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Impact of Rock Failure on Hydrocarbon Migration and Accumulation and other Characteristics: A Case Study of the Mishrif Formation in West Qurna Oilfield, Southern Iraq

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Abstract

This study critically examines the role of rock failure in controlling hydrocarbon migration and accumulation, with particular emphasis on the Mishrif Formation in the West Qurna oilfield of southern Iraq. It tests the hypothesis that rock failure significantly enhances directional permeability, facilitating secondary hydrocarbon migration, analysis of migration routes and reservoir distribution, understanding rock behavior under stress that could influence hydrocarbon migration, simulating the effects of burial (pressurization) and uplift (depressurization) on rock permeability and understand how geological processes influence reservoir quality, quantifying the enhancement of permeability caused by fracturing and assess its significance in hydrocarbon transport and accu-mulation. Using full-diameter core samples from 12 wells, permeability was measured in directions both horizontal and vertical to bedding planes. Results indicate significantly higher permeability and better pore connectivity in the horizontal direction. Experimental simulations of pressurization and depressurization showed that burial reduces permeability drastically, while uplift can partially restore it, particularly in the direction of structural alignment. Fracturing was found to dramatically enhance permeability, in some cases by up to a factor of 20,500. These findings underscore the importance of understanding rock anisotropy and fracture behavior in predicting hydrocarbon migration pathways and optimizing exploration strategies. Also understanding fracture types, orientations, and behaviors in natural conditions is therefore vital for accurate reservoir modeling and effective exploration. The study contributes valuable insights into reservoir modeling, aiding in more effective field development and risk reduction in hydrocarbon exploration.

Keywords: *Rock failure; Hydrocarbon migration; Mishrif Formation; Pressurization and depressurization; Permeability enhancement; Burial and uplift effects.*

1. Introduction

Rock failure is a geological process that occurs when stresses acting on rocks exceed their strength, formation of fractures in the rocks, which can provide corridors for the migration of hydrocarbons (oil, gas). It can increase the permeability of rocks, facilitating the migration of hydrocarbons [1]. Fractures can also help to form traps that may trap hydrocarbons and prevent them from migrating. Examples of the influence of rock failure on the migration and retention of hydrocarbons include fractures, which can also help form traps that trap hydrocarbons, such as Rift traps and fracture traps [2]. In oil and gas exploration and production, it is vital to understand how rocks break down and how hydrocarbons move and become trapped. To successfully extract oil and gas, geologists need to pinpoint where these deposits are and comprehend the migration paths and trapping mechanisms that hold the hydrocarbons in place [3]. Various techniques, such as seismic surveying and analysis of rock samples, are used to help geologists determine the best sites for drilling wells and extracting hydrocarbons [4].

Hydrocarbon migration is a fundamental process in petroleum geology essential for understanding the formation and accumulation of oil and gas resources. This process involves the movement of hydrocarbons from their source rocks, where they are generated, to various subsurface reservoirs where they can accumulate and be extracted [5]. Migration occurs through a series of geological pathways, influenced by the physical and chemical properties of the hydrocarbons, as well as the characteristics of the surrounding rocks [6]. The onset of hydrocarbon migration is typically associated with the maturation of organic matter within source rocks, primarily shale [7]. As sediments undergo burial and increasing heat and pressure, organic matter transforms into hydrocarbons through a process known as kerogen maturation [8]. Once these hydrocarbons are generated, they begin to migrate due to buoyancy and pressure differentials in the subsurface environment [9].

Understanding hydrocarbon migration is crucial not only for resource exploration but also for assessing environmental impacts, such as the potential for oil spills and groundwater contamination [10]. As exploration and production techniques evolve, a deeper understanding of migration processes aids the development of more efficient, less invasive extraction methods, ultimately contributing to responsible resource management [11]. Hydrocarbon migration is a vital aspect of petroleum systems that provides insight into the lifecycle of hydrocarbons from their generation to their accumulation in reservoirs [12]. It is a subject of extensive study and research, shedding light on the complexities of subsurface geology and the economic viability of hydrocarbon resources [13-14].

Understanding the influence of rock failure on migration pathways is critical for preventing unintended hydrocarbon leaks, which can lead to environmental contamination and helps in the development of monitoring strategies to detect and manage subsurface changes due to rock failure.

Knowledge of how rock failure influences migration and trapping can lead to more efficient exploration strategies, reducing the number of dry wells and associated costs. Understanding the impact of fractures and faults on reservoir performance can optimize production strategies, improving overall recovery rates [15].

In fault-bound hydrocarbon reservoirs, faults play a fundamental role in governing the migration and retention of fluids within sedimentary basins [16]. Evaluating the consistency and detaining susceptibilities of faults promotes the comprehension of the mentioned systems, which leads to recognizing tracks of fluid migration [17].

A three-dimensional fluid overrun simulation model has been developed and integrated into an advanced geological modeling framework to investigate secondary hydrocarbon migration, employing the concept of the “unit element” notion [18]. The simulation process is successfully utilized for basin-scale hydrocarbon migration, leveraging the mathematical efficiency inherent in the Invasion Percolation Theory (IPT) [19]. Fault-bounded traps, particularly along active faults, are recognized as a sophisticated technique for detention and leakage in cases where studying hydrocarbon leakage is necessary. A comparison of the actual hydrocarbon column heights and trap heights was made in three traps of the Es1x sub-member in the hanging wall of the NDG fault, and showed that only the NDG-3 trap is underfilled; the others are filled [20]. A hydrocarbon migration model was applied according to the IPT to imitate the formation of hydrocarbon migration tracks in heterogeneous beds. These tracks and hydrocarbon cumulation in reservoirs may not form symmetrical traditional models when persistent low-permeability layers (created through depositional or diagenetic processes within reservoir rocks at multiple scales) appear as networks within reservoirs [21]. An identification of the term “data archives” might be referred to petroleum accumulations in the deactivated basins, where this acquaintance can be advantageous for knowledge of how the hydrocarbons were generated and emigrated, and provide a time-resolved view of hydrocarbon transmigration according to constraints with progressive burial processes (occurrence and periodic activity of faults, especially) [22].

The theory of hydrocarbon trapping relies on static capillary pressure gradients and assumes negligible viscous effects at low flow rates during secondary migration [23]. Utilizing numerical simulations and hypothesis analysis, viscous pressure drops are significant even at low flow rates, causing pressure gradients within fluid phases to differ from static assumptions. A new theory that incorporates both capillary and viscous forces was proposed. This theory models migration and trapping as the reflection and refraction of nonlinear saturation waves at heterogeneity edges. Including viscous forces allows seals to trap more hydrocarbons than previously predicted. Seals can be classified as static or dynamic based on capillary pressure curves and carrier bed properties. The theory also provides a timescale for accumulation and explains other observed features in secondary migration. Numerical simulations confirm these results [24].

Several numerical experiments were run using TEMISPACK TM to estimate the volume that can migrate through high-permeability damaged zones and close into a fault. The influence of fault region intensity, the link between fault and hydrocarbon-containing beds, and entrance time on fluid flux was deliberated when permeability was raised [25]. The significant role of fault zones in influencing hydrocarbon migration, even when they have low thickness (2 meters), are temporarily open, and moderately permeable (< 10 mD), can focus the migration of hydrocarbons. The flow is intense in narrow, provisional faults, but the volumes in circulation remain substantially the same. Links that connect faults and/or source rock are migration path nodes. These node connections have the utmost leverage on the volume of outgoing hydrocarbons than the real fault permeability. The fault regions are less efficient in terms of hydrocarbon withdrawal exhaustion to the reservoirs than narrow zones due to the main hydrocarbon losses according to the rock's porosity [26].

A novel examination of secondary migration of hydrocarbons that employs wave theory and characteristics rather than capillary forces for trapping. Upon encountering layers with varying flow capacities, the waves alter their velocity and either reflect or refract (or partially reflect and partially refract). A particular wave's reflection from a boundary initiates the buildup of hydrocarbons beneath that boundary. The approach is simple to use and easily adapts to a graphical solution [27].

The above reviews consolidate a wide range of research highlighting the complexity of hydrocarbon migration and trapping, emphasizing the interplay of structural geology, sedimentology, and fluid dynamics. These studies underscore the importance of structural elements, such as faults and fault-bounded traps, in directing hydrocarbon migration and accumulation. The behavior of faults varies with their sealing effectiveness and tectonic history, allowing them to serve either as conduits that enable fluid movement or as barriers that impede it. Sedimentary facies and rock properties significantly affect migration pathways and accumulation patterns. Favorable petrophysical characteristics in carrier beds enhance hydrocarbon accumulation, while heterogeneity and low-permeability layers can alter migration route. Fault zones, even narrow and temporarily permeable ones, focus hydrocarbon migration. The connectivity between faults and carrier beds is more influential than fault permeability alone.

The reviews lack a cohesive synthesis that integrates these findings into a unified conceptual framework for hydrocarbon migration and trapping. The reviews do not address recent advancements such as machine learning, AI-driven seismic interpretation, or enhanced 3D geological modelling techniques that could improve understanding and prediction of hydrocarbon systems. The environmental impact of hydrocarbon migration or the economic considerations in exploration and production are still not widely discussed in relation to these geological processes. The review is largely theoretical and model-based, with limited application to specific basins or real-world case studies that illustrate the practical implications of the discussed mechanisms. The reviews do not include visual aids such as seismic profiles, geological maps, or schematic diagrams that would help clarify complex migration pathways and trapping mechanisms.

The relevance between rock failure and hydrocarbon migration pathways within the Mishrif Formation in the West Qurna oilfield was inspected. The objectives of this study are to:

1. Evaluate the impact of bedding planes, pressure variations, and fracturing on the permeability and pore connectivity of carbonate reservoir rocks,
2. Measure and compare the permeability of carbonate rocks horizontal and vertical to bedding planes using full-diameter core samples from multiple wells.
3. Simulate the effects of burial (pressurization) and uplift (depressurization) on rock permeability and understand how geological processes influence reservoir quality.
4. Quantify the enhancement of permeability caused by fracturing and assess its significance in hydrocarbon transport and accumulation.
5. Analyze the role of rock anisotropy and fracture behavior in controlling hydrocarbon migration and trap formation.
6. Contribute insights towards improving reservoir modeling, field development planning, and risk reduction in hydrocarbon exploration.

2. Geological setting

The West Qurna/1 (WQ1) Oilfield is located approximately 50km Northwest of Basra city in southeastern Iraq (Figure 1), and it is part of a large anticline oriented north-northwest and extending more than 120km. The Mishrif formation is rated the ultimate profitable reservoir of this oilfield [28]. Petroleum was discovered on the Rumaila anticline at South Rumaila in 1953 and at North Rumaila in 1959 [29]. Production was not started until 1973 when the WQ1 discovery well (WQ1-001) was drilled [30]. WQ1 commenced production in 1999, predominantly from the Middle Cretaceous Mishrif formation (approximately 2,100 to 2,600m true vertical depth subsea) with minor oil production from the Zubair, Sadi, Mauddud, and Khasib formations [31].

The Mishrif Formation in the Mesopotamia Basin and in the Arabian plate (western part of the Gulf specifically) is essential [28]. The formation is a carbonate sequence represented predominantly by shallow open marine carbonates deposited during the Middle Cenomanian-Lower Turonian cycle as a part of the Wasia Group (Albian-Turonian). It is affected by different diagenetic processes that affect porosity and permeability. The formation is represented in many fields such as, in Amara oil fields (Buzurgan, Amara, Halfaya, and Majnoon), Basra oil fields (Rumaila, Zubair, and West Qurna), and in Nasiriya oil fields. Twelve selected wells were taken from West Qurna oilfields [29] (Figure 1).

The Mishrif Formation is part of the Cretaceous carbonate platform. It consists of marine carbonate rocks, including limestone and dolomites, which serve as both reservoirs and source rocks. The Formation at the base of the Mishrif represents the transference from the basinal Rumaila to the shallow open marine facies of the Mishrif Formation [30]. The upper limit of Mishrif with the Khasib Formation is intersected by an unconformity roof disconnecting the Middle from the Late Cretaceous [31] (Figure 2). The Mishrif Formation is stratigraphically equivalent to the Giraibi Formation in the northern region, the Balambo Formation and the upper section of the Sarvak Formation in Iran, as well as the Magwa Formation in Kuwait, [32].

The region has well-developed source rocks and reservoir systems formed in an environment influenced by marine or transitional depositional settings. It contains organic-rich carbonates that act as source rocks capable of generating hydrocarbons [33]. The reservoir is composed of sedimentary rocks, including fractured carbonates, which play a crucial role in enhancing reservoir quality and facilitating hydrocarbon migration in the region [34]. The traps are primarily stratigraphic or combination traps, with sealing provided by overlying impermeable formations like the Khasib Shale, that require advanced techniques to model reservoir heterogeneity and predict hydrocarbon migration pathways effectively [35]. The formation thickness varies due to the position within the Mesopotamian basin. Thickness could be of (268- 427 m) in southeastern Iraq, and thins or squeezes out to the west and southwest [36-37]. The prime hydrocarbon-bearing strata, according to the depositional process (from oldest to youngest), are the mB2, mB1, and mA [38]. Cap rock barriers, linked to sequence boundaries, are present at the upper boundary of the mA unit and between the mB1 and mA units [39]. The Rumaila Formation correlates with the mC zone located at the base of the Mishrif Formation [40]. An overall shoaling trend was listed in the West Qurna due to the progression of the sedimentary medium [41]. The mB1 unit was deposited in a restricted sub-sea environment characterized by tidal channels and/or spillover lobes, occurring within non-reservoir platform lithofacies [37].

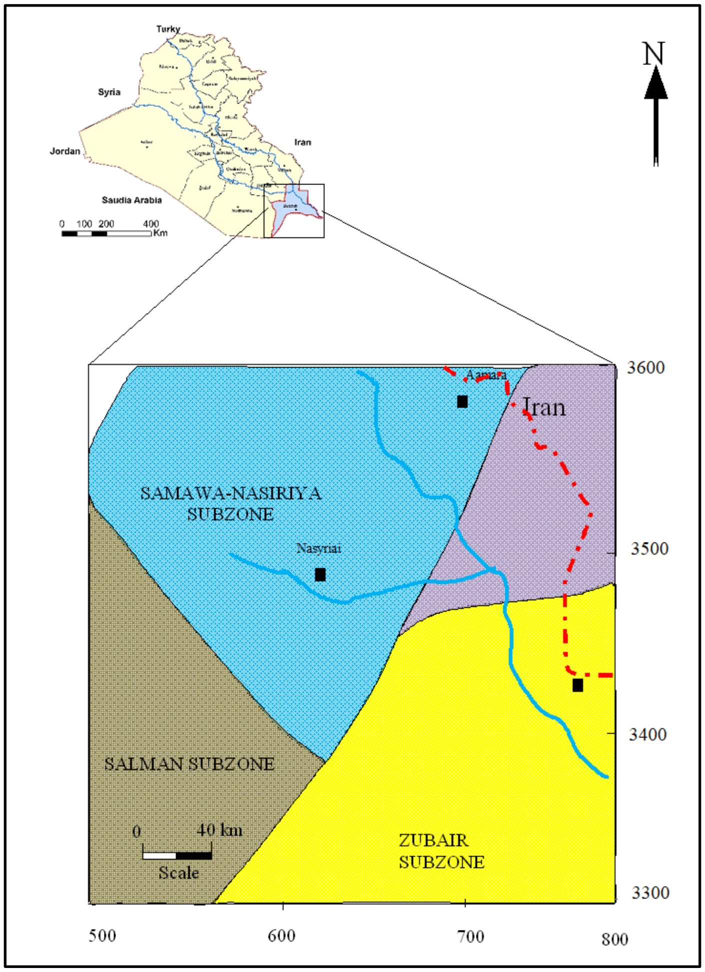

Figure 1. Location map with Tectonic subdivisions of Southern Iraq (modified after [42]).

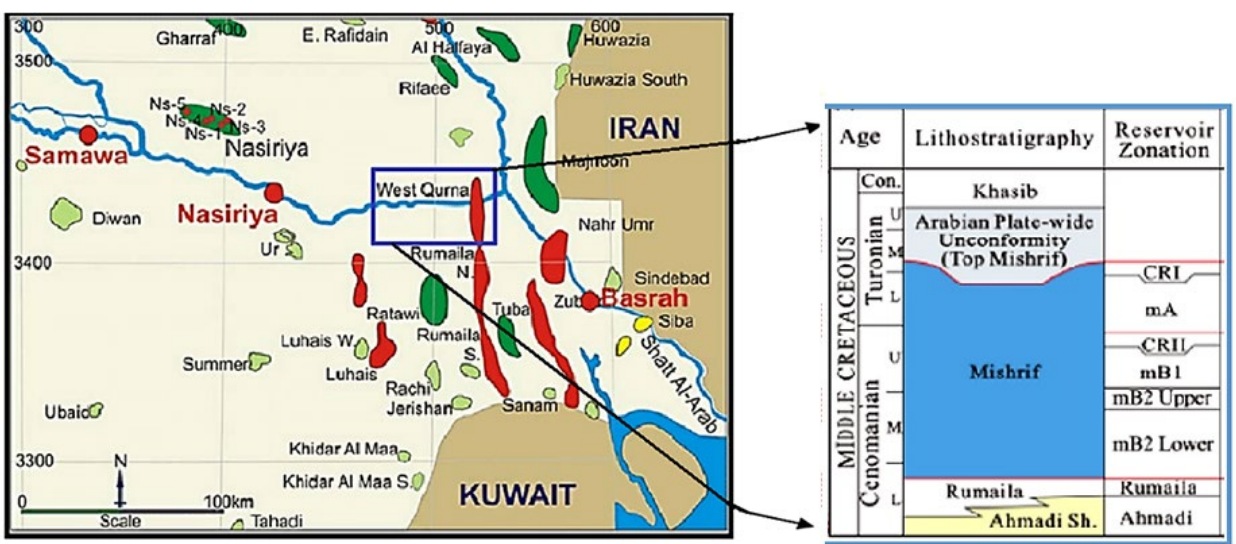

Figure 2. Left- Location of West Qurna oil field, Right- Units of Mishrif Formation and the Sequence Stratigraphy of the top and bottom Formations (modified after [43]).

The correlation between the maximum (S_H), minimum horizontal stress (S_h), and vertical stress (Sv) can be expressed by the equation [44]: $S_H \geq S_v \geq S_h$. This led to considering the possible fault type that can exist in the Mishrif formation in the West Qurna oilfield as a strike-slip fault [44].

3. Data and methods

3.1. Full-diameter permeability testing for the Mishrif Formation

The information of the Mishrif Formation has been obtained from the tests measured vertical and horizontal permeabilities for 250 core wells samples (Figure 3) to bedding planes in heterogeneous rocks (Conducted in cooperation with the Petroleum Research and Development Centre/Baghdad/Iraq), including fractured carbonate rocks of the Mishrif core samples. Figure 4 illustrates the permeameter device that used for measuring gas permeability for limestone rocks of the Mishrif Formation.

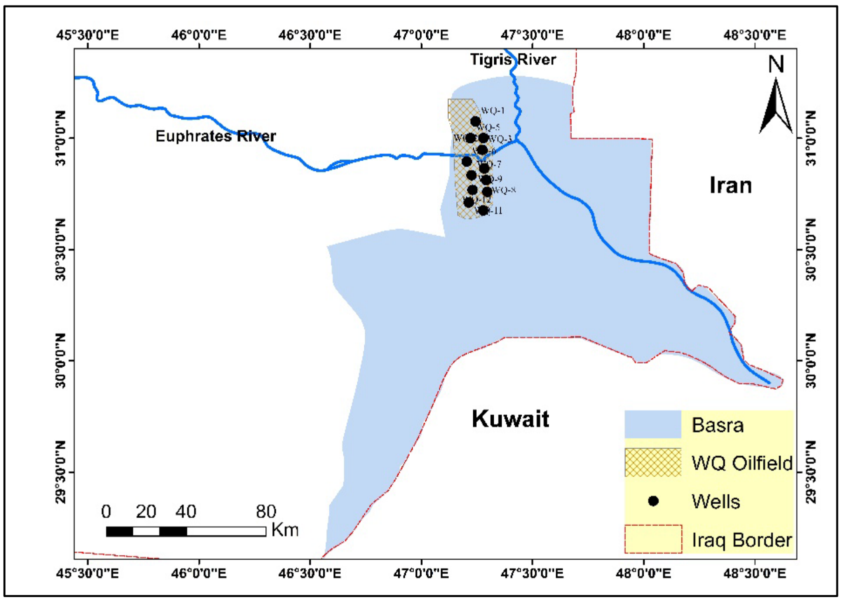

Figure 3. The spatial distribution of the West Qurna Oilfield and the well locations considered in this study.

3.2. Measurement principle

Gas permeability can be determined by measuring influxes through a rock sample and applying the standard formula derived from Darcy's law for one-dimensional steady-state gas flow, [45].

$$K_a = \frac{2P_a \, . \, Q_o \, . \mu \, . L . \times \, 10^2}{A \, . (P_1^2 - \, P_2^2 \,)} \qquad (1)$$

3.3. Instruments and equipment

1. Sample chamber: The compartment where the sample is placed to measure its permeability, sealed to prevent leaks.
2. Pressure gauge: Measures the pressure of the fluid or gas inside the device.
3. Flow meter: Determines the volumetric flow rate of fluid traversing the sample.
4. Control valves: Regulate the rate and pathway of fluid movement.
5. Tubing: transports the fluid between different parts of the device.
6. Isolation system: Shields the sample from external interference to ensure measurement accuracy.

3.4. Experimental steps

1. The machine does not need calibration
2. The model is placed inside the CORE HOLDER

3. P1 and P2 indicate the pressure differentials across the rock sample, measured in megapascals (MPa), before and after fluid flow.
4.The first valve is placed on the core holder.
5.The second valve is placed on the pressure.
6.After opening the program window and entering the form information and choosing Start Standard shown in Figure 4.
7. After the end of the scan and the appearance of the result, the total results are saved and the file is exported as Excel sheet.

After completing the inspection, the form is unloaded using the following steps: -

- The bypass gas valve of the bottle is closed.
- Zeroing device pressure.
- The first valve is placed on the Vent and second valve is placed on the Vacuum.
- The model is extracted from the core holder.

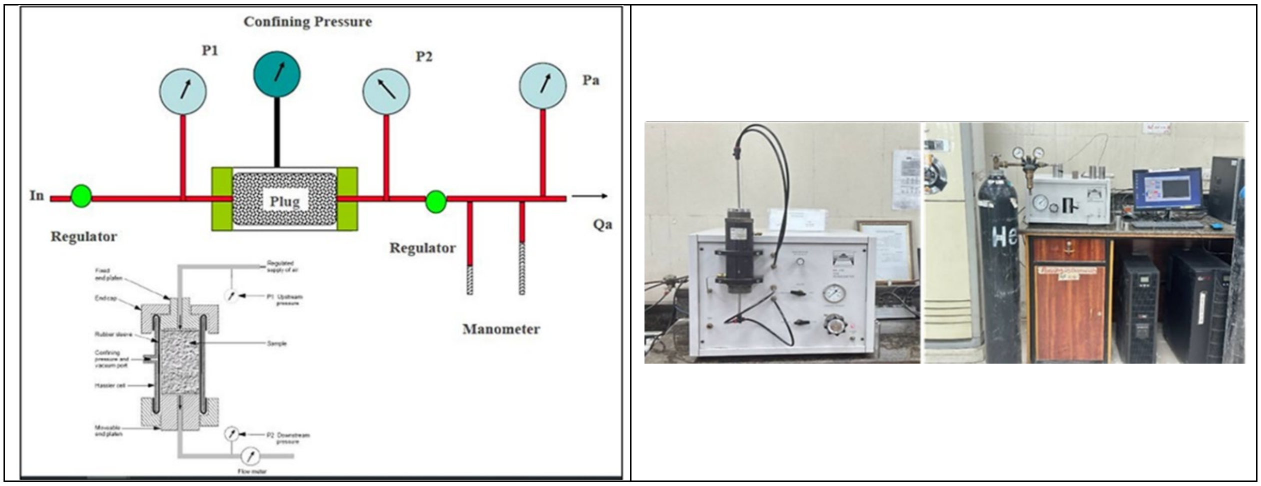

Figure 4 Schematic diagram of the permeameter for measuring gas permeability Top- from [46].

4. Results

4.1. Bedding plane impact on rock permeability

12 samples of limestone cores for the Mishrif Formation with the results shown in the Table 1.

Table 1. Comparison of vertical and horizontal permeabilities (Kv and Kh) to the layer plane for L.st Mishrif Formation core samples in the West Qurna Oilfield

Well No.	Depth (m)	Lithology	Permeability-Kh ($10^{-3}\mu m^2$)	Permeability-Kv ($10^{-3}\mu m^2$)	Average permeability- HV
WQ-1	2225	L.S. Grey Col..	0.01	0.01	1.00
WQ-2	2227	L.S. Grey Col..	1.7	1.09	1.56
WQ-3	2230	L.S. Grey Col..	4.2	1.1	3.82
WQ-4	2232	L.S. Grey Col..	6.1	4.7	1.30
WQ-5	2235	L.S. Grey Col..	7.5	1.3	5.77
WQ-6	2237	L.S. Grey Col..	6.3	1.4	4.50
WQ-7	2240	L.S. Grey Col..	5.9	3.7	1.59
WQ-8	2242	L.S. Grey Col..	9	4	2.25
WQ-9	2244	L.S. Darken Grey Col.	7.9	2	3.95
WQ-10	2248	L.S. Darken Grey Col.	5.5	2.2	2.50
WQ-11	2250	L.S. Grey Col..	13	4.3	3.02
WQ-12	2256	L.S. Grey Col..	16	7.6	2.11
Max.			16	7.6	
Min.			0.01	0.01	
Average			7.08	2.93	

The variation between the Kv and Kh for the limestone bedding plane was considerable in the Mishrif Formation. The average horizontal permeability is 6.92 $\times 10^{-3}$ μm^2, while the vertical permeability was 2.78 $\times 10^{-3}$ μm^2. The horizontal permeability was higher than the vertical permeability for the bedding plane (Figure 5).

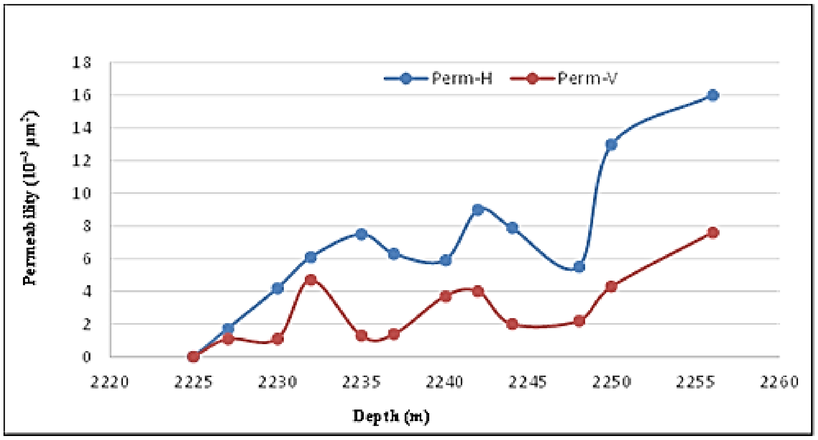

Figure 5 Comparison between horizontal permeability (Kh) and vertical permeability (Kv) in the Mishrif Formation.

4.2. Changes in permeability of carbonate rock in response to varying pressure conditions

Limestone core samples from the selected wells in the field were vertically pressurized to simulate the inhumation and lifting processes and their impact on hydrocarbon source rocks under veritable reservoir conditions. The shifts in core permeabilities with the variation in pressure were estimated during the pressurization process. Following the pressurization process, the samples underwent depressurization, during which changes in permeability in response to decreasing pressure were recorded concurrently.

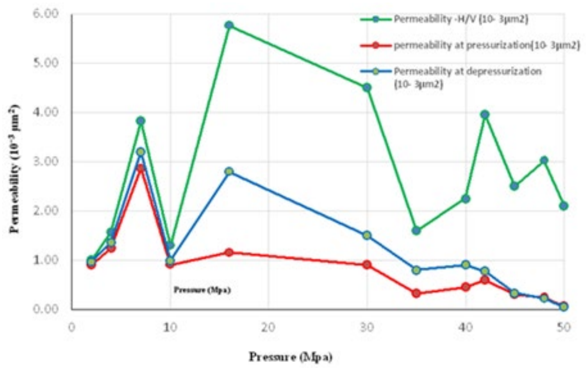

Figure 6. The pattern of permeability variation in limestone samples under two different conditions.

Figure 6 illustrates three permeability diversity curves for a sample under the pressurization, depressurization, and no pressurization procedures. Permeability exhibited a rapid decline of 80% as pressure increased from the initial state to 10 MPa during the pressurization phase. As the pressure increased from 10 MPa to 30 MPa, the permeability decreased more gradually. By the end of the pressurization process, the limestone's permeability had reduced to about 5% of its initial value. During depressurization, permeability progressively recovered, rising by approximately 75%.

Empirical data from multiple sample sets were analyzed to determine the ranges of permeability reduction and recovery during pressurization and depressurization. During pressurization, permeability decreased between 92.22% and 97.46% across the different groups, with an average reduction of 95.88%. At a pressure of 50 MPa, permeability dropped to just 4% of its original value. Conversely, during depressurization, several sample groups exhibited a significant increase in permeability, ranging from 74.01% to 1385.26%, with an average rise of 356.13%, demonstrating a substantial recovery of limestone permeability throughout the depressurization phase.

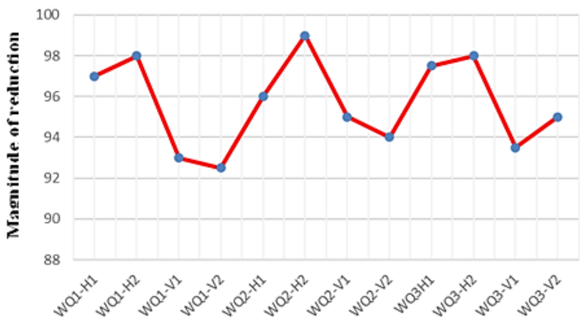

Figure 7. The pattern of permeability changes observed in limestone samples under pressurization conditions.

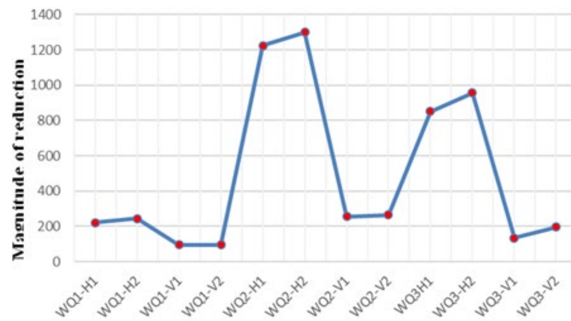

Figure 8: The pattern of permeability changes observed in limestone samples under depressurization condition.

Figures 7 and 8 depict the changes in permeability of limestone samples measured in both horizontal and vertical directions relative to the bedding plane during pressurization and depressurization experiments. During pressurization, permeability sharply declined, with an average reduction of 97.58% horizontally and 93.83% vertically, reflecting significant permeability loss during burial across both orientations. Conversely, during depressurization, permeability partially recovered, showing a greater increase horizontally averaging 210.30% compared to a smaller vertical increase of 168.89%. These findings indicate that permeability restoration during subsurface uplift is more pronounced in the horizontal direction relative to the bedding plane than in the vertical direction.

4.3. Effect of fracturing in the rock samples on permeability estimation

In natural underground environments, increasing burial depth often leads to the formation of fractures in limestone, which can dramatically affect its permeability. This experiment was conducted to explore how permeability changes before and after the rock is fractured. As shown in figure 9, permeability measurements taken before and after fracturing reveal a significant increase. On average, permeability rose by approximately 35.8 times, with the most extreme case showing an increase of up to 20,500 times.

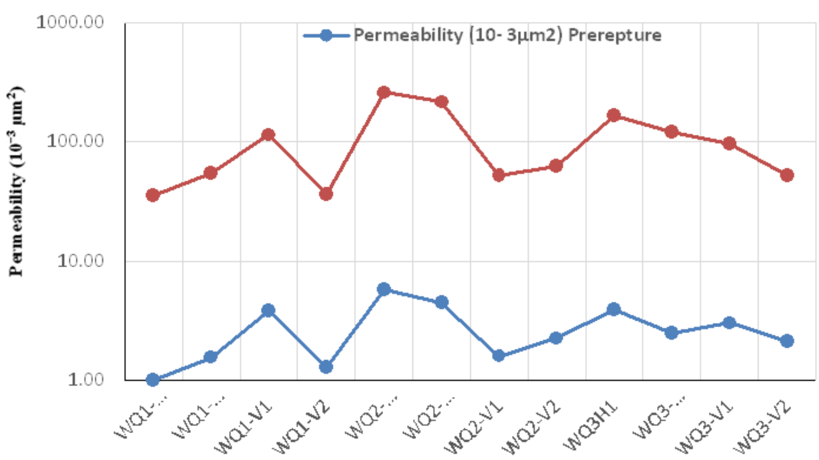

Figure 9. Comparison of limestone sample permeability prior to and following rupture.

These results clearly demonstrate that fracturing plays a major role in enhancing the permeability of limestone. The findings also emphasize that both the rock itself and its fractures can act as important pathways for oil and gas migration. Based on the data in figure 8, it's evident that fracturing leads to a substantial improvement in the rock's ability to transmit fluids.

4.4. Permeability distribution within the Mishrif reservoir

Figure 9 illustrates the distribution of horizontal permeability within the Mishrif reservoir. A significant heterogeneity was observed in CRI, CRII, mB1, and lower mC when the horizontal permeability was plotted versus the depth. Some heterogeneities in mA indicate that the mA unit is not a high-quality reservoir. The upper, lower mB2, and upper mC are relatively homogeneous.

Figure 10 illustrates the distribution of the fraction of maximum over minimum permeability (Kmax/Kmin range estimated) within the Mishrif reservoir, showing that a significant heterogeneity in CRI, CRII, mB1, and lower mC units also exists. As in Figure 9, there are some heterogeneities in mA (not a higher-quality reservoir), and the homogeneity is clearly observed in mB2U, mB2L, and upper mC units.

Distribution of (Kv/Kh), which refers to the heterogeneity of the Mishrif Formation in the West Qurna oil field versus Kh, indicates that the core plug Kv/Kh varies significantly, with a mean of approximately 0.8 (Figure 11).

Referring to the anisotropy (variation of permeability values for vertical and horizontal), there is minimal permeability anisotropy for the Mishrif formation in the West Qurna oil field (Figure 12).

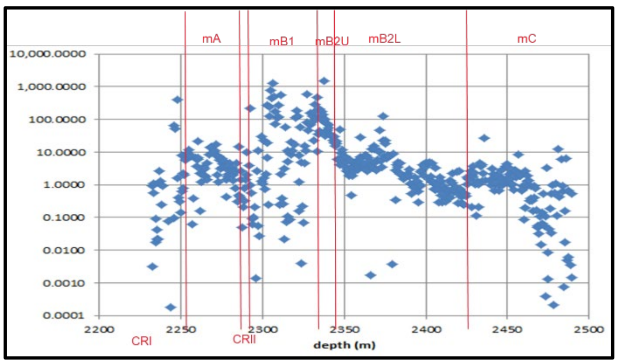

Figure 9. Distribution of horizontal permeability within the Mishrif reservoir.

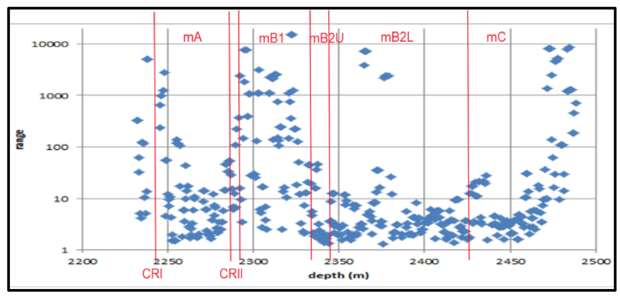

Figure 10. Distribution of the fraction of maximum over minimum permeability within the Mishrif reservoir.

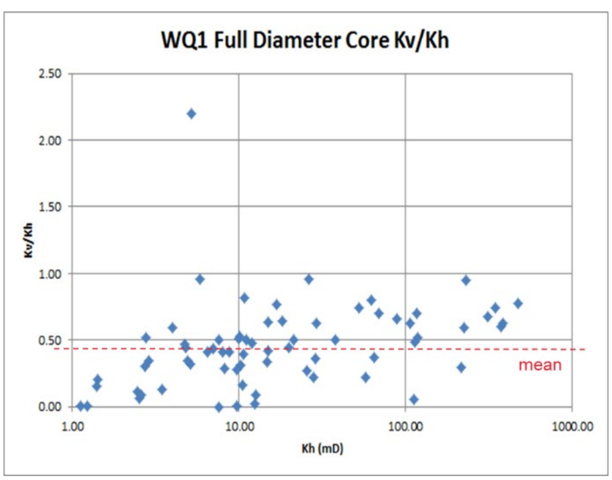

Figure 11. Heterogeneity of the Mishrif Formation in the West Qurna oil field by the relationship of Kv/Kh versus Kh.

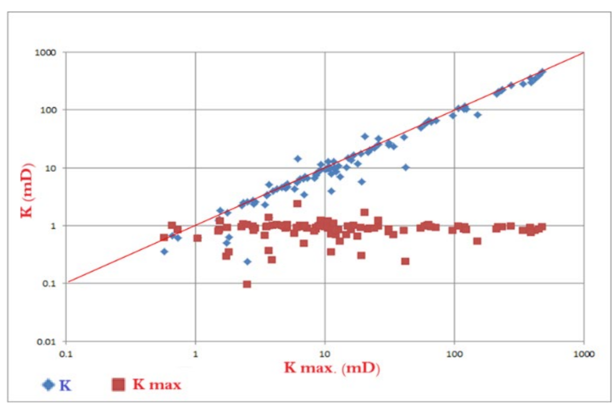

Figure 12. Permeability anisotropy exhibited by the Mishrif Formation in the West Qurna oil field.

4.5. Quantitative implications for reservoir productivity

The dramatic increase in permeability due to rock failure and fracturing in the Mishrif Formation markedly affects reservoir productivity and hydrocarbon flow rates. According to Darcy's law, the volumetric flow rate *Q* of fluid through a porous medium is directly proportional to permeability k, as mentioned in equation 1, the rate will be:

$$Q=k\cdot A\cdot \Delta P/\mu\cdot L \qquad (2)$$

where *A* is the cross-sectional area, ΔP is the pressure differential, *μ* is the fluid viscosity, and *L* is the flow path length.

The study shows permeability increases by an average factor of 41, reaching as high as 20,500 in some fractured samples. Assuming constant pressure gradient and fluid properties, this translates to a proportional increase in flow rate. For example, if the original permeability were 0.1 millidarcies (mD), fracturing could enhance permeability to 4.1 mD on average or up to 2050 mD in extreme cases. Enhanced permeability channels enable faster fluid migration from source to reservoir and within reservoir compartments, improving effective drainage radius and well productivity. Wells intersecting highly fractured zones with permeability enhanced by 10s to 100s of times would likely exhibit significantly higher initial production rates and recovery factors. For a typical carbonate reservoir flow scenario with a pressure drop $\Delta P\approx$ 10 MPa, fluid viscosity $\mu\approx 1$ cP (oil), reservoir thickness *h*, and well drainage radius *r*, increased permeability by fracturing can augment Darcy flow rates, thus reducing pressure drawdown required for desired production.

Studies in the Mishrif Formation indicate permeability values vary widely, with effective permeabilities closely linked to fracture density and orientation. Flow Zone Indicator (FZI) analyses suggest discrete hydraulic units within the formation, and permeability-porosity correlations improve the accuracy of permeability predictions. Applying these relationships in reservoir simulators calibrates production forecasts realistically. Since permeability is higher horizontal to bedding, flow rates in that direction are naturally favored, leading to anisotropic drainage patterns. Fractures aligned with principal flow directions further improve productivity. Conversely, fractures vertical to flow may not enhance permeability as much and could locally restrict flow. The reduction in permeability during burial compaction (up to 95% decrease) corresponds to reduced reservoir deliverability, while permeability recovery during uplift implies restoration of production potential over geological timeframes or during reservoir pressure drawdown.

5. Discussion

Permeability measurements indicate that limestone exhibits markedly higher permeability parallel to the bedding plane than perpendicular to it. Furthermore, pore connectivity is notably more developed along the bedding plane. These results demonstrate a distinct correlation between the rock's pore structure and its directional permeability; whereby enhanced permeability is generally linked to improved pore connectivity.

This study investigates the impact of bedding planes, pressure variations, and fracturing on the permeability of limestone. Gaining a comprehensive understanding of these factors is critical for elucidating hydrocarbon migration and reservoir development processes. The subsequent section offers an in-depth analysis of the findings.

5.1. Impact of bedding planes on permeability

A more pronounced difference in permeability is observed between horizontal and vertical directions. Average permeability: Horizontal: $6.92\times10^{-3}\mu m^2$; Vertical: $2.78\times10^{-3}\mu m^2$.
This significant anisotropy highlights how bedding planes influence fluid flow pathways in carbonate rocks. These results underscore that bedding planes play a substantial role in controlling rock permeability, with horizontal directions generally being more conducive to fluid flow.

5.2. Permeability variations under pressure changes

The study simulated burial and uplift processes by applying pressure to limestone samples and observing their permeability changes during pressurization and depressurization:
Pressurization: Permeability decreased significantly with increasing pressure, particularly at higher pressure ranges (10–30 MPa). At a pressure of 50 MPa, permeability was reduced to approximately 5% of its original value. Reduction rates: horizontal direction: 97.58%; vertical direction: 93.83%
Depressurization: Permeability recovered partially but remained lower than initial values. Increase rates: horizontal direction: 210.30%; vertical direction: 168.89%.

These findings assert that during burial, compaction drastically reduces pore spaces and permeability in both directions. However, during uplift, recovery is greater in the horizontal direction because structural alignment facilitates pore reopening.

5.3. Influence of fracturing on permeability

Fracturing was observed to significantly enhance limestone permeability. Following fracturing, the average permeability increased by approximately 41 times relative to pre-fracturing levels, with some instances showing increases up to 20,500-fold. When pressure was applied parallel to the fractures, permeability rose with increasing pressure and further improved during depressurization. Conversely, when pressure was applied perpendicular to the fractures, permeability sharply declined as pressure increased but exhibited partial recovery during depressurization.

These results highlight that fractures act as critical conduits for fluid flow in limestone reservoirs. The orientation and density of fractures significantly influence how permeability evolves under varying stress conditions.

The mA reservoir exhibits significant vertical and lateral heterogeneity. Accurately quantifying the three-dimensional distribution of reservoir quality is challenging due to the lack of a clear relationship between porosity and permeability. The mA unit is characterized by mounds and shoals interspersed with drapes of lower-quality grainstone or packstone, set against a background of highly porous microporous rock. Higher-quality reservoir rock is predominantly observed in the northern part of the lower (mA_a) interval and in the southern part of the upper (mA_a) interval. The mA_a interval displays a depositional dip from the northeast to the southwest, marked by subtle clinoforms. Elevated flow layers near faults are likely influenced by diagenetic processes and potentially the presence of fractures.

5.4. Effect of heterogeneity

According to the results obtained, as in Figures 9, 10, and 11, Kv/Kh equal to 0.8 is adopted for relatively homogeneous rock, Kv/Kh equal to 0.4 for heterogeneous rock, and Kv/Kh of 0.1 for cap rocks, CRII based on full cores. Test results of the recommendation showed reduced mA and mB1 recovery.

6. Conclusions

The comprehensive analysis conducted in this study confirms that rock failure, particularly fracturing, has a profound impact on hydrocarbon migration and trapping and other characteristics. As demonstrated by permeability experiments limestone samples cores from the Mishrif Formation, Permeability is generally higher in the horizontal direction to bedding planes. This directional preference indicates that natural anisotropy in the rock structure facilitates lateral fluid migration more than vertical migration. The results revealed that rock failure leads to a dramatic enhancement in permeability by an average of 41 times and up to 20,500 times in some cases. This substantial increase emphasizes that fractures serve as critical migration pathways, allowing hydrocarbons to travel more efficiently from source rocks to reservoir traps. Stress simulation through pressurization and depressurization tests shows that burial depth and the resulting compaction drastically reduce permeability in all directions. However, permeability can recover partially during uplift, especially in the direction horizontal to the bedding planes. Findings suggest that structural reactivation or pressure reduction during geological uplift could reopen migration pathways, which is essential in understanding secondary migration phases. Furthermore, the orientation of fractures under stress conditions (fractures align with the stress direction) plays a crucial role in increasing permeability. When fractures are in vertical alignment to stress, permeability tends to decrease under pressure but may partially recover during depressurization. These observations highlight the dual nature of rock failure; while it can improve migration, it may also influence hydrocarbon trapping if sealing occurs, especially in complex geological settings. Hence, understanding the type, orientation, and behavior of fractures under in-situ conditions is essential for accurate reservoir modeling and exploration planning.

7. Recommendations

1. Incorporate fracture analysis into reservoir characterization to enhance the prediction of hydrocarbon migration pathways and optimize drilling targets.
2. Utilize high-resolution 3D seismic surveys to map subsurface fracture networks and bedding plane orientations accurately.
3. Integrate permeability anisotropy data into basin modeling software to improve the accuracy of hydrocarbon migration simulations.
4. Conduct further studies on the long-term evolution of fracture conductivity under cyclic stress (burial/uplift) to understand permeability retention.
5. Expand comparative research between different lithology (e.g., carbonates vs. sandstones) to identify rock types most sensitive to stress-induced permeability changes.
6. Promote field validation of laboratory results through well log analysis, core studies, and production data from fractured reservoirs in the Mishrif Formation.

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