

**DIGITAL OUTCROP PROPERTIES AND FACIES
MODELLING OF THE LOWER SILURIAN
QUSAIBA MEMBER AND SHARAWRA MEMBER,
QALIBAH FORMATION**

BY

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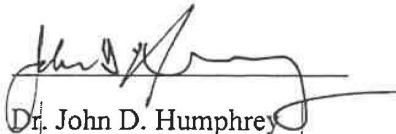
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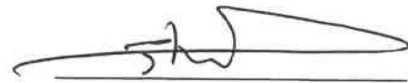
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Dedication

To the Aziz, Abo Elyazed, and Elmessery families |

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TABLE OF CONTENTS

ACKNOWLEDGMENTS.....	IV
TABLE OF CONTENTS.....	V
LIST OF TABLES.....	VII
LIST OF FIGURES.....	VIII
LIST OF ABBREVIATIONS.....	XI
ملخص الرسالة.....	XIV
CHAPTER 1 INTRODUCTION.....	1
1.1 Study Area.....	6
1.2 Problem Statement	8
1.3 Objectives	9
CHAPTER 2 LITERATURE REVIEW	10
2.1 Geological Setting.....	10
CHAPTER 3 METHODOLOGY.....	14
3.1 Field Work.....	14
3.2 Sample Preparation.....	16
3.3 Laboratory Work	17
3.3.1 Petrophysical Measurements:.....	17
CHAPTER 4 RESULTS.....	26

4.1 Facies Analysis	26
4.2 Petrophysical Analysis.....	26
4.3 Geochemical Analysis.....	39
4.3 3D Geological Models	49
4.3.1 Digital Outcrop Models.....	49
4.3.2 Petrophysical Models.....	56
Chapter 5 Discussion.....	64
5.1 Facies Analysis.....	64
5.2 Petrophysics Analysis.....	65
Chapter 6 Conclusion	68
REFERENCES.....	70
VITAE	78

LIST OF TABLES

Table 1	Helium porosity results.....	28
Table 2	Gravimetric and NMR Porosity.....	29
Table 3	Nitrogen Permeability results from the Qalibah Formation.	30
Table 4	Spot Permeability results from the Qalibah Formation.	31
Table 5	Elemental Analysis of the studied Formation.....	41

LIST OF FIGURES

Figure 1	Stratigraphic chart of the Ordovician-Silurian periods, displaying the Sarah Formation, Qalibah Formation, and Tawil Formation with corresponding lithologies and depositional environments (modified after Mahmoud et al. 1992).....	5
Figure 2	Satellite image of the study area near Qusaiba Village, showing the locations of outcrops (OC1, OC2, OC3, OC4) and a shallow core.....	7
Figure 3	A stratigraphic representation of the Qalibah Formation, illustrating the Tawil Formation, Sharawra Member, and Qusaiba Member, labeled with corresponding colors.	13
Figure 4	The point cloud to create a Triangulated Irregular Network (TIN) mesh with the points where we capture the photographs to construct the DOM.	23
Figure 5	Representative core plugs used for petrophysical measurements.	24
Figure 6	Showing the Trimble R10 device	25
Figure 7	Massive, sparsely bioturbated mudstone lithofacies (LF1).	32
Figure 8	Sandstone lenses observed in lithofacies 1 (LF1)	33
Figure 9	Heterolithic sandstone and mudstone alternation in lithofacies 2 (LF2).....	34
Figure 10	Hummocky cross-stratified sandstone in lithofacies 3 (LF3).....	35
Figure 11	Medium-grained massive sandstone (LF4)	36
Figure 12	Boxplot representation of porosity values for the Tawil Formation, the Sharawra Member, and the Qusaiba Member outcrops and a subsurface core. The upper right plot summarizes overall porosity across all samples, highlighting central tendencies and variability. Outliers are marked individually.	37
Figure 13	Boxplots illustrate the distribution of permeability (measured in millidarcies, mD) for the Tawil Formation, the Sharawra Member, and the Qusaiba Member, along with a summary boxplot for overall permeability. The x-axis is in log-scaled to accommodate the wide range of measurements. Outliers are identified as discrete points, providing insights into the permeability characteristics of each geological unit.	38
Figure 14	Stacked bar charts showing XRD-derived mineral percentages in the Tawil Formation, Sharawra Member, and Qusaiba Member. Each color corresponds to a mineral, depicting its abundance in each geological unit.	47
Figure 15	The figure presents geochemical well log-like displays of elemental concentrations from X-Ray Fluorescence (XRF) analysis for the Qusaiba Member, the Sharawra Member, and the Tawil Formation. Elements sulfur (S), magnesium (Mg), potassium (K), calcium (Ca), iron (Fe), nickel (Ni), and	

	zinc (Zn) are graphed, revealing the geochemical variations within each geological unit.....	48
Figure 16	Digital outcrop model (DOM) of outcrop 1 (OC1; Figure 2) illustrating stratigraphic architecture. The lowermost unit is the Qusaiba Member (LF 1), overlain by the Sharawra Member (LF2 and LF 3), and capped by the Tawil Formation (LF 4). Please note that the Tawil Formation is mostly eroded and is limitedly exposed. This high-resolution DOM provides a detailed representation of the large-scale sedimentary structures, bed geometries and lithological variations within the outcrop facilitating geological interpretations, and static models.....	50
Figure 17	Digital outcrop model (DOM) of outcrop 4 (OC4; Figure 2) showing two geological units. The base is the Qusaiba Member (LF 1), and the top is the Tawil Formation (LF 4). Note that the Sharawra Member (LF 2 and LF 3) are missing due to erosion.	51
Figure 18	Digital outcrop model (DOM) of outcrop 3 (OC 3; Figure 2), showing four geological units. The base is the Qusaiba Member (LF 1), overlain by the Sharawra Member (LF 2 and LF 3), and capped by the Tawil Formation (LF 4).	52
Figure 19	Petrel facies static model of outcrop 1 (OC1; Figure 2) representing the distribution of sedimentary lithofacies. The model includes four stratigraphic units: the Qusaiba Member (LF 1) at the base, followed by the Sharawra Member (LF 2 and LF 3), and the uppermost Tawil Formation (LF 4).	53
Figure 20	Petrel facies static model for outcrop 4 (OC4; Figure 2) showing two distinct geological units. The Qusaiba Member (LF 1) is at the base and the Tawil Formation (LF 4) is at the top.	54
Figure 21	This is the Petrel facies static model of outcrop 3 (OC3; Figure 2), which includes three geological units. The Qusaiba Member (LF 1) at the base, followed by the Sharawra Member (LF 2 and LF 3), and topped by the Tawil Formation (LF 4).	55
Figure 22	Porosity static model of outcrop 1 (OC1; Figure 2), visualizing porosity distribution across four geological units. The color gradient represents porosity values, with white arrows indicating areas of ambiguity within the Qusaiba Member (LF 1). Yellow arrows highlight significant porosity changes at the boundaries between LF 1 and LF 2, and between LF 2 and LF 3. Light blue arrows point to zones of high porosity within the Tawil Formation (LF 4).	58
Figure 23	Porosity static model for outcrop 4 (OC4; Figure 2) illustrating the variation in porosity within the geological units. The color scale represents different porosity levels, with white arrows indicating regions of increase porosity within the Qusaiba Member (LF 1).	59

Figure 24	Porosity static model for outcrop 3 (OC3; Figure 2) displaying porosity variations across its stratigraphy. The model uses a color gradient to show porosity levels, with white arrows marking ambiguous porosity in the Qusaiba Member (LF 1). Yellow arrows highlight areas of significant porosity changes at the boundaries between LF 1 and LF 2, and LF 2 and LF 3.	60
Figure 25	Permeability static model for outcrop 1 (OC1; Figure 2), showing the distribution of permeability values within the geological units. The color scale ranges from low (purple) to high (yellow) permeability. White arrows indicate zones of permeability ambiguity in the Qusaiba Member (LF 1), and light blue arrows point to areas of high permeability within the Tawil Formation (LF 4).	61
Figure 26	Permeability static model for outcrop 4 (OC4; Figure 2), illustrating the permeability variations across the stratigraphic sequence. The gradient color scale indicates permeability levels from low (purple) to high (yellow). White arrows highlight areas with higher permeability readings in the Qusaiba Member (LF 1).	62
Figure 27	Permeability static model for outcrop 3 (OC3; Figure 2), showing a range of permeability levels within the geological units. The color scale from purple to yellow represents low to high permeability values. White arrows point to regions within the Qusaiba Member (LF 1) where permeability data is higher.	63

LIST OF ABBREVIATIONS

DOM: Digital Outcrop Model

XRD: X-Ray Diffraction

XRF: X-Ray Fluorescence

LF: Lithofacies

OC: Outcrop

|

ABSTRACT

Full Name : Osama Ahmed Abdrabo Ibrahim Aziz

Thesis Title : Digital outcrop properties and facies modelling of the Lower Silurian
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The vast majority of unconventional reservoirs display substantial vertical and horizontal heterogeneity issues in both space and time. In order to better explain this heterogeneity issue, multidisciplinary approaches such as sedimentology and petrophysics should be integrated along with remote sensing models (e.g., digital outcrop model) to construct high-resolution reservoir models (e.g., static modelling). Constructing high-resolution 3D digital outcrop models offers a faster and cheaper alternative solution for addressing such issues, and it can potentially fill the gap between surface (e.g., outcrop) and subsurface correlation. In order to test the application of 3D digital outcrop modelling, extensive outcrops of the Qalibah Formation in the Qassim Region, Saudi Arabia, were utilized. This formation, particularly its Qusaiba Member, is the main source rock for the entire Palaeozoic successions in Saudi Arabia, and its exposures in the Qassim Region provide an unparalleled opportunity to test 3D static modelling applications. In this study detailed sedimentological, petrophysical analysis and remote sensing applications were applied into three extensive outcrops. Our static models revealed that integration of these

disciplines provide higher resolution models, taking into account better vertical and lateral bed distributions and geometries compared to other conventional methods, and, therefore, allowing to construct more realistic and accurate models. Such models can potentially be better analogs for subsurface reservoir models and used to reduce uncertainties.

ملخص الرسالة

الاسم الكامل: أسامه أحمد عبدربه إبراهيم عزيز

عنوان الرسالة: خصائص الكتل الصخرية الرقمية ونمذجة الوحدات الطبقيّة لعضو قصيبة وعضو شرورة في تكوين

القليبة من السيلوري الأدنى

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تُظهر غالبية الخزانات غير التقليدية مشكلات تباين كبيرة في كلٍ من الزمان والمكان. ولأجل توثيق وعرض تبايناتها العمودية والأفقية بالتفصيل، يجب دمج فترات أخذ العينات المكثفة والتحليل ضمن نماذج الخزانات. ومع ذلك، يمكن أن تكون هذه التقنيات مكلفة وتستغرق وقتًا طويلاً، خاصة في صخور الطين. يُقدم دمج نماذج الكتل الصخرية الرقمية ثلاثية الأبعاد المفصلة حلاً بديلاً أسرع وأرخص لهذه المشكلات، ويمكن أن يسد الفجوة بين التوافقات السطحية (مثل الكتل الصخرية) وتلك تحت سطحية. لاختبار تطبيق نمذجة الكتل الصخرية الرقمية ثلاثية الأبعاد، تم استخدام تكوينات كبيرة من تكوين القليبة في منطقة القصيم، المملكة العربية السعودية. هذا التكوين هو المصدر الرئيسي للصخور في كل تعاقيات العصر الباليوزوي في المملكة، وتوفر تعرضاته في منطقة القصيم فرصة فريدة لاختبار تطبيقات النمذجة ثلاثية الأبعاد.

تم بناء ثلاثة نماذج رقمية ثلاثية الأبعاد واسعة النطاق لتوليد نموذج خزان ثابت قوي باستخدام التصوير الفوتوغرافي بالطائرات بدون طيار والتصوير الأرضي. تم دمج هذه النماذج الرقمية مع تحليلات مفصلة للكتل الصخرية والنوى، بما في ذلك الخصائص الرسوبية والبتروفيزيائية. تم تحديد ورقمنة وتحليل خمس وحدات طبقية متكررة للخصائص البتروفيزيائية، حيث تتراوح قيم المسامية والنفاذية بين 2.37% و 37.58% و 0.002 ميلي دارسي و 83.69 ميلي دارسي على التوالي. ثم تم معالجة هذه النتائج في برنامج بتريل لبناء نموذج خزان ثابت.

CHAPTER 1

INTRODUCTION

The Qalibah Formation consisting of the Qusaiba Member and Sharawra Member was accumulated as post-glacier deposits. The Qusaiba Member uncomfortably overlies the Sarah Formation, serves as the main source rock unit for the entire Paleozoic successions in Saudi Arabia (Figure 1) (Mahmoud et. al., 1992). It was deposited during the Silurian period as pro-deltaic deposits, while the Sharawra Member conformably overlies the Qusaiba Member acts as gradational contact (Mahmoud et. al., 1992) and uncomfortably underlies the Tawil Formation and serves as a good siliciclastic reservoir unit in the Paleozoic epoch (Ayranci et al., 2022). The Sharawra Member deposited as offshore settings (Figure 1). At that time, the Arabian plate was situated in high paleolatitudes and experienced major clockwise rotation until the beginning of the late Carboniferous period (Abu-Ali et al., 1991; Cole, 1994; Jones & Stump, 1999; Lüning et al., 2000; İnan et al., 2016; Inan et al., 2017; Senalp & Al-Duaiji, 2001).

The Qalibah Formation named different with different terminologies. The stratigraphical terminology applied to it in Saudi Arabia's geological records has seen various iterations over approximately sixty years. Initially, it was recognized as a standalone formation. However, subsequent studies have often referred to it as a member within a larger formation, leading to some inconsistencies in its classification. Helal (1964) initially labeled the entire Silurian sequence in the region as the Sharawra Formation. Later, Janjou et al. (1996) incorporated it within the Qalibah Group, still referring to it as the

Sharawra Formation. In a significant reclassification, Vaslet (1987) reorganized the Silurian units into the Tayyarat Formation, demoting Qusaiba and Sharawra to member status. Further refining this understanding, Mahmoud et al. (1992) adopted the Qalibah Formation terminology, distinguishing its lower shale-dominant section as the Qusaiba Member and the sand-rich upper section as the Sharawra Member.

Geographically, the Sharawra Member is prominently exposed in northwestern and central Saudi Arabia. Al-Laboun (2009, 2013) notes that it mainly consists of micaceous sandstone interspersed with occasional thin siltstone layers and lenses. A key characteristic of the Sharawra Member is its sandstone predominance, especially when compared to the Qusaiba Member. The Sharawra Member is marked by a coarsening upward trend, transitioning from a silty lower section to a sandier upper part (Al-Laboun 2009,2013).

The discovery of Eurypterid remains and their polymorphs in the Sharawra Member points to a possible shallow marine setting during its formation (Al-Hajri and Paris, 1998). The upper section of the Sharawra Member, in contrast with the Qusaiba Member, is distinguished by bioturbation and the presence of offshore facies (Al-Hajri and Paris, 1998). The deposition phases of the Qusaiba Member and Sharawra Member were markedly different. While the Qusaiba Member was formed during a transgressive phase,

the Sharawra Member deposition occurred through a series of alternating transgressions and regressions (Janjou et al., 1996).

Dating the Sharawra Member involves a multidisciplinary approach, integrating chitinozoan facies and palynological analyses. The identification of three distinct chitinozoan facies, along with palynological evidence, suggests an Early to Middle Silurian age for the Sharawra Member, placing it specifically within the Wenlock period (Janjou et al., 1996; Paris, 1995). Additionally, the presence of trilobites and tentaculites supports this age assignment.

The Qalibah Formation represents a critical geological sequence whose comprehensive study remains incomplete. While existing research has elucidated aspects of its depositional environments, palynology, and paleontological characteristics, there is a conspicuous gap in the detailed application of modeling techniques. Such models are indispensable for advancing our understanding of the formation's distribution and potential resource applications. This study aims to bridge this research gap by employing robust modeling methodologies to provide a detailed characterization of the Qalibah Formation. By doing so, it will not only enhance the geological model of the formation but also contribute significantly to the broader field of sedimentary basin analysis, with implications for both academic research and industry exploration.

Digital outcrop modelling (DOM) is a relatively new approach mainly used to better understand reservoir properties, flow simulation, facies distribution, aquifer

characteristics, forward modelling, and fracture network distribution in outcrops (Bellian et. al., 2005; Eltom et. al., 2022; Walter et. al., 2022; Pringle et. al., 2004) which can further be applied to subsurface models. Conventional reservoir modeling techniques integrates one or more outcrop sections (i.e., pseudo-wells) that are used as representative inputs in static models. However, this approach can overlook the horizontal variations in lithologies and their geometries. For example, complex mound-shaped lithology distribution in carbonate rocks can be challenging to capture in outcrop descriptions, but digital outcrop modelling can display these mounds in detail and enhance reservoir models (Ramdani et. Al., 2022). The Qalibah Formation outcrops in the Qassim Region of Saudi Arabia provide an unparalleled opportunity to test digital outcrop modeling applications due to its extensive exposure and frequent changes in lithologies and their geometries in space and time.

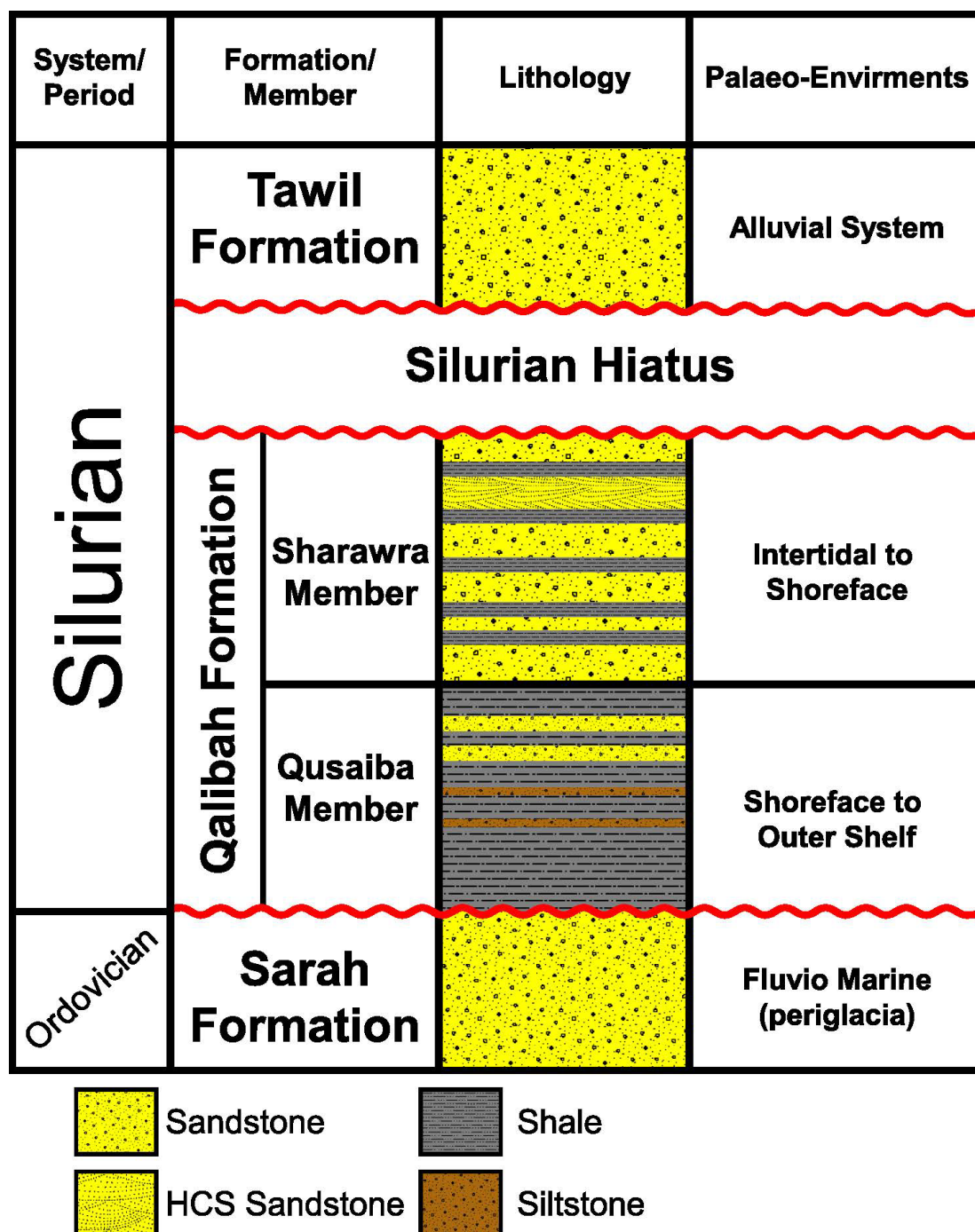


Figure 1 Stratigraphic chart of the Ordovician-Silurian periods, displaying the Sarah Formation, Qalibah Formation, and Tawil Formation with corresponding lithologies and depositional environments (modified after Mahmoud et al. 1992).

1.1 Study Area

The study area for the Qusaiba Member and Sharawra Member of the Qalibah Formation is located in Central Saudi Arabia, west of Qusaiba village in the Al-Qassim area (Figure 2). The outcrops were sampled and all of them were stratigraphically logged to digital outcrop modelling. The Qusaiba Member in the study area reaches up to 41 meters, while the Sharawra Member reaches up to 20 meters (Mahmoud et al., 1992).

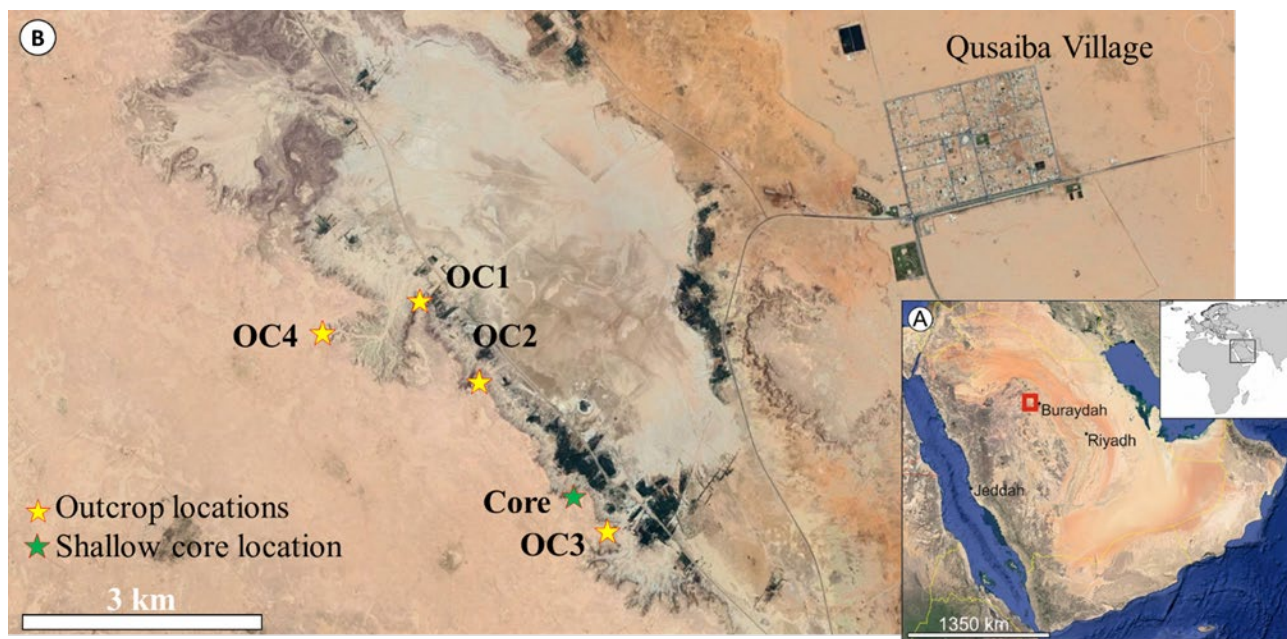


Figure 2 Satellite image of the study area near Qusaiba Village, showing the locations of outcrops (OC1, OC2, OC3, OC4) and a shallow core.

1.2 Problem Statement

The Qalibah Formation has been of significant interest, and it is currently at the forefront of challenges in reservoir characterization due to its inherent reservoir heterogeneity. This complexity necessitates a more profound and detailed analysis to elucidate its characteristics at surface and subsurface levels. The formation is characterized by frequent vertical and horizontal variations, such as changes in facies, which complicate its study. Moreover, these variations are compounded by steep outcrops, which pose significant challenges for conventional geological and geophysical methods.

A notable gap is the scarcity of digital outcrop modeling and detailed petrophysical analysis in the outcrops of the Qalibah Formation in the Qassim Region. This lack of comprehensive digital representation and petrophysical data hinders the ability to characterize the reservoir properties of the Qalibah Formation. Integrating these advanced methodologies is critical for developing a more robust understanding of the heterogeneity. This understanding is not only pivotal for academic pursuits but also has practical implications in industry. Therefore, addressing these gaps through advanced modeling and analysis is essential for unlocking the full potential of the Qalibah Formation.

1.3 Objectives

The study aims to achieve several objectives related to the petrophysical characteristics of the Qalibah Formation in the Qassim Region, Saudi Arabia, with the utilization of 3D outcrop modeling. The main objectives can be summarized as follows:

- 1) Construction of facies analysis in order to better understand lithological variations in space and time.
- 2) Obtaining petrophysical properties which provide valuable information about the reservoir characteristics, including fluid storage and flow potential. Various petrophysical properties include porosity, permeability, geochemical composition, and spectral gamma ray.
- 3) Constructing 3D static model utilizing outcrop facies and petrophysical properties. The acquired petrophysical data, along with photogrammetric data obtained through drone imaging, will be integrated to develop a 3D static model.

CHAPTER 2

LITERATURE REVIEW

2.1 Geological Setting

The Qalibah Formation, is stratigraphically divided into two formal members: the Qusaiba Member and the Sharawra Member (Figure 1 and Figure 3). The Qusaiba Member is primarily composed of laminated shale and mudstone, with the upper section containing thin interbeds of siltstone and sandstone (Mahmoud et al., 1992; Cole et al., 1994; Luning et al., 2000). This member is distinguished by the presence of graptolites (Mahmoud et al., 1992).

The basal part of the Qusaiba Member garners particular attention due to its rich organic matter content, also informally known as "hot shale". This unofficial terminology, as used by Mahmoud et al. (1992), Luning et al. (2000), and Cole et al. (1994), stems from its exceptionally high gamma ray values, which surpass 150 API. The thickness of this hot shale layer is variable, typically extending from 9 to 31 meters (Mahmoud et. al., 1992). Compared to the rest of the Qusaiba Member, hot shale is less impacted by bioturbation, thus is the primary source rock for the Paleozoic Petroleum System in Saudi Arabia (Jones and Stump, 1999); and Cantrell et al., 2014). This hot shale plays a crucial role in the region's petroleum geology, underlying the importance of the Qusaiba Member within the broader Qalibah Formation. Despite its overall importance, hot shale unit is not present in the Qassim Region.

The Sharawra Member of the Qalibah Formation has a conformable gradual contact with the underlying the Qusaiba Member. The Sharawra Member consists mainly of sandstone, with interbedded siltstones and mudstones that have a high mica content (Mahmoud et al., 1992). In the reference section between Tayma and Al Qalibah towns, the Qusaiba Member is found to rest disconformably on the Sarah Formation, indicating an erosional or non-depositional gap (Mahmoud et al., 1992). Similarly, the Sharawra Member is overlain disconformably by the Tawil Formation, with truncation occurring at the uppermost part of the formation (Mahmoud et al., 1992). The Qalibah Formation has a total thickness of approximately 499 meters in the reference section. The Qusaiba Member accounts for approximately 256 meters of this thickness, while the Sharawra Member makes up the remaining 243 meters (Mahmoud et al., 1992).

In the Upper Silurian stratigraphy, there's a notable hiatus in the uppermost sections of the geological succession. This hiatus is generally attributed to the uplift events associated with the Caledonian Orogeny, a significant tectonic phenomenon occurring in the Late Silurian to Early Devonian periods (Mahmoud et al., 1992; Melvin, 2015). This orogeny involved the convergence of continental plates and resultant mountain-building processes. The uplift from the Caledonian Orogeny is thought to have led to erosion and the lack of deposition in the uppermost parts of the Qusaiba and Sharawra Members, resulting in a discernible stratigraphic hiatus. This regional geological perspective offers valuable insights into the tectonic activities and their impact on the formation and preservation of these members in northern Gondwana during the Silurian period (Melvin, 2015).

The absence of carbonate deposition in the Lower Silurian Qusaiba and Sharawra sequences can be linked to the high-latitude positioning of the Gondwanan continent during this era. Additionally, the presence of a thick, progradational clastic sequence, indicative of a high rate of sediment influx, further discouraged carbonate development, as documented by Mahmoud et al. (1992).

The sedimentological characteristics and the faunal content within the Qusaiba Member offer further understanding of its depositional environment. The formation's gray shale, rich in diverse benthic fauna, and its coarsening upward succession with interbedded thin silt and sand layers, suggest a shoaling upward depositional pattern, as analyzed by Jones & Stump (1999).

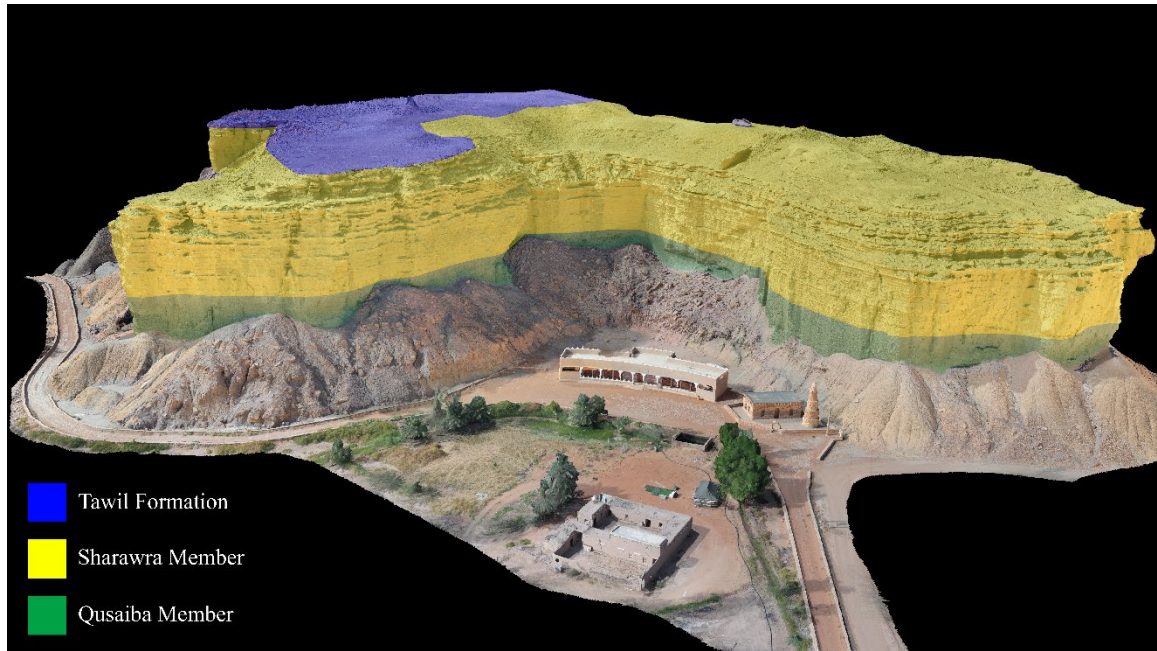


Figure 3 A stratigraphic representation of the Qalibah Formation, illustrating the Tawil Formation, Sharawra Member, and Qusaiba Member, labeled with corresponding colors.

CHAPTER 3

Methodology

3.1 Field Work

The fieldwork conducted for the study involved several key activities and methodologies.

1. Sedimentological and stratigraphic investigations: Four outcrops were selected near the old Qusaiba Village (Figure 2). Detailed sedimentological and stratigraphic investigations were carried out in these sections to analyze the vertical succession of the rocks. Several key parameters were recorded in order to construct facies analysis. These parameters include lithology, grain size, sedimentary structures, bed geometries, and bioturbation intensity.

2. Sample collection: The collection of samples played a pivotal role in our study, directly influencing the accuracy and reliability of subsequent measurements, such as petrophysical and geochemical analyses. To ensure comprehensive representation and high certainty in our data, we adopted a systematic sampling technique. This technique involved selecting samples at each sampling point showing changes in facies, with special attention given to shale layers which require distinct handling in later stages. The dimensions of the samples were standardized to a minimum of 3 inches in thickness and about 10 inches in width. This hand sample size was chosen to facilitate extraction of core plugs which are necessary for further analysis. At each sampling point, three samples were collected horizontally from

the same stratigraphic bed. These samples were labeled as 'A', 'B', and 'C'. This tripartite sampling approach was designed to validate our measurements and ensure that the data were not biased by anomalies in any single sample. Overall, from each outcrop, we collected a total of 42 samples from each outcrop. This was achieved by multiplying 14 vertical sampling points by 3 horizontal samples taken from each of these points. This extensive and systematic sample collection strategy was critical to achieve the desired level of precision and reliability of our results in this study.

3. Photogrammetry: We used a combination of ground-based and drone photogrammetry to capture the Qalibah Formation outcrops in the Qassim Village location. We took almost 40,000 pictures from different angles and locations, covering four exposures of the formation.

4. Survey-grade GPS system: To ensure accurate coordinates and georeferencing, a survey-grade GPS system was employed. The system utilizes the Trimble R10®, consisting of two units: one for the base station and one for the rover. A survey tripod was used for the base station, while a 2-meter bipod pole was utilized for the rover (Figure 6). This equipment allowed precise positioning and control points during the fieldwork.

3.2 Sample Preparation

1. Core plug preparation: The core plugs with a diameter of 1.5 inches were prepared from the hand specimens to facilitate porosity and permeability measurements (Figure 5). This technique is similar to other studies (Squelch et. al., 2019). The samples were divided into two main categories: sandy and shaly samples. Water was used to cool the core bit during the plugging process for only sandy samples. However, a different approach was employed for shale samples to prevent shale swelling and reactivity with water when dealing with shaly samples. Nitrogen was used in the plugging process to mitigate these issues (Squelch et. al. 2019; Wang et. al. 2017; Zhang et. al. 2019).

2. Petrophysical analysis: We obtained a total of 126 core plugs from the outcrops and 14 core plugs coming from the shallow sub-surface core, each meticulously crafted into a cylindrical shape with a diameter of 1.5 inches. The dimensions and weight of these core plugs were precisely measured using a Vernier caliper, ensuring accuracy in subsequent analyses. The core plugs were drilled perpendicular to bedding planes.

3. Powdered XRD and XRF analysis: For geochemical analysis, powdered X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) techniques were employed. Samples were disaggregated using a mortar and pestle to break down any clumps and to achieve a homogenous grain size distribution. This step is critical as it aids in reducing particle size effects that might skew the diffraction patterns or the fluorescence signals. To further

ensure uniformity in particle size, which is particularly crucial for XRD analysis, the samples were sieved through a 63-micron mesh.

3.3 Laboratory Work

3.3.1 Petrophysical Measurements:

The petrophysical analysis of core plugs included helium porosimeter, nitrogen permeameter, Nuclear Magnetic Resonance (NMR), and spot permeability measurements. Helium porosimeter measures the pore volume of a sample, while nitrogen permeameter measures the permeability of a porous medium. NMR is used to determine porosity and fluid saturation of the samples to validate the other porosity measurements. Spot permeability measurements were used to measure the permeability of a rock sample. The device then applies a known pressure differential across the sample, forcing a gas—usually air or a calibrated liquid—through the core. Sensors within the apparatus measure the flow rate of the gas, which is inversely proportional to the permeability of the sample. The permeability is calculated by considering the sample's cross-sectional area, the pressure drops, the fluid viscosity, and the flow rate. This non-destructive measurement technique enables the determination of permeability at specific spots along the core. These measurements were crucial as they provided fundamental parameters for calculating grain volume, pore volume, and bulk volume, which are essential components in petrophysical assessments.

1.1 Porosity Measurements

The porosity of the core samples was determined using a combination of gas expansion and saturation techniques, employing helium as the medium. Helium's exceptionally small molecular size allows it to penetrate even the most minute pore spaces, thereby enabling a comprehensive analysis of the total porosity. This includes the assessment of tiny pore structures which are critical in unconventional reservoir studies (Jarrahi et. al. 2019). To ensure the reliability of our porosity measurements, we conducted a calibration process. This involved comparing the grain density derived from the porosity measurements with that obtained from X-RF analysis. Cross-validation of porosity results was further reinforced by employing additional methodologies such as Nuclear Magnetic Resonance (NMR) and gravimetric porosity. These methods were particularly valuable in handling different types of samples – saline water was used under a pressure of 2000 psi for sandy samples to prevent fluid invasion, while kerosene was utilized for shale samples to avoid the swelling effect (Jarrahi et. al., 2019).

1.2 Permeability Measurements

Permeability was assessed using the gas permeability method, where nitrogen gas was the chosen medium. This choice was based on nitrogen's larger molecular size relative to helium, making it ideal for simulating the flow of gases or liquids through porous materials (Jarrahi et. al. 2019). The flow rates for these measurements varied from 500 cc per minute to 5000 cc per minute under 2000 psi of confined pressure, a range that was particularly suited to the nature of unconventional reservoirs examined. This method's effectiveness stems from nitrogen's ample and availability, cost-effectiveness, and its inert gas, ensuring that the interaction with the sample does not affect the results. Additionally,

spot permeability measurements were conducted to further calibrate and cross-validate our permeability data.

1.3 X-ray Fluorescence (XRF) Analysis:

For the purpose of determining the major and trace elements in our study that is going to help us later in the horizontal correlation between all of the studied outcrops, XRF analysis was meticulously employed. This analysis was conducted on powdered samples derived from the entirety of the collected samples. It is crucial to note that the homogeneity of these powdered samples was a paramount consideration, as it directly impacts the accuracy of the XRF results. Inhomogeneity, particularly in the form of larger grain sizes, can introduce significant sampling errors. Therefore, careful attention was paid to ensure that the powder reached an optimal grain size range, specifically between 10 to 60 microns, as recommended by Ben Amar et al. (2022). This grain size range is critical to achieve reliable analytical outcomes. This method allowed for a comprehensive evaluation of the elemental composition, thus providing vital insights into the petrophysical characteristics of the samples under study (Buhrke et. al. 1998).

1.4 X-ray Diffraction (XRD) Analysis:

In the pursuit of detailed mineralogical characterization, XRD analysis was systematically conducted. This analysis was performed using the same powdered samples that were previously utilized for the XRF analysis. The XRD analysis was carried out using a PANalytical Empyrean X-ray Diffractometer, a choice informed by its advanced

capabilities in accurately determining mineral structures (Ben Amar et al. 2022). Upon analyzing the samples, the XRD spectra generated were meticulously analyzed. This analysis was facilitated by leveraging the comprehensive database of the International Center for Diffraction Data (ICDD). The ICDD database is renowned for its extensive collection of diffraction patterns, which allowed for a precise identification of the mineral composition within our samples. This step was crucial as it provided a clear understanding of the mineralogical makeup, complementing the elemental analysis obtained from XRF and enriching our understanding of the petrophysical properties of the studied reservoir.

1.5 Digital Outcrop Modeling:

I used the captured photographs to build a 3-dimensional (3D) digital outcrop model, following the steps suggested by Alfarhan et al. (2020). First, we located the photographs to generate a sparse point cloud. Then, we processed the point cloud to create a Triangulated Irregular Network (TIN) mesh (Figure 4). Finally, we simplified the mesh, added realistic textures, and imported the model into ArcGIS for further analysis. This method allowed us to capture the geological features of the Qalibah Formation with high accuracy.

ArcGIS® software was used to visualize the 3D digital outcrop model of the Qalibah Formation, and to select geo-referenced surfaces corresponding to the exact exposure location. These surfaces provide realistic data for building a 3D structure grid in Petrel® software. I picked several surfaces from the 3D digital outcrop model using the

following method: we identified points on the bed boundaries that were clearly visible and created a strike-dip plane at each surface. Then, I picked the outer and inner rings of points lying on that plane for each surface. I imported the surfaces into Petrel as point attributes with X and Y coordinates and depth values. I transformed these points into horizons in a 3D grid and created 3 reservoir zones in the grid. The first zone had 125 layers, the second zone had 225 layers, and the third zone had 50 layers to capture the fine-scale heterogeneity. The cell size was 1 m X 1 m. The final 3D grid had a horizontal base of 463 m X 393 m, a thickness of 35 m, and a total of 400 layers distributed in these 3 reservoir zones, resulting in 727,83600 cells.

1.6 Petrel facies models:

Creating a 3D facies model using Petrel, with input from a high-resolution Digital Outcrop Model (DOM), allows for detailed layer mapping and accurate geological representation. The DOM's superior resolution is instrumental in identifying various strata with precision, providing an invaluable reference for model construction. In Petrel, this detailed layer information from the DOM is integrated, enabling the creation of highly guided models that closely mimic the actual outcrop conditions. This approach ensures a more realistic and detailed geological model, capturing the nuances of the facies distribution and structural variations observed in the outcrop. The synergy between high-resolution DOM data and Petrel's modeling capabilities offers a robust framework for constructing accurate and detailed geological models.

1.7 Petrel porosity models:

In the geological modeling of the Qalibah Formations, we employed Petrel software to develop comprehensive models. The porosity within the Qusaiba Member was estimated to vary significantly, ranging from the lowest to the highest results, and occasionally spiking coming from the sand lenses. Transitioning to the Sharawra Member, a broader range of porosity was observed, having higher porosity range, with shale beds within this member exhibiting a narrower porosity. Qalibah Formation porosity was measured from both outcrop and shallow subsurface core samples. These varied porosity ranges were incorporated into our Petrel models using Sequential Gaussian Simulation (SGS) geostatistical methods guided by the facies model. Our modeling was further refined by integrating surface data acquired from ArcGIS and pseudo-well data, which included laboratory-measured porosity values. This multifaceted approach allowed for a more accurate and comprehensive representation of the subsurface geological characteristics across the studied formations.

1.8 Petrel permeability models:

In the construction of permeability models for the Qalibah Formation using Petrel, we applied a methodology similar to our porosity models, but with distinct permeability ranges. For the Qusaiba Member, permeability predominantly ranged from the lowest to the highest, with notable exceptions in sand lenses where it is located. In the Sharawra Member, a wider permeability range was observed higher than the Qusaiba Member, although significantly lower values were noted in shale beds.

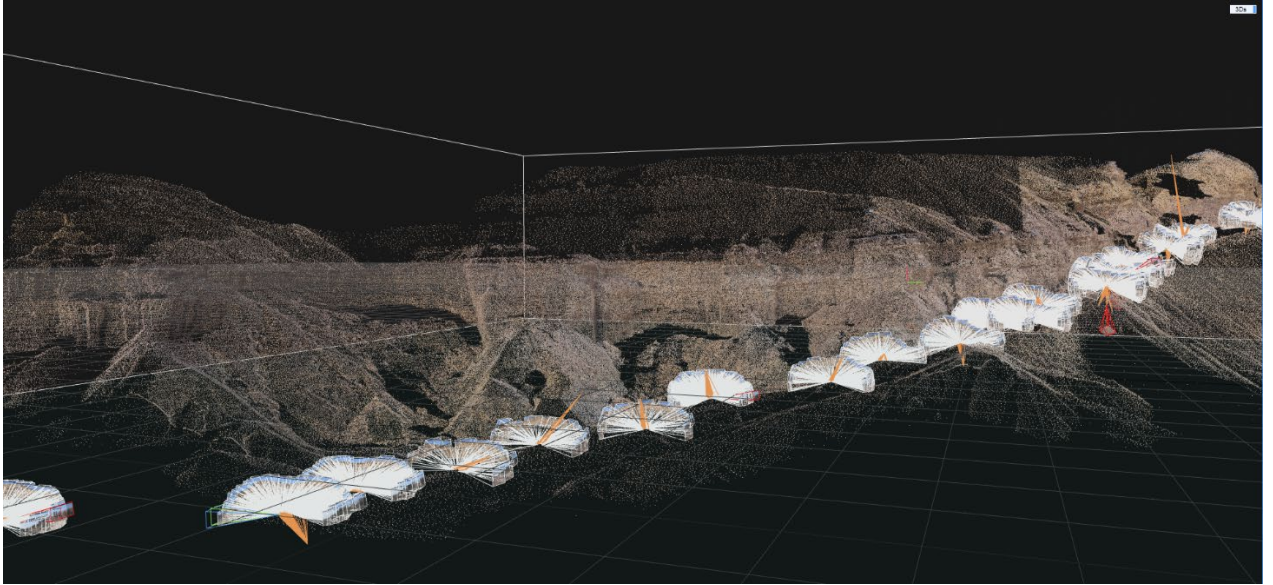


Figure 4 The point cloud to create a Triangulated Irregular Network (TIN) mesh with the points where we capture the photographers to construct the DOM.

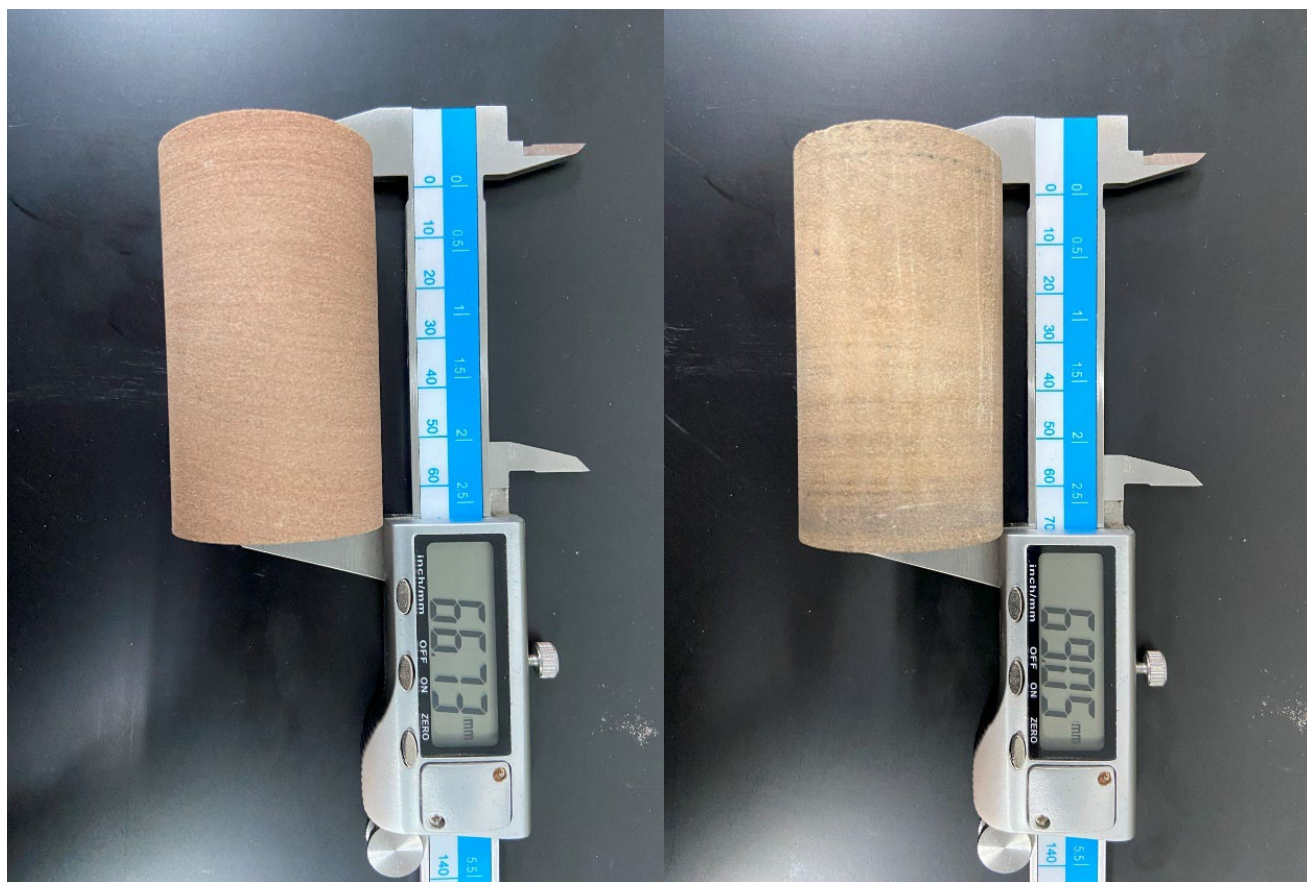


Figure 5 Representative core plugs used for petrophysical measurements.



Figure 6 Showing the Trimble R10 device

Chapter 4

Results

4.1 Facies Analysis

The Qalibah Formation reveals a stratigraphic sequence characterized by four distinct lithofacies. The Qusaiba Member is primarily characterized by fissile shale lithofacies, displaying greenish to dark grey colors, and occasional sandstone lenses and siltstone layers particularly close to the top of the Qusaiba Member (LF1) (Figure 6, Figure 7 and Figure 8). The Sharawra Member is represented by two main lithofacies. The first lithofacies are interbedded massive sandstone and massive mudstone lithofacies (LF2) (Figure 9). The LF2 is predominantly observed in the lower part of the Sharawra Member. The second lithofacies exhibit sandstone with distinctive hummocky cross-stratification and are located predominantly in the upper part of the Sharawra Member (LF3) (Figure 10). The Tawil Formation, on the other hand, is characterized by medium-grained massive sandstone and carbonate alternation (LF4) (Figure 11). It should be noted that there is a major erosion surface between the Qalibah Formation and Tawil Formation. Although the main focus of this study is the Qalibah Formation, we also briefly analyzed the Tawil Formation in order to make our models more realistic and accurate.

4.2 Petrophysical Analysis

Porosity and permeability results show significant variation within the Qalibah Formation. Overall porosity values ranges from 0.5% to 34% while permeability values ranges from 0.01 mD to 550 mD (Figure 12, Figure 13, Table 1, Table 2, Table 3 and Table 4). Both values correlate well with certain facies. In other words, each facies display somewhat consistent porosity and permeability ranges, with rare local positive or negative

spikes. Lithofacies 1 (LF1) exhibit the lowest porosity and permeability values. Porosity values ranges from 1% to 5% while permeability values range between 0.01 millidarcies (mD) and 0.1 mD (Figure 12, Figure 13, Table 1, Table 2, Table 3 and Table 4). Slight, local increases in these values were observed in LF1, particularly close to the top of the Qusaiba Member due to the presence of sand lenses. These lenses are represented by occasionally porosity spikes up to 20%. The highest porosity and permeability measurements were recorded in hummocky cross stratified sandstone (LF3) in the Sharawra Member with porosity values ranging from 17% to 35%, and permeability values ranging from 70 mD to 550 mD, although significantly lower values (0.1 mD to 0.02 mD) were noted in shale-rich beds. The enhanced porosity and permeability in LF3 can be attributed to the coarser grain size and the less compacted nature of the sandstone. This variation in petrophysical properties across different lithofacies underlines the heterogeneity of the Qalibah Formation, offering insights into its depositional history and potential reservoir quality. This petrophysical analysis, therefore, not only corroborates the facies interpretation but also provides a critical understanding of the reservoir characteristics within the formation.

Table 1 Helium porosity results

Porosity		OC1	OC2	OC3	Core
Tawil	Average	12%	13%	13.2%	12.7%
	Maximum	17.6%	16.8%	17.2%	15.3%
	Minimum	2%	5.6%	4.2%	2.4%
Sharawra	Average	27%	26%	25%	24%
	Maximum	31%	33%	32%	32%
	Minimum	23%	22%	22%	21%
Qusaiba	Average	2.2%	2.1%	2.8%	3%
	Maximum	4%	5%	5.7%	5%
	Minimum	0.9%	3%	5.4%	1.1%

Table 2 Gravimetric and NMR Porosity

Stratigraphic unit	Gravimetric Porosity (%)	NMR POROSITY (%)
Tawil Formation	17.3%	19.8%
	10.4%	10.6%
	2.4%	2%
	6.4%	5.6%
Sharawra Member	31.1%	31.1%
	32.7%	32.4%
	26.7%	27.7%
	29.9%	29.9%
Qusaiba Member	2.6%	3.0%
	3.5%	4.1%
	7.9%	18.7%
	10.5%	21.2%

Table 3 Nitrogen Permeability results from the Qalibah Formation.

		Permeability (mD)				
		OC1	OC2	OC3	Core	Overall (avg.)
Tawil Fm.	Average	0.25	0.26	0.27	0.27	0.26
	Maximum	0.35	0.34	0.35	0.34	0.34
	Minimum	0.23	0.22	0.22	0.21	0.22
Sharawra Mbr.	Average	219	258	230	270	244
	Maximum	409	370	380	480	409
	Minimum	21	23	22	21	21
Qusaiba Mbr.	Average	0.2	0.1	0.9	0.19	0.34
	Maximum	0.3	0.24	1.9	0.22	0.66
	Minimum	0.02	0.03	0.02	0.01	0.02

Table 4 Spot Permeability results from the Qalibah Formation.

Permeability(mD)		OC1	OC2	OC3
Tawil	Average	0.07	0.8	0.08
	Maximum	0.08	0.87	0.08
	Minimum	0.07	0.73	0.08
Sharawra	Average	212.12	86.19	213.14
	Maximum	672.56	265.42	672.56
	Minimum	41.37	11.33	41.37
Qusaiba	Average	0.26	0.81	0.27
	Maximum	0.92	0.8	0.97
	Minimum	0.19	0.16	0.07



Figure 7 Massive, sparsely bioturbated mudstone lithofacies (LF1).

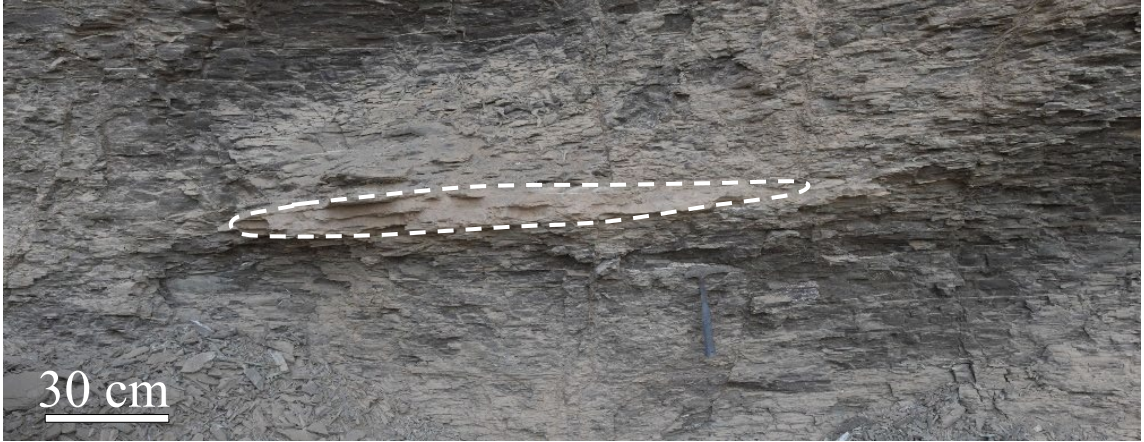


Figure 8 Sandstone lenses observed in lithofacies 1 (LF1)



Figure 9 Heterolithic sandstone and mudstone alternation in lithofacies 2 (LF2)



Figure 10 Hummocky cross-stratified sandstone in lithofacies 3 (LF3)



Figure 11 Medium-grained massive sandstone (LF4)

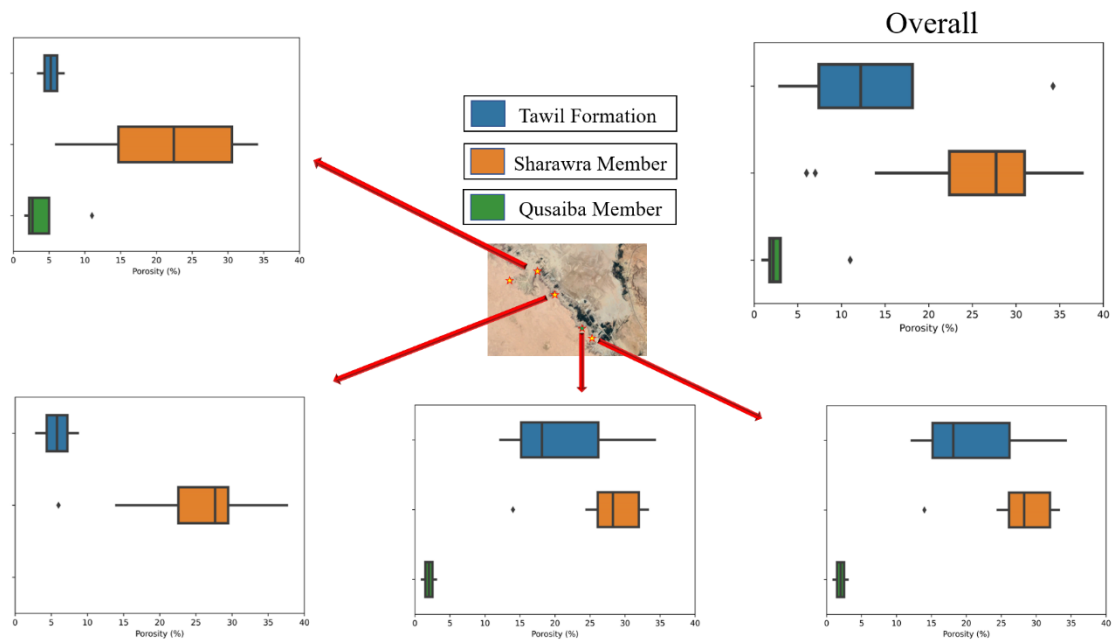


Figure 12 Boxplot representation of porosity values for the Tawil Formation, the Sharawra Member, and the Qusaiba Member outcrops and a subsurface core. The upper right plot summarizes overall porosity across all samples, highlighting central tendencies and variability. Outliers are marked individually.

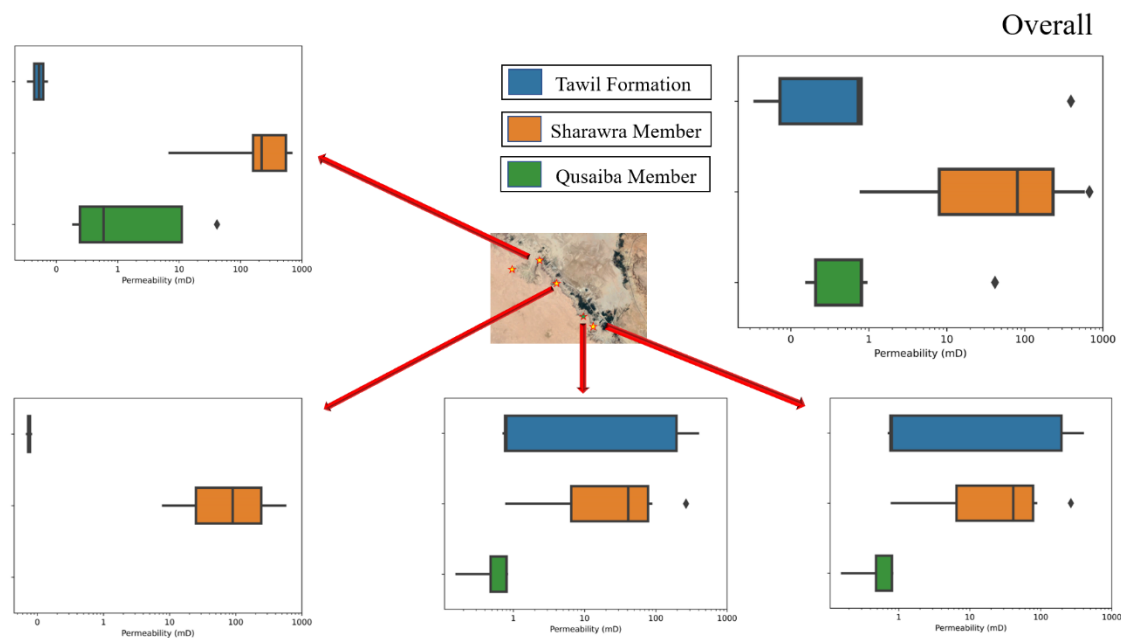


Figure 13 Boxplots illustrate the distribution of permeability (measured in millidarcies, mD) for the Tawil Formation, the Sharawra Member, and the Qusaiba Member, along with a summary boxplot for overall permeability. The x-axis is in log-scaled to accommodate the wide range of measurements. Outliers are identified as discrete points, providing insights into the permeability characteristics of each geological unit.

4.3 Geochemical Analysis

The geochemical analysis, employing X-ray fluorescence (XRF) and X-ray diffraction (XRD), played a pivotal role in elucidating the complex stratigraphy of the Qalibah Formation. This approach was crucial for two primary objectives: firstly, to delineate the intricate vertical boundaries between members, particularly where interbedding of shale and sand posed challenges in conventional stratigraphic identification. Secondly, it facilitated the horizontal lithofacies correlation between studied outcrops and corresponding subsurface shallow cores.

In order to pinpoint the boundaries, major trends and patterns were analyzed in the Qalibah Formation. In the Qusaiba Member, XRF results revealed a high concentration trend of sulfur (S) and iron (Fe), while XRD results are represented by low Si content and high illite and kaolinite trends compared to the rest of the Qalibah Formation. The Sharawra Member showed a rapid decrease in sulfur content, coupled with an increasing trend in potassium (K) and a decreasing trend in iron (Fe) and zinc (Z) in XRF results (Figure 15). XRD results indicate an increased trend in quartz percentage and a decreased trend in illite and kaolinite content (Figure 14). However, in the shale beds interbedded within this member, the geochemical signature is similar to that of the Qusaiba Member, with high illite and kaolinite content in XRD and increased sulfur in XRF, reflecting the complex interplay of lithologies.

In the Tawil Formation, XRF data revealed a positive spike in calcium (Ca) concentration unlike any other units, while XRD analysis showed a predominance of calcite. This distinct geochemical signature further demarcates the Tawil Formation from the underlying members. These findings not only enhance our understanding of the

formation's geochemical properties but also aid in constructing a more detailed and accurate stratigraphic model (Table 5, Figure 14 and Figure 15)

Table 5 Elemental Analysis of the studied Formation

Formation	Al₂O₃	SiO₂	K₂O	CaO	Fe₂O₃	Ni	Cu	Zn	Ba	Th	U
Tawil	0.7	3.6	0.2	47.8	0.4	20		10			
Tawil	1.0	4.4	0.3	47.7	0.5	20		9			
Tawil	2.0	35.9	0.9	0.1	1.4	6	274	14			
Tawil	11.1	39.5	4.2	0.3	5.2	10	129	28	1228		
Tawil	15.0	32.8	3.2	0.3	19.1	67	23	135	432	20	
Tawil	16.4	39.1	3.9	0.2	2.7	11		64	963	11	
Sharawra	16.1	39.1	4.1	0.2	2.4	9		50	1219		
Sharawra	13.5	42.0	3.5	0.1	5.7	8	14	27	1169		
Sharawra	14.8	33.3	3.9	1.8	17.5	57	18	231	489		
Sharawra	13.8	49.1	4.4	0.0	1.8		13	18	1246	12	
Sharawra	14.7	45.5	4.0	0.1	2.6	6	61	18	1177	16	
Sharawra	13.6	48.3	4.4	0.1	2.9	11		29	1071		
Sharawra	12.7	30.4	2.9	0.8	16.2	41	30	100	567		
Sharawra	16.3	33.8	3.1	1.0	14.5	51	28	133	572	17	
Sharawra	14.9	41.5	4.0	0.3	3.4	18	31	32	1305		
Sharawra	16.8	38.6	3.7	0.5	11.6	49	87	148	706	17	

Sharawra	14.1	44.1	4.0	0.4	2.2	7	48	51	1202		
Sharawra	13.4	41.0	4.0	0.1	1.7	9	71	36	1035	10	
Sharawra	15.6	39.8	3.5	0.4	4.4	17	40	169	974	16	13
Sharawra	18.0	39.4	3.5	0.4	9.2	29	35	169	836		
Sharawra	18.0	39.1	3.5	0.5	7.7	30	46	178	705	14	
Sharawra	17.7	41.0	3.7	0.4	9.5	29	24	186	808		
Sharawra	17.1	37.9	3.5	0.5	11.2	37	24	173	716	18	
Sharawra	13.3	42.3	4.0	0.1	8.5	7	18	168	1055		
Sharawra	19.8	39.2	3.3	0.3	6.8	36	56	166	429	16	
Sharawra	18.4	37.5	3.2	0.2	7.8	34	154	164	439	16	
Sharawra	16.2	38.6	3.6	0.3	8.7	24	21	143	826	16	
Sharawra	18.0	36.6	3.0	0.3	7.4	31	85	156	420	18	
Sharawra	18.0	37.6	3.3	0.5	7.7	31	18	155	409	19	
Sharawra	18.9	39.0	3.4	0.3	9.4	35	43	166	628	18	
Sharawra	4.3	14.8	1.2	20.0	11.9	11		55	242		
Sharawra	13.5	36.6	3.7	1.4	7.0	16	25	332	958		
Sharawra	18.3	37.7	3.2	0.3	10.4	29	43	183	445	20	
Sharawra	15.6	34.4	3.1	0.6	10.7	33	39	177	751	20	

Sharawra	18.2	37.0	3.1	0.1	8.2	36	60	165	516	19	
Sharawra	17.2	36.6	3.1	0.2	7.1	35	48	136	476	18	
Sharawra	15.4	37.5	3.5	0.2	7.9	14	495	86	1129	13	
Sharawra	15.4	40.1	3.8	0.2	6.8	11	26	134	1035		
Sharawra	19.3	40.3	3.3	0.3	7.3	27	113	117	477	22	
Sharawra	15.5	37.6	3.5	0.6	14.6	34	23	291	876	13	
Sharawra	21.3	41.4	3.1	0.2	11.6	34	37	139	392	16	
Sharawra	20.9	40.8	3.1	0.2	7.4	32	71	128	521	24	
Sharawra	13.2	31.1	2.8	0.4	9.5	35	25	222	639	17	
Sharawra	9.4	32.6	3.1	1.2	3.5	12	12	73	1009		
Sharawra	17.6	38.7	3.2	0.6	11.0	31	25	142	473	16	
Sharawra	11.1	40.3	3.6	5.2	5.7	9	11	40	947		
Sharawra	12.0	33.4	3.3	1.7	7.6	30	14	99	864		
Sharawra	17.8	39.6	3.3	0.4	11.6	34	51	139	713	16	
Sharawra	14.8	38.9	3.6	0.2	6.0	15	15	82	1127		
Sharawra	19.5	38.4	2.9	0.1	11.6	32	27	213	387	20	
Sharawra	17.7	37.4	3.0	0.3	10.5	35	59	172	472	17	15
Sharawra	15.3	37.4	3.3	0.7	10.0	39	65	193	684	23	

Sharawra	18.1	42.6	3.7	0.3	7.3	23	57	104	837	14	
Sharawra	13.1	31.6	3.0	0.2	10.1	42	19	293	716	18	
Sharawra	13.9	35.4	3.3	0.1	15.1	18	9	172	860	37	
Sharawra	17.0	41.0	3.7	0.2	7.0	22	32	151	957		
Qusaiba	6.0	16.3	1.8	0.2	10.4	35	35	208	676	14	
Qusaiba	19.5	37.7	2.9	0.2	13.5	48	86	318	421	16	
Qusaiba	19.4	39.5	3.0	0.1	6.6	50	34	189	482	15	
Qusaiba	19.7	38.4	2.9	0.0	16.8	35	77	443	351	18	
Qusaiba	15.7	36.6	3.3	0.4	12.3	20	38	196	618	21	19
Qusaiba	7.5	20.8	1.8	0.2	11.6	25	46	164	457	21	
Qusaiba	16.0	34.1	2.6	0.1	10.2	19	47	150	381	20	15
Qusaiba	17.6	38.3	3.0	0.0	4.0	18	51	91	539	16	
Qusaiba	12.4	27.0	2.4	0.6	13.9	24	33	158	444	22	
Qusaiba	14.3	34.1	2.6	0.4	4.2	17	310	75	442	20	
Qusaiba	4.6	14.0	1.4	0.1	4.9	20	54	108	540	16	12
Qusaiba	11.0	26.4	2.1	0.1	6.5	22	57	119	409	13	
Qusaiba	19.5	39.6	2.5	0.1	3.6	18	53	78	323	18	11
Qusaiba	17.7	37.0	2.7	0.0	5.1	17	57	123	400	19	

Qusaiba	11.7	25.5	1.7	0.1	23.1	22	74	140	341	49	39
Qusaiba	17.0	38.0	3.0		14.2	31	59	242	408	18	
Qusaiba	17.1	37.1	3.0	0.1	13.9	27	35	189	370	21	11
Qusaiba	2.4	8.5	0.8	0.1	4.3	24	20	117	515	14	
Qusaiba	6.0	18.6	1.8	0.0	11.7	32	39	226	361	22	
Qusaiba	7.8	18.6	1.5	0.1	24.2	30	30	261	360	37	
Qusaiba	6.2	17.8	1.7	0.1	4.7	29	24	117	512	13	
Qusaiba	9.0	21.3	1.9	0.5	4.8	21	42	115	446	15	
Qusaiba	6.6	18.1	1.6	0.0	4.6	18	37	104	486	10	
Qusaiba	16.1	33.0	2.3	0.0	4.0	19	32	119	425	13	
Qusaiba	17.5	36.8	2.6		4.1	21	60	119	416		
Qusaiba	0.9	4.3	0.5	0.0	4.2	20	30	106	461	13	
Qusaiba	20.0	39.2	2.8	0.0	5.2	19	24	114	399	13	
Qusaiba	19.1	38.0	2.8		4.9	20	39	116	439	17	17
Qusaiba	7.1	17.9	1.6	0.0	5.0	20	22	129	485	16	
Qusaiba	6.6	16.4	1.1	0.1	3.8	19	17	88	486	11	
Qusaiba	20.5	39.7	2.6		4.0	19	35	104	382	16	
Qusaiba	20.4	39.9	2.7		4.2	19	32	110	356	18	

Qusaiba	5.8	16.2	1.3	0.1	4.5	20	30	108	471	14	
Qusaiba	17.3	34.2	2.5		3.7	20	37	99	409	17	15
Qusaiba	12.0	24.7	1.8	0.0	3.0	19	58	88	269	15	
Qusaiba	19.3	37.8	2.7		3.9	17	21	88	426	13	
Qusaiba	16.9	33.6	2.4	0.0	5.2	18	21	101	364	13	14
Qusaiba	20.1	39.1	2.8		4.7	19	32	119	347	16	
Qusaiba	19.2	38.4	2.9		4.3	21	38	105	398	15	
Qusaiba	17.7	36.0	2.6	0.0	12.7	39	33	200	322	25	
Qusaiba	14.8	29.9	2.1	0.5	16.5	22	23	257	284	27	
Qusaiba	19.1	38.9	3.0		6.2	20	29	122	446	16	
Qusaiba	17.6	37.3	3.0	0.0	8.3	19	34	126	405	17	
Qusaiba	17.2	34.9	2.7		5.4	22	30	111	406	18	
Qusaiba	5.6	15.5	1.5	0.1	10.7	26	28	192	455	15	
Qusaiba	7.8	18.7	1.6	0.1	8.3	25	42	180	435	16	14
Qusaiba	9.9	25.0	2.3		11.9	32	31	201	450	15	

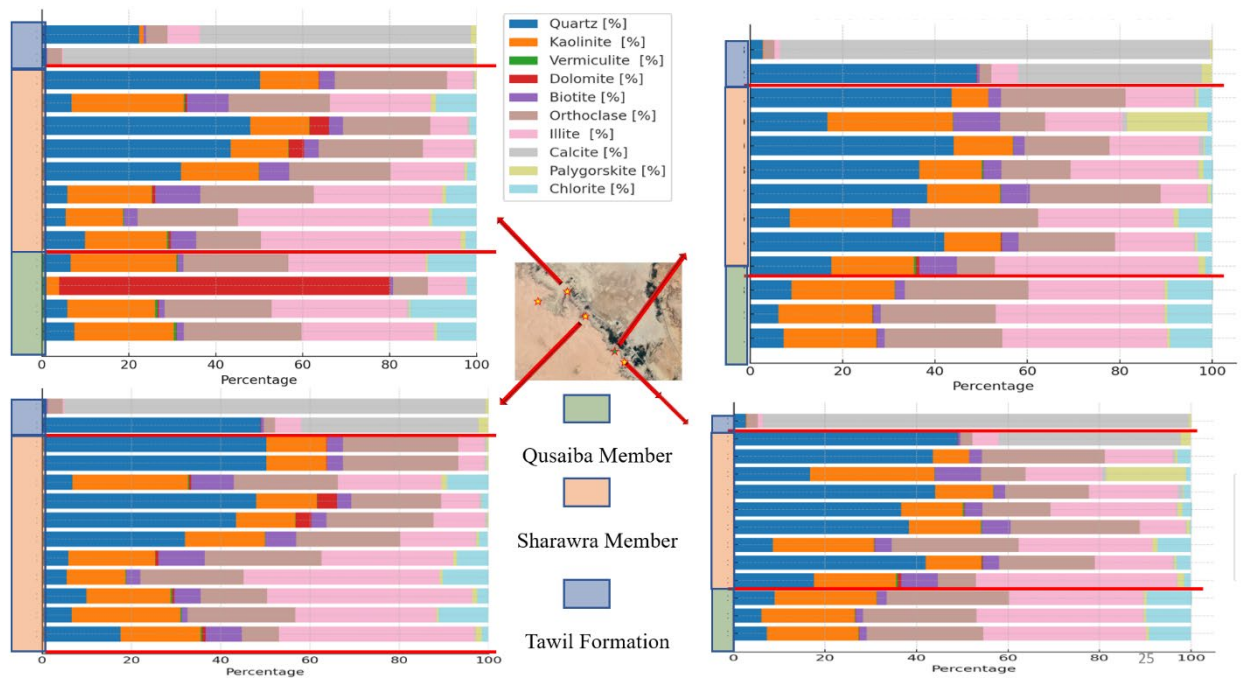


Figure 14 Stacked bar charts showing XRD-derived mineral percentages in the Tawil Formation, Sharawra Member, and Qusaiba Member. Each color corresponds to a mineral, depicting its abundance in each geological unit.

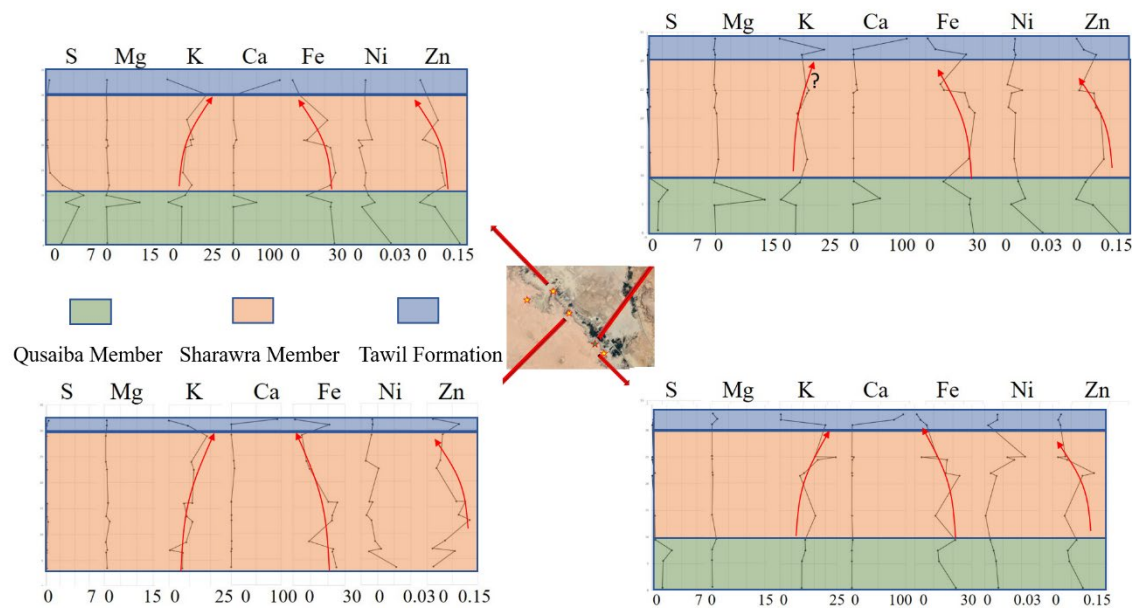


Figure 15 The figure presents geochemical well log-like displays of elemental concentrations from X-Ray Fluorescence (XRF) analysis for the Qusaiba Member, the Sharawra Member, and the Tawil Formation. Elements sulfur (S), magnesium (Mg), potassium (K), calcium (Ca), iron (Fe), nickel (Ni), and zinc (Zn) are graphed, revealing the geochemical variations within each geological unit.

4.3 3D Geological Models

4.3.1 Digital Outcrop Models

This study developed a comprehensive 3D static model over a 10 km² area to elucidate the distribution of lithofacies and petrophysical properties within the Qalibah Formation (Figure 2). This model was constructed by integrating data from detailed digital outcrop modeling (DOM) as shown in Figure 16, Figure 17 and Figure 18, which accurately illustrate the real-world geological features of the formation in a digital form. The DOM enabled us to delineate critical surfaces (e.g., facies boundaries and erosion surfaces) and bed geometries (e.g., tabular *versus* lensoidal) enabling construction of deterministic static models in Petrel. These static models effectively integrate lithofacies distribution, offering a high-resolution depiction of the formation's complexity.



Figure 16 Digital outcrop model (DOM) of outcrop 1 (OC1; Figure 2) illustrating stratigraphic architecture. The lowermost unit is the Qusaiba Member (LF 1), overlain by the Sharawra Member (LF2 and LF 3), and capped by the Tawil Formation (LF 4). Please note that the Tawil Formation is mostly eroded and is limitedly exposed. This high-resolution DOM provides a detailed representation of the large-scale sedimentary structures, bed geometries and lithological variations within the outcrop facilitating geological interpretations, and static models.

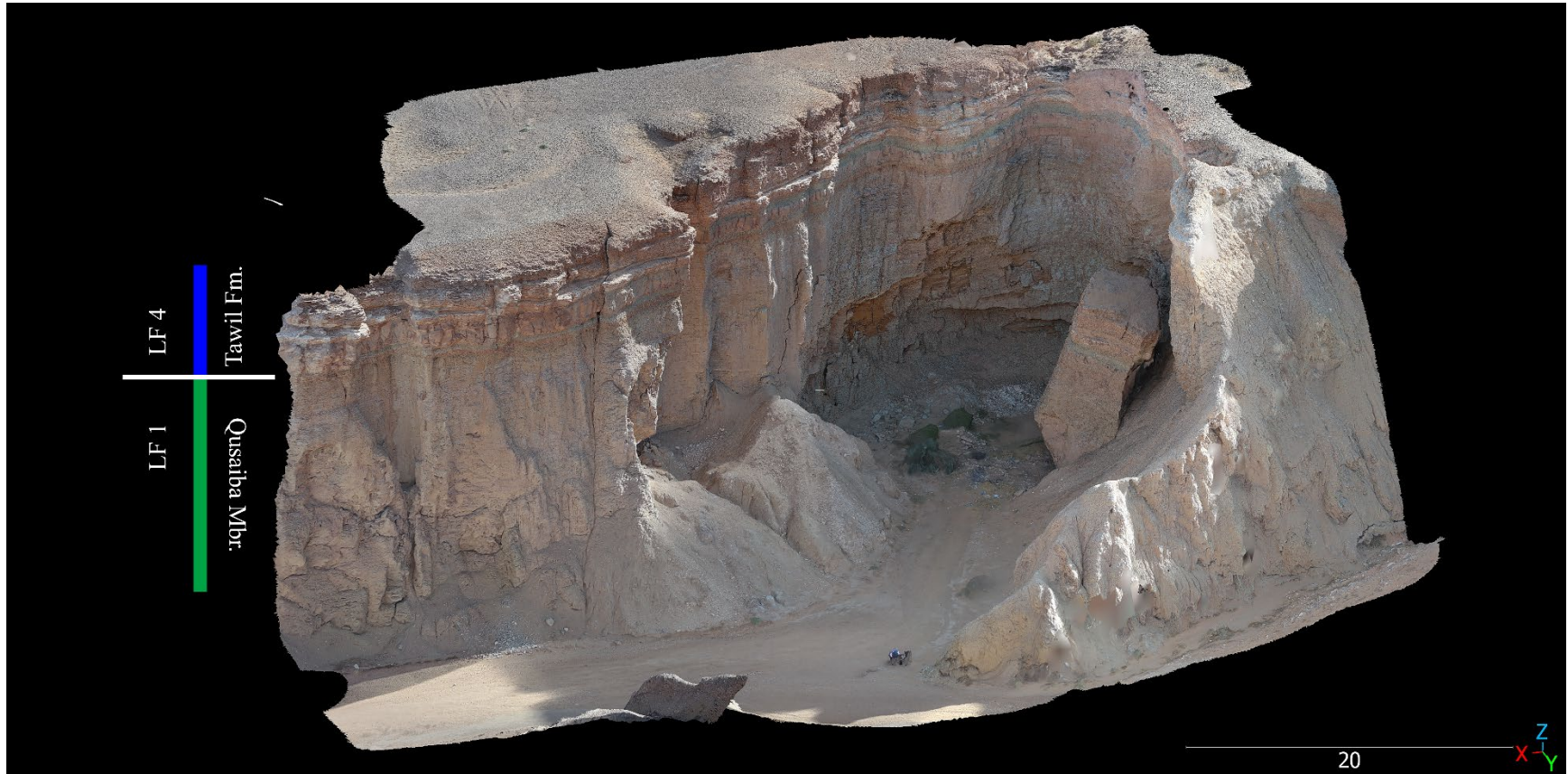


Figure 17 Digital outcrop model (DOM) of outcrop 4 (OC4; Figure 2) showing two geological units. The base is the Qusaiba Member (LF 1), and the top is the Tawil Formation (LF 4). Note that the Sharawra Member (LF 2 and LF 3) are missing due to erosion.

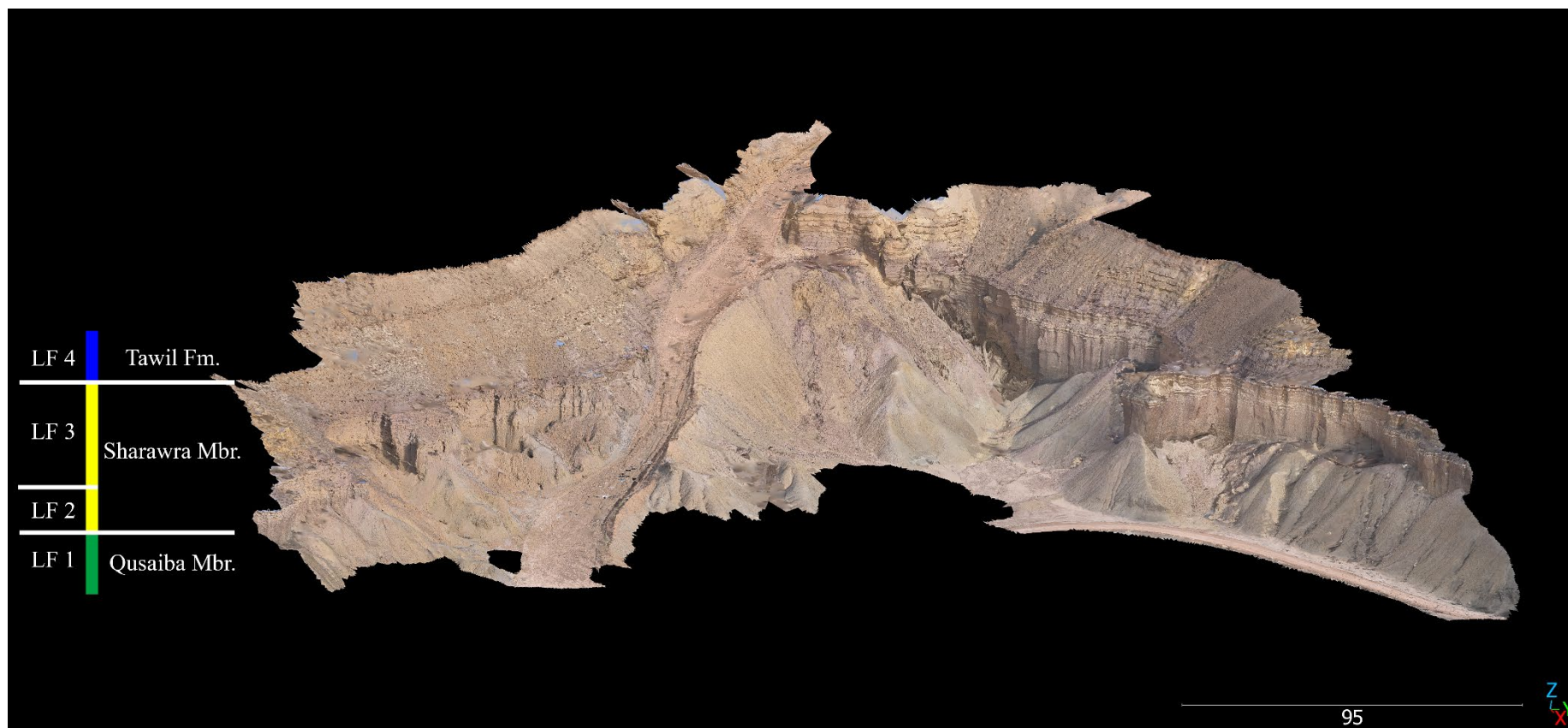


Figure 18 Digital outcrop model (DOM) of outcrop 3 (OC 3; Figure 2), showing four geological units. The base is the Qusaiba Member (LF 1), overlain by the Sharawra Member (LF 2 and LF 3), and capped by the Tawil Formation (LF 4).

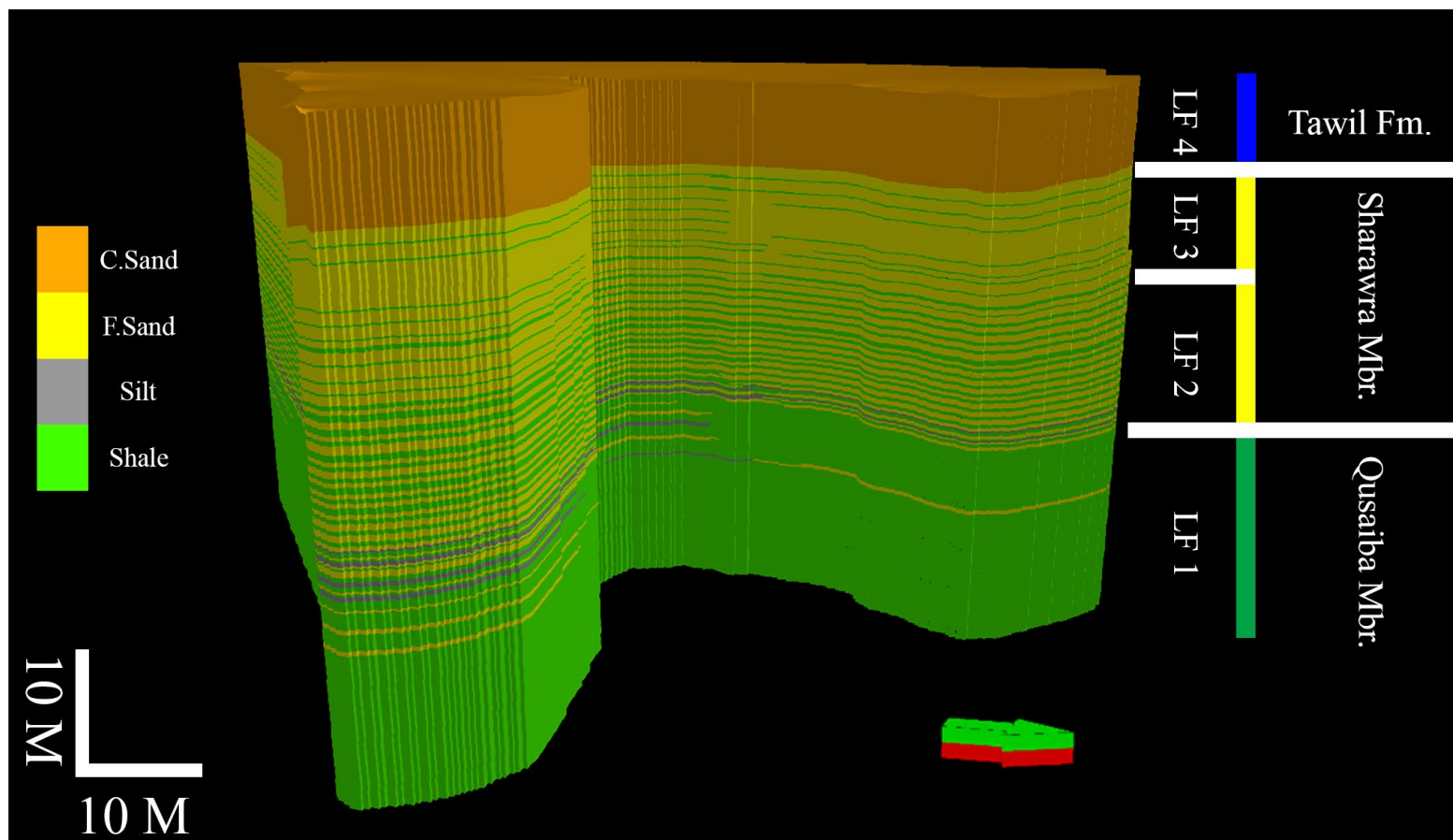


Figure 19 Petrel facies static model of outcrop 1 (OC1; Figure 2) representing the distribution of sedimentary lithofacies. The model includes four stratigraphic units: the Qusaiba Member (LF 1) at the base, followed by the Sharawra Member (LF 2 and LF 3), and the uppermost Tawil Formation (LF 4).

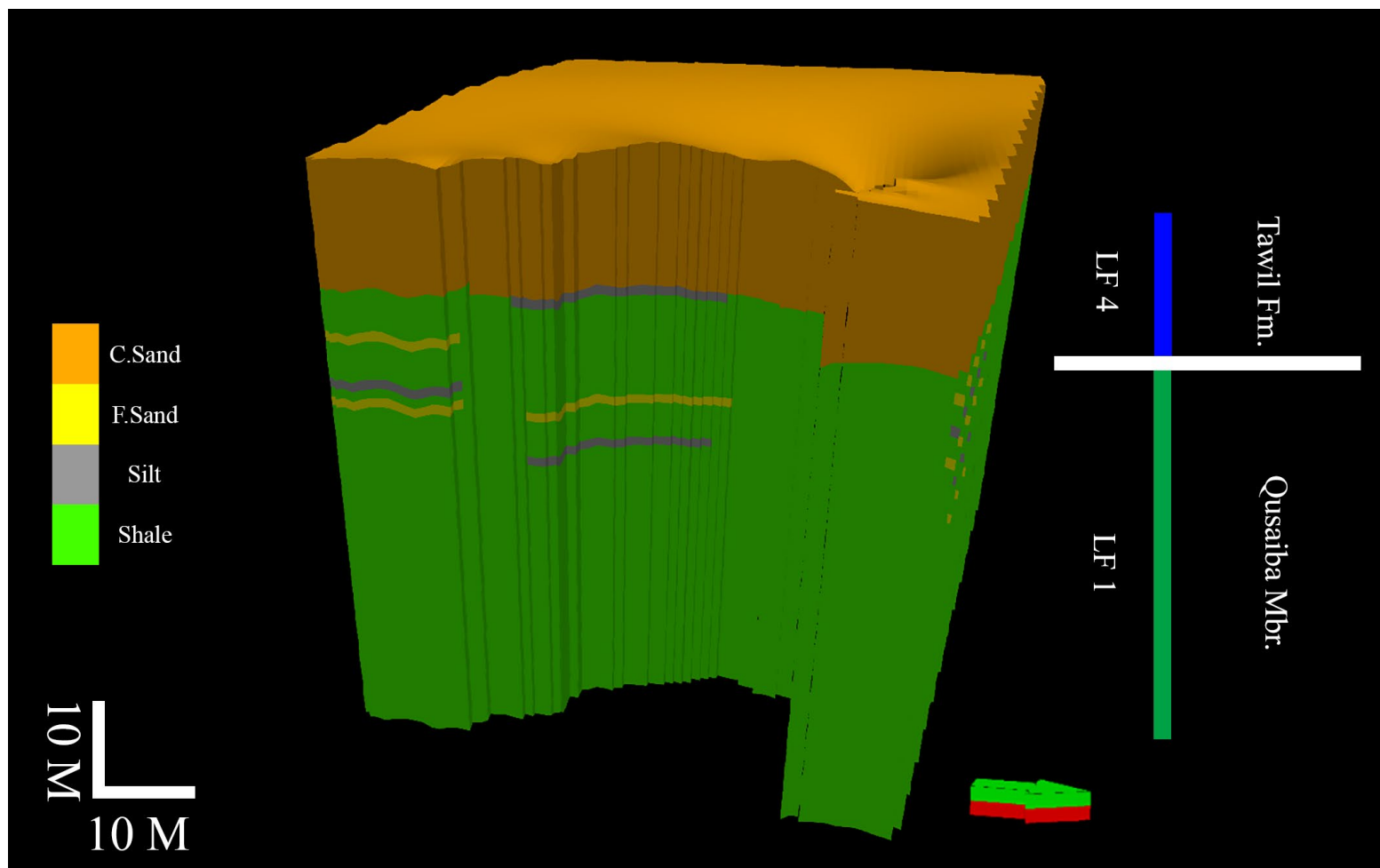


Figure 20 Petrel facies static model for outcrop 4 (OC4; Figure 2) showing two distinct geological units. The Qusaiba Member (LF 1) is at the base and the Tawil Formation (LF 4) is at the top.

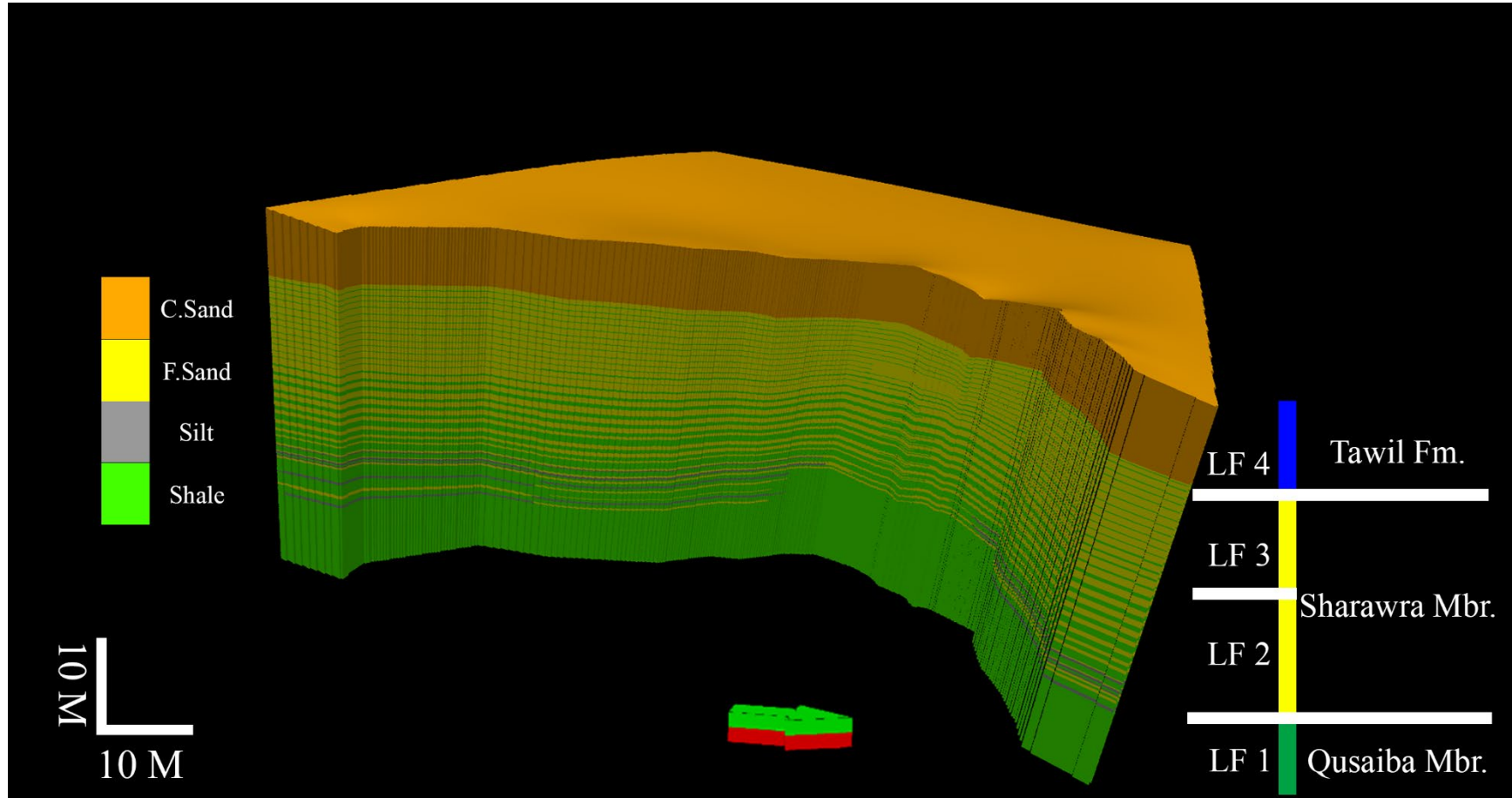


Figure 21 This is the Petrel facies static model of outcrop 3 (OC3; Figure 2), which includes three geological units. The Qusaiba Member (LF 1) at the base, followed by the Sharawra Member (LF 2 and LF 3), and topped by the Tawil Formation (LF 4).

4.3.2 Petrophysical Models

Petrophysical property (i.e., porosity and permeability) models show significant vertical and horizontal variations in each outcrop in the Qalibah Formation (Figure 22, Figure 23, Figure 24, Figure 25, Figure 26 and Figure 27). The petrophysical modeling of the Qalibah Formation addressing porosity as shown in Figure 22, Figure 23 and Figure 24, as well as permeability in Figure 25, Figure 26 and Figure 27 was aligned with laboratory measurements to ensure accuracy in the distribution of these properties across various facies. This alignment enabled a detailed visualization of how porosity and permeability vary within the formation. The overall vertical and horizontal distribution patterns of these properties show similarities between outcrops and within each lithofacies, although there are some slight variations.

In OC1 static model for porosity is characterized by an overall increasing pattern from the bottom to top of the LF1 (Figure 22). It should be noted that local and isolated increases in porosity (white arrows in Figure 22) are results of isolated sandstone/siltstone layers. The permeability static model shows a similar increasing pattern in LF1 (Figure 25). The porosity static model in the LF2 (lower section of the Sharawra Member) is characterized by a sudden increase at the bottom followed by a decreasing trend. The permeability static model in the same lithofacies (LF2) starts with a slight increase, similar to the porosity profile albeit in a lower magnitude. The LF3 starts also is characterized by first a sudden decreasing trend in both porosity and permeability, followed by an increasing trend up to the bottom of the LF4. Please note that some layers, particularly towards the

top of LF3, are characterized by horizontal variations probably due to the significant changes in differences in samples collected from the same layer. The LF4 in static models of both porosity and permeability starts with high porosity and permeability values followed by a decrease trend.

In OC4 static model for the porosity also shows vertical variations. The LF1 is characterized by low porosity and low permeability values with local isolated relatively high values (Figure 23). The LF4, on the other hand, in the static model of both porosity and permeability is characterized by an overall all increasing trends.

In OC3 static model for porosity is characterized by an overall increasing pattern from the bottom to top of the LF1 (Figure 24). It should be noted that local and isolated increases in porosity (white arrows in Figure 24) are results of isolated sandstone/siltstone layers. The permeability static model shows a similar increasing pattern in LF1 (Figure 27). The porosity static model in the LF2 is characterized by a sudden increase at the bottom followed by a decreasing trend. This trend is identically the same as the permeability static model. The LF3 in porosity static model characterized by a very high porosity value then goes with a decreasing trend until we reach the boundary with the Tawil Formation. The permeability static model in the same lithofacies (LF3) characterized by with a smooth transition. The Tawil Formation in the porosity static model characterized by high porosity results but, in the permeability, static model it is almost the same trend as LF3, so it is hard to identify the boundary between LF3 and LF3.

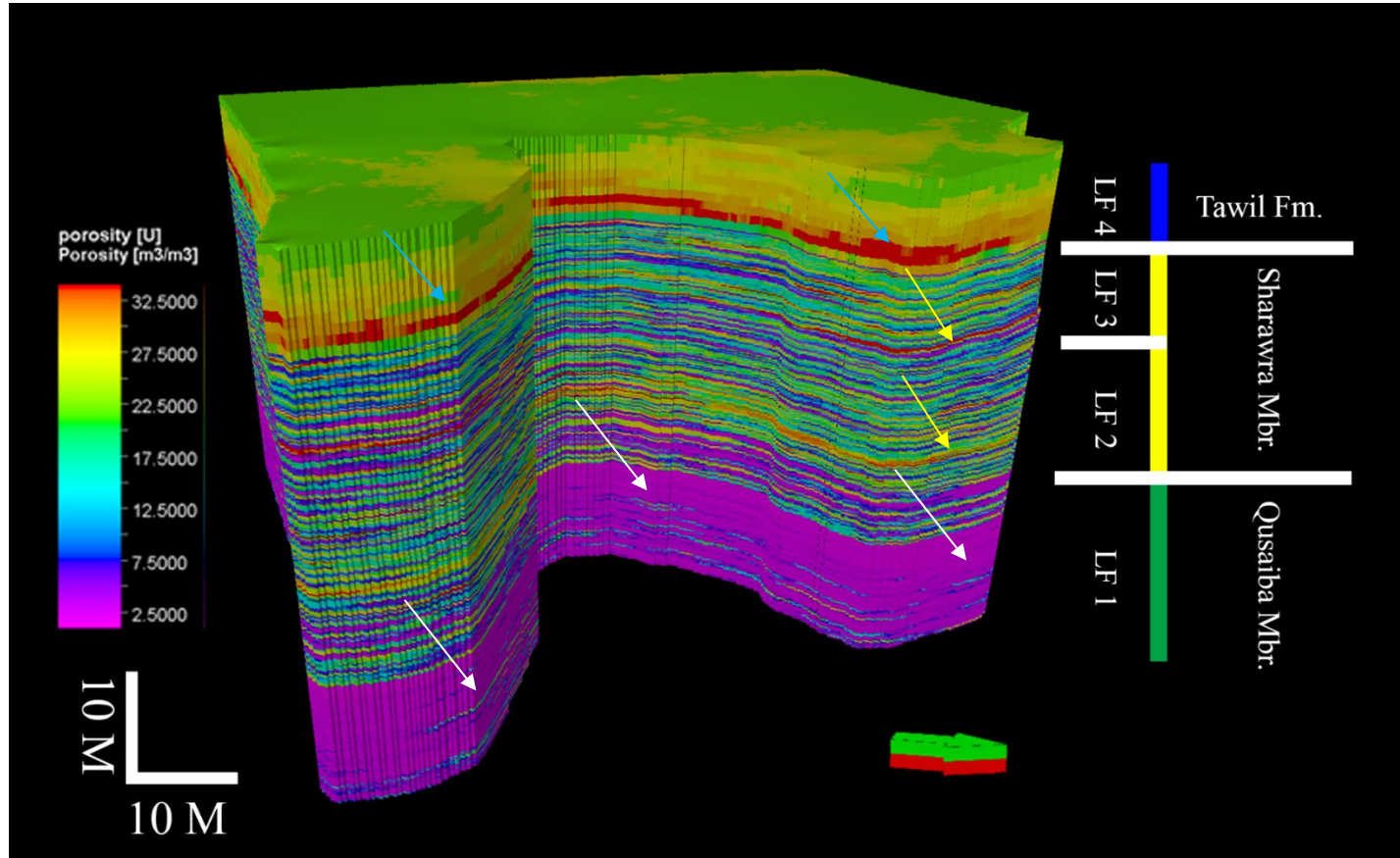


Figure 22 Porosity static model of outcrop 1 (OC1; Figure 2), visualizing porosity distribution across four geological units. The color gradient represents porosity values, with white arrows indicating areas of ambiguity within the Qusaiba Member (LF 1). Yellow arrows highlight significant porosity changes at the boundaries between LF 1 and LF 2, and between LF 2 and LF 3. Light blue arrows point to zones of high porosity within the Tawil Formation (LF 4).

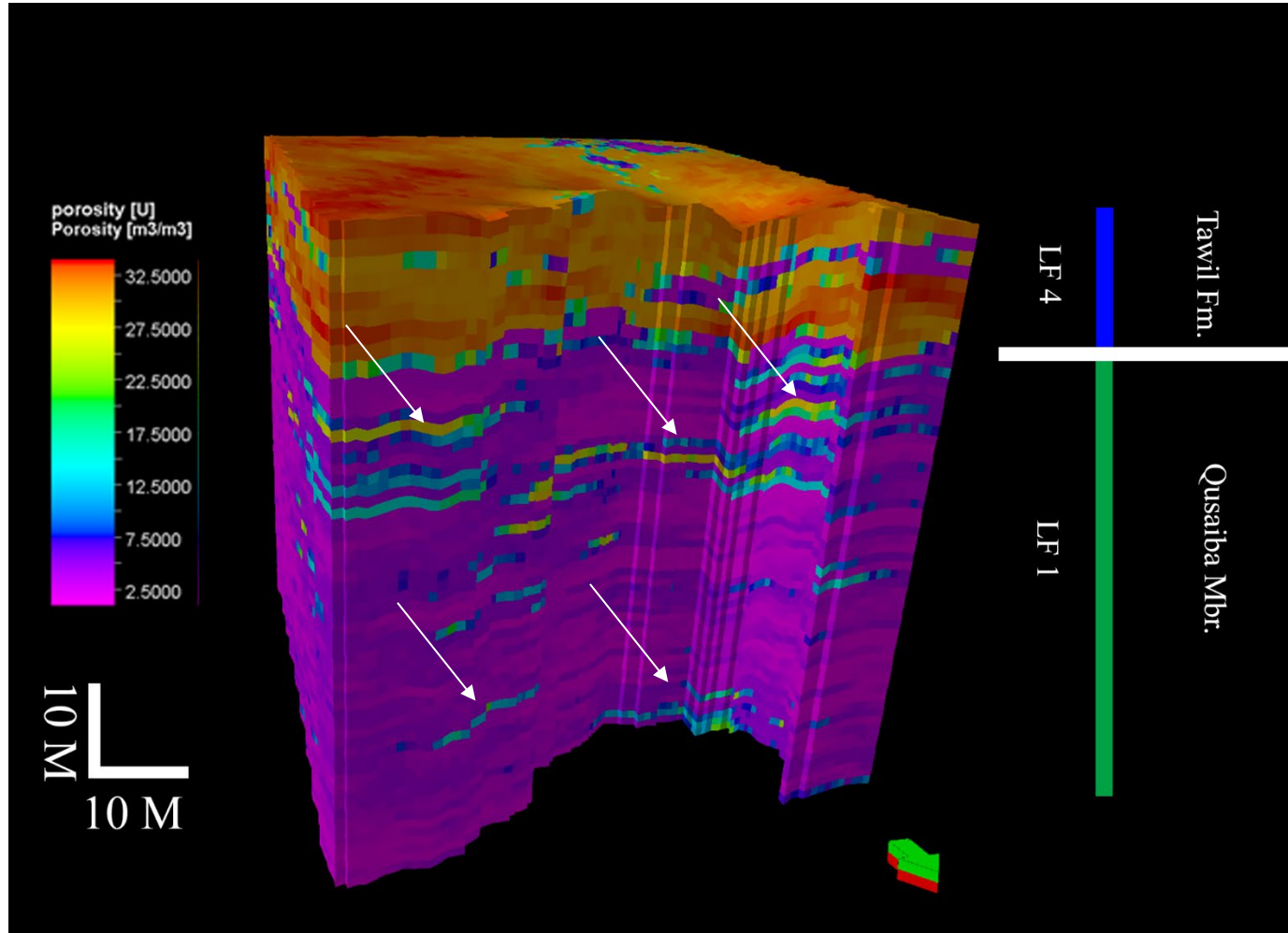


Figure 23 Porosity static model for outcrop 4 (OC4; Figure 2) illustrating the variation in porosity within the geological units. The color scale represents different porosity levels, with white arrows indicating regions of increase porosity within the Qusaiba Member (LF 1).

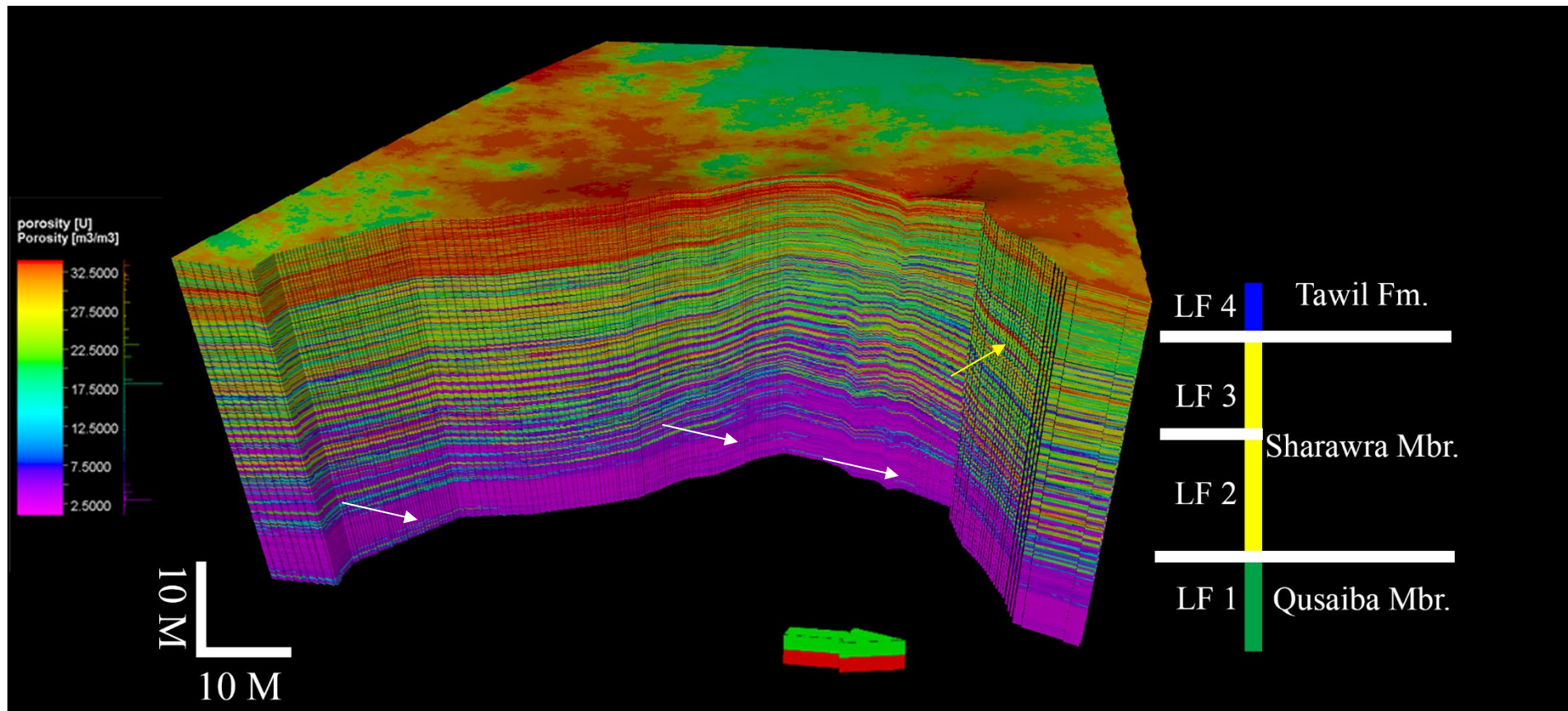


Figure 24 Porosity static model for outcrop 3 (OC3; Figure 2) displaying porosity variations across its stratigraphy. The model uses a color gradient to show porosity levels, with white arrows marking ambiguous porosity in the Qusaiba Member (LF 1). Yellow arrows highlight areas of significant porosity changes at the boundaries between LF 1 and LF 2, and LF 2 and LF 3.

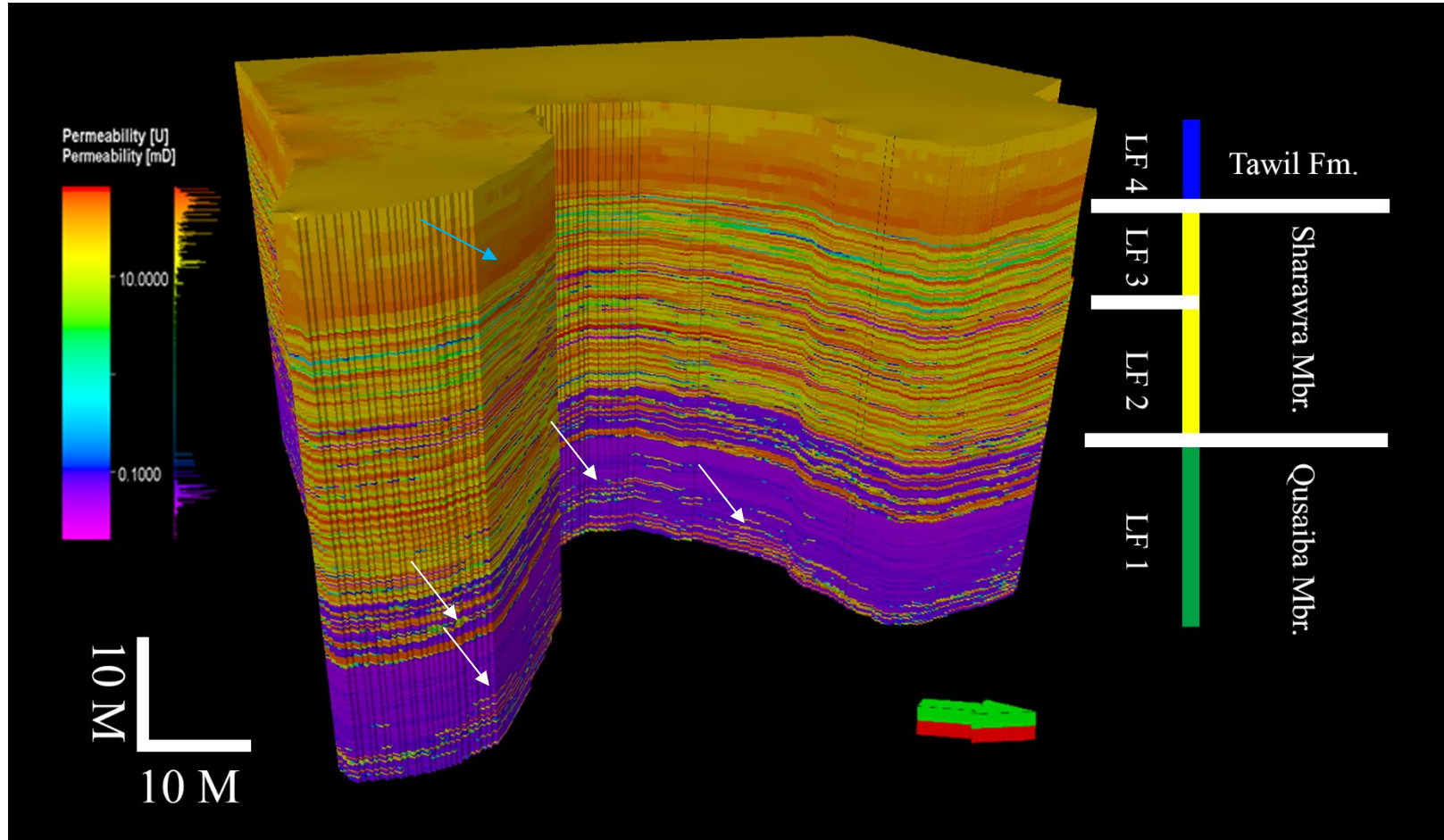


Figure 25 Permeability static model for outcrop 1 (OC1; Figure 2), showing the distribution of permeability values within the geological units. The color scale ranges from low (purple) to high (yellow) permeability. White arrows indicate zones of permeability ambiguity in the Qusaiba Member (LF 1), and light blue arrows point to areas of high permeability within the Tawil Formation (LF 4).

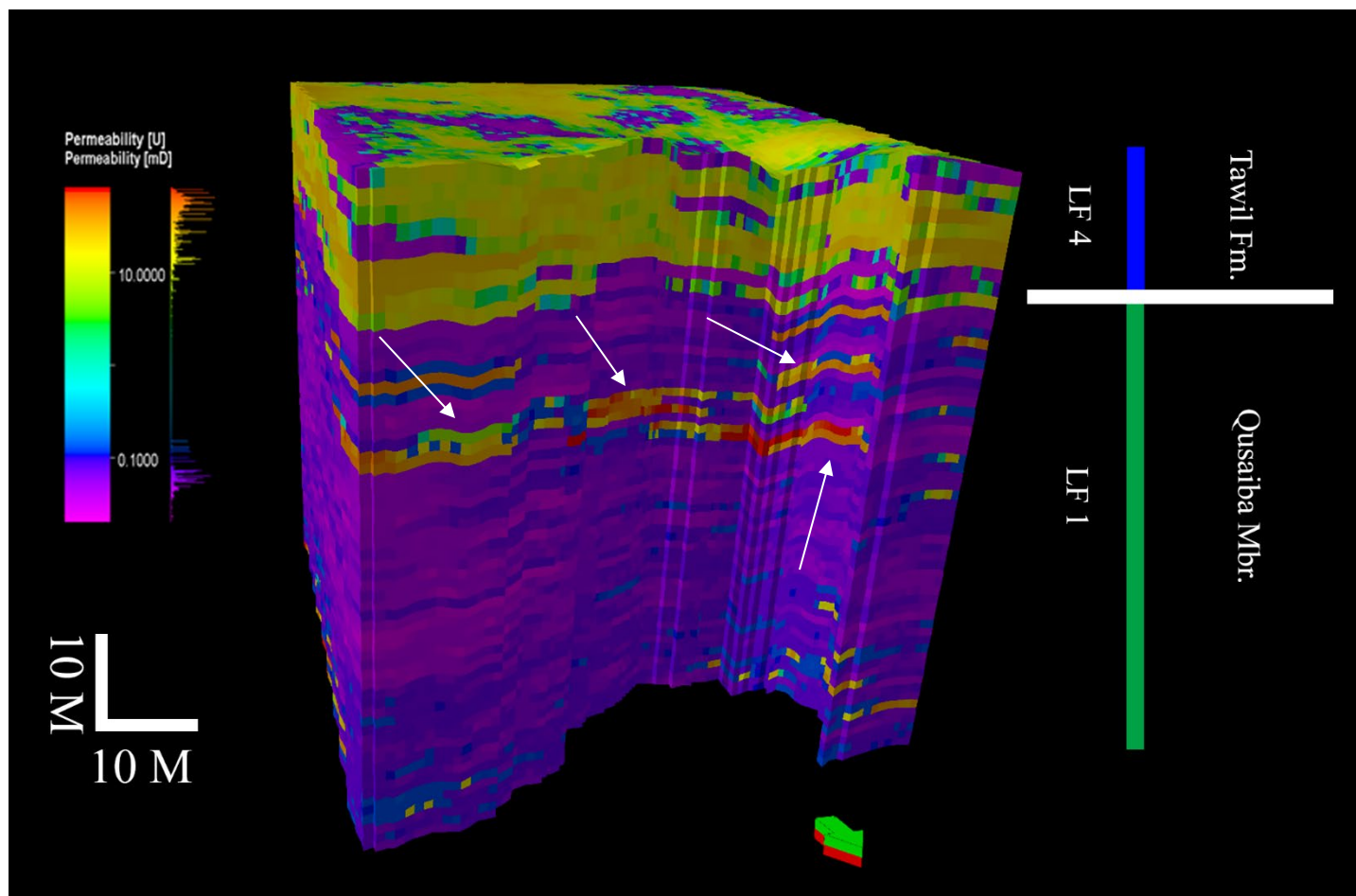


Figure 26 Permeability static model for outcrop 4 (OC4; Figure 2), illustrating the permeability variations across the stratigraphic sequence. The gradient color scale indicates permeability levels from low (purple) to high (yellow). White arrows highlight areas with higher permeability readings in the Qusaiba Member (LF 1).

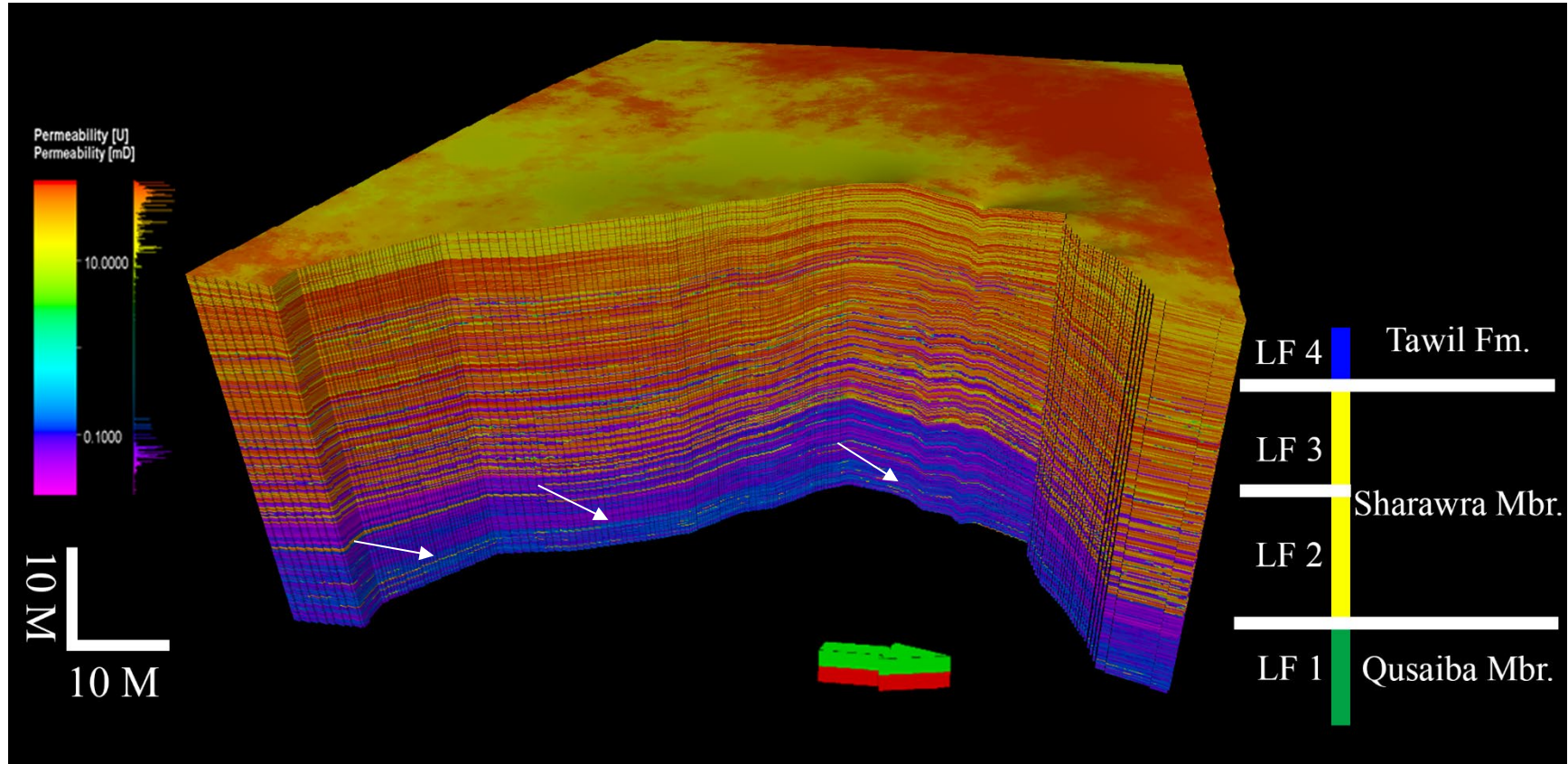


Figure 27 Permeability static model for outcrop 3 (OC3; Figure 2), showing a range of permeability levels within the geological units. The color scale from purple to yellow represents low to high permeability values. White arrows point to regions within the Qusaiba Member (LF 1) where permeability data is higher.

Chapter 5

Discussion

5.1 Facies Analysis

The detailed lithofacies analysis of the Qalibah Formation provides significant insights into its stratigraphic complexity and paleo depositional environment. The identification of four distinct lithofacies within the formation illustrates a diverse and dynamic depositional history. The fissile shale lithofacies (LF1) of the Qusaiba Member, characterized by its varied coloration and occasional sandstone lenses, suggesting relatively low energy conditions, probably deposited in suspension settling. The presence of sandstone and siltstone alternation close to the top of the member probably suggests the onset of changes in the energy conditions. Similar lithofacies have been observed in other unconventional reservoirs (Passy et. al., 2010). The Sharawra Member is characterized by two main lithofacies (LF2 and LF3). The LF2 is predominantly located in the lower part of the Sharawra Member and it shows heterolithic sandstone and mudstone suggesting frequent changes in the energy conditions. The massive nature of the sandstone beds is interpreted as turbidity current deposits (Zavala and Arcuri, 2016). The LF3 is located in the upper half of the Sharawra Member, and it displays well-preserved hummocky cross-stratification. LF3 is interpreted to represent storm events deposited above the storm weather wave base (Peters et al., 2012). The Tawil Formation is characterized by sandstone and carbonate alternation. This Formation has previously been interpreted as fluvial deposits (Mahmoud et al., 1992).

5.2 Petrophysics Analysis

The petrophysical analysis of the Qalibah Formation provides essential insights into the reservoir characterization. The Qusaiba Member shows the lowest porosity and permeability values in each outcrop and core (Figure 12 and Figure 13) (Abdlmutalib et al., 2022). However, it is also characterized by local internal fluctuations (Figure 22, Figure 23, Figure 24, Figure 25, Figure 26 and Figure 27) these fluctuations are mainly due to the presence of sandstone and siltstone layers and lenses, particularly in the upper Qusaiba Member (Table 1, Table 2, Table 3 and Table 4) (Mahmoud et al., 1992; AlGhamdi et al., 2023; Kaminski et al., 2019; Ayranci et al., 2022). The Sharawra Member, on the other hand, is characterized by the highest porosity and permeability values in the boundaries between LF1 and LF2 also between LF2 and LF3 (Figure 12 and Figure 13) (Abdlmutalib et al., 2022; AlGhamdi et al., 2023) However, this member is also characterized by vertical and horizontal variations.

The observed variation in porosity and permeability across different lithofacies is indicative of the complex interplay between geological processes and the resulting rock properties. The low porosity and permeability values in lithofacies 1 (LF1) of the Qusaiba Member are consistent with the compact and fine-grained nature of these lithofacies, suggesting limited fluid flow potential (Mahmoud et al., 1992). This is a critical factor for evaluating the formation's suitability as a hydrocarbon reservoir.

Overall trends in porosity and permeability values between each outcrop show similarities within each formation and member. The Qusaiba Member is consistently low in porosity and permeability values; however, local changes were observed. For example, the upper part of the Qusaiba Member shows beds displaying horizontal variations with same beds (Figure 24 and Figure 27) (AlGhamdi et al., 2023; Abdmutalib et al., 2022). This variation is probably due to the different porosity values recorded in the same bed, but different subsamples (Table 1 and Table 3). the Sharawra Member displays two major vertical trends: two consecutive decreasing trends (Figure 24 and Figure 27). The boundary between these two trends is consistent with the change between LF2 and LF3, suggesting that the changes in porosity and permeability are controlled by the main shift in the hydrodynamic conditions resulting changes in the lithofacies (AlGhamdi et al., 2023). The Tawil Formation shows the most significant horizontal changes between outcrops. This is probably due to the fact that carbonate and sandstone samples collected randomly in this formation.

The highest porosity and permeability, observed in lithofacies 4 (LF4) of the Tawil Formation, points to a significantly different depositional environment, likely characterized by higher energy conditions leading to a coarser and more loosely packed sediment (Mahmoud et al., 1992). This suggests a more favorable scenario for fluid migration and storage, underlining the potential heterogeneity in reservoir quality within the formation.

The integration of these petrophysical data with the facies analysis provides a more comprehensive understanding of the formation. It highlights the need to consider both geological and petrophysical properties in assessing the overall potential of sedimentary basins for hydrocarbon exploration. Furthermore, the correlation between lithofacies characteristics and petrophysical properties underscores the importance of detailed geological studies in predicting reservoir behavior. This comprehensive approach to petrophysical analysis not only enhances our understanding of the Qalibah Formation but also sets a precedent for evaluating similar formations, ensuring more accurate predictions and efficient resource management.

Chapter 6

Conclusion

This study has explored the Qalibah Formation to unravel its stratigraphic, petrophysical, and geochemical intricacies leading to a comprehensive understanding of its depositional history and reservoir potential. The integration of facies analysis, petrophysical evaluation, and geochemical profiling has painted a multidimensional picture of the formation.

The facies analysis identified four distinct lithofacies, revealing a stratigraphic sequence marked by varied depositional environments. The Qusaiba Member fissile shale lithofacies with interspersed sandstone lenses, the heterolithic and hummocky cross-stratified sandstones of the Sharawra Member, and the Tawil Formation's sandstone and carbonate alternations are indicative of a dynamic geological past ranging from low-energy settings to high-energy fluvial systems which probably led to the variations in porosity and permeability values and resulted in heterogeneity in the Qalibah Formation.

In the Qalibah Formation each facies are represented by different petrophysical characteristics, thus each member has unique trends. The Qusaiba Member overall shows the lowest porosity and permeability reflecting its compact nature, whereas the Sharawra Member is characterized by higher values indicating a coarser grains and probably more connected pore spaces due to the increase in the energy conditions.

Geochemical analyses provided precise delineation of member boundaries and facilitated lithofacies correlation. This data delineated the geochemical fingerprint of each member.

The construction of 3D static models using Digital Outcrop Modeling (DOM) and Petrel software offered a high-resolution visualization of the formation's lithofacies and petrophysical properties. These models are instrumental in digitalizing the facies distribution and assessing the reservoir's heterogeneity, crucial for hydrocarbon exploration.

In conclusion, the Qalibah Formation exhibits significant heterogeneity in its lithofacies and petrophysical properties. The study's findings enhance our understanding of its depositional history and reservoir quality, which is vital for accurate hydrocarbon exploration and efficient resource management. The systematic approach adopted in this thesis underscores the value of integrating geological, petrophysical, and geochemical analyses in sedimentary basin studies, paving the way for more refined exploration strategies in similar formations.

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