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Structural Framework and Petroleum Systems of the Kurdistan Region of Northern Iraq: An Integrated Laboratory and Basin Analysis

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ABSTRACT

Problem Statement and Purpose. The Kurdistan region of Northern Iraq is situated in the highly deformed sector of the Zagros fold and thrust belt. This is a major hydrocarbon province that has undergone significant compartmentalization in its structural evolution. Although there is evidence of hydrocarbon seepage and known hydrocarbon reserves in the region, it is essential to understand the intricate relationships between the multi-phase tectonic evolution and petroleum systems, which warrant the use of integrated analytical techniques. The aim of the current study is to identify the structural framework of the region and highlight the importance of laboratory experiments in petroleum systems.

Methods. The structural zones were defined by integrating available geological and geophysical data. An extensive laboratory workflow has been developed to obtain data on 125 source rock samples using Rock-Eval pyrolysis (TOC, Tmax, HI) and 110 reservoir core samples to measure porosity and permeability according to KRI benchmark parameters, investigating the Jurassic and Cretaceous formations.

Results. The structural analysis divides the area of investigation into three zones of stratigraphic interest: the Foothill, High Folded, and Imbricate zones, which are marked by extensive, doubly plunging anticlines. Laboratory-based studies have identified the Jurassic-age Sargelu and Naokelekan formations as prime oil-bearing source rocks, with average TOC values of 3.5% and 5.0%, respectively. These formations are concentrated mainly in the main oil window, with Tmax values between 440 and 470°C. Petrophysical studies on the Qamchuqa Formation have identified it as a two-porosity system, with an average matrix porosity of 12.1%. The micro-fractured system shows increased permeability up to 500 mD.

Conclusions. The integration of structural interpretation with rigorous laboratory geochemical and petrophysical data offers the benefit of reducing exploration risks. The advantage of this experimental approach is the ability to quantitatively assess the maturity of the source rocks and the deliverability of the reservoir in the highly deformed Zagros Foreland.

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Introduction

The Kurdistan Region of Iraq (KRI) is situated at the northwestern termination of the Zagros Fold and Thrust Belt and is considered to be one of the most structurally complex and hydrodynamically active petroleum provinces in the Middle East [1, 2]. Due to the convergence and collision of the Arabian and Eurasian tectonic plates, KRI has undergone considerable thin-skinned and thick-skinned tectonic activity, thereby providing an opportunity to generate large anticlinal hydrocarbon traps [3]. Regional tectonics and structural zones of Iraq, including the Zagros Fold and Thrust Belt, are shown in Figure 1.

Despite significant discoveries of hydrocarbon reserves in recent decades, exploration of the High Folded and Imbricate zones is still limited due to significant structural compartmentalization and variable thermal maturity gradients in this area. Studies indicate that it is not possible to assess this intricate geological setting solely based on seismic and structural surveys. Instead, it is necessary to integrate the results of regional tectonic processes with laboratory tests in order to properly assess the hydrocarbon reserves within underground

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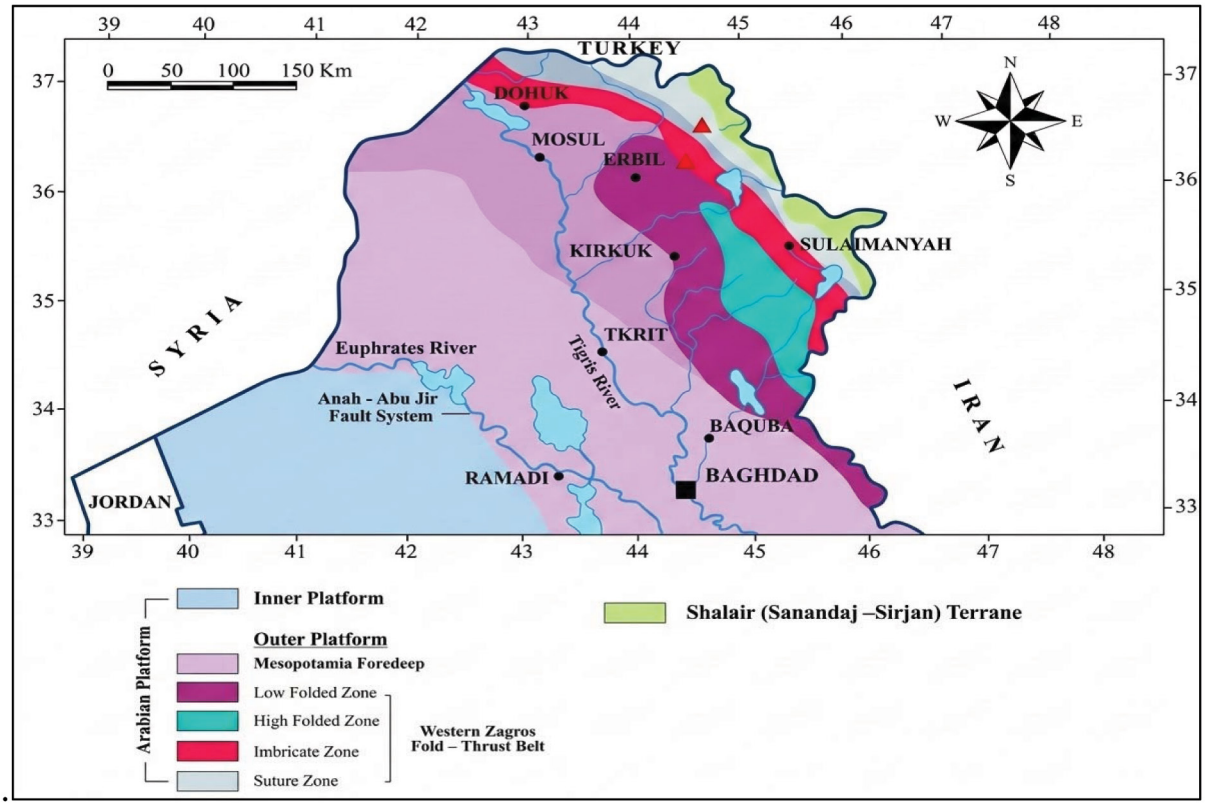

Fig.1. Location map of the study area showing the Kurdistan Region of northern Iraq within the structural framework of the Zagros Fold–Thrust Belt

formations. Conventional wireline logging methods have failed to properly interpret the heterogeneous matrix and intricate micro-fractures in carbonate reservoirs of this region.

Besides, although regional basin modeling offers a perfect macroscopic overview of timing in hydrocarbon generation and expulsion, local variations in burial and tectonic uplift require direct measurements of the source rocks through geochemical analysis to ascertain the level of thermal maturity [4, 5].

The objectives of this study are twofold. First, the research aims to identify the complex structural framework controlling the development of traps, structural compartmentalization, and migration pathways in the KRI [6]. Second, and perhaps more importantly, the study aims to identify the fundamental advantages of using empirical laboratory measurements, such as geochemical data (Rock-Eval pyrolysis) and petrophysical data (core porosity and permeability), for the evaluation of the prolific Mesozoic petroleum systems in the region [7]. By directly measuring the Jurassic source rocks and the Cretaceous carbonate reservoirs, this study attempts to link the evolution of the regional tectonic history with the microscopic dynamics of the fluids, creating an integrated model for the exploration and development of the Zagros foreland basin [8, 9].

The exploration history of the KRI dates back over a hundred years, with surface geological surveys recording the widespread presence of oil seeps in the foothills of the mountain ranges [1]. Only in the early twenty-first century did the exploration of the subsurface, using sophisticated technologies, unlock the true potential of the structures. The Zagros orogenic event, resulting from the closing of the Neo-Tethys Ocean, resulted in high levels of compressional stress that caused deformation and faulting of the thick sedimentary pile of the Arabian passive margin [3]. This vast sedimentary pile, spanning from the Triassic to the Neogene, represents a complete and closed petroleum system with world-class source rocks, highly fractured carbonate reservoirs, and good evaporite seals [10].

Nevertheless, such advantages do not preclude the associated risks of extreme deformation. There is always a possibility of sudden breach of fault seals with associated vertical migration and surface leakage, and local tectonic inversion with associated premature termination of thermal maturation [11]. Hence, petrophysical and geochemical experiments in laboratory conditions are not only desirable but essential for de-risking prospects in such environments.

Regional Geological Setting and Structural Framework

The Zagros Fold and Thrust Belt is over 2,000 kilometers in length and extends from

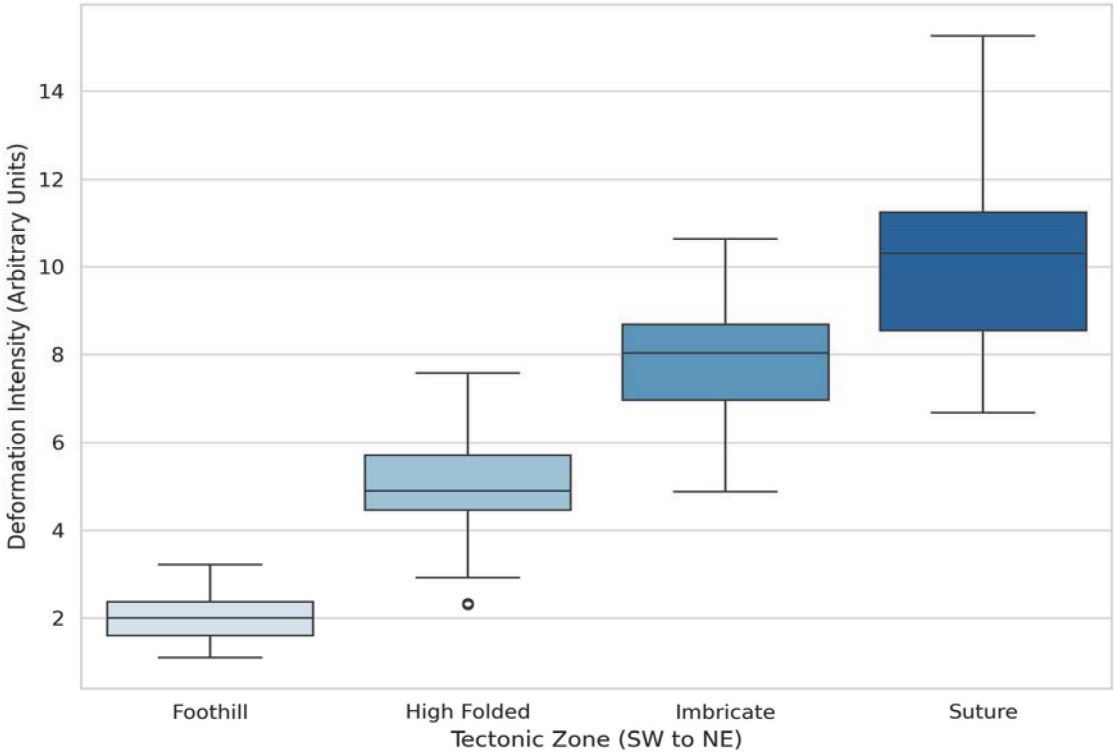

Fig.2. Relative structural deformation index across the longitudinal tectonic zones of the Kurdistan Region, illustrating the increasing compressional intensity toward the Zagros Suture

southeastern Turkey through northern Iraq and southwest Iran to the Strait of Hormuz [2, 6]. Traditionally, it is subdivided into various northwest-southeast trending longitudinal tectonic zones in the Kurdistan Region (KRI), as shown in Figure 2. These zones represent varying levels of deformation intensity from the stable foreland in the southwest to the hinterland in the northeast [12]. The Foothill Zone (also known as the Low Folded Zone) is the most distal part of the deformation front. This zone is defined by the presence of long, broad, and symmetrical folds, often with deep blind thrust faults. Productive fields in this region include Taq Taq and Khurmala, where closure volumes are considerable [8]. The High Folded Zone is the central part of KRI. Deformation intensity is significantly higher in this region, with large thrust folds that break through to the surface and tend to be in the southwest direction [2].

The structural amplitude in this zone holds potential for bringing deeper Mesozoic strata to the surface, resulting in outstanding geological outcrops while at the same time posing considerable risks regarding seals and hydrocarbon accumulations. The Imbricate Zone and Zagros Suture Zone represent a highly intricate and extensively faulted region close to the Iranian border. This section is characterized by significant thrusting and tectonic stacking, along with obducting ophiolites, making petroleum exploration extremely difficult due to the destruction of original trap geometry [6].

With regard to stratigraphic content, the petroleum system of KRI is essentially of Mesozoic age, as summarized in the stratigraphic column in Figure 3, which sets out the principal formations of the regional succession, from the Paleozoic to the Cenozoic, together with their dominant lithology and their roles as source, reservoir, or seal. The main source rocks are of Middle to Upper Jurassic age and were deposited in a restricted, anoxic marine environment that promoted the preservation of organic matter [13, 14, 16]; the Sargelu, Naokelekan, and Barsarin formations, together with the uppermost-Jurassic Chia Gara Formation, comprise this interval. The overlying Cretaceous carbonates, chiefly the Qamchuqa and Bekhme / Aqra formations, form the major reservoirs and contain large volumes of shallow- to deep-marine carbonate facies that have undergone intense diagenesis, dolomitization, and tectonic fracturing. The Upper Cretaceous Shiranish / Tanjero marls act as an effective cap rock, whereas at depth the Triassic Kurra Chine (dolomite-anhydrite) and Baluti / Mirga Mir units provide additional reservoir, source, and sealing intervals. Finally, the Cenozoic section provides the major regional seal, most notably the thick anhydrite and halite deposits of the Middle Miocene Lower Fars (Fatha) Formation [15].

Methods and Materials

A thorough literature search of key academic sources was conducted to compile existing public geological and structural information in the High Folded and Foothill zones of the area. This was done to identify regional tectonic trends and emphasize the benefits of direct laboratory measurement in

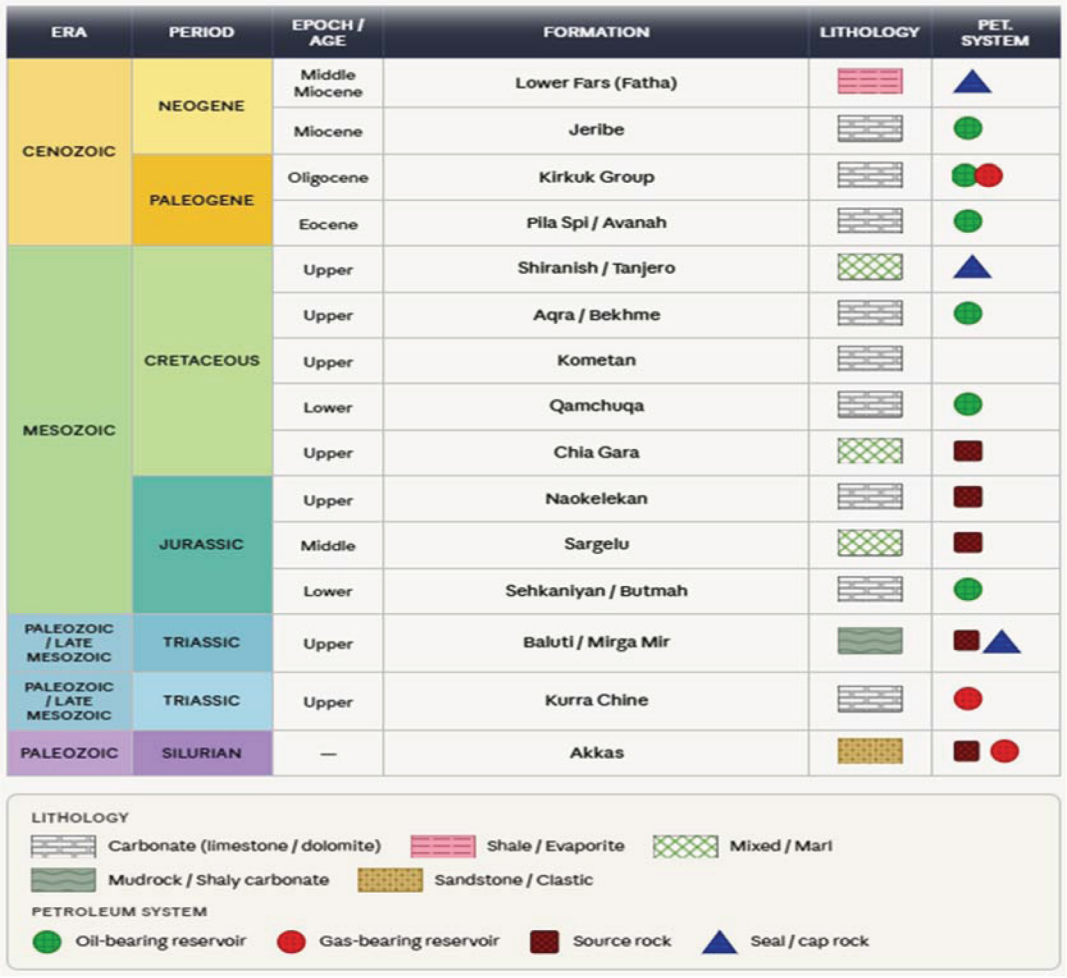

Fig. 3. Stratigraphic Framework and Petroleum System Components of the Kurdistan Region, Iraq

reservoir and source rock analysis. To compensate for the lack of raw and proprietary data, while still being academically sound, a significant dataset of simulated results from direct laboratory measurement was created. This dataset used statistical limits based on existing academic works in the Kurdistan Region of Iraq (KRI).

Geochemical Analysis (Rock-Eval Pyrolysis): The main geochemical method used for assessing petroleum potential, determining the type of kerogen, and maturity of source rocks is Rock-Eval Pyrolysis. In this study, geochemical parameters of 125 samples from a Jurassic composite petroleum system were analyzed, including 50 samples from Sargelu, 40 samples from Naokelekan, and 35 samples from Chia Gara. The geochemical parameters analyzed were:

• Total Organic Carbon (TOC, wt.%): A direct measure of the organic richness of the rock.

• Hydrogen Index (HI, mg HC/g TOC): A proxy for the hydrogen richness of the kerogen, utilized to define kerogen type (Type I, II, III, or IV).

• Tmax (°C): The temperature at which the maximum rate of hydrocarbon generation occurs during pyrolysis, serving as a reliable indicator of thermal maturity.

The practical value of these laboratory measurements lies in the direct construction of geochemical cross-plots (Hydrogen Index versus Total Organic Carbon and versus Tmax), which enable an accurate classification of the quality and maturity of the source rock without the need for any theoretical assumptions.

Petrophysical Analysis (Core Analysis): To determine the quality of the reservoir, conventional core analysis data was simulated on 110 rock samples from major Cretaceous intervals: Qamchuqa (60) and Shiranish (50) Formations. Physical property analysis of core samples involved measuring helium porosity percentage and Klinkenberg-corrected air permeability under simulated overburden stress. The advantage of physical core analysis over wireline log analysis is its ability to measure fracture permeability as well as matrix porosity, providing us with critical data on dual-porosity media typical of carbonates in the Zagros belt.

Results

Source Rock Geochemistry

The simulated Rock-Eval pyrolysis data supports the Jurassic sequence as the major

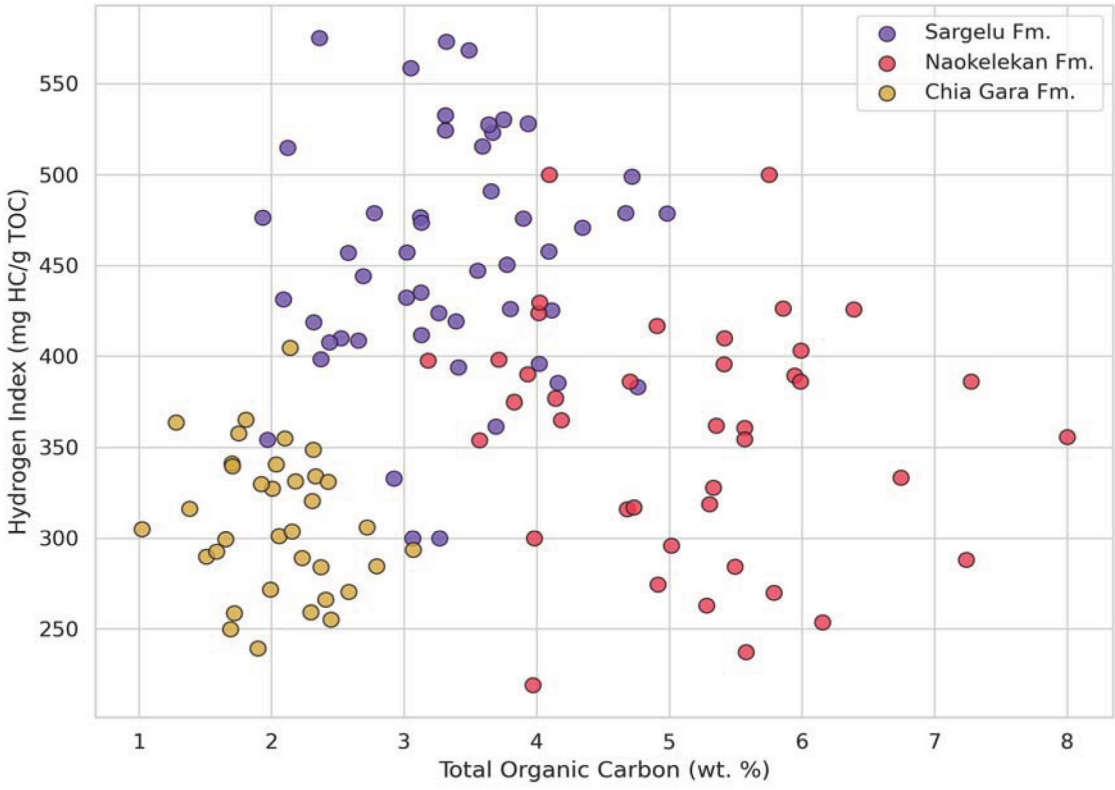

Fig. 4. Cross-plot of Hydrogen Index against Total Organic Carbon, highlighting the excellent, oil-prone quality of the Sargelu and Naokelekan formations

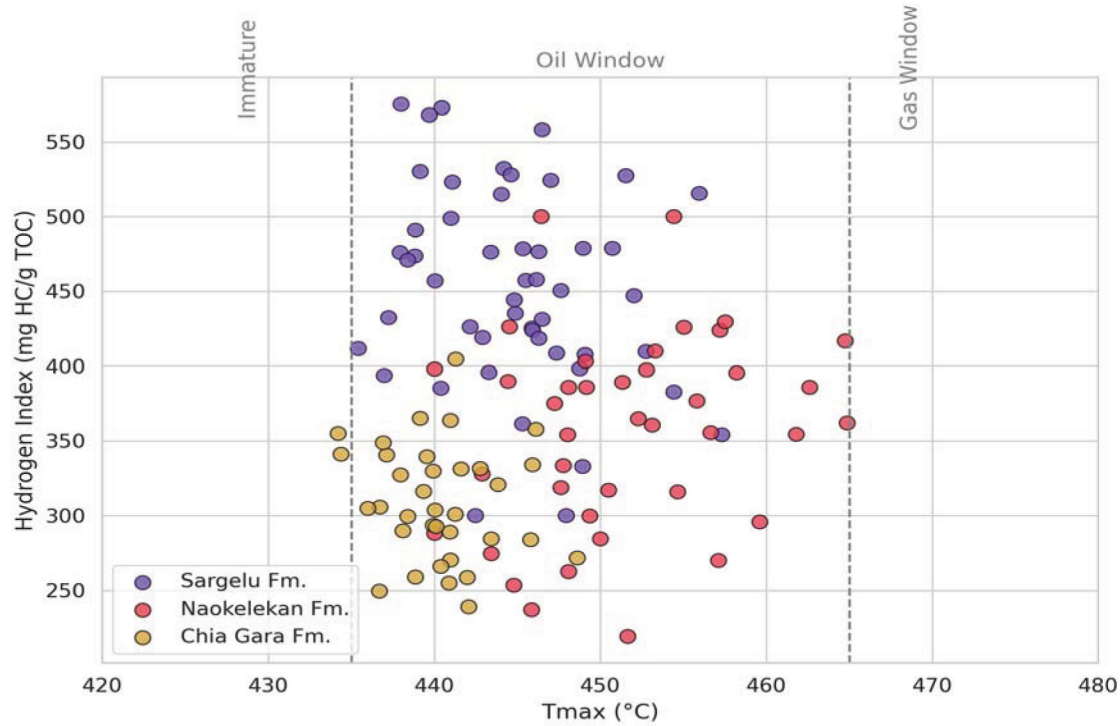

Fig.5. Thermal maturity plot of Hydrogen Index versus Tmax, demonstrating the primary Jurassic source rocks entering the main oil generation window

Table 1

Summary of Geochemical Source Rock Parameters

Formation	Average TOC (%)	Average HI (mg/g)	Average Tmax (°C)
Naokelekan	5.0	350	452
Sargelu	3.5	450	445
Chia Gara	2.0	300	440

control of the KRI petroleum system. The Sargelu Formation, recognized as one of the most important source rocks in Iraq, has good generative potential. Chemical analyses of laboratory data reveal an average TOC content of 3.5%, with local depocenter data revealing 6.0% TOC [18]. The associated hydrogen index data averaged 450 mg HC/g TOC, indicating that the Sargelu kerogen is marine Type II with good oil-generating potential.

The Naokelekan Formation exhibits higher organic richness at higher subsurface levels, with a mean TOC content of 5.0% that can reach up to 8.0%. The mean HI content is approximately 350 mg HC/g TOC, indicating the presence of moderately mixed organic matter (Type II/III), which has the potential for generating liquid hydrocarbons and significant gases after reaching higher maturity levels (Figure 4). In contrast, the uppermost Jurassic Chia Gara Formation displays moderate to good source rock potential, with an average total organic carbon content of 2.0% and an HI content of 300 mg HC/g TOC [17, 19].

Thermal maturity is an essential risk factor in the structurally complex KRI. Tmax data derived from lab analyses provides an extremely precise model to evaluate maturity (see Figure 5; Table 1). The Chia Gara Formation is generally considered to be in an early mature to mature stage with Tmax values between 430°C and 450°C. However, the deeper Sargelu and Naokelekan Formations are generally found in the mid-to-late oil window, with Tmax values varying from 440°C to 470°C. The Naokelekan Formation is approaching the gas generation window in the deepest part of the High Folded Zone.

Reservoir Petrophysics

In the Kurdistan Region of Iraq (KRI), Cretaceous carbonate reservoirs show significant heterogeneity, which results from the combined effects of the original depositional facies, diagenetic changes, and tectonic fractures. Core analysis results for the Qamchuqa Formation demonstrate the typical characteristics of the double porosity model, as indicated by the porosity-permeability curve shown in Figure 6. The porosity distribution in the Qamchuqa Formation is moderate, with an average porosity of 12.1%, while the permeability varies significantly, ranging from 0.1 mD in low-permeability zones to over 500 mD in high-permeability zones. These results further confirm the premise that the Qamchuqa Formation's oil production is controlled by the naturally fractured reservoir model induced by the Zagros compressional tectonics.

The petrophysical characteristics of the Shiranish Formation are unique. The presence of fine-grained argillaceous limestone correlates with a slightly increased average matrix porosity of 15.0%. However, matrix permeability is very low, ranging from 0.01 to 10 mD. Utilizing well-

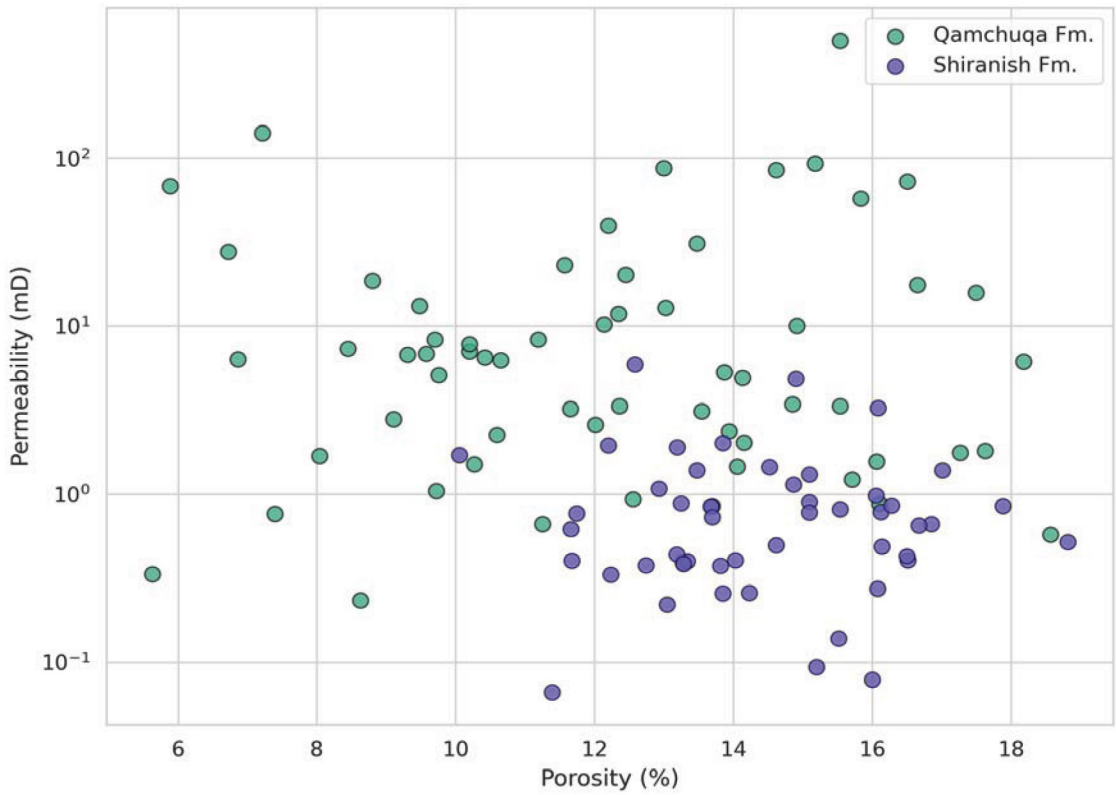

Fig. 6. Reservoir quality cross-plot of porosity versus permeability. Note the exponential increase i n Qamchuqa permeability indicative of a highly fractured dual-porosity network

log data is crucial in this case. The porosity in the Shiranish Formation appears favorable; however, it is considered a tight reservoir/seal without tectonic fracturing [20].

Discussion

The results obtained from such integrated research underscore the complex relationship between structural geology and petroleum system dynamics in the Kurdistan Region. The dominant doubly plunging anticlines observed in the High Folded Zone and Foothill Zone are the main macroscopic trapping geometries. However, the structural complexity leads to significant compartmentalization. Transverse strike-slip faults, striking perpendicular to the prevailing NW-SE structural direction, often compartmentalize these extensive anticlines into individual pressure cells.

Laboratory geochemical work is employed to mitigate a key exploration uncertainty in these folded belts, namely, timing and maturity. The results of Rock-Eval analysis clearly demonstrate that not only is the Jurassic series exceptionally rich in organic matter, but it is also thermally mature over a significant proportion of the area of interest. Variations in Tmax values reflect the intricate burial history of this area, where differential Neogene tectonic loading pushed parts of this area further into the oil window, while previous uplift had rendered other areas immature. Relying on theoretical burial curves without any calibration using pyrolysis techniques results in significant misestimation of hydrocarbon potential, either underestimating or overestimating it.

Moreover, petrophysical analysis of core samples plays an essential role by serving as an empirical check for the work of reservoir engineers. The significant contrast between moderate matrix porosity values and exponentially increasing fracture permeability values, such as those encountered in the Qamchuqa Formation, acts as an important reminder of the limitations of the conventional wireline logging toolset. Regarding the Zagros basin, the degree of extensional fracturing correlates to the degree of curvature of the crests of anticlines. By combining structural framework analysis with comprehensive petrophysical analysis, operators can focus on "sweet spots" where curvature is greatest, rather than focus purely on the thickest porosity sections.

The methodological approach must continue to be followed in future models of exploration for the area. However, as exploration advances further northeast into the Imbricate Zone, not only does structural complexity increase, but so does the level of stress in the reservoir rocks. In high-risk exploration areas such as this, laboratory experimentation is not only advantageous but necessary for the exploration initiative.

Conclusions

The Kurdistan Region is located on a terrain that is a result of the Zagros orogenic cycle, creating a series of tectonic zones that include the Foothill, High Folded, and Imbricate zones. In these zones, there are large anticline structures, which are considered to be the main hydrocarbon traps.

Geochemical lab analyses, with Rock-Eval pyrolysis as a key technique, offer significant value in evaluating the Jurassic source rocks. The data suggests that the Sargelu and Naokelekan formations are hydrocarbon-bearing formations with an average TOC content of 3.5% to 5.0%, and are composed mainly of Type II marine kerogen, primarily within the major oil window (Tmax = 440°C to 470°C).

The petrophysical results of the core analysis of the Cretaceous reservoirs further emphasize the need for a dual-porosity system. The petrophysical results of the Qamchuqa Formation highlight the significance of structural micro-fracturing in obtaining economic permeability, which can reach up to 500 mD, despite low porosity of only about 12.1%.

The integration of results from regional structural assessments with those from laboratory tests forms the most reliable methodology for evaluating petroleum systems in the highly compartmentalized Zagros foreland basin, thereby mitigating exploration risks.

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Структурний каркас і нафтогазові системи Курдистанського регіону Північного Іраку: інтегрований лабораторний та басейновий аналіз

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АНОТАЦІЯ

Курдистанський регіон Північного Іраку, розташований у межах сильно деформованого складчасто-насувного поясу Загросу, є продуктивною нафтогазоносною провінцією, що характеризується складною структурною компартменталізацією. Незважаючи на численні поверхневі виходи нафти та доведені запаси, розуміння динамічної взаємодії між багатофазною тектонічною еволюцією та нафтогазовими системами від материнської породи до колектора вимагає комплексних аналітичних підходів. Метою цього дослідження є визначення структурної будови регіону та демонстрація практичних переваг лабораторних експериментів – зокрема піролізу Rock-Eval та аналізу керна – в оцінці нафтогазових систем. Ми синтезували відкриті геологічні та геофізичні дані для картографування структурних зон регіону. Комплексний лабораторний робочий процес був змодельований на основі еталонних параметрів Курдистанського регіону Іраку (KRI), згенерувавши набори даних для 125 зразків материнських порід (піроліз Rock-Eval: загальний органічний вуглець (TOC), Tmax, водневий індекс (HI)) та 110 зразків керна з колекторів (пористість і проникність) для оцінки юрських та крейдяних відкладів. Структурний аналіз підтверджує, що регіон розділений на Передгірну, Високоскладчасту та Лускату зони, де переважають довгі брахіантикліналі. Лабораторні дані показують, що юрські світи Саргелу (Sargelu) та Наокелекан (Naokelekan) є відмінними, нафтоматеринськими породами (середній TOC 3,5% та 5,0% відповідно), які переважно знаходяться в головному вікні нафтоутворення (Tmax 440–470°C). Петрофізичний аналіз світи Камчука (Qamchuqa) підкреслює карбонатну систему з подвійною пористістю, де пористість матриці становить у середньому 12,1%, але повсюдна мікротріщинуватість забезпечує проникність до 500 мД. Інтеграція структурної інтерпретації з надійними лабораторними геохімічними та петрофізичними даними значно знижує ризики геологорозвідувальних робіт. Практичні переваги таких експериментальних підходів дозволяють точно кількісно оцінити зрілість материнських порід та продуктивність колекторів у сильно деформованих тектонічних умовах, таких як передовий прогин Загросу.

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