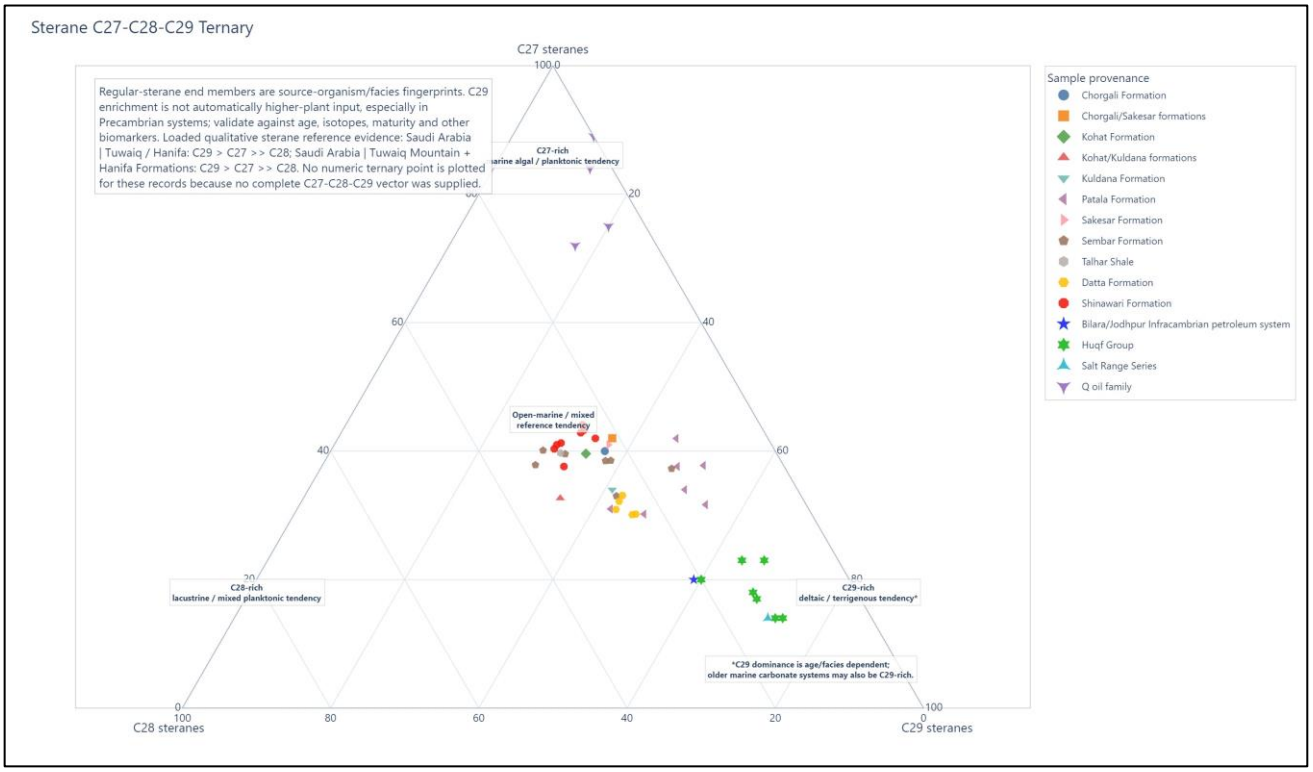


Figure 12: Regular-sterane ternary comparison across principal Infracambrian, Jurassic and Paleogene source families (Note. Individual source-rock extract/oil values from the harmonized project workbook. Baghewala-Karampur-Huqf affinity is contrasted with Oman Q oils and with younger Pakistan source families. Ternary proximity indicates compositional affinity, not genetic identity). *Click here for Brill-Viz Interpreteive Summary*

Figure 13 shows TOC-S2 relationships for these Jurassic and Cretaceous populations. Logarithmic axes are used only because the combined data span several orders of magnitude, especially where Datta contains coal-rich end members; the log scale prevents the majority of ordinary shale samples from collapsing near the origin. The geological message does not depend on the transformation: Chiltan and Sembar both contain high-yield samples, Shinawari contains a broad fair-to-good population with local richer points, Datta is heterogeneous, and mature Zindapir Sembar retains comparatively low residual generative potential. Figure 14 adds maturity context through HI-Tmax. The distribution shows why low residual HI in a high-Tmax source cannot be interpreted in the same way as low HI in an immature sample.

Arabian Jurassic systems are useful as functional analogues because they demonstrate how organic-rich Jurassic intra-shelf or deeper-water facies can lie adjacent to prolific carbonate reservoirs, but the analogy must be process-based rather than age-based. Tuwaiq Mountain and Hanifa source systems are regionally established and have well-developed oil-source geochemical relationships (Cole et al., 1994b; Carrigan et al., 1995).

The relevant prediction for Pakistan is not that Chiltan is equivalent to Tuwaiq or Hanifa. It is that source-rich facies may preferentially occupy Jurassic paleolows, deeper-water transitions, or hanging-wall depocentres adjacent to carbonate platforms. In Kirthar, later inversion means those original lows must be restored before source distribution and migration distance are assessed (Hinsch et al., 2019).

Biomarkers provide a second discriminator. In the available source-rock extracts, Shinawari generally has low Pr/Ph and C29 sterane percentages near the low 30s, consistent with a stronger marine-aquatic contribution; Datta has higher C29 sterane proportions in the low-to-mid 40s; Zindapir Sembar spans a broader intermediate field; and Patala occupies a more C29-rich field with generally higher Pr/Ph values. Figure 15 shows that these source families are not geochemically identical. This is encouraging for future mixture analysis because a produced fluid can, in principle, be tested against multiple candidate end members. It is not yet proof that any specific Sulaiman gas or condensate is Jurassic-sourced.

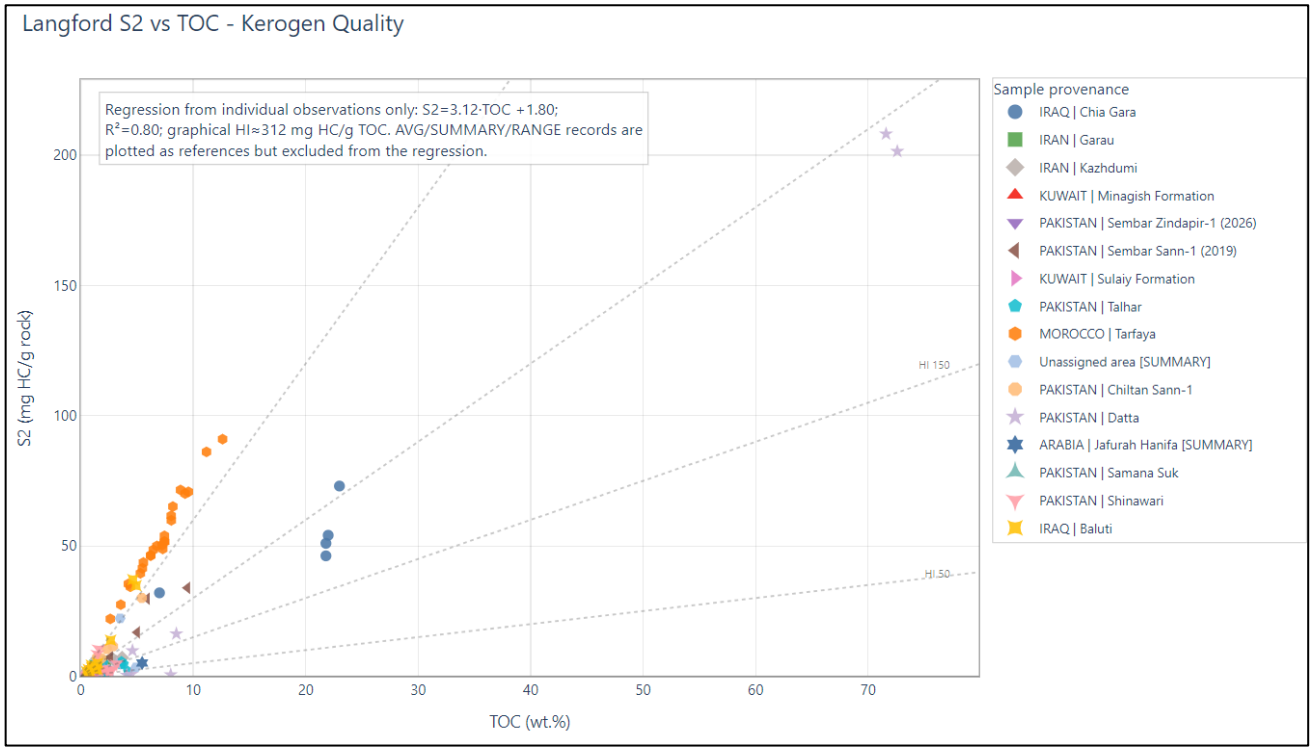


Figure 13: Mesozoic source-rock quality: Jurassic candidates and Sembar controls (Note: TOC-S2 crossplot using sample-level Chiltan, Shinawari, Datta, Sembar Sann-1, and Sembar Zindapir-1 data compiled from Ahmad et al. (2019), Khan et al. (2026), and Ahmed et al. (2026). Coal-rich Datta samples with over 70% TOC are cropped from the chart for better readabiloty; no other values were transformed for interpretation beyond plotting position). *Click here for Brill-Viz Interpretive Summary*

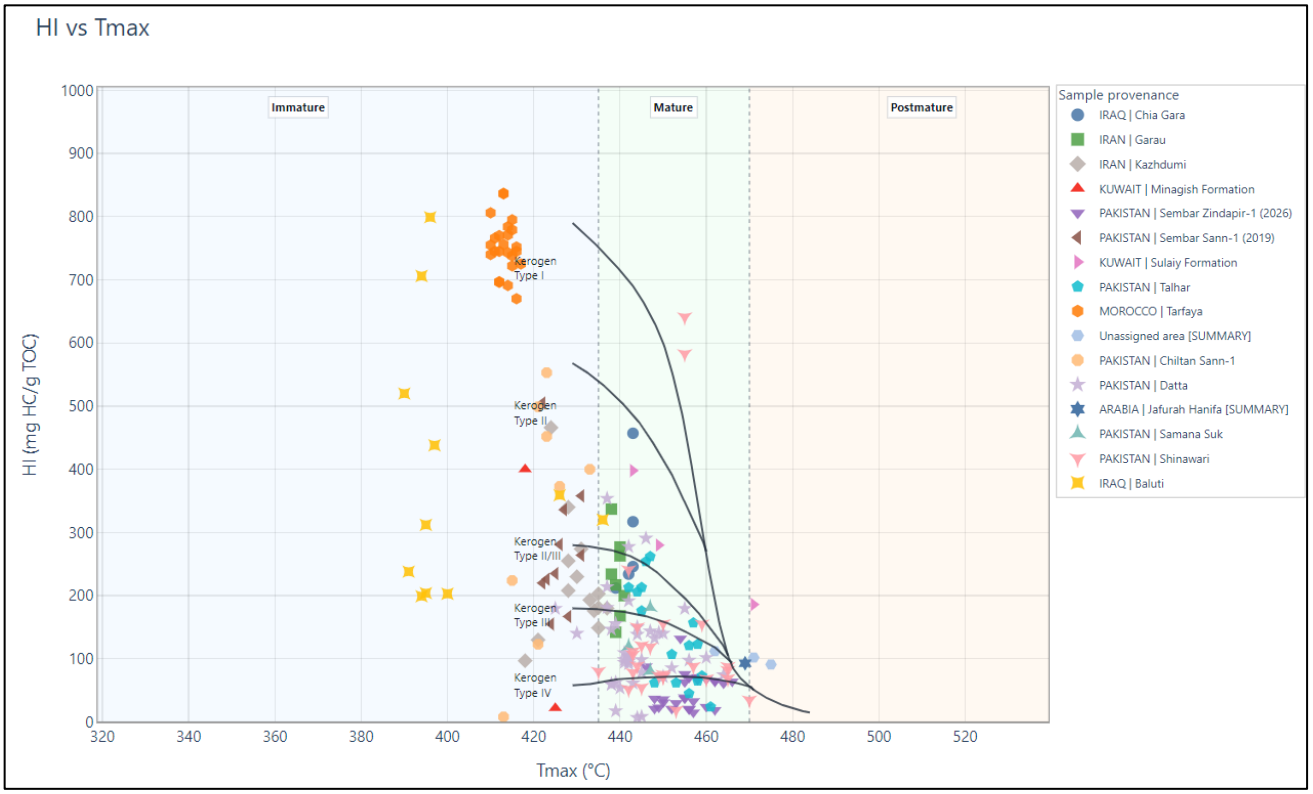


Figure 14: Mesozoic kerogen quality and maturity contrast (Note: Hydrogen index versus Tmax for the same principal Mesozoic populations. Broad labels indicate qualitative kerogen-potential fields only. Residual HI decreases with increasing maturity, so mature Zindapir Sembar should not be compared with less mature populations without thermal context (Cole et al., 1994a; Ahmed et al., 2026). *Click here for Brill-Viz Interpretive Summary*

The field-scale implication is a three-model test. In a Jurassic-dominant model, mature Chiltan-Anjira source facies in adjacent deep synclines or inherited rift lows charge Chiltan and younger reservoirs. In a Cretaceous-dominant model, Sembar-Goru kitchens charge older Jurassic reservoirs through cross-formational migration. In a mixed model, Jurassic and Cretaceous kitchens contribute in different proportions or at different times. Reported compositional variation among wells along the Sulaiman trend is compatible with a multi-source or multi-maturity system but cannot by itself identify source age. Gas carbon isotopes, molecular composition, condensate biomarkers, maturity matching, fluid inclusions, and prospect-scale burial/migration modeling are required to discriminate the models.

The Pr/n-C17 versus Ph/n-C18 relationship provides a complementary depositional and maturity-sensitive view. Most Pakistan points fall within the central oil-window/mixed-organic-source domain of the integrated Brill-Viz chart, while Arabian, Indian, Oman, Jordan and Iraq controls expand the regional field. The plot is useful because the two axes respond to both organic-matter input and post-depositional maturity or alteration; consequently, movement on the chart should not be translated mechanically into a unique facies interpretation. The key publication message is the overlap itself: Pakistan samples occupy both reducing/marine and more oxidizing/terrestrial tendencies, which is consistent with the facies-partitioned model for Shinawari, Datta, Sembar and their regional analogues. Range symbols are retained separately from individual samples so aggregate envelopes are not treated as measured points. Figure 16 presents this regional comparison.

Maturity-proxy ratios provide a further guard against confusing facies with maturity. Shinawari and Datta extracts overlap substantially in C29 sterane 20S and C32 homohopane 22S space, although individual values scatter around their group means. The overlap indicates broadly compatible maturity levels for molecular comparison; it does not demonstrate that the two formations generated the same oils. This distinction is important because biomarker proportions may be modified as maturity increases, while source-facies indicators and isotopes can retain different sensitivities. In other words, source-family separation is more persuasive where samples are compared at reasonably compatible maturity than where a mature/overmature population is contrasted with immature source rock. Figure 17 summarizes the Shinawari-Datta biomarker maturity-proxy relationship.



Figure 15: Biomarker separation of source families in Pakistan (Note: Pr/Ph versus C29 sterane percentage for source-rock extracts from Shinawari, Datta, Sembar Zindapir-1, and Patala datasets. Bilara/Jodhpur sample is from Baghewala-1 of India. The separation demonstrates distinct source-family fingerprints in the compiled data and supports future mixture testing. It does not establish the source of produced oils or gases without matched fluid data and maturity/burial compatibility (Khan et al., 2026; Ahmed et al., 2026; Ishaq et al., 2026). [Click here for Brill-Viz Interpretive Summary]

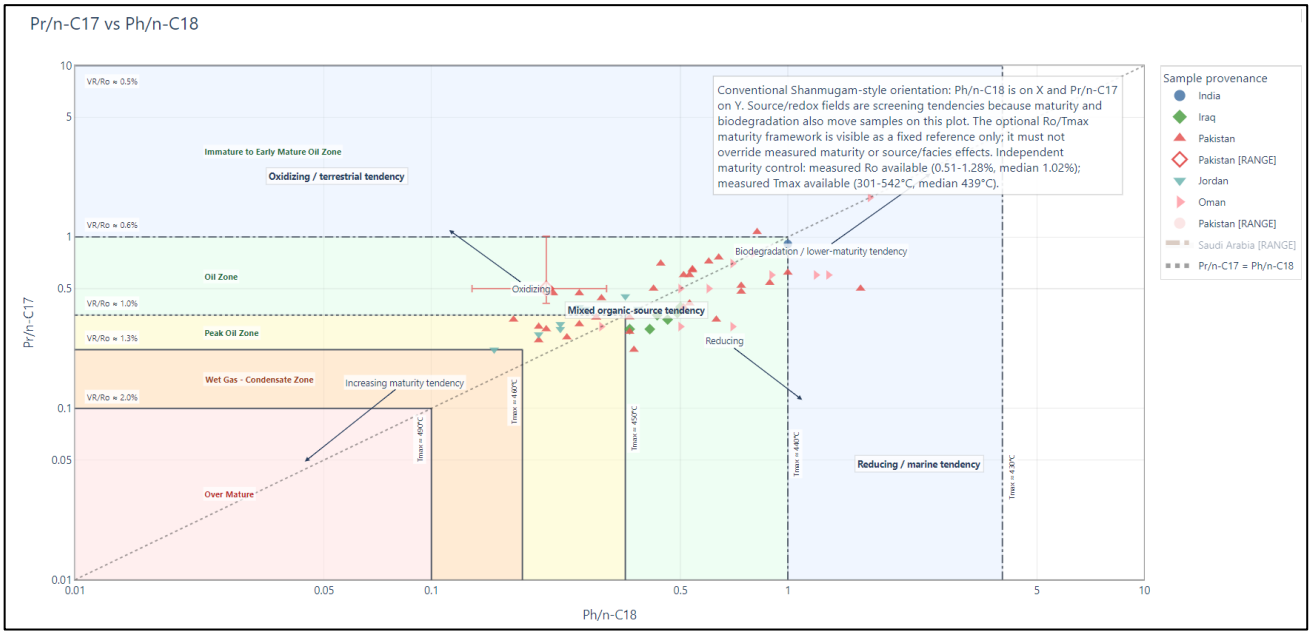


Figure 16: Pr/n-C17 versus Ph/n-C18 regional comparison generated in Brill-Viz (Note: Pakistan samples and published regional controls are shown together with interpretive maturity/depositional domains. Because both ratios are maturity- and alteration-sensitive, the chart is used as supporting evidence and not as a stand-alone source-age classifier). [Click here for Brill-Viz InterpretiveSsummary]

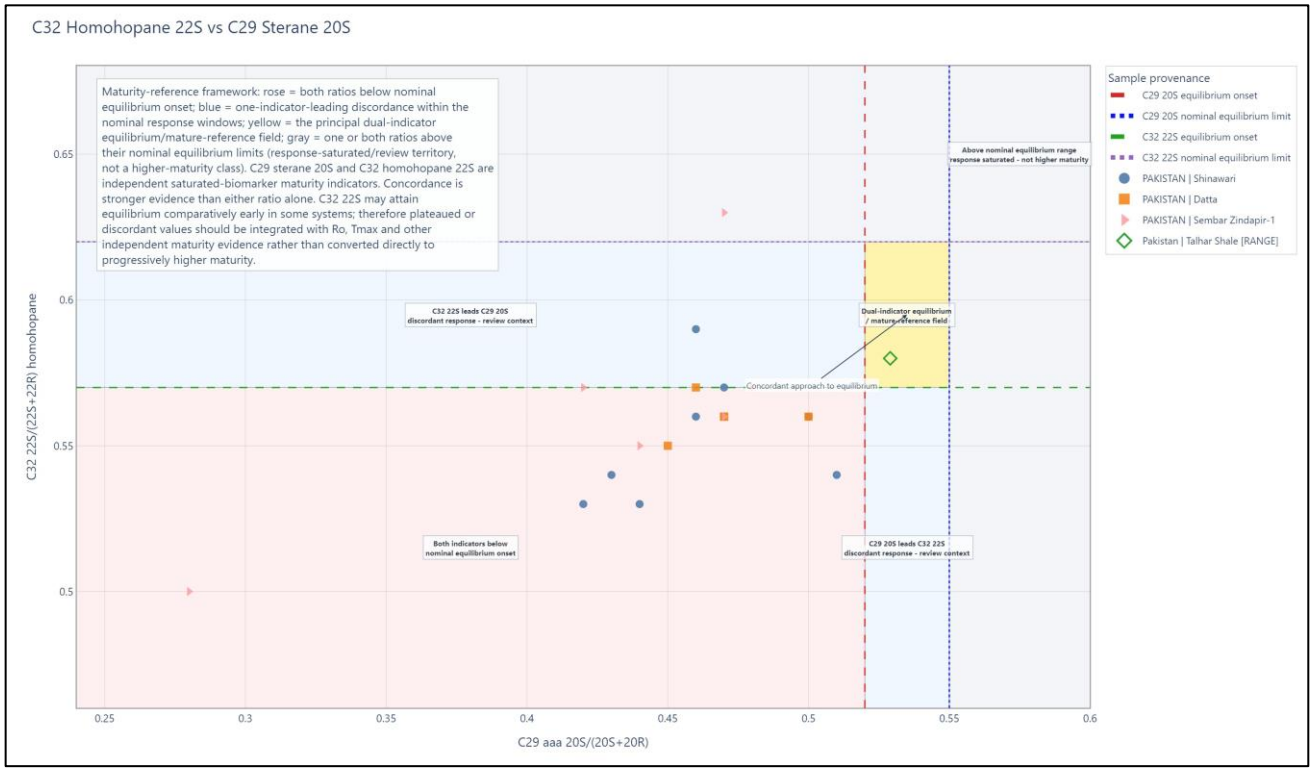


Figure 17: Mesozoic biomarker maturity-proxy comparison for Shinawari and Datta source-rock extracts (Note. C29 sterane 20S/(20S+20R) versus C32 homohopane 22S/(22S+22R). Open large symbols show group means. Dashed reference guides are visual aids only and are not used as genetic-correlation thresholds). Click here forBrill-Viz Interpretive Summary

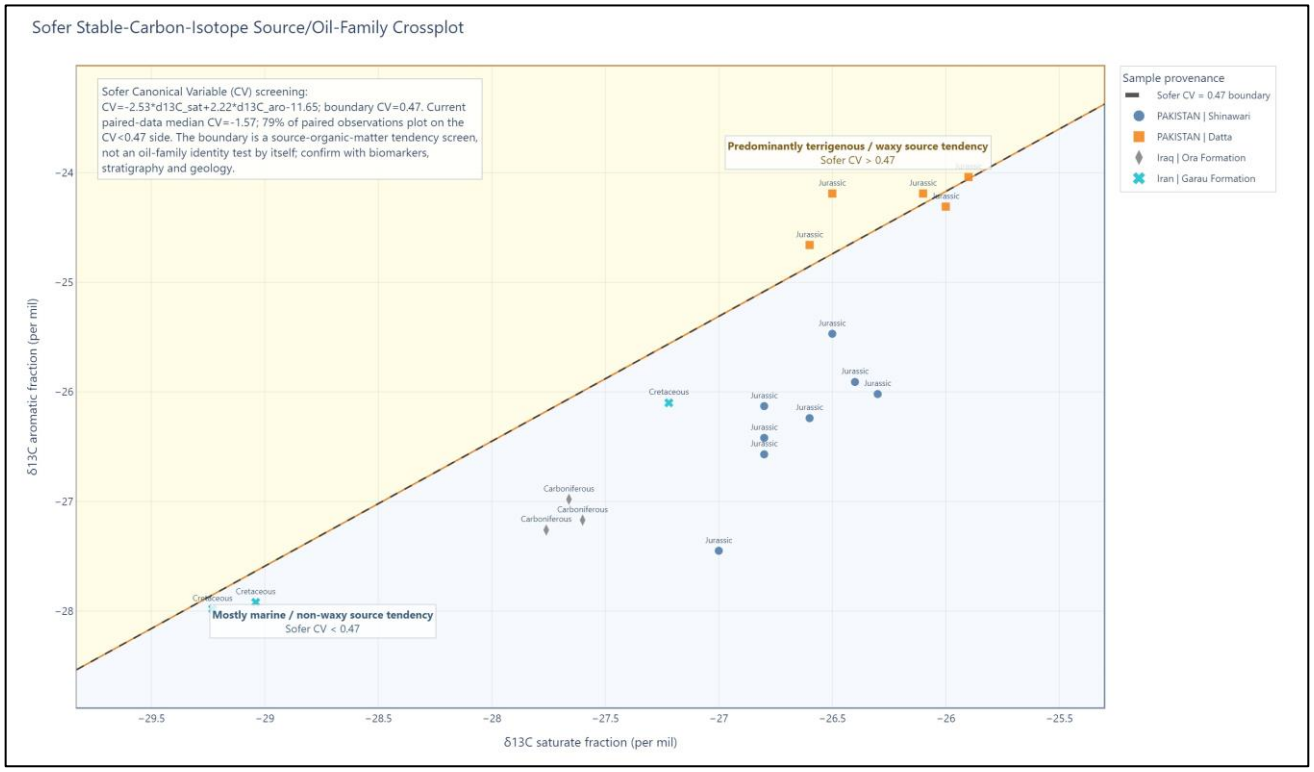


Figure 18: Stable-carbon-isotope separation of Shinawari and Datta source-rock extracts and their comparison with other source rocks in Arabian Penisula (Note: δ13C of saturated versus aromatic fractions from the regional dataset. The plot is a source-family discrimination tool; an oil or condensate should be evaluated with additional biomarkers and maturity compatibility before assigning genetic affinity). Click here forBrill-Viz Interpretive Summary

Stable-carbon-isotope fractions add a more source-sensitive discriminator. The Shinawari extracts cluster with saturated and aromatic fractions that are comparatively close, whereas Datta aromatic fractions are consistently

isotopically heavier than their saturated fractions. The separation is compatible with different organic-matter assemblages and depositional influences already suggested by the sterane and isoprenoid data. It is therefore useful for testing whether produced fluids lie closer to a Shinawari-like marine/marginal-marine source family or to the more terrestrial-influenced Datta end member. A decisive oil-source test would require produced-fluid fractions analyzed by the same or cross-calibrated method, rather than comparison of unmatched literature values alone (Khan et al., 2026). The corresponding isotopic separation is shown in Figure 18.

4.4 Paleogene Source Selectivity: Why Patala Is Effective but Not Universally Replicated

Patala is the most useful younger-source calibration in the country-wide synthesis because it proves that a Paleocene source can effectively charge much older reservoirs where source quality, burial, migration, and trap development align. The Kohat-Potwar province is formally treated as the Patala-Nammal Composite Total Petroleum System, and Paleocene Patala rocks are widely regarded as the principal source for much of its oil (Wandrey et al., 2004b). The question is therefore not whether Paleogene shales can generate petroleum, but why comparably effective Patala-type systems are not demonstrated throughout the Middle, Lower, and Offshore Indus basins.

The geochemical comparison argues against a simple age-control explanation. In the compiled Kohat Patala dataset, seven Manzalai-1 subsurface samples have mean TOC near 0.86 wt.%, mean S2 near 3.13, and mean HI near 381, whereas sixteen Panoba outcrop samples have higher mean TOC near 1.29 wt.% but much lower mean S2 and HI. The contrast is consistent with the effect of weathering/exposure and sample context on preserved Rock-Eval indices and cautions against treating an outcrop mean as the original subsurface generative quality (Ishaq et al., 2026).

Regional Eocene comparators further show that Patala is not the only source-capable Paleogene system. Ten Sakesar samples in the project compilation average approximately 4.27 wt.% TOC and HI near 181. Middle Eocene Cambay Shale data from India include hydrogen-rich source intervals with sample-set mean TOC above 2 wt.% and mean HI near 294 in one dataset, while Eocene Jaddala samples from Iraq have mean TOC around 2.04 wt.% and mean HI near 460 (Fazeelat et al., 2010; Kumar et al., 2017; Baban, 2015). Figure 19 demonstrates substantial overlap and heterogeneity. A rich Paleogene source rock is therefore regionally plausible outside the Patala system.

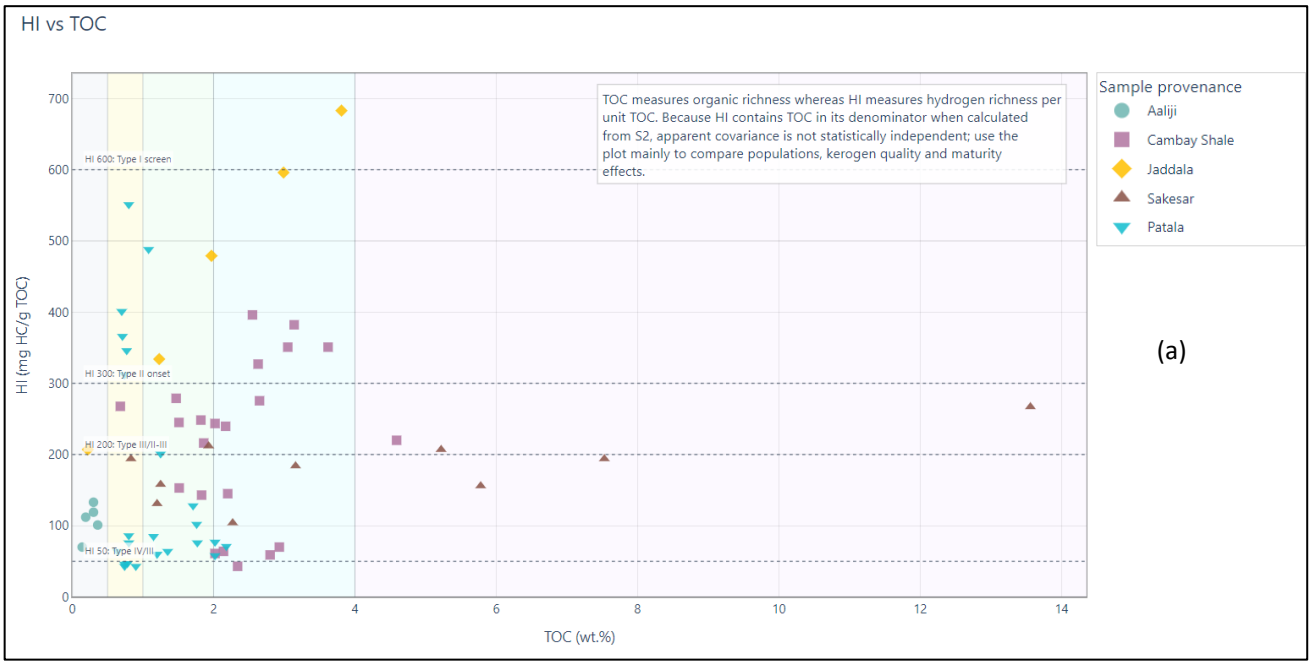
What distinguishes an effective petroleum system is the conjunction of five factors. First, source facies must be sufficiently rich and oil- or gas-prone. Second, the source must be thick and laterally extensive enough to create a material kitchen. Third, burial and heat flow must place that kitchen in the appropriate generative window at the right time. Fourth, seals and carrier systems must preserve a connected migration network. Fifth, trap formation and preservation must overlap generation and migration. Patala in Kohat-Potwar satisfies that combination demonstrably. An age-equivalent shale on a shallow shelf, in a poorly buried segment, or separated from traps by ineffective migration pathways may be geochemically good yet petroleum-system ineffective.

This distinction is especially important offshore. Paleocene-Eocene carbonate and clastic packages are recognized in the Offshore Indus, but direct deepwater source-rock calibration is sparse and younger burial varies strongly between shelf and deepwater depocentres. The defensible wording is therefore that a Patala-type regional source system is not comparably demonstrated, not that Paleogene source rocks are absent. Offshore testing should prioritize deep-burial maturity, organic-facies mapping, and produced-fluid fingerprints rather than transferring the Kohat-Potwar model by age alone.

Paleogene source selectivity also helps resolve an apparent contradiction in the country-wide synthesis. Pakistan contains source-capable rocks at several ages, yet only some become regionally dominant. The explanation is not simply which formation has the highest TOC; effective charge is an emergent property of deposition, preservation, maturation, structural plumbing, and timing. That same logic applies backward in time to the Infracambrian and Jurassic hypotheses and is the principal reason that direct source-to-fluid correlation is weighted more heavily than stratigraphic proximity.

The Patala comparison should therefore be interpreted as a positive-control experiment. If effective Paleogene source systems are primarily age-controlled, then Paleocene-Eocene source candidates across Middle, Lower and Offshore Indus should commonly reproduce the same combination of source quality, maturity and fluid affinity. If H4 is correct, effective Patala kitchens should instead cluster where organic-rich and low-oxygen facies coincide with adequate thickness, appropriate foreland burial, trap timing and migration connectivity. Elsewhere, similar-

age shales may remain immature, be too terrestrially diluted or oxidized, occur in thin/discontinuous packages, or lack hydraulic access to the tested accumulations. Offshore Indus is especially important because sparse shallow-well calibration cannot rule out deeper mature Paleogene kitchens beneath thick Cenozoic cover; the absence of a demonstrated Patala-like system must therefore be treated as an evidence gap rather than proof of absence.



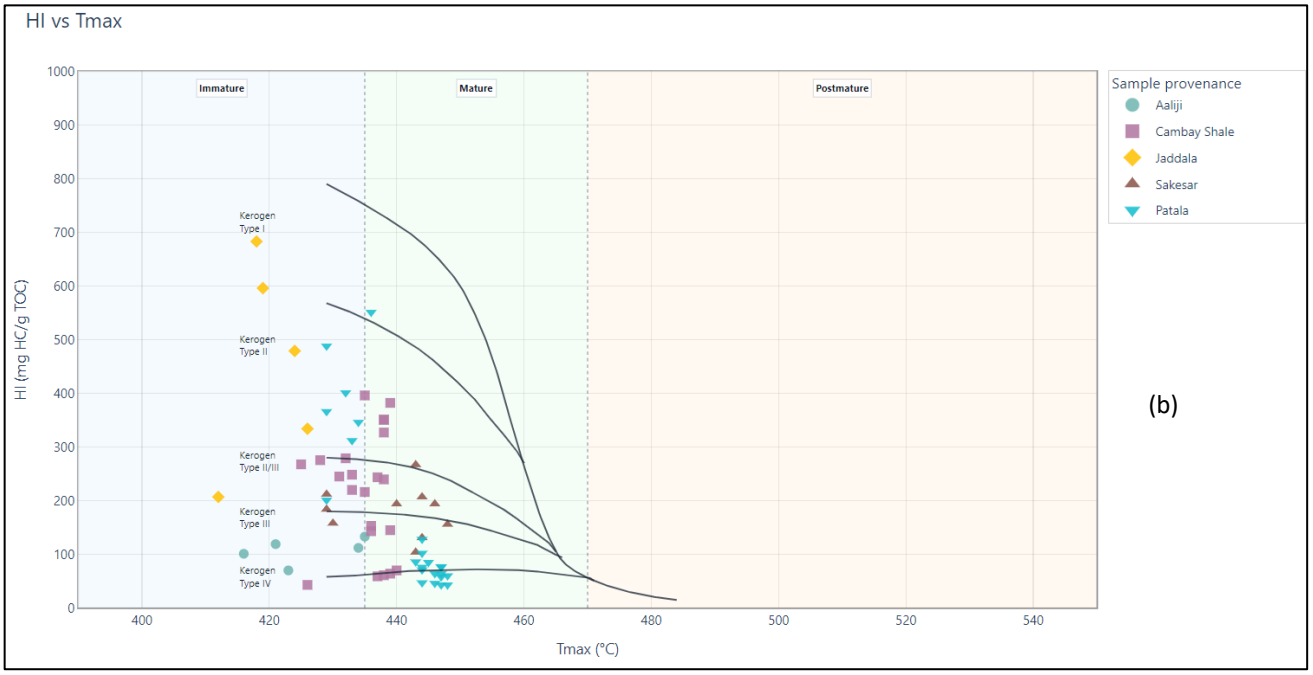


Figure 19a, b: Paleogene source selectivity: Patala compared with regional source-rock candidates (Note: TOC-HI and HI-Tmax comparison of Patala subsurface and outcrop populations with Sakesar (Pakistan), Cambay Shale (India), and Jaddala (Iraq). The figure demonstrates that high-quality Paleogene source rocks are not unique to Patala; effectiveness must therefore be tested at the petroleum-system level. Patala data: Ishaq et al. (2026); Sakesar: Fazeelat et al. (2010); Cambay: Kumar et al. (2017) and *companion project data; Jaddala: Baban (2015).* *Click here for Brill-Viz HI-TOC Interpretive Summary* *and* *Click here for Brill-Viz HI-Tmax Interpretive Summary*

5. Discussion

5.1 Preservation Partitioning as the First-Order Control

The combined results support a preservation-partitioning model in which the petroleum significance of a source interval depends first on whether the relevant depositional system was preserved in the later basin architecture. The largest example is the Middle Paleozoic gap. Arabia preserves a regionally extensive basal Qusaiba source despite its own unconformities and erosional episodes, allowing later burial to generate and expel hydrocarbons into Paleozoic reservoirs. Across the recognized Indus-Punjab-western fold-belt succession, the corresponding stratigraphic interval is absent or unproven over large areas. Pakistan, therefore, lost or never developed a major potential Paleozoic kitchen function in those domains, even though separate northern belts demonstrate that Silurian-Devonian rocks existed regionally.

This model is preferable to a single-event erosion explanation because the geographic pattern is too heterogeneous. Northern preservation, southern hiatuses, and local structural relief imply differences in accommodation and paleogeographic position before later exhumation was superimposed. The model remains falsifiable. Discovery of a widespread concealed Silurian-Devonian section beneath the main Indus basins, supported by reliable age control and deep seismic/well evidence, would require revision. Conversely, subcrop relationships, provenance, and thermochronology that document prolonged exposure and differential erosion would strengthen the preservation-partitioning interpretation.

5.2 Regional Analogues: Function Before Age

The regional comparisons used here are deliberately functional rather than lithostratigraphic. Qusaiba is a benchmark for a regionally persistent, organic-rich marine Silurian source that is genetically linked to oils; it is not a template that every Silurian shale must resemble. Huqf provides a biomarker-defined Ediacaran petroleum family; it does not establish direct lateral continuity to every Infracambrian rock in Pakistan. Tuwaiq-Hanifa demonstrates the petroleum-system effectiveness of Jurassic source-rich depocentres adjacent to carbonate platforms; it does not make Chiltan a stratigraphic equivalent. Cambay and Jaddala demonstrate that Paleogene source systems can be highly generative outside Kohat-Potwar; they do not prove that Middle or Lower Indus Paleogene shales charged fields in Middle and Lower Indus basins.

This functional approach has a practical advantage: each analogue provides a discriminating test rather than a predetermined answer. A candidate Pakistani Silurian source should be compared for organic facies, source quality, maturity, biomarkers, isotopes, continuity, and migration function. A Jurassic candidate should be tested for its paleogeographic position relative to rift lows and carbonate reservoirs and then compared genetically with produced fluids. An Ediacaran candidate should reproduce a distinctive molecular family and have a compatible burial history. A Paleogene candidate should demonstrate not merely high TOC but a mature kitchen and a viable pathway to reservoirs.

5.3 Burial, Exhumation, and the Danger of Present-Day Thermal Proxies

The cross-province synthesis highlights a recurring thermal problem. Present depth and present geothermal gradient can be misleading in areas that experienced substantial burial followed by uplift and erosion. Zindapir provides a quantitative example, where modeled maximum burial and temperatures are much greater than present structural depth would suggest (Ahmed et al., 2026). Similar logic applies to the northern fold belts, where deformation and exhumation may leave organic-rich rocks overmature at outcrop, and to the Punjab Platform, where a currently cool section could have experienced a different maximum burial state before erosional episodes.

This does not justify assuming deep paleoburial wherever it is convenient for a source hypothesis. The correct response is to reconstruct it. Maturity measurements, apatite fission-track or (U-Th)/He constraints where available, erosion estimates, sonic-density trends, vitrinite/bitumen reflectance, basin subsidence, and heat-flow scenarios should be integrated in one-dimensional and two-dimensional histories. For the Punjab Platform Infracambrian hypothesis, this is the largest remaining analytical gap indicated in the present paper. A future quantitative burial figure could either strengthen the model by showing an earlier generative window or reject it by demonstrating that the candidate source never reached effective maturity. Figure 10 should therefore be read as a temporal petroleum-system event framework rather than as a present-day geothermal profile.

5.4 Tectonic Timing, Collision Diachrony, Burial and Exhumation

The petroleum hypotheses require a time-dependent tectonic context because source maturity, trap formation and preservation were not synchronous across Pakistan. Competing collision chronologies illustrate the problem. Kohistan arc growth, western ophiolite emplacement, India-Kohistan contact, alternative final India-Asia collision definitions and later western fold-belt compression occupy overlapping but distinct age windows. Selecting one 'collision age' and applying it country-wide would therefore obscure the processes that actually matter to petroleum systems: when loading began, when foreland subsidence accelerated, when older rift faults inverted, when traps formed, and when uplift or exhumation reduced burial (Petterson, 2010; Treloar et al., 1989, 1996; Rehman et al., 2011; Hu et al., 2016). The competing process chronologies are summarized in Figure 20.

The structural response propagated outward through time. High-grade metamorphism and exhumation in the Karakoram-Himalayan hinterland preceded much of the deformation at the external foreland front, while Miocene-Recent shortening progressively affected Main Boundary Thrust, Sub-Himalayan, Kohat-Potwar and Salt Range domains. This southward transfer explains why late structures can overprint source rocks that matured during earlier deeper burial. It also cautions against using the present-day position of a sample in a fold crest to infer its maximum burial or maturity. Inversion can exhume a previously mature kitchen, while deep synclines can retain mature source rocks adjacent to comparatively shallow reservoirs. Zindapir provides a direct example in the broader synthesis: present structural depth is much less than the maximum paleoburial inferred from modelling, demonstrating that exhumation can decouple modern geothermal conditions from peak thermal history. Figure 21 summarizes the broad southward propagation of compression and exhumation.

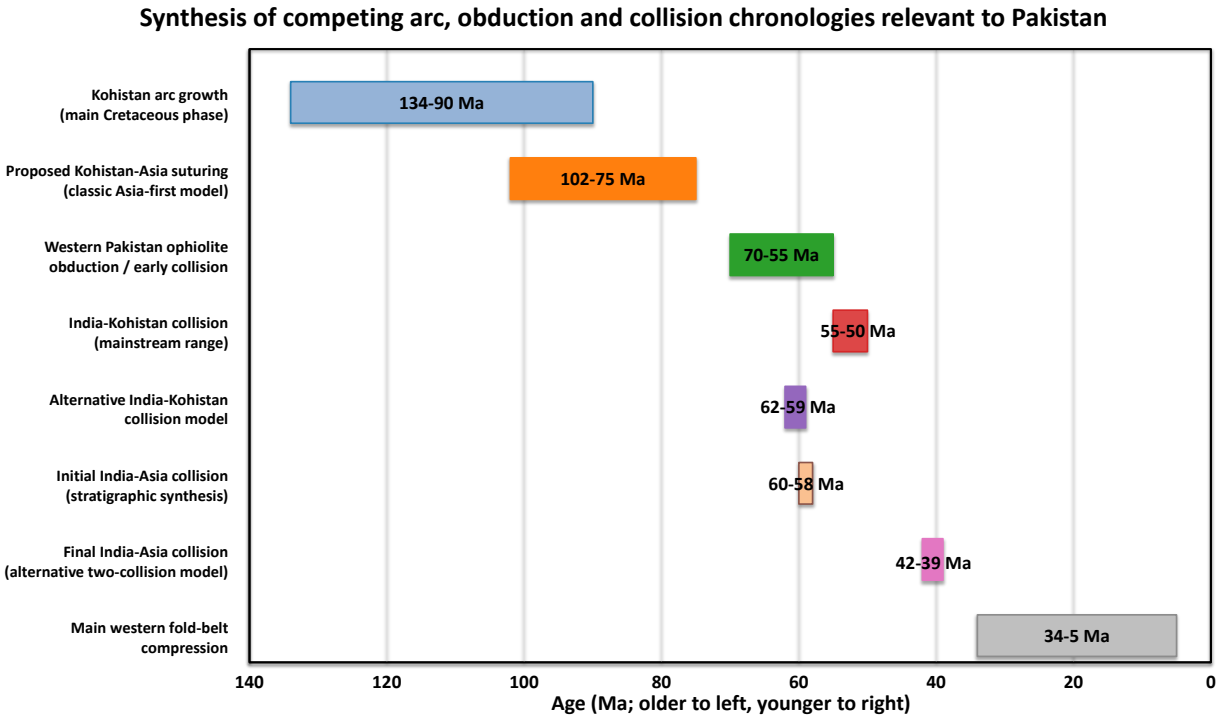


Figure 20: Competing arc, obduction and collision chronologies relevant to Pakistan (Note: The purpose of this plot is to show overlap and uncertainty, not to equate the events).

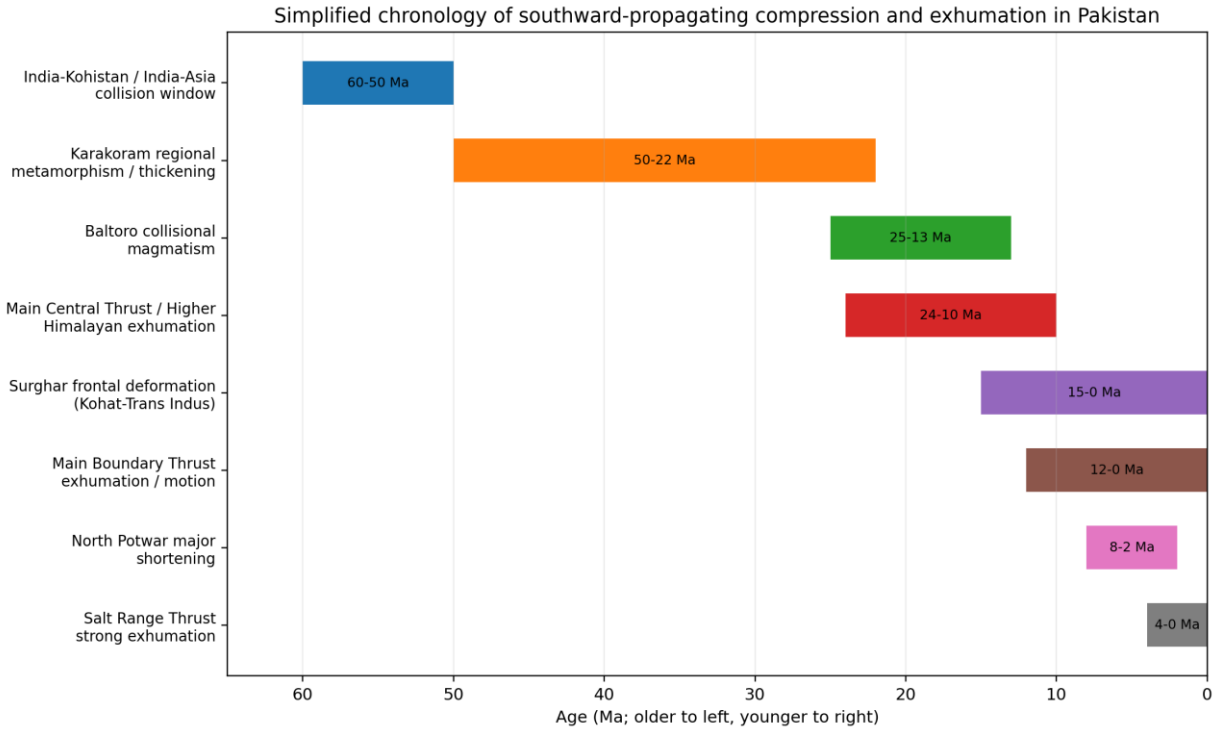


Figure 21: Simplified chronology of southward-propagating compression and exhumation in Pakistan (Note: Age windows synthesize constraints from references cited in text. Ranges are schematic and do not imply that deformation ceased at the younger bound).

5.5 A Multi-Source, Multi-Stage Charge Architecture

Taken together, the data do not support a single universal source rock for Pakistan. Sembar-Lower Goru remains the strongest demonstrated regional onshore source family in the Middle-Lower Indus and western fold-belt systems, but Jurassic sources are viable locally and Paleogene sources dominate or contribute in the northern foreland. Ediacaran sources remain plausible in selected older petroleum systems, while Middle Paleozoic source opportunities are spatially restricted by preservation. The appropriate national model is, therefore, an evidence-ranked mixture of source families whose relative importance changes by province and through time.

This model also provides a framework for interpreting heterogeneous fluid compositions without over-interpreting them. Different gas wetness, condensate yields, API gravity, biomarker ratios, or isotopic compositions can reflect different source facies, maturity levels, mixing proportions, migration fractionation, alteration, or reservoir processes. Fluid variability is therefore a reason to test multiple source models, not proof of multiple sources by itself. The strongest future studies will combine source-rock fingerprints with produced-fluid chemistry and explicitly model whether the inferred source was generating when the trap and migration pathway existed.

5.6 Event-Response Integration across Tectonic Provinces

A country-wide event-response matrix provides the bridge between tectonics and geochemistry. The same regional geodynamic event can generate accommodation in one province, non-deposition or erosion in another, inversion of inherited faults elsewhere, and strike-slip transfer or subduction along a different boundary. Four recurring response types are particularly relevant to petroleum systems: creation of accommodation, creation of omission, reactivation of inherited architecture, and partitioning of strain among mechanically distinct domains. These responses control where source facies can accumulate, whether they survive later erosion, how deeply they are buried, and whether faults subsequently connect or breach source-reservoir pairs (Mandal et al., 2022; Hinsch et al., 2019; Szeliga et al., 2012; Mokhtari et al., 2019). Figure 23 illustrates the western Pakistan strain-partitioning linkage, while Figure 24 summarizes the broader tectonic-event versus province-response framework.

For the Sulaiman-Kirthar system, the priority is to restore Jurassic-Cretaceous rift geometry beneath later folds and identify mature paleolows. For the Punjab Platform, the priority is the deep Infracambrian thermal history and fluid correlation. For northern Pakistan, the priority is to characterize the TOC-rich Silurian-Devonian rocks beyond TOC alone. For Middle-Lower-Offshore Indus, the priority is to establish whether Paleogene and deep Jurassic source intervals are locally effective or whether the proven Sembar system remains sufficient. These are direct exploration tests that can change source risk and migration-fairway ranking prospect by prospect. These domain-scale petroleum-system contrasts are summarized in Figure 22.

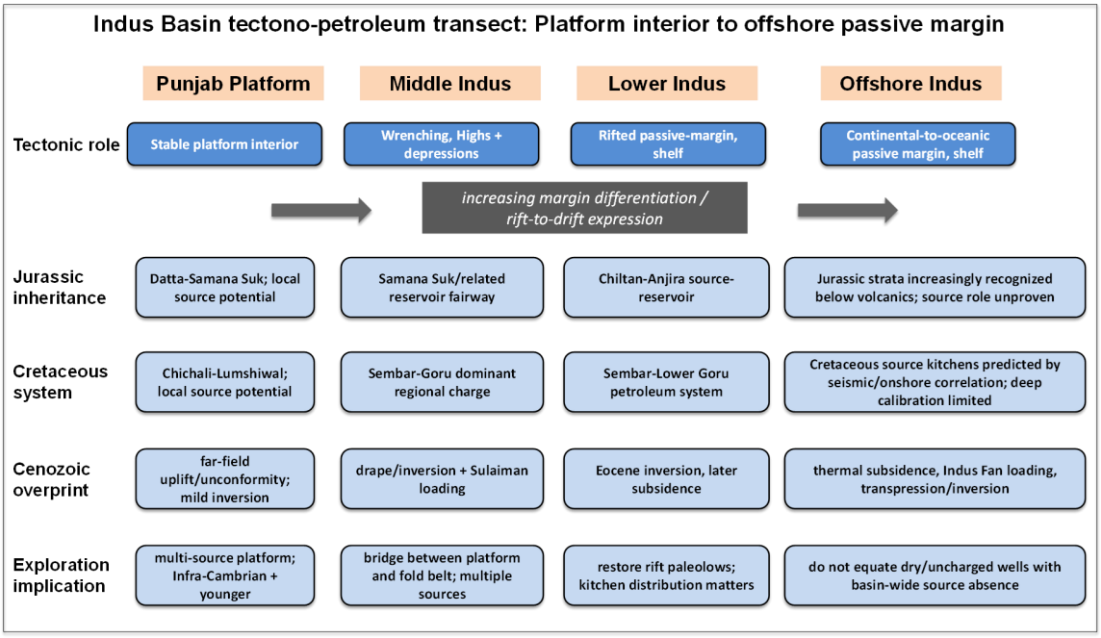


Figure 22: Conceptual petroleum-system variation across the Punjab Platform, Middle Indus, Lower Indus, and Offshore Indus (Note: The schematic summarizes first-order structural style, dominant source-reservoir fairways, and key exploration cautions across the principal Indus domains. It is a conceptual synthesis, not a strict stratigraphic correlation.)

Reference system	What it legitimately contributes	What it does not prove	Pakistan test
Basal Qusaiba, Arabia	Benchmark for a regionally effective Silurian marine source, maturity depletion, and source-oil correlation.	That every Pakistani Silurian rock is Qusaiba-equivalent or effective.	Rock-Eval + maturity + biomarkers/isotopes of Khyber-Peshawar/other preserved Silurian intervals.
Huqf/Baghewala Infracambrian family	Distinctive Ediacaran biomarker/isotope template and proof of an older regional petroleum system.	A continuous Huqf source beneath the entire Punjab Platform.	Full source-fluid molecular match plus Punjab Platform burial/migration reconstruction.
Tuwaiq-Hanifa Jurassic system	Process analogue for source-rich Jurassic depocentres adjacent to carbonate reservoirs.	Direct lithostratigraphic equivalence to Chiltan, Datta, or Shinawari.	Restore Jurassic paleolows; match source extracts with oils/condensates/gases.
Patala-Nammal, Kohat-Potwar	Proof that a Paleocene source can charge much older reservoirs when timing and connectivity align.	That all Paleogene shale elsewhere is effective or ineffective by age alone.	Common source-quality/maturity/fluid workflow across Middle, Lower, and Offshore Indus.

Table 4: Regional analogues and the limits of inference (Note. Analogue means functional or process analogue unless direct genetic equivalence has been demonstrated. Age similarity is treated as a screening relationship, not proof of source identity.)

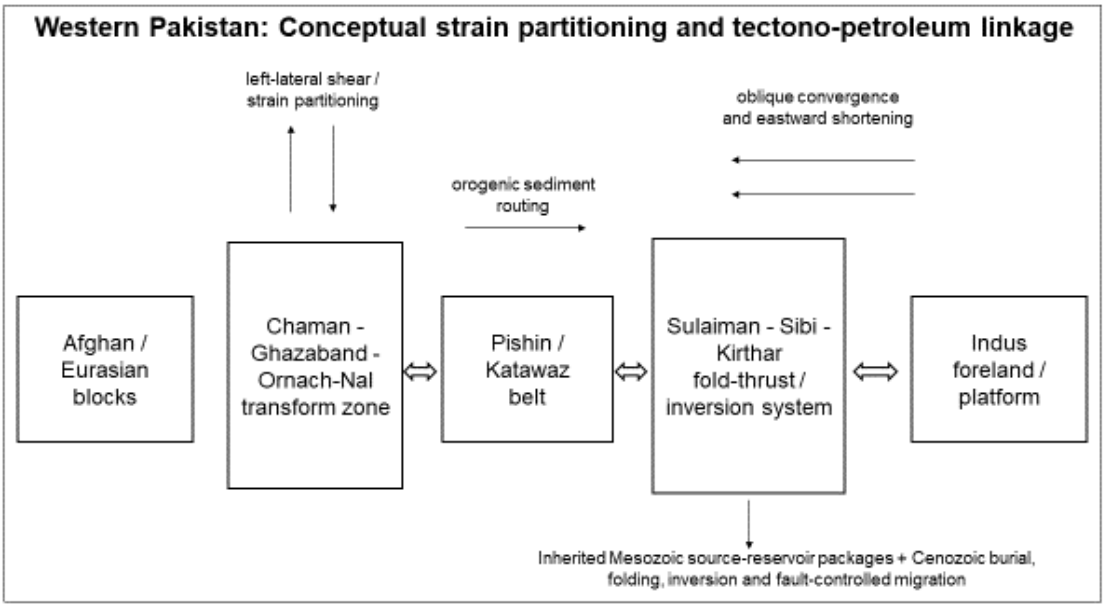


Figure 23: Western Pakistan conceptual strain partitioning and tectono-petroleum linkage (Note: The diagram summarizes the kinematic linkage among the Chaman-Ghazaband-Ornach-Nal transform zone, the Pishin-Katawaz belt, the Sulaiman-Sibi-Kirthar fold-thrust/inversion system, and the Indus foreland-platform, emphasizing inherited Mesozoic source-reservoir packages and later Cenozoic burial, folding, inversion, and fault-controlled migration).

5.7 Arabia-Pakistan Petroleum-System Architecture: Functional Analogy Without Genetic Assumption

The regional comparison can now be stated in a single architecture. Arabia provides well-calibrated examples in which regionally persistent Silurian and Jurassic source systems are integrated with long-lived reservoir-seal stacks. Pakistan lacks a proven regional Qusaiba-style Silurian source across the principal Indus-western fold-belt succession, but it contains several alternative source families: Infracambrian restricted-marine candidates, proven/local Jurassic source facies, the regional Cretaceous Sembar baseline, and selective Paleogene systems such as Patala. The critical distinction is between analogy and affinity. An Arabian source interval can define a depositional or petroleum-system function that should be tested in Pakistan; it cannot assign the source of a Pakistani fluid without matched molecular and isotopic evidence. The functional Arabia-Pakistan petroleum-system comparison is summarized in Figure 25.

This architecture leads to a disciplined multi-source interpretation. Sembar-Lower Goru remains the strongest demonstrated regional onshore baseline. Jurassic contribution should be added only where mature Jurassic paleolows, migration access and fluid fingerprints require it. Infracambrian contribution should be invoked where old reservoirs or deep platform plays show biomarker-isotope affinity compatible with a restricted-marine Precambrian source and a viable burial/migration history. Patala and other Paleogene candidates should be treated independently and not generalized by age. A mixed-charge model becomes scientifically persuasive only when several molecular parameters indicate mixing and the burial/structural history permits two or more source kitchens to charge the same reservoir at compatible times.

5.8 Seven-Stage Tectonic Model and Its Petroleum-System Meaning

The seven-stage country-wide model provides a final time-space framework for the four objectives addressed in this paper. Precambrian inheritance established heterogeneous basement and structural grain. Neoproterozoic-Cambrian rifting created the oldest sedimentary accommodation and Infracambrian petroleum elements. Paleozoic evolution produced both preserved northern successions and the major Indus-Punjab preservation gap. Mesozoic rifting and passive-margin development created the Jurassic-Cretaceous source-reservoir architecture that dominates much of the Indus province. Neo-Tethyan closure and collision initiated diachronous loading and deformation; foreland propagation then matured older sources and created younger traps, while western transpression and modern Makran subduction continued to reorganize the boundary. The model is deliberately

broad and overlapping because each stage began and ended at different times in different provinces. Figure 26 summarizes this integrated tectonic model and its petroleum-system context.

Tectonic Event	Punjab Platform	Central/Middle Indus	Lower/Offshore Indus	Potwar-Kohat	Sulaiman	Kirthar	Pishin/Chaman	Northern Pakistan	Makran
Recent plate-boundary deformation	Generally stable; minor seismicity	Ongoing subsidence and deformation; compartmentalized faults	Reactivation and seismicity; local offshore deformation	Active shortening; seismic slope basins	Active shortening; seismic fold–thrust belt	Active deformation; seismic uplift and erosion	Active strike-slip and transpression; seismic	Active seismic mountain belt; glaciated relief	Active accretion; seismic and tsunami hazard
Neogene foreland propagation	Gentle foreland subsidence; thin clastics	Foreland basin widening; continued wrench compartment-alization	Continued subsidence offshore; local inversion onshore	Thin-skinned shortening; foreland basin	Major fold–thrust belt development; shortening	Inversion and uplift; foreland shortening	Oblique shortening; transpression; strike-slip corridors	Uplift and exhumation; mountain building	Continued accretion; forearc basin evolution
Paleogene collision	Broad flexure; subsidence and wrenching	Wrench reactivation and inversion; Miano–Sawan structural-stratigraphic traps	Broad flexure; local inversion; volcanic and reactivation effects	Flexure and inversion intensify	Flexure; foredeep development	Foredeep development and loading	Oblique convergence; strike-slip transfer; transpression	Collisional orogenesis; thickening	Accretionary-prism growth; forearc development
Neo-Tethys closure	Far-field flexure; minor inversion	Broad flexure; local inversion; onset of wrench reactivation	Margin inversion; foredeep initiation	Inversion begins; uplift of structural highs	Flexure and uplift; incipient thrusting	Foredeep initiation; uplift	Neo-Tethys closure; remnant basins	Neo-Tethys closure; arc accretion; ophiolites	Neo-Tethys / Arabian–plate subduction
Cretaceous drift	Mild subsidence; open-marine shelf	Lower Goru fairway; NW–SE wrench faults; structural-stratigraphic traps	Passive-margin subsidence; Sembar–Goru; continued fault-block growth; local transtensional or sinistral reactivation	Open shelf; carbonate–clastic system	Passive-margin buildup; marine shelf	Passive-margin buildup; Sembar-related system	Mesozoic oceanic basins; arc / microplate activity	Passive-margin evolution along northern margin	Oceanic crust; trench–arc system
Jurassic rifting	Far-field flexure; mild reactivation	Wrench-dominated fairway; transfer segmentation; local rift inheritance	Extensional depocentres; horst–graben rift basins	Shelf to local extensional depocentres	Rift–sag development; extension	Extensional architecture; rift basins	Mesozoic basins; oceanic/arc-related development	Triassic–Jurassic arc / back-arc development	Jurassic oceanic basins; trench–system context
Permian–Triassic reorganization	Reoccupation; epeiric platform deposition	Platform renewal; marine transgression	Shelf renewal; marine cover develops	Marine return; platform to shelf sedimentation	Permian shelf development; marine cover	Permian shelf deposition	Sparse record; variable local basin fill	Passive-margin cover; carbonate platforms	Mostly not comparable pre-Cenozoic
Middle Paleozoic uplift/hiatus	Major hiatus; erosion on highs	Strong hiatus; erosion on basement highs	Major hiatus / absence; deep preservation uncertain	Regional hiatus; karst and unconformity	Prolonged hiatus; local uplift and erosion	Pronounced hiatus; subaerial exposure	Early record poorly constrained	Largely preserved Middle Paleozoic section	Mostly not comparable
Neoproterozoic rifting	Limited rifting expression	Neoproterozoic–Cambrian sag / rift roots	Early margin extension; basement segmentation	Early extensional influence; limited record	Pre- to early rift influence; local syn-rift	Early rift influence; margin fragmentation	Poorly constrained; not directly comparable	Limited direct expression	Mostly not comparable in prism setting
Precambrian inheritance	Basement highs; stable platform	Inherited highs; deep fault trends	Inherited basement fabric; rift-prone margin	Salt-detachment foundation; inherited structure	Transitional crust; inherited margin architecture	Inherited western Indian-margin architecture	Mosaic of basins, sutures and strike-slip corridors	Arc / microplate fragments; high-grade basement	Accretionary-prism basement complex
LEGEND	Inheritance / basement control	Rifting / extension	Non-deposition or hiatus / erosion	Shelf or passive-margin subsidence	Inversion / collision / flexure	Foreland thrusting / uplift	Strike-slip / transpression	Active subduction / accretion	Uncertain or not directly comparable

Interpretive note:
Inherited crustal architecture, preservation history, and later reactivation explain the contrasting province responses to the same tectonic events across Pakistan.
In the Middle Indus, NW–SE wrench faults commonly compartmentalize and seal reservoirs, whereas more oblique faults may be more leakage-prone.

Figure 24: Tectonic-event versus province-response framework for Pakistan (Note: Major geodynamic events are related to contrasting structural and stratigraphic responses across the principal provinces. The matrix explains why one plate-scale event need not produce synchronous or equivalent petroleum-system consequences).

6. Exploration Predictions and Falsifiable Tests

The scountry-wide ynthesis (in-progress) generates four exploration predictions. First, if the Middle Paleozoic preservation model is correct, the probability of a regionally continuous Silurian kitchen should remain low across the standard Indus-Punjab-western fold-belt stratigraphy, but preserved remnants should become more likely toward northern tectonostratigraphic domains and structurally protected local depocentres. A widespread deep Silurian discovery in the main Indus succession would falsify the current regional model.

Second, if the Infracambrian alternative-charge model is important on the Punjab Platform, produced fluids from prospects with access to deep Ediacaran sections should show reproducible biomarker-isotope affinity to the Karampur-Baghewala-Huqf family, and a reconstructed burial history should place the candidate source in a generative window before or during effective trap formation. Persistent mismatch to produced fluids, or a thermal model showing no effective generation, would materially weaken the hypothesis. A subsidiary prediction is that, where equivalent organofacies are demonstrated, a more deeply buried Pakistani continuation could have generated higher-maturity, lighter petroleum than Baghewala; fluid quality alone would not prove this because biodegradation, mixing, migration and reservoir alteration can modify API gravity and viscosity.

Third, if Jurassic kitchens contribute to Sulaiman-Kirthar hydrocarbons, the contribution should be strongest where restored Jurassic paleolows contain source-rich facies and where faults or carrier beds connect those kitchens to Chiltan and younger reservoirs. Produced-fluid fingerprints should require a Jurassic end member after maturity effects are accounted for. If Sembar fingerprints and generation-migration timing explain the fluids without residual mismatch, the simpler Sembar-dominant model should be preferred.

Fourth, if Patala source selectivity reflects petroleum-system integration rather than unique age, comparable Paleogene source rocks elsewhere should sometimes be geochemically rich but fail because of inadequate burial, limited thickness, poor preservation, or migration isolation. Deep mature Paleogene kitchens in the Offshore or

Lower Indus that are genetically linked to produced fluids would weaken a strongly Potwar-Kohat-selective interpretation and require expansion of the national Cenozoic source model.

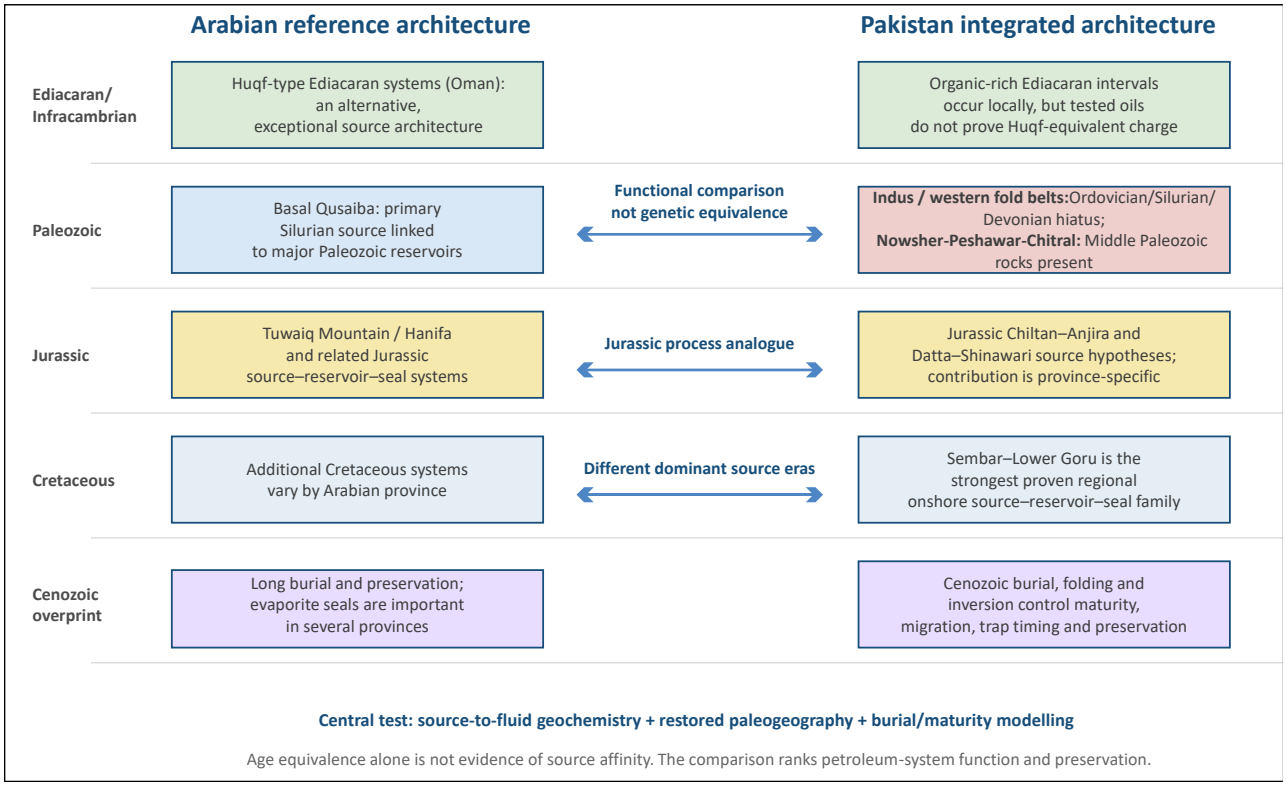


Figure 25: Functional comparison of Arabian reference petroleum architectures and the integrated Pakistan petroleum-system framework (Note: The comparison emphasizes source function, preservation and architecture rather than direct stratigraphic or genetic equivalence. The central test remains source-to-fluid geochemistry integrated with restored paleogeography and burial/maturity modelling)

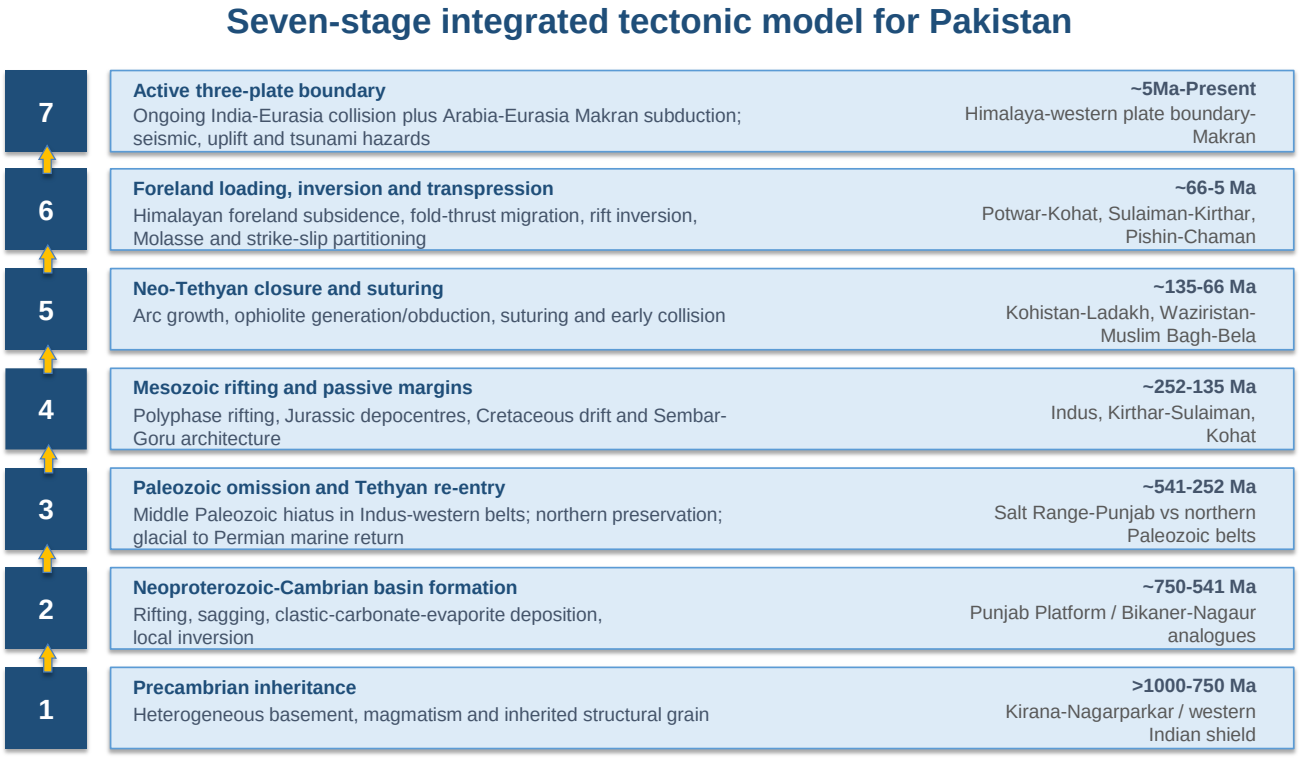


Figure 26: Seven-stage integrated tectonic model for Pakistan (Note: Broad, overlapping age ranges emphasize diachronous processes. The figure links Precambrian inheritance, Neoproterozoic-Cambrian rifting, Paleozoic preservation partitioning, Mesozoic rifting, Tethyan closure, foreland deformation and active plate-boundary processes to the petroleum-system hypotheses)

6.1 Prioritized Geochemical and Basin-Model Tests

For H2, the highest-value analytical program is a controlled north-south transect rather than additional presence/absence mapping alone. Fresh, minimally weathered Silurian-Devonian samples from Peshawar-Nowshera-Khyber and, where feasible, Chitral-Karakoram should be analyzed for TOC, Rock-Eval, petrographic maturity, reflectance proxies, biomarkers, stable isotopes and inorganic redox proxies. Results should be compared with Qusaiba and regional Silurian controls after maturity normalization. If the northern samples are thermally overprinted, their petroleum significance may still survive as evidence of former organic-rich facies, but their present-day generative potential must not be back-calculated without thermal reconstruction. Subcrop mapping and thermochronology across the Punjab-Indus gap should independently test non-deposition versus erosion.

For H3, the Punjab Platform requires an integrated paleothermal experiment. Rock-Eval and biomarker screening of Salt Range/Bijnot/Fort Abbas intervals should be combined with well-specific stratigraphic restoration, eroded-overburden estimates, heat-flow scenarios and maturity calibration. The central falsifiable prediction is that prospects positioned near deeper preserved Infracambrian paleolows should show greater maturity and a higher probability of compatible source-fluid signatures than shallow platform crests. Present geothermal gradient is an input to the current thermal state, not a substitute for maximum paleoburial. The Baghewala-Karampur-Huqf molecular field provides a useful comparator, but any Punjab Platform charge claim must be demonstrated locally. Where equivalent organofacies can be established, the same model should test whether greater pre-erosional burial on the Pakistan side could have produced higher maturity and lighter petroleum than Baghewala. Any such comparison must separate thermal maturity from biodegradation, source-facies, migration and reservoir-alteration effects.

For H5 and H6, the priority is matched fluid-source correlation along the Sulaiman-Kirthar and Middle/Lower Indus system. Produced gases, condensates and oils from Chiltan and other reservoirs should be analyzed for stable carbon isotopes, molecular maturity, sterane/hopane distributions, tricyclic terpanes, aromatic maturity and, for gas, hydrocarbon and carbon-isotope composition. Candidate Chiltan-Anjira, Shinawari/Datta, Sembar and Paleogene sources must be sampled within restored paleodepocentres rather than only on fold crests. The result should be evaluated against three explicit models-Sembar-dominant, Jurassic-dominant and mixed charge-so that every new sample increases or decreases the likelihood of a stated model rather than merely adding another descriptive plot.

For H4, a common Paleogene workflow is required across Kohat-Potwar, Middle Indus, Lower Indus and Offshore Indus. Equivalent TOC/Rock-Eval, redox, biomarker, isotope and maturity criteria should be applied to Patala, Sakesar/Chorgali and other Paleocene-Eocene candidates, followed by direct comparison with produced fluids. Offshore data should be interpreted with particular caution because shelf wells can underrepresent maturity in deeper depocentres. A regional genetic match to multiple non-Patala Paleogene sources would weaken the selectivity hypothesis; persistent Patala affinity confined to the northwestern foreland would strengthen it.

6.2 What Would Falsify the Preferred Integrated Model?

The integrated model is deliberately vulnerable to falsification. Discovery of a widespread, regionally continuous Silurian-Devonian section beneath the main Indus-Punjab system would require revision of H2. Consistent biomarker-isotope mismatches between Punjab Platform fluids and all tested Infracambrian sources would weaken H3. A robust Sembar-family match to Chiltan-reservoired fluids across the Sulaiman-Kirthar system, with no need for Jurassic input, would reduce H5 to a local source-rock occurrence rather than a material charge hypothesis. Conversely, reproducible Jurassic-fluid matches with compatible maturity and migration timing would require expansion of the deeper-source model. Broad genetic correlation of Middle/Lower/Offshore Indus fluids to Paleogene sources would weaken H4's regional selectivity. The purpose of retaining H1-H9 is, therefore, not to protect a preferred narrative but to make explicit which future observation would force that narrative to change.

7. Conclusions

This publication reduces the country-wide synthesis to four petroleum-system questions that can be tested directly with geochemistry and burial history. The first conclusion is that the Ordovician-Silurian-Devonian gap is regional, but not Pakistan-wide. The recognized Indus, Punjab Platform, and much of the western fold-belt succession lack a proven Qusaiba-style Silurian source interval, whereas northern Pakistan preserves Silurian-Devonian rocks and

locally very high TOC. Those northern rocks are important source-system candidates and paleogeographic controls, but their generative potential remains unproven until maturity and Rock-Eval/biomarker data are obtained.

Second, Ediacaran-Infracambrian source systems are a legitimate alternative charge hypothesis, particularly for the Punjab Platform and older reservoirs. Source-quality measurements and the Karampur-Baghewala-Huqf biomarker family provide a strong regional rationale for testing them. They should not, however, be described as a basin-wide substitute for the missing Silurian system without source-to-fluid correlation and a quantitative burial-maturity history. Accordingly, the presently low geothermal gradient of the Punjab Platform does not preclude earlier source maturation; maximum paleoburial before erosion, rather than present burial alone, is the parameter that must be reconstructed when evaluating the Infracambrian charge hypothesis. If comparable organofacies on the Pakistan side reached greater peak burial than the Baghewala system, a higher-maturity and potentially lighter petroleum charge is a testable exploration outcome, not a conclusion that can be drawn from modern depth alone.

Third, Jurassic source contribution in Pakistan is no longer merely an age analogy. Chiltan, Shinawari, and Datta contain source-capable intervals, and their geochemical fingerprints are distinguishable from Sembar and Patala source families. The evidence nevertheless favors a conservative additive model: Sembar remains the proven regional Cretaceous baseline, while Jurassic contribution should be invoked prospect by prospect where fluid fingerprints, restored kitchen geometry, and generation timing require it.

Fourth, Patala demonstrates source selectivity rather than the universal petroleum effectiveness of Paleogene rocks. Regional Eocene and Paleocene comparators can be equally or more source-capable geochemically, so the difference between a source rock and an effective source system lies in thickness, preservation, maturity, kitchen geometry, migration connectivity, and trap timing. The absence of a comparably demonstrated Patala-type system in Middle, Lower, or Offshore Indus should therefore be treated as an evidence gap and petroleum-system question, not as proof that Paleogene source rocks do not exist there.

The broader conclusion is that Pakistan is best modeled as a multi-source, multi-stage petroleum system superimposed on a strongly partitioned tectono-stratigraphic framework. Geochemical richness defines possibility; maturity defines generative capability; biomarkers and isotopes define affinity; and restored burial-migration history determines whether that affinity could have produced the observed accumulation. Future exploration value will come from integrating all four levels rather than from assigning source solely by reservoir age, stratigraphic proximity, or regional analogy.

8. Data Availability and Reproducibility

All geochemical values used in the figures and summary tables were compiled from the cited published sources and project-held source tables. Sample-level observations, published aggregate benchmarks, and weathered/outcrop subsets are maintained as separate data classes. The additional sterane ternary, maturity-proxy and stable-isotope plots in this expanded version are derived directly from the same project-held source tables/workbook; published aggregate/range values remain segregated from individual observations.

9. Declarations

Funding. This research received no external funding. The study was undertaken independently by the author.

Conflict of interest. The author is the developer of Brill-Viz, which was used as an analytical and visualization tool in this study. No external commercial organization influenced the study design, data selection, interpretation, or conclusions. The author declares no other competing interests.

Author contributions. Khan Arshad is solely responsible for the conceptualization, literature review, methodology, data compilation and integration, geochemical analysis, visualization, interpretation, manuscript preparation, and revision of this study.



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Khan Arshad is a petroleum geologist and oil and gas exploration professional with nearly three decades of experience in oil and gas exploration, regional geological studies, prospect evaluation, petroleum economics, and exploration project management. He holds M.Sc. in Petroleum Geology from the University of Aberdeen, UK, and M.Sc. in Geology from the University of Karachi. His career has included technical and managerial roles in Pakistan with Baker Hughes INTEQ, OMV, PETRONAS, MND, Eni, and Dewan Petroleum, covering wellsite and operations geology, regional studies, new ventures, exploration team leadership, and exploration project management.

His professional work has involved geological and petroleum-system evaluation of Pakistan's sedimentary basins, including the Middle and Lower Indus basins, Kirthar and Sulaiman fold belts, Potwar Basin, and Punjab Platform. His experience includes seismic and petrophysical interpretation, sequence stratigraphy, regional fairway analysis, prospect generation, reserves and risk assessment, and evaluation of conventional and unconventional exploration opportunities.

He is currently self-employed as the founder of enerbrill, where he has combined his petroleum exploration experience with data analytics and software development. He has independently developed Brill-Viz, an integrated data analysis and visualization platform, together with several specialized petroleum-industry applications for probabilistic volumetrics, geological chance of success, petrophysical evaluation, TOC estimation, decision analysis, mind mapping, and AI research and document intelligence.

The present synthesis brings together this long-standing professional exposure to Pakistan's petroleum geology with a systematic review and integration of publicly available tectonic, stratigraphic, geochemical, and petroleum-system information.

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