

**(Unravelling the Provenance, Geochemical,
and Diagenetic Characteristics of the Silurian Sharawra
Formation, NW Saudi Arabia)**

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Geology

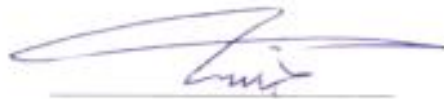
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DEDICATION

This Thesis is dedicated to my parents, whose steadfast prayers and encouragement have been pivotal in helping me achieve my goals, to my wife for her unwavering inspiration, and to my brothers and sisters for their constant support.

I firmly believe that my father and mother are consistently proud of me in my personal and professional endeavors.

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LIST OF ABBREVIATIONS

Abbreviation Meaning

XRD	X-ray Diffraction
XRF	X-ray Fluorescence
SEM	Scanning Electron Microscope
REE	Rare Earth Elements
CIA	Chemical Index of Alteration
ICV	Index of Compositional Variability
KFUPM	King Fahd University of Petroleum and Minerals
QFL	Quartz-Feldspar-Lithics
COPL	Compactional Porosity Loss
CEPL	Cementational Porosity Loss
mD	Millidarcy (unit of permeability)
Å	Angstrom (unit of length used in XRD patterns)
ppm	Parts per million (unit of concentration)
wt.%	Weight Percent

ABSTRACT

Full Name : Bandar Dhaifallah Al-Otaibi

Thesis Title : UNRAVELLING THE PROVENANCE, GEOCHEMICAL, AND
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This study investigates the provenance, geochemical, and diagenetic characteristics of the Silurian Sharawra Formation in northwest Saudi Arabia through an integrated multi-proxy approach. Petrographic analyses, major and trace element geochemistry, and mineralogical investigations were employed to establish the complex interplay between sediment supply, depositional environments, and post-depositional alterations within the formation. Major oxide discrimination diagrams and geochemical tectonic setting plots indicate that the sediments originate predominantly from the weathered products of the Arabian Shield, with the Jarish and Khanafriyah members indicating derivation from an intermediate to felsic igneous source, the Nayyal member being primarily sourced from felsic igneous rocks, and the Zubliyat member exhibiting a recycled sedimentary signature.

Quantitative measurements reveal significant variability in reservoir properties among the members. The Zubliyat member, for example, experienced mechanical compaction leading to porosity losses of approximately 25–35% and early cementation contributing an additional 5–8% reduction, resulting in porosities ranging from 18% to 30% and permeability values often exceeding 1000 mD. In contrast, the Jarish and Khanafriyah members display lower reservoir quality with porosities below 5% and permeabilities under 10 mD, while the Nayyal member presents intermediate characteristics. The study

also infers depositional conditions ranging from semi-arid to intermediate climates, underscoring a passive margin tectonic setting during deposition.

The findings enhance our understanding of how sediment provenance and diagenetic processes govern reservoir quality in siliciclastic systems, providing a robust framework for predicting reservoir performance and guiding hydrocarbon exploration. Recommendations for future research include detailed petrophysical studies, core analysis, and the integration of interdisciplinary approaches to further refine reservoir models and development strategies in similar geological settings.

Keywords: Silurian Sharawra Formation, Provenance, Geochemical Characteristics, Diagenetic Processes, Reservoir Quality, Passive Margin Tectonic Setting, Sedimentary Environments, Petrophysical Analysis

ملخص الرسالة

الاسم الكامل: بندر ضيف الله بدر المرشدي العتيبي

عنوان الرسالة: كشف خصائص المنشأ، و الجيوكيمياء و عمليات التحور التجانسية لمكون شرورا السيلوري في شمال غرب المملكة العربية السعودية

التخصص: جيولوجيا

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تتناول هذه الدراسة خصائص المنشأ، والجيوكيمياء، والعمليات التجانسية (الدياغينيتيك) لتكوين شرورا السيلوري في شمال غرب المملكة العربية السعودية، من خلال منهجية متعددة المؤشرات المتكاملة. وقد تم استخدام التحليلات البتروجرافية، وتحليل العناصر الأساسية والعناصر النادرة، والدراسات المعدنية لفهم العلاقة المعقدة بين مصدر الرواسب، وظروف الترسيب، والتغيرات التي تطرأ على الصخور بعد الترسيب. وتشير مخططات تمييز الأكاسيد الرئيسية والمخططات الجيوكيميائية للإعداد التكتوني إلى أن الرواسب مستمدة بشكل أساسي من منتجات تآكل الدرع العربي؛ إذ يُظهر كلٌّ من عضوي "جريش" و"الخانافية" تأثيرات مصادر متوسطة إلى حمضية، بينما تُستمد عضو "نيال" بشكل رئيسي من صخور حمضية، وتُظهر عضوية "الزبيليات" توقيماً لإعادة تدوير رواسب مستمدة من صخور حمضية.

وتكشف القياسات الكمية عن تفاوت ملحوظ في خصائص المكامن بين العضويات؛ فمثلاً، يُظهر أعضاء "الزبيليات" تأثيرات الضغط الميكانيكي التي أدت إلى فقدان مسامية بنحو 25–35٪، يضاف إليها فقدان ناتج عن الإسمنت المبكر بنحو 5–8٪، مما يؤدي إلى تراوح المسامية بين 18٪ و 30٪ وقيم نفاذية غالباً ما تتجاوز 1000 ملليدارسي. وعلى النقيض من ذلك، فإن أعضاء "جريش" و"الخانافية" تظهر جودة مخزنية أقل حيث تقل المسامية عن 5٪ وتكون قيم النفاذية أقل من 10 ملليدارسي، بينما تتوسط عضو "نيال" بينهما. كما تشير الدراسة إلى ظروف ترسيب تراوحت بين مناخ شبه جاف إلى متوسط، مما يعكس بيئة ترسيب على هامش مستقر للمحيط.

تساهم النتائج في تعزيز الفهم حول كيفية تأثير مصدر الرواسب والعمليات التجانسية على تطور جودة المكامن في الأنظمة الرسوبية السيليكالكستية، مما يوفر إطاراً قوياً للتنبؤ بأداء المكامن وتوجيه أنشطة استكشاف النفط والغاز. وتوصي الدراسة بإجراء المزيد من الدراسات التفصيلية للتحليلات البتروفيزيائية والنواتج النواة، فضلاً عن دمج المناهج متعددة التخصصات لتعزيز نماذج التنبؤ بتطور المكامن وتحسين استراتيجيات تطويرها في البيئات الجيولوجية المماثلة.

الكلمات المفتاحية: تكوين شرورا السيليوري, المنشأ, الخصائص الجيوكيميائية, العمليات التجاسية, جودة المكامن, البيئة التكتونية
على هامش القارة, البيانات الرسوبية, التحليل البتروفيزيائي

CHAPTER 1

INTRODUCTION

1.1 Introduction

Understanding the evolution, depositional history, and reservoir potential of the Paleozoic sedimentary formations in Saudi Arabia is crucial for hydrocarbon exploration and for academic research. The Arabian Peninsula Silurian Sharawra and Qusaiba Formations are important intervals within the stratigraphic record in which complex sedimentary processes, controls on the tectonic influence of hydrocarbon generation, and reservoir quality have acted to modify the strata. Petrographic, geochemical, and petrophysical analyses have made valuable multidisciplinary studies on these processes (Abbas, 2017; Al-Laboun, 2009).

The sediments that make up the Sharawra and Qusaiba Formations are evaluated in their entirety, the sedimentary provenance, the environments of deposition, and the diagenetic overprints. This study refines the understanding of how these processes control reservoir characteristics through detailed investigation and integration of advanced analytical techniques. The study provides insights into how these Silurian units evolved and then evaluates whether they can be used in this region as effective hydrocarbon reservoirs by synthesizing recent research outcomes using the multi-faceted analytical framework.

1.2. Background

Primary succession of the Silurian rocks in Saudi Arabia is dominantly associated with the northeastern margin of the Arabian Shield, where the rocks sit either on or immediately adjacent to the extensive Cambro–Ordovician sequence. In particular, the Sharawra Formation is important among these deposits. The Sharawra Formation lithologically is interbedded (silty, sandy, or shaly) and is widespread across northwest and central Saudi Arabia. There has been development in the historical nomenclature of these deposits. The term Sharaura sandstone member was first introduced by S. J. Roach (Bramkamp, 1951) after Jabal Sharaura (Sharawra) the upper sandstone member of the obsolete Tabuk Formation. Janjou (state the year of publication) and colleagues later elevated the Qalibah Formation (Mahmoud et al.1992) to group rank, the “Qalibah Group”, and further elevated the Qusaiba and Sharawra to formation rank (Mahmoud, Vaslet, & Hussein, 1992). The Sharawra Formation is disconformable to the base and unconformable to the top of the Early Devonian Tawil Formation (Al-Laboun, 2009), and is defined by its notably disconformable lower contact with the Qusaibah Formation.

Further insights into internal stratigraphy and depositional dynamics of the Sharawra Formation in recent studies have been also provided. The members Jarish, Khanafriyah, Nayyal, and Zubliyat consist mainly of purple, micaceous siltstones, and sandstones and are intercalated by minor shale (Janjou, 1996). The formation is dominantly micaceous (Jones, 1999) with moderately to well-sorted sandstone grains interbedded with shale and siltstone thin layers. These observations suggest that the deposition alternated among

higher energy conditions that promoted well-sorted sands and occasional quieter intervals for finer sediment deposition.

. Whereas Bramkamp et al. (1951) state that in the Tabuk Basin the formation reaches thicknesses up to ~600 m, in the Widyan Basin ~ 89 m and in the northern part of the Qusaibah depression the formation is eroded or missing (Bramkamp, 1951; Al-Laboun, 2009). Section of the Silurian sequence is mainly clastic (sand and silt) and limited other Lower Paleozoic series make a small contribution to the excessive sedimentary cover of the Arabian cratonigeria (Mandura, 1983)

Field studies also show that the wide Tabuk exposure is almost planar and interrupted broadly by NW–SE trending structural ridges and drainages that split the rock sequences into distinct blocks (Powers, 1966). Owing to such structural features, along with observed thinning trends towards the southwest, Late Silurian tectonic uplifts due to Caledonian movements have been attributed (Abbas, 2017; Al-Laboun, 2009). These tectonic events not only shaped the first deposition of the Sharawra Formation, but they also affected the erosion of the Sharawra later to reduce its overall thickness and lateral extent.

Sharawra Formation was mainly deposited in shallow water, pro-delta environment with an accumulation of sediment within a coarsening upward sequence (Janjou, 1996; Al-Hajri, 1998). The Sharawra was the third episode of post-glacial depositional cycles in the region as per Al-Laboun (2013). Additional fossil evidence including bivalves, gastropods, and bioturbation marks like tracks and trails also supports an interpretation of shallow marine dynamics (Powers, 1966). Although the formation has been noted as having potential for

hydrocarbon production and while the formation has been highlighted, commercial discoveries have not been reported.

In recent research, these depositional models have been refined by modern integration of petrographic, geochemical, and petrophysical methods. For instance, Abbas et al. (2017) offered new impetus on the facies distribution and tectonic controls on the Sharawra Formation, whereas other investigations e.g. Lashin (2023) highlighted the relation between mineralogical changes and diagenetic modification of reservoir quality. However, such integrated approaches have helped greatly to improve understanding of the controls on sediment thickness, lateral continuity, and post-depositional modification in this complex formation.

1.3. Problem Statement

The Silurian Sharawra Formation, part of the Qalibah Group, is a critical stratigraphic unit in the Tabuk Basin and northwest Saudi Arabia. While significant advances have been made in understanding its depositional framework, considerable gaps remain in the analysis of its provenance. Specifically, limited data exist on the sediment sources and transport mechanisms that contributed to the Sharawra deposits in northwest Saudi Arabia, particularly in the Tubaiq area in which the Sharawra Formation is widely exposed. The geological survey and study of the Sharawra Formation, specifically the Tubaiq area, were not fully completed by Aramco geologists due to the incomplete demarcation of the Saudi-Jordanian border (Fig.1). The absence of comprehensive provenance studies hinders a full understanding of sediment routing systems and tectonic controls during the Silurian period.

Recent hydrocarbon discoveries within the Sharawra Formation in the subsurface have further underscored the need for detailed diagenetic studies to understand reservoir quality.

Reservoir performance is largely controlled by diagenetic processes such as cementation, compaction, and secondary porosity development, all of which are influenced by the depositional and post-depositional history of the formation. However, the extent to which diagenesis affects porosity and permeability across the Sharawra Formation remains poorly constrained, particularly in the context of spatial variability across different structural and depositional settings.

Additionally, there is a lack of basin-wide geochemical fingerprinting and depositional environment analysis of the Sharawra Formation outcrops. Existing studies are limited in scope, often focusing on specific localities without providing a regional context. This lack of integrated geochemical data prevents a comprehensive understanding of how sediment provenance, depositional conditions, and subsequent diagenetic alterations interact to control reservoir properties. Furthermore, variations in depositional environments, such as shallow marine, deltaic, and storm-dominated settings, have not been fully characterized, leaving gaps in reconstructing the paleoenvironmental evolution of the formation.

The need for an integrated study that combines geochemical, petrographic and diagenetic analyses is critical. Such an approach would address the current knowledge gaps by unraveling sediment source regions, depositional processes, and diagenetic controls, thereby improving predictions of reservoir quality and hydrocarbon potential in the Sharawra Formation. This research aims to fill these gaps and contribute to a more comprehensive understanding of the formation's geological history and resource potential.

1.4. Significance of the Study

The implications of this study are derived from an ability to add to our knowledge regarding the interaction between depositional environments, tectonic activity, and diagenetic processes that have molded the Qusaibah, Sharawr, and Tawil Formations. This study works toward developing a comprehensive model of how sedimentary processes are linked to reservoir quality, a key factor in which hydrocarbons can be found.

The approach is particularly useful in the Arabian Peninsula where the Paleozoic successions are also important from academic perspective as well as from hydrocarbon potential. New insights regarding the depositional and tectonic history of these formations were recently developed in studies such as Abbas et al., 2017; Al-Laboun, 2009; and Lashin et al., 2023; however, the proper control of sediment thickness, lateral continuity, and diagenetic modification not yet understood. The contribution of this study is to address these gaps and therefore provide more accurate predictive models to reduce exploration risk and provide resource managers with tools to guide effective development strategies.

There are also wider implications for such basin analysis in the Arabian Peninsula, as additional information regarding the depositional and diagenetic history of the Sharawra Formation is warranted. The results can contribute not only to the hydrocarbon exploration but also to groundwater resources management and CO₂ sequestration projects, for the sustainable development of the subsurface resources in this critical region.

1.5. Research Objectives

1. Investigate the provenance of the Sharawra Formation through petrographic analysis, and major and trace elements geochemistry.

2. Characterize the geochemical signatures of the Sharawra Formation using X-ray fluorescence (XRF), to understand its depositional environments and conditions.
3. Assess the role of detrital mineralogy on diagenetic characteristics of the Sharawra Formation.
4. Evaluate the diagenetic alterations (i.e., compaction, cementation, and mineral dissolution/replacements) within the Sharawra Formation through petrographic microscopy, scanning electron microscopy (SEM), and X-ray diffraction (XRD) analyses.

1.6. Organization of the Thesis

This thesis is structured into seven chapters that systematically build upon one another to develop a comprehensive understanding of the sedimentary evolution, diagenetic processes, and reservoir potential of the Silurian Sharawra Formation in northwest Saudi Arabia. The organization is as follows:

- **Chapter 1: Introduction**

This chapter establishes the research framework by outlining the background, significance, and objectives of the study. It also presents the problem statement and provides a brief overview of the geological setting and depositional context of the Sharawra Formation.

- **Chapter 2: Literature Review**

In this chapter, previous studies related to sediment provenance, depositional environments, and diagenetic alterations are critically examined. The review

identifies existing gaps in knowledge and sets the stage for the integrated analytical approach adopted in this research.

- **Chapter 3: Methodology**

Detailed descriptions of the field work, sampling techniques, and laboratory analyses are provided in this chapter. It outlines the quantitative and qualitative methods employed—ranging from petrographic analysis to geochemical measurements—designed to characterize the formation's depositional and diagenetic histories.

- **Chapter 4: Provenance**

This chapter focuses on determining the sediment sources and tectonic influences that contributed to the formation of the Sharawra Formation. Using major oxide discrimination diagrams and other geochemical tools, it elucidates the diverse sedimentary inputs and complex depositional processes that have shaped the formation.

- **Chapter 5: Diagenesis**

The evolution of diagenetic processes is explored in this chapter. It discusses how early and burial diagenesis, including mechanical compaction, cementation, and mineral transformations, have modified the rock fabric and influenced reservoir quality.

- **Chapter 6: Geochemical Boundaries Between Members**

Here, the thesis delineates the geochemical transitions among the different members of the Sharawra Formation. Variations in mineralogy, elemental composition, and grain size are analyzed to establish distinct boundaries that reflect changes in depositional conditions and diagenetic regimes.

- **Chapter 7: Conclusion and Recommendations**

The final chapter synthesizes the major findings of the study, drawing conclusions about the interplay between sediment provenance, depositional processes, and diagenetic alterations. It also outlines recommendations for future research and exploration strategies, with an emphasis on further characterizing the most promising reservoir units.

Each chapter is designed to contribute a critical piece to the overall understanding of the Sharawra Formation, providing a logical progression from fundamental concepts to detailed analytical findings and practical implications for hydrocarbon exploration.

CHAPTER 2

LITERATURE REVIEW

2.1 Regional Geology and Stratigraphic Framework

Northwest Saudi Arabia has undergone a long and complex tectonostratigraphic evolution, which has important geological implications for hydrocarbon exploration. The late Paleozoic Arabian shelf passive margin on which the Sharawra Formation is deposited is broad (Al-Laboun, 2009). Early mapping and stratigraphic investigations have also shown that the Sharawra Formation is interpreted to lie on the organic-rich “hot shale” of the Qusaiba Formation as a key stage for a transition from deeper marine, low-energy deposition into more clastic-dominated, shallower environments (Abbas, 2017; Qadrouh, 2021).

Regional tectonic reconstructions indicate that the Arabian Plate was located at the southern margin of the paleo-Tethys and that overall the position of the passive margin is mainly a control of the underlying Precambrian Arabian Shield (Jones, 1999; Golonka, 2023). Extensive weathering of the shield supplied a persistent sediment supply, which is recorded in the siliciclastic deposits. In terms of distribution, such a unit, which is observed in the Old Qusaiba Village (the localities of the Sharawra Formation) is laterally extensive with systematic thinning to the southeastern peripheries which is attributed to differential subsidence and subsequent erosion (Al-Laboun, 2009; Abbas, 2017). Concerning fluid flow and chemical alteration patterns, such lateral variations are critically important for understanding the diagenetic history of the formation because subtle differences in sediment thickness and facies distribution may affect those patterns.

According to Golonka et al. (2023) and Muirhead et al. (2017), the regional sedimentary architecture is also a product of global plate dynamics. Cyclic Silurian deposits were preserved because the Arabian Plate evolved from a tectonically active margin during the Pan-African orogeny to a stable cratonic platform in which sediment was deposited (Golonka, 2023; Muirhead, 2017). These regional concepts are key to understanding both the provenance of the sediments and subsequent diagenetic modifications that have resulted in observed reservoir quality.

2.2 Provenance and Tectonic Setting

Many studies have revolved around determining the provenance of the Sharawra Formation because the source area affects not only the sediment composition but also the diagenetic evolution of the unit. Although major and trace element geochemistry were combined with the petrographic observations of Abbas et al. (2017), the dominant detrital load in the Sharawra Formation was determined to be of felsic to intermediate igneous and metamorphic rocks of the Arabian Shield. The sediments had a high quartz content, minimal feldspar, and well-rounded grains and these were subjected to prolonged weathering and reworking before deposition (Nesbit, 1982; Morad, 2003).

This provenance interpretation is also supported by heavy mineral analyses. For instance, Wanas and Abdel-Maguid (2006) studied the Wajid Sandstone, Cambro-Ordovician in age, which, although different in stratigraphy, has similar provenance signals to the Sharawra Formation, and they found an assemblage that includes zircon, tourmaline, and rutile (Wanas, 2006). They are consistent with a mature, granitic source from the interior of the Arabian Shield. In support of these results, Qadrouh et al. (2021) combined integrated REE and trace element analyses of underlying Qusaiba shale and confirmed a uniform source

area using a marine-dominated REE pattern exhibiting subtle hydrothermal overprints (Qadrouh, 2021).

The Sharawra Formation deposition also occurred in a passive continental margin according to tectonic discrimination diagrams as developed by Dickinson and Suczek (1979) and later modified by Dickinson et al. (1983), Bhatia (1983), and Bhatia and Crook (1986). Its high SiO₂ values and mature lithic fabric suggest prolonged, recycling and weathering sediment (Abbas, 2017). Global reconstructions (Golonka, 2023). put the region into a wider Gondwanan framework, confirming that despite the major tectonic change, the sediment source remained relatively unchanged and the tectonic regime was relatively quiescent when these units were deposited.

2.3 Depositional Environment and Sedimentology

Repeated deposition and erosion patterns represent cycles of sea level and energy conditions within the Sharawra Formation depositional environment. Field observations of the type locality in Old Qusaiba Village permit initial identification of a coarsening-upward sequence. The lower part of the formation of Abbas et al. (2017) is fine-grained, laminated shales upward into coarser, micaceous sandstones. The vertical gradation pertains to a change from conditions of deeper, transgressive situations to conditions of shallower, regradational situations where processes with higher energy prevail.

Detailed facies analysis of the sands of the Sharawra Formation has defined up to nine lithofacies. Laminated siltstones, interbedded shales, and massive, cross-bedded sandstones are some of these. Trough crossbedding and hummock cross-stratification are taken to indicate storm-dominated shoreface environments (Dott, 1982; Swift, 1983). Such

structures occur below the fair-weather wave base and are usually associated with high-energy sites subjected to episodic storm forcing.

Comparative studies provide additional context. The underlying Qusaiba shale, for example, records deposition in an anoxic, deep-marine environment with limited clastic input (Qadrouh, 2021). The siliciclastic content shows a marked increase in the Sharawra Formation, reflecting a change in the depositional framework most likely related to regression and the progradation of a deltaic system. Wadjid Sandstone (Wanas, 2006) is a similar wad with a repetition of fining upward cycles of braided stream deposits. Global sea level fluctuations in association with local tectonic forces were the main controlling factors of the Arabian Paleozoic depositional environments, given the regional similarity shown by them.

In addition, the Sharawra Formation is laterally none uniform in depositional architecture. Detailed outcrop studies (Abbas, 2017) have demonstrated lateral facies changes of great importance for diagenetic heterogeneity. Variations of energy conditions across the depositional system produced variations of grain size, sorting and sedimentary structures that subsequently influence subsequent diagenetic and reservoir quality of the formation.

2.4 Diagenetic Processes

Diagenesis of the Sharawra Formation involves a complex interaction of many modifying processes that affect the primary depositional fabric and porosity, permeability, and reservoir performance. Diagenetic evolution is broadly described as first shallow burial diagenesis then more later damage brought by tectonic uplift or magmatic intrusions.

2.4.1 Early (Eodiagenetic) Processes

Shallow burial diagenesis is early diagenesis manifested by mechanical compaction, early cementation, and the formation of antigenic clays. The Sharawra sandstones are dominated by very well-rounded detrital quartz with only a minor feldspar content (a texture that is believed to reflect little reworking and moderate compaction) reported by Abbas et al. (2017). Primary porosity is reduced by mechanical compaction, even though early cementation by calcite is often present (Young, 1984). Furthermore, the diagenetic process of precipitation of kaolinite from the feldspar and mica alteration is a major cause of pore space decrease (Morad, 2003).

This early diagenetic framework of the Sharawra Formation has provided a base upon which further change could occur. Thin section petrography studies (Abbas, 2017) show that compaction and early cementation are variable across different facies and impart more cementation to finer grained offshore facies when compared to coarser more high energy shoreface deposits.

2.4.2 Later (Telodiagenetic) Alterations and Magmatic-Induced Effects

In NW Saudi Arabia, both the traditional early diagenetic and later diagenetic processes have been connected with tectonic uplift and magmatic activity. According to Bello et al. (2023), tertiary basaltic sills have also intruded the sedimentary sequence in the Qasim Formation, which is also in the same regional system. Local temperature anomalies were generated and the mineralogical composition of the host rocks was altered by these intrusions as it produced localized temperature anomalies and acidic pore fluids (Bello, 2023). Although the Qasim Formation is stratigraphically different from the Sharawra Formation, the evolution of detrital quartz and conversion of kaolinite into dickite and

chlorite are two mechanisms observed that provide an important analog for understanding possible magmatic-induced diagenesis in the Sharawra Formation.

Worden and Morad (2003) report the transformation of kaolinite to dickite and this is generally associated with high temperatures (70–90°C) together with acidic fluids (Morad, 2003). That is, in such zones, secondary clay phases such as dickite and occasional chlorite are detected in the Sharawra Formation, indicating that secondary transformations in localized zones may be recorded. Because the precipitation of new diagenetic cements may further occlude porosity or the dissolution of detrital minerals may create secondary porosity which is partially compensating for these losses, these processes are significant.

The advanced geochemical studies (e.g. REE and trace element analysis by Qadrouh et al., 2021) indicate also that the original geochemical signatures may be somewhat hydrothermally or magmatically influenced even under a predominant marine condition (Qadrouh, 2021). Such evidence is also provided by small enrichments or depletions in some trace elements which are known to respond to temperature and fluid composition (Basu A. B., 1982).

2.4.3 Implications for Reservoir Quality

Reservoir properties of the Sharawra Formation have been affected by the cumulative effect of diagenetic processes. Mechanical compaction and cementation decrease porosity as noted through quantification by Abbas et al. (2017), which shows that compaction is the main porosity loss mechanism, where calcite and clays can further decrease effective porosity. Reservoir quality is the balance between porosity destruction (by cementation)

and creation (dissolution). In the Qasim Formation, Bello et al. (2023) show that intrusion-induced dissolution generates secondary porosity, although in most cases it was localized.

Also, independent constraints on diagenetic modifications are given by geochemical proxies (stable isotopes ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$), REE patterns). The isotopic values reported by Abbas et al. (2017) are considered relatively unshifted, indicating that the diagenetic effects have modified the original depositional fabric but have generally conserved the marine signature. As the Sharawra Formation has suffered compaction and cementation, the reservoir quality of the Sharawra Formation may survive even with a limited amount of heterogeneity capable of being developed provided diagenetic overprinting can be mapped in detail.

2.5 Geochemical Characterization and Proxy Applications

Geochemical analyses have been developed as critical tools for the reconstruction of depositional and diagenesis of sedimentary systems. Both provenance and diagenetic pathways have been probed with major element, trace element, and REE analyses applied to units from NW Saudi Arabia by several studies.

The REE patterns of the Qusaiba shale were differentiated by Qadrouh et al. (2021) as hydrothermal and marine, respectively. They find that the pattern is dominated by a marine signal with depleted (in LREEs relative to HREEs) and a negative cerium anomaly indicative of oxic to dysoxic conditions. Such patterns are consistent with other studies of marine siliciclastic deposits in the region (Basu A. e., 1975; Nesbit, 1982).

In Sharawra Formation, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values in the Sharawra Formation are stable isotope studies reported by Abbas et al. (2017) demonstrate a range of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$

values in the Sharawra Formation that fall within the ranges expected for marine carbonate systems. Interpretation of both depositional environment and diagenetic overprinting depends on these isotopic signatures. Stable isotope data, however, when combined with trace element data, can be incorporated into complete geochemical models that consider the interaction of the depositional and diagenetic processes and fluid flow (Coniglio, 2000; Worden, 2020).

Tectonic discrimination diagrams (Dickinson W. R., 1983; Dickinson W. R., 1979; Bhatia M. R., 1986), that first allowed the geochemical composition of sandstones to be related to their tectonic setting, have also been used. Like in Abbas et al. (2017) such diagrams were used to prove the record of Sharawra Formation is a passive margin setting. Additionally, this is a standard multi-proxy approach of integrating petrography with geochemical proxies for reconstructing the evolutionary history of sedimentary basins (Bhatia M. R., 1986; Young, 1984).

Integrated geochemical work on the Lower Cretaceous Yamama Formation (Khalil, R., 2024) gives further evidence of the very real utility of such work, placing constraints on depositional facies, which have proven resistant to other methods, and also refining recognition of diagenetic alteration of otherwise chemically conservative REE and stable isotope compositions. Even though the Yamama Formation is a carbonate system, these methodologies are directly applicable to siliciclastic systems such as the Sharawra Formation and expand the context of diagenetic evolution for those units.

2.6 Synthesis of Regional Diagenetic and Provenance Trends

Based on a synthesis of the literature that is available, the Silurian Sharawra Formation emanated from a stable, passive margin system on the Arabian shelf during a time of relative tectonic quiescence. According to the stratigraphic framework as described by Al-Laboun (2009) and further elaborated by Abbas et al. (2017), the formation was formed through a series of transgressive–regressive cycles. Geochemical analyses (Qadrouh, 2021) and heavy mineral studies (Wanas, 2006) support the assumption that the sediments mainly originated from erosion of the Arabian Shield.

The Sharawra Formation contains fine, low-energy shales alternating with coarser, high-energy sandstones that relate to a change from deeper offshore to more proximal delta front situations. Knowledge of the depositional variability is crucial for understanding diagenetic evolution because it determines the primary texture and the initial degrees of porosity distribution within the unit. Early diagenetic processes (i.e. compaction, early calcite cementation, precipitation of authigenic clays (kaolinite) further modify these primary properties (Worden, 2020; Abbas, 2017).

Regional tectonic uplift as well as localized magmatic intrusions influence the following diagenetic modifications. Sills of basaltic composition in the Qasim Formation provide evidence that they can generate high-temperature anomalies, and acidic pore fluids, and cause the dissolution of detrital quartz and transformation of clay minerals, as Bello et al. (2023) show. Processes documented in the Qasim Formation were still likely going on in the Sharawra Formation because of a similar setting and provenance. These diagenetic processes result in a heterogeneous reservoir with the balance between porosity destruction due to cementation and creation due to dissolution controlling reservoir quality.

Integrated geochemical proxies (REE patterns and stable isotope) that continually indicate a relatively moderate diagenetic over-printing from a marine depositional environment support these interpretations (Du, 2022). Cerium anomalies, high SiO₂ contents, and isotopic values that match those of the marine carbonate are all consistent with primary deposition at water conditions typical of seawater. At the same time, there are subtle variations in trace element distributions that point out the influence of local hydrothermal or magmatic fluids (Qadrouh, 2021; Nesbit, 1982).

However, these studies result in an overall regional model in which the Sharawra Formation reflects the interaction between a stable passive margin input deposition, the consistent sediment supply from the Arabian Shield, and diagenetic evolution dominated by normal burial processes and subsequent magmatic events. Data are abundant, from all of the petrographic, heavy mineral, major and trace element geochemical, REE, and stable isotopic studies, all of which collectively form a robust working framework regarding the evolution and implications for reservoir quality of this formation.

2.7 Literature Gap

Large progress certainly has been made in defining the Sharawra Formation and its regional context, but there still are several gaps for which research in the future will need to yield. However, studies on the overall stratigraphic framework (Abbas, 2017; Al-Laboun, 2009) are thorough, yet high-resolution lateral studies that relate facies changes to local diagenetic alterations are relatively less. Because such studies are necessary to accurately predict reservoir heterogeneity at a smaller scale, they were conducted.

Second, no equivalent studies of the effects of magmatic diagenesis in the Sharawra Formation are available. However, what remains an important area of research need is to determine whether similar magmatic events altered the Sharawra Formation similarly and quantify the effects of mineral transformations and porosity.

Third, the bulk rock samples have been studied in most geochemical studies. In situ analytical techniques (e.g., LA-ICP-MS, MicroRaman) also could be applied at the grain scale to provide higher resolution for diagenetic processes to solve ambiguities in the timing and extent of mineral transformations.

However, multivariate statistical analysis is needed to distinguish more than one source and heavy mineral assemblages and REE geochemistry have been used to infer provenance but these may be misleading if weathering of the source rocks locally modifies their geochemical signal (Basu A. e., 1975; Nesbit, 1982).

Finally, whilst the depositional environments have been described qualitatively, a correlation has not been fully established between facies variability, diagenetic pathways, and reservoir performance. Such integrated, multi-proxy studies would be highly beneficial for academic research as well as hydrocarbon exploration to address this gap.

CHAPTER 3

Methodology

An integrated approach to unravel provenance, geochemical and diagenetic characteristics of the Silurian Sharawra Formation is applied in the present study. This study bridges the field by detailed laboratory observations to create a broad spectrum to evaluate depositional processes and diagenetic alteration of reservoir quality.

Table 1: Methodology Framework

Step	Title	Description
1	Field Trip: Scouting & Planning	Initial reconnaissance and logistical planning for sampling strategy.
2	Field Observations & Sampling	On-site observations, lithological descriptions, structural measurements, and collection of rock samples.
3	Sample Preparation	Cleaning, crushing, and pulverizing samples to prepare them for lab analysis.
4	Analytical Experiments	Conducting petrographic analysis, XRF, XRD, SEM, and other lab investigations.
5	Quantitative Geochemistry & Data Interpretation	Integration and interpretation of multiscale data to understand provenance, diagenesis, and reservoir quality.

3.1 Field Work and Sample Collection

Field investigations of the Sharawra Formation were carried out in these quadrangles (Tubaiq and Tabuk) where they are widely exposed. The apparent outcrops exposures of the formation were detailed mapped and fully documented, as well as four of its members, Jarish, Khanfriyah, Nayyal, and Zubliyat. These field campaigns were used to record high-resolution facial variability as well as structural settings. High-resolution photographs and structural measurements were taken. Then, diverse lithologies and stratigraphic intervals were collected with specially chosen, representative rock samples coming from outcrop locations.

Two field trips were conducted. The first trip was for initial assessment of Tubaiq outcrops and sample collection of four members of the Sharawra Formations: Nayyal, Zubliyat members. The second was to complete the survey and cover the Sharawra Silurian rock outcrops in the Tubaiq Area, including the Jarish and Khanafriyah members, and integrate these in early field evaluation. The study area is in the area of Tubaiq, northwest Saudi Arabia. Researchers obtained 127 representative samples essential for the objectives of this study. Identify the study area and perform field scouting for geological features. During these field trips, we focused on 4 members of Sharawra Formation in the Tubaiq Area, northwest Saudi Arabia

3.2 Study Area

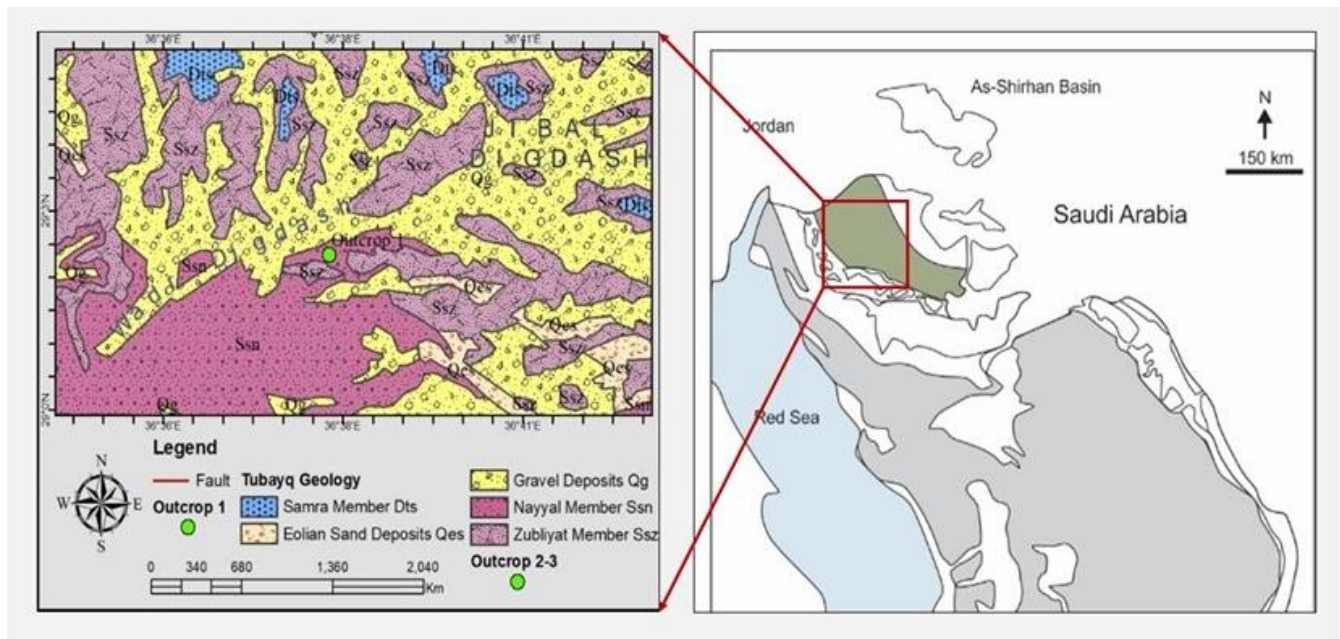


Figure 1: Map of the Tubaiq quadrangle showing locations of the studied outcrops of Sharawra Formation



Figure 2: Jarish Member outcrop showing horizontally bedded fine-grained micaceous sandstones and siltstones with minor shale interbeds, representing a low-energy offshore depositional setting



Figure 3: Khanfriyah Outcrop showing alternating thin-bedded sandstones and shales with visible lamination and moderate dip, indicative of a tidal-influenced depositional setting such as estuarine or tidal flat.



Figure 4: Nayyal–Zubliyat members outcrop showing a distinct contact, marked by the dashed white line, between the finer-grained, darker-colored Nayyal Member and the overlying coarser, lighter-colored Zubliyat Member.

The study area section clearly illustrates the geological setting of the Sharawra Formation in the Tubaiq quadrangle. Figure 1 provides a helpful map showing the locations of the outcrops studied. Figures 2 to 4 effectively display key outcrop characteristics of the different members: Figure 2 shows the Jarish Member with its horizontally bedded, fine-grained micaceous sandstones and siltstones indicative of a low-energy offshore environment; Figure 3 highlights the Khanfriyah outcrop with alternating thin-bedded sandstones and shales, suggesting a tidal-influenced setting; and Figure 4 depicts the sharp contact between the finer-grained Nayyal Member and the coarser Zubliyat Member, emphasizing the changes in depositional conditions. Together, these figures visually support the detailed sedimentological descriptions and reinforce the complexity of depositional environments within the Sharawra Formation.

3.3 Sample Preparation

127 samples were collected from the examined sections, covering the entire outcrops of all members of the Sharawra Formation. The samples collected were standard prepared in the laboratory before analysis. The samples were cleaned, crushed and pulverized to break samples apart into uniform particle size, for the petrographic and geochemical analysis to be uniform. Special care was taken for the mineralogical and textural characteristics in the preparation phase.

3.4 Laboratory Analyses

This is a multifaceted analytical framework of this study using both qualitative and quantitative techniques.

- **Petrographic analysis:** Thin sections were prepared from the samples to undertake a microscopically examination of textural and mineralogical features. Insights into this analysis were grain size distribution, sorting, and early diagenetic compaction and cementation.
- **Bulk Rock Geochemistry:** XRF techniques were utilized to measure primary and trace elements in bulk rock geochemistry. These data serve as geochemical discrimination trends to illuminate the depositional environment and tectonic setting.
- Bulk samples and clay isolates were analyzed by XRD to ascertain mineral phases in these rocks and to quantify the amount of later diagenetic alteration.
- The high-resolution images of diagenetic features were obtained by use of the SEM, as well as the microstructural properties of the samples. To better constrain their depositional and diagenetic conditions, stable isotope analysis was used as a complimentary technique.

3. 5 Laboratory Work:

Various analytical techniques were employed to examine the samples:

Polarized Microscope (PM):

Thin sections were examined using an Olympus EX51 (Figure 5) polarizing microscope.

The study of the thin sections (127 samples) provides information about framework and clay components, porosity types, texture types, and cement presence.



Figure 5: Olympus EX51 polarizing microscope used for petrographic analysis.

X-Ray Powder Diffraction (XRPD):

Powdered bulk of 127 samples siliciclastic and clay rocks were employed for quantitative phase analysis and mineral identification using X-Ray Powder Diffraction (XRPD) on the in-house empyrean XRD (Malvern-PANalytical) (Figure 6). The apparatus operates at 40

mA and 45 kV current and voltage, respectively, and is furnished with a copper tube and Cu K α 1 radiation with a wavelength of 1.5406 Å. The Rietveld Method was used to fit the XRD result, and the proprietary Malvern-PANalytical Highscore Plus software was used for processing.



Figure 6: XRD (Malvern-PANalytical) Model: Empyrean

Scanning Electron Microscope (SEM):

Representative of 25 rock chips from all members of Sharawra Formation were fixed on stubs and examined using a Zeiss Gemini 550 scanning electron microscope (SEM) (Figures 7- 9). The instrument was equipped with a backscattered electron (BSE) detector

and an Aztec energy-dispersive spectroscopy (EDS) system (Oxford Instruments, UK) to facilitate detailed mineralogical and textural analysis. Prior to SEM imaging, the samples were coated with a 30 nm platinum layer using a Quorum Q150R sputter coater (Figure 8) to enhance conductivity and imaging quality.



Figure 7: A Zeiss Gemini 550 scanning electron microscope (SEM)

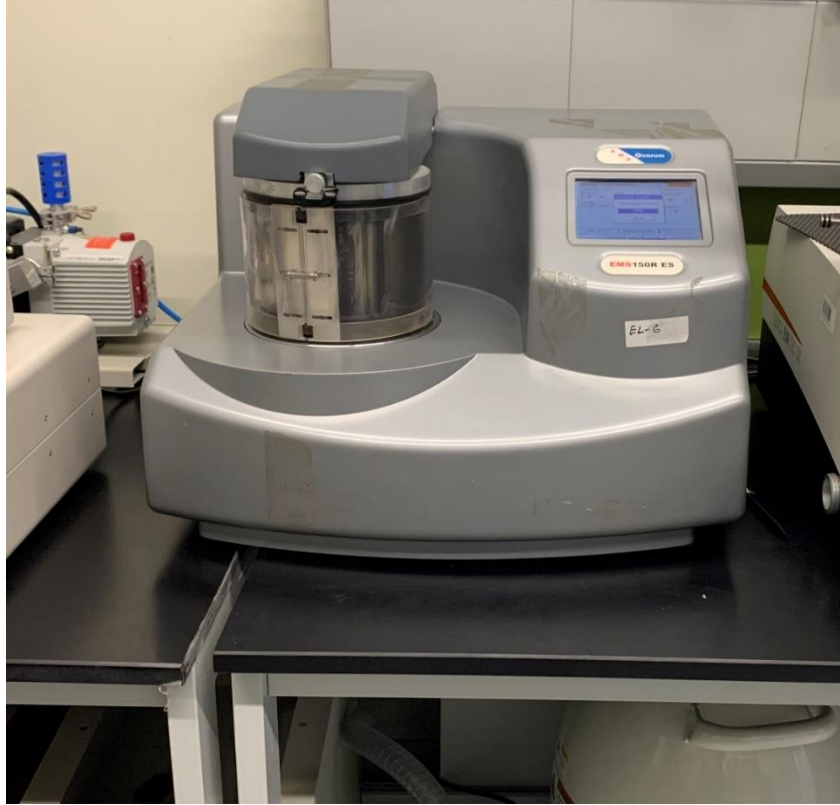


Figure 8: Quorum Q150R sputter coater



Figure 9: Representative rock chips

WD-XRF analyses:

The elemental composition of 127 representative samples was analyzed utilizing wavelength-dispersive X-ray fluorescence (WD-XRF) spectroscopy performed with a PANalytical Zetium spectrometer (Malvern PANalytical Figure 11). The samples were prepared as pressed powder pellets of 37 mm diameter (Figure 12). Approximately 12 g of finely ground rock powder by The Mortar Grinder RM 200 (Retsch-Figure 13) ,was blended thoroughly with 10 wt% XRF grinding aid (C10: cellulose), then pressed at 2 Nm pressure using a hydraulic press (PP 35 Pellet Press Retsch- Figure 14). The Zetium spectrometer features a 4 kW sequential XRF Spectrometer with configuration ED channel :HiPer ED channel ,position 2 ,detector :SDD30P, Attenuator holder :Conical collimator. And small spot mapping option. A high-resolution, drift-free copper (Cu) anode X-ray tube was utilized in conjunction with a wavelength-dispersive X-ray fluorescence (WD-XRF) detector, which was equipped with five analytical crystals: PE002 for elements ranging from aluminum to chlorine (Al–Cl), LiF200 for potassium to americium (K–Am), PX-1 for oxygen to magnesium (O–Mg), Ge111 for enhanced sensitivity in (P–Cl) range, and LiF220 for improved resolution of elements between vanadium and americium (V–Am). The acquired data were processed using PANalytical’s SuperQ software, which facilitated spectral acquisition, matrix correction, and comprehensive data analysis, incorporating integrated quality control protocols to ensure analytical accuracy and reliability.



Figure 10: PANalytical Zetium spectrometer (Malvern PANalytical)

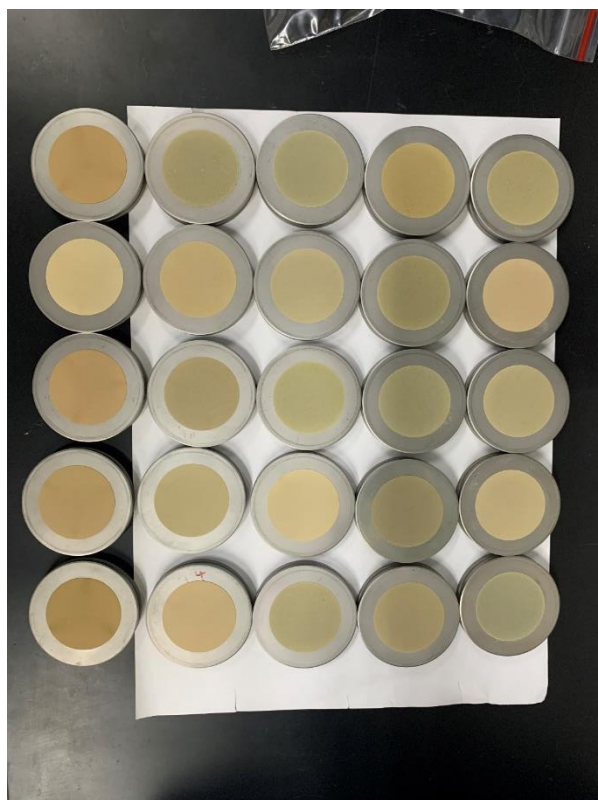


Figure 11: Pressed powder pellets samples



Figure 12: The Mortar Grinder RM 200 (Retsch)



Figure 13: PP 35 Pellet Press Retsch

Permeability measurements:

Permeability measurements were performed using a TinyPerm 3 permeameter (New England Research, USA-Figure 15,16) at multiple locations on polished surface slabs derived from the 127 collected rock samples. Permeability measurement was made up from 127 collected rock samples by polishing them to polished surface slabs and with a TinyPerm 3 portable air permeameter (New England Research, USA). To obtain representative readings, the instrument was placed directly onto the flat surfaces of the slabs at multiple places. Permeability values in the millidarcies (mD) were estimated using the air injection method, under ambient laboratory conditions, by sealing the probe against the rock surface to minimize leakage. Because of this nondestructive method, rock permeability could be rapidly and repeatably assessed over a variety of lithologies and diagenetic features.



Figure 14: TinyPerm 3 permeameter (New England Research, USA)

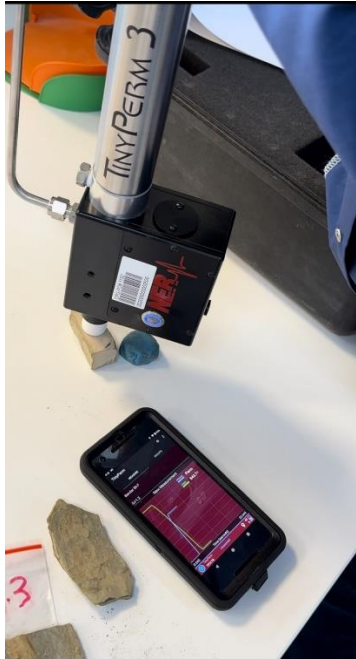


Figure 15: TinyPerm 3 permeameter

3. 6 Sedimentary Logs

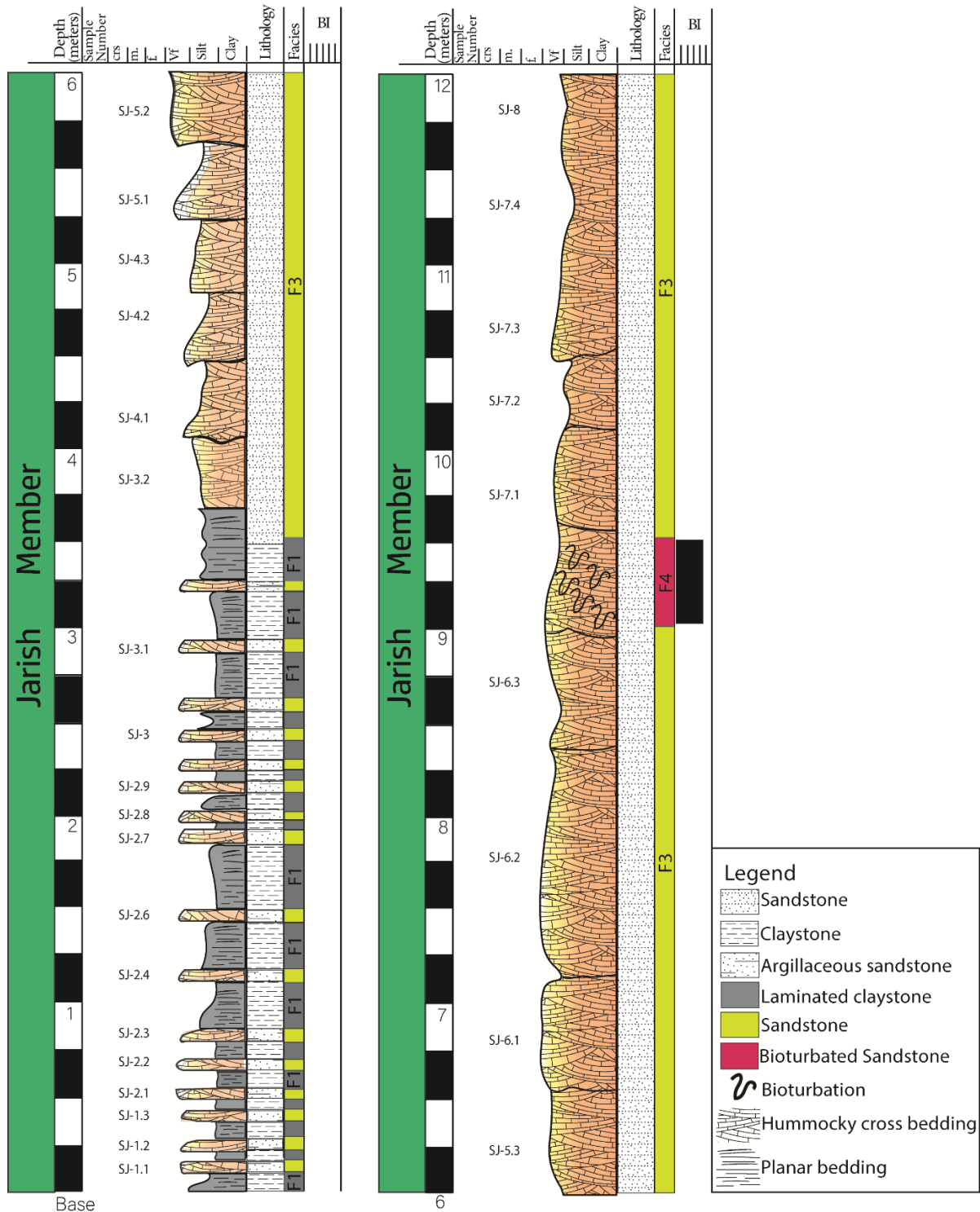


Figure 16: Graphic sedimentary log of the studied Jarish Member showing detailed lithological variations, including sandstone, claystone, laminated claystone, and bioturbated intervals, along with sedimentary structures such as hummocky and planar cross-bedding.

Jarish Member

Fine-grained sandstones and siltstones containing minor shale interbeds overlay parallel laminations in the Jarish Member, with occasional cross bedding. Deposition in lower to middle shoreface environments is indicated by these characteristics, with a possibility of transitioning to offshore environments toward the top of the section. The depositional energy is moderate to low, and the upward fining trend indicates the sequence of shallowing up and deeper water setting (Figure 16).

Khanafriyah Member

The sandstones and shales of the Khanafriyah Member are andesitic, andesitic, or pumicitic and are often interbedded with coarser beds. Cross-bedding and trace evidence of bioturbation are present, which are indicative of depositional conditions. Such features indicate an estuarine or tidal flat setting with an influence of tides. This member is transgressive-regressive and variable in depositional energy, as associated with tidal systems (Figure 17).

Nayyal Member

The shales and mudstones of the Nayyal Member are fine-grained sediments deposited in fine sand. The unit consists of laminated mudstones with very few indications of high-energy sedimentary structures. In combination, this lithological and structural assemblage implies a low-energy offshore marine or distal shelf environment that provided a favourable environment for fine sediment deposit accumulation (Figure 18).

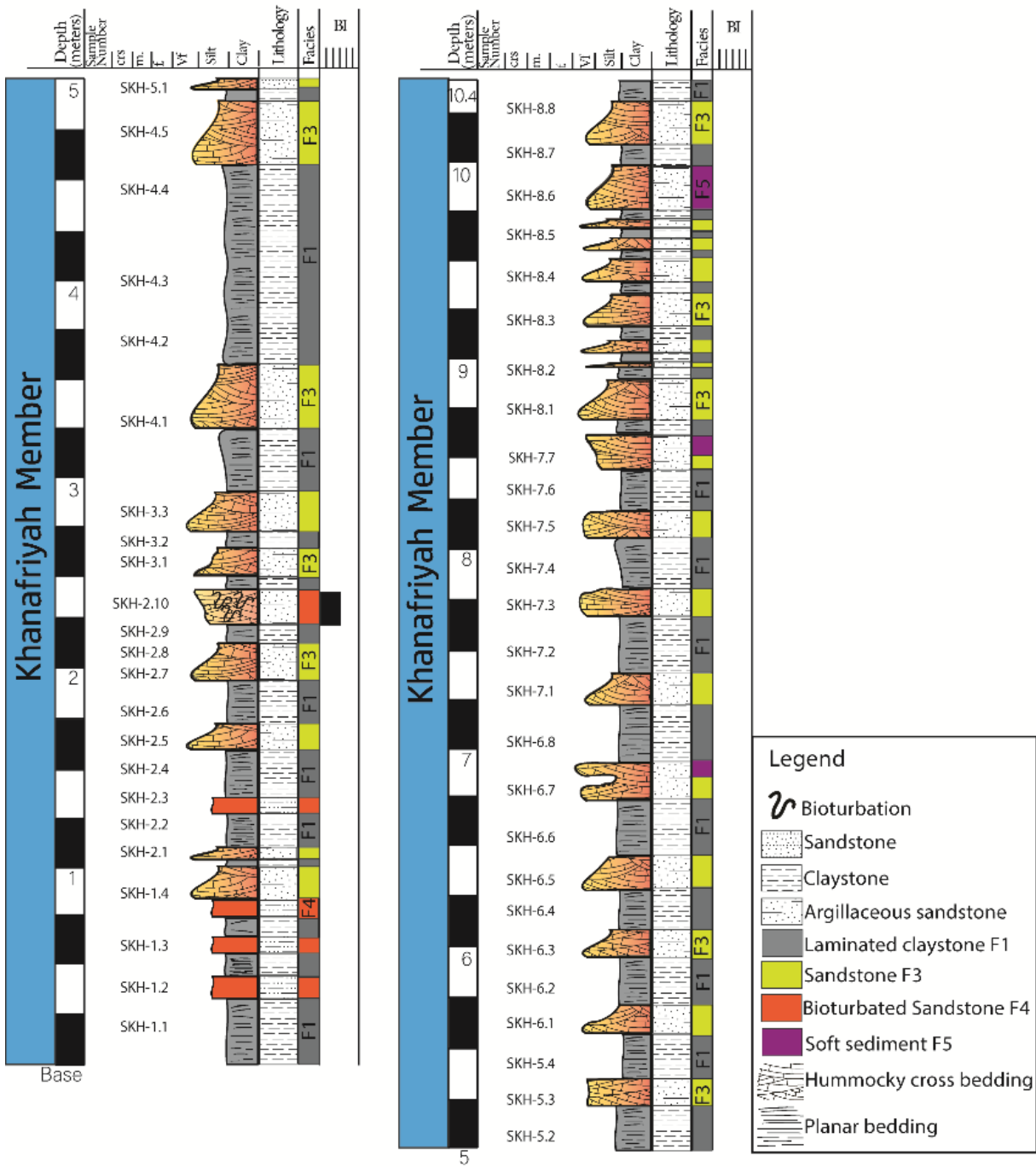


Figure 17: Graphic sedimentary log of the studied Khanafriyah Member showing alternating sandstone, claystone, and laminated claystone units with features such as bioturbation, soft-sediment deformation, and sedimentary structures including hummocky

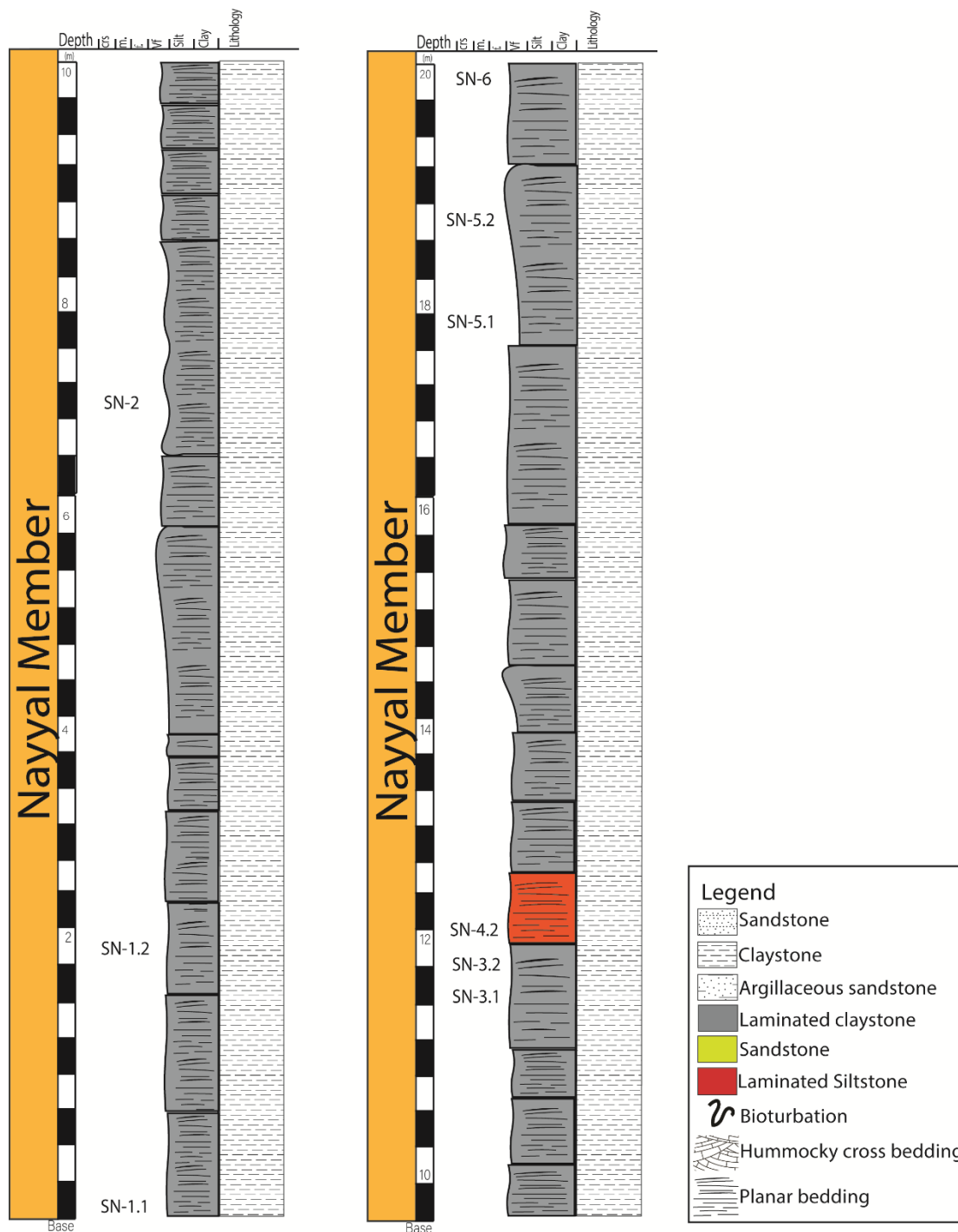


Figure 18: Graphic sedimentary log of the studied Nayyal Member showing predominantly laminated claystone and argillaceous sandstone with occasional laminated siltstone and minor sandstone layers, reflecting a low-energy offshore depositional environment

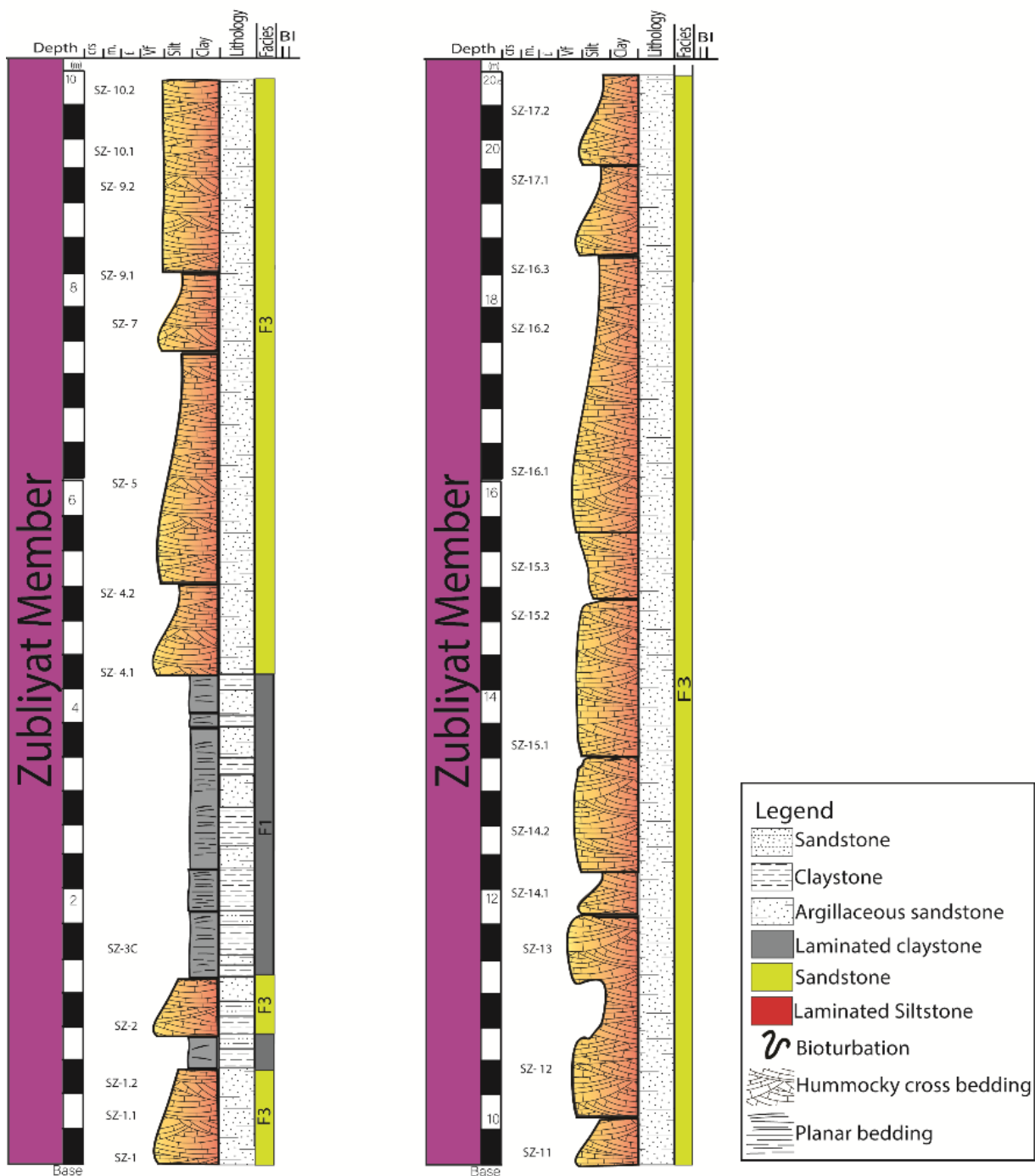


Figure 19: Graphic sedimentary log of the studied Zubliyat Member showing thick-bedded sandstone units interbedded with laminated claystone and laminated siltstone, along with hummocky and planar cross-bedding and bioturbation features, indicative of a high-energy

Zubliyat Member

The sediments indicated by the Zubliyat Member consist of coarser-grained sandstones with minor shale interlayers and show strong sedimentary structures like cross bedding, troughs, and ripples. The deposition of these features is interpreted based on deposition in a high-energy shoreface to deltaic environment. The progradational patterns suggest a regressive sequence that is likely to be delta front facies, and moderate to high depositional energy is indicated by the overall sedimentary architecture (Figure 19).

3. 7 Integration of Multiscale Data

The integrated model of the Sharawra Formation, derived from a synthesis of data, in part, based on extensive field observations and, until then extensive detailed laboratory analyses. We observe in the fieldwork a set of outcrop-scale sedimentological features like stratification change, lateral facies changes, and structural discontinuity, which are necessary to interpret the depositional environment in the field. However, at the same time, mineralogical composition and diagenetic alteration at the grain scale were investigated by laboratory methods including petrographic microscopy, XRF, SEM, and XRD analyses.

By integrating these datasets, we were able to associate the depositing process at the macroscopic scale with the mineral transformation at the microscopic scale. In particular, our lab and field observation integration resulted in the discovery that the geochemical signatures and mineralogical patterns observed in the lab match those observed in the field. This synthesis demonstrated that the depositional history, sediment provenance, and diagenetic changes control the reservoir quality of the formation. Our results also show that in most cases, variations in the degree of diagenetic overprinting, including cementation

and compaction, largely contributed to a large extent the variations in porosity and permeability on different facies.

CHAPTER 4

PROVENANCE

In this chapter a petrographic, geochemical, and mineralogical study was made to analyze the provenance of the Silurian Sharawra Formation comprehensively. The sedimentary source, depositional history and associated tectonic influences have to be well understood as they relate to the hydrocarbon exploration potential for the formation. The sedimentary characteristics of the formation and the climatic conditions during deposition during the formation are revealed by careful analysis of major oxide and trace element geochemistry. The provenance data also determines the tectonic setting, which is essential for deciphering the regional setting of the Sharawra Formation deposition.

4.1 Sediment Source

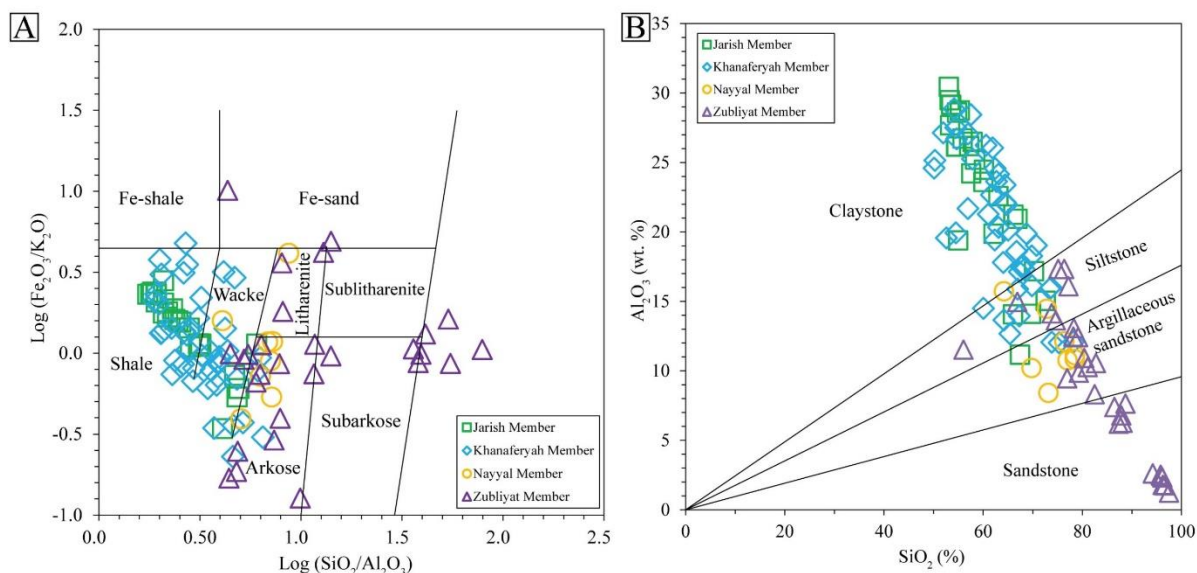


Figure 20: Plot of $\text{Log}(\text{Fe}_2\text{O}_3/\text{K}_2\text{O})$ against $\text{Log}(\text{SiO}_2/\text{Al}_2\text{O}_3)$ & Plot of Al_2O_3 (wt. %) versus SiO_2 (%)

Based on the results of several geochemical analyses, including major oxides (e.g., SiO_2 , Al_2O_3 , Fe_2O_3 , K_2O , and Na_2O) indicating mineralogical composition of the sediments, the Sharawra Formation's sediment source is identified. The composition of the sediments across various members of the Sharawra Formation is evident in Figure 20, which compares $\log(\text{Fe}_2\text{O}_3/\text{K}_2\text{O})$ vs. $\log(\text{SiO}_2/\text{Al}_2\text{O}_3)$. This plot is used to group the sedimentary rocks, like shale, wacke, arkosic sandstone, and quartz arenite. The data confirms that:

- **Jarish Member:** The geochemical signature of this member indicates that it is primarily composed of shale. The field description of the Jarish Member is consistent with mudstone lithology; the plot for Jarish Member lies in the shale region. This supports the interpretation that the Jarish Member is a deposit of lower energy environments, offshore or more offshore, and deeper marine environments.
- **Khanafriyah** starts with shale and becomes a sandstone in a way that shows a shift from finer-grained sediments to even coarser sand deposits. The variation in the composition of this sedimentary formation is a result of changes in energy levels within the depositional environment and, most likely, a change from deeper to shallower marine or deltaic conditions.
- **The Nayyal Member** shows a high content of feldspar as plotted by them in the arkosic region, which is a characteristic feature of a feldspar-rich sandstone. This implies that a proximal source area was present from which the sediments were derived, known to be from the erosion of feldspar-bearing granitoid rocks of the Arabian Shield. Then the Nayyal Member is interpreted to be deposited in a relatively high-energy environment, such as a braided stream or a delta front.

- **Zubliyat Member:** The Zubliyat has variability; some samples are arkosic sandstone, and others plot as quartz arenite. This implies mixed provenance since sediments are feldspar-rich and sediments are quartz-rich. Since the same depositional processes or mixed sediment sources did not significantly influence the Zubliyat Member, these variations may be caused by changes in the local climate and/or changes in the sediment supply system to the site of deposition.

The variations in the sediment composition among the four members, therefore, suggest variations in sediment supply, transport mechanisms, and depositional environment of the Sharawra Formation: a complexity of its provenance.

This is also supported by the information about the lithology of the sediments in Figure 5 (B). The Jarish and Khanafriyah Members plot predominantly in the claystone region, consistent with their fine-grained lithologies. However, on the other hand, the Nayyals and Zubliyat Members plot in the sandstone region characteristic of coarser, more energy rich depositional settings for these members. Using these plots, it is possible to see the type of sedimentary rocks deposited in the Sharawra Formation, including diversity in lithology and a range of depositional environments extending from mud to sand-dominated conditions.

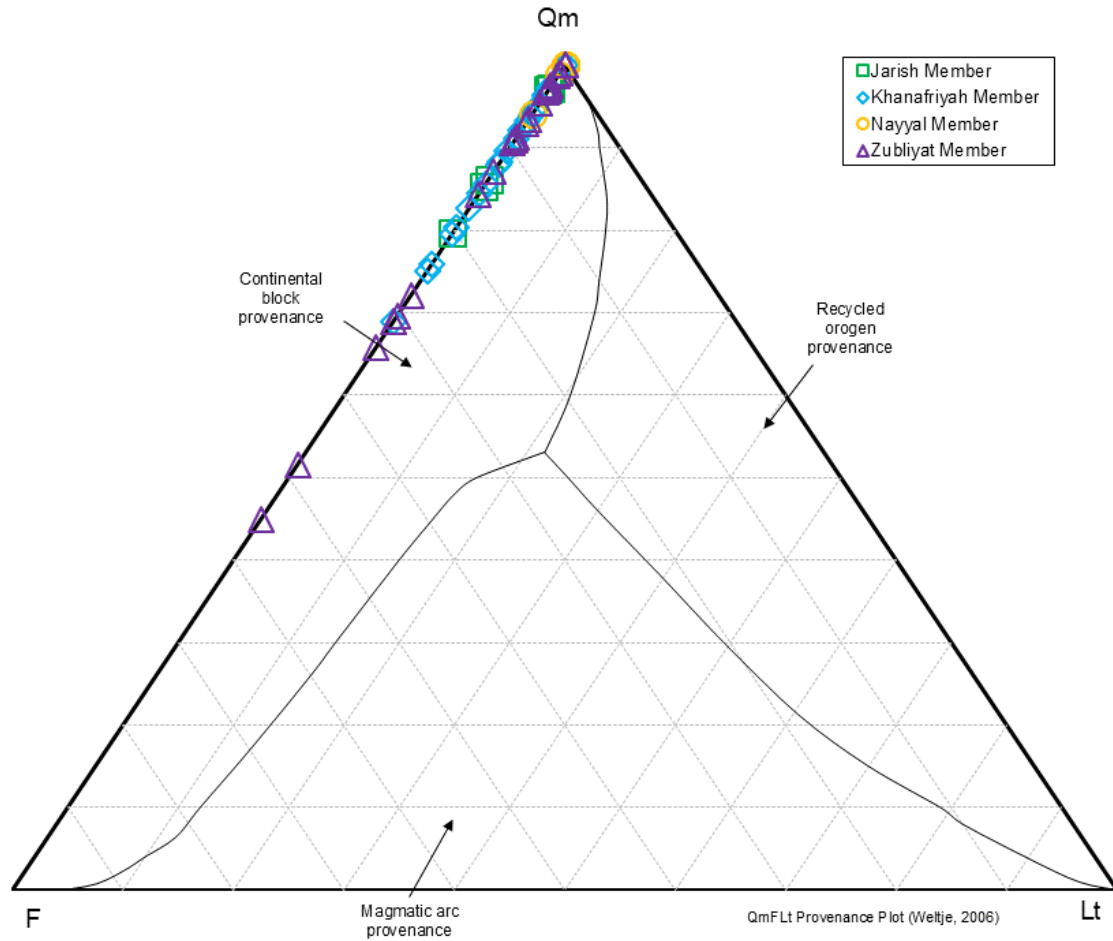


Figure 21: Continental block Provenance

Figure 6 shows the provenance of Sharawra formation sediments in a detailed grain composition of the framework. The data is distributed across the quartzose sedimentary rocks and felsic igneous rocks regions of the plot, which represent the main sources of the formation's sediments.

- **Samples of the Jarish, Khanafriyah, Nayyal, and Zubliyat Members** fall within the continental block provenance area, which is consistent with the interpretation that a felsic igneous source is responsible for the Sharawra Formation sediments. From this, you can infer the sediments were mostly derived from the Arabian Shield, a spot populated with granitic and felsic igneous rocks.

- **The Zubliyat Member**, has a minor deviation showing some deviation from recycled sedimentary rocks. This supports the notion that some of the sediments of the Zubliyat Member were recycled from older sedimentary deposits, implying a more complicated progradation of this member. The further presence of quartzose sedimentary rocks in this region expresses once again the idea of a mixed provenance for the Zubliyat sediments, in which the igneous and the recycled sedimentary materials entered into the deposition.

4.2 Tectonic Setting

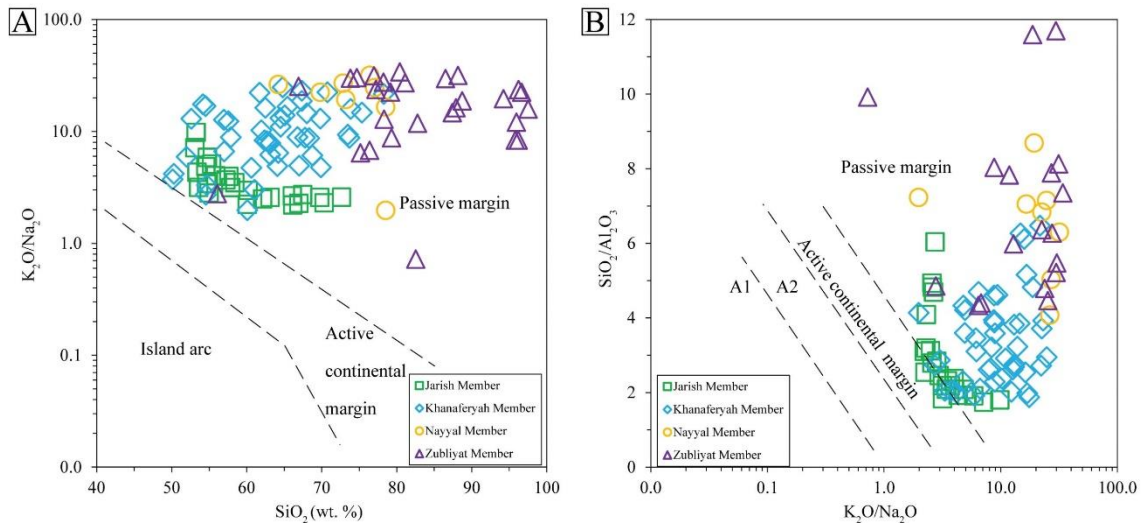


Figure 22 : Provenance discrimination plot

The tectonic setting controls provenance and deposition of the Sharawra Formation. In Figure 3, the tectonic discrimination plots indicate that the Sharawra Formation was deposited in a passive margin setting. The Sharawra Formation ratios of major oxides (e.g., $SiO_2 / Al_2O_3 / SiO_2$, $K_2O/Na_2O/SiO_2$) are used to plot and discriminate between tectonic settings, and the results place the Sharawra Formation, except for one sample, consistently within the passive margin setting.

- **Plotting K_2O/Na_2O vs. SiO_2** showing the K_2O/Na_2O vs. SiO_2 histogram of the Sharawra Formation sample, including the Jarish, Khanafriyah, Nayyal, and Zubliyat Members, as shown in figure 7 (A), depicts the samples in most of the samples fall in the passive margin region (figure 7A). Therefore, the Sharawra sediments were deposited in a relatively quiet tectonic environment where the source was a steady source of sediment with little tectonic disturbance.
- **Further support for passive margin interpretation is figure 7 (B)**, which is Al_2O_3/SiO_2 vs K_2O/Na_2O . Data points from the Sharawra Formation fit well with passive margin deposit characteristics that are generally characterized by stable, high quartz sediment with a similar amount of tectonics during deposition. Such settings are consistent with passive margin tectonics characteristic of the southern edge of the Arabian Plate that occurred during Silurian time.

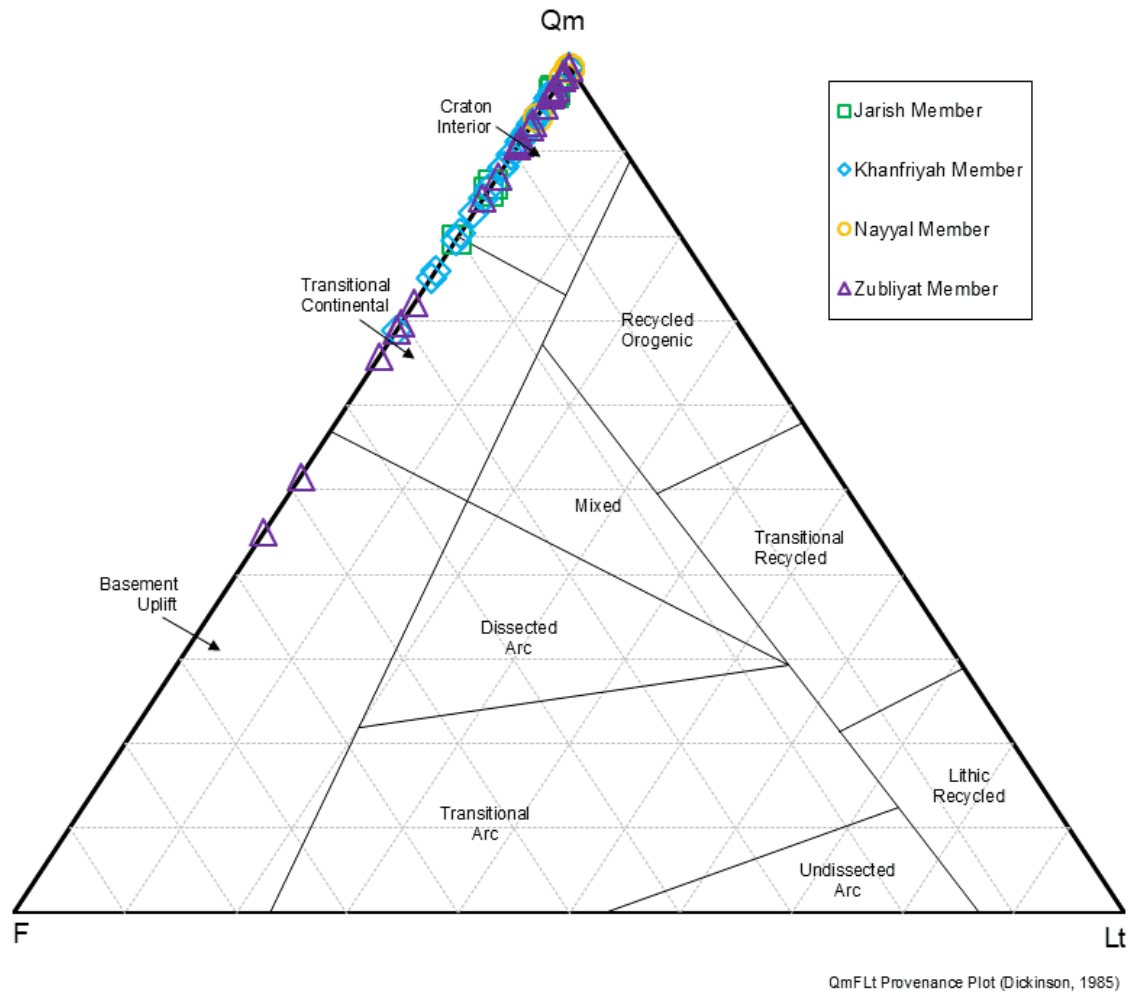


Figure 23: Tectonic of sediment provenance areas

Figure 8 adds further insights into the tectonic configurations in plotting QmFLt provenance. This plot of Sharawra sediments classifies them according to values obtained for quartz (Qm), feldspar (F), and lithic fragments (Lt). The majority of the Sharawra samples collected from the Jarish, Khanafriyah, Nayyal, and Zubliyat Members fall in the Craton Interior/Transitional region. Such a sediment source indicates that the Arabian Shield was probably the only source of sediments and, hence, consistent with the interpretation of the Arabian Shield as a source of sediments. In addition, the plot demonstrates some data points that trend towards the Basement up Uplift region, meaning

that the provenance of the Sharawra formation could also be fed by more dynamic uplifted areas within the region.

The results of Figure 8 are consistent with felsic igneous rocks and recycled sediments as being the main components of the Sharawra sediments that were deposited from a stable passive margin. Of these tectonic characteristics, these are compatible with the previous discussion of Sharawra Formation depositional history and are additional evidence for the hypothesis that much of the Sharawra Formation deposition occurred in a tectonically quiescent setting with contribution from areas proximal to the uplift.

4.3 Paleoclimatic Conditions

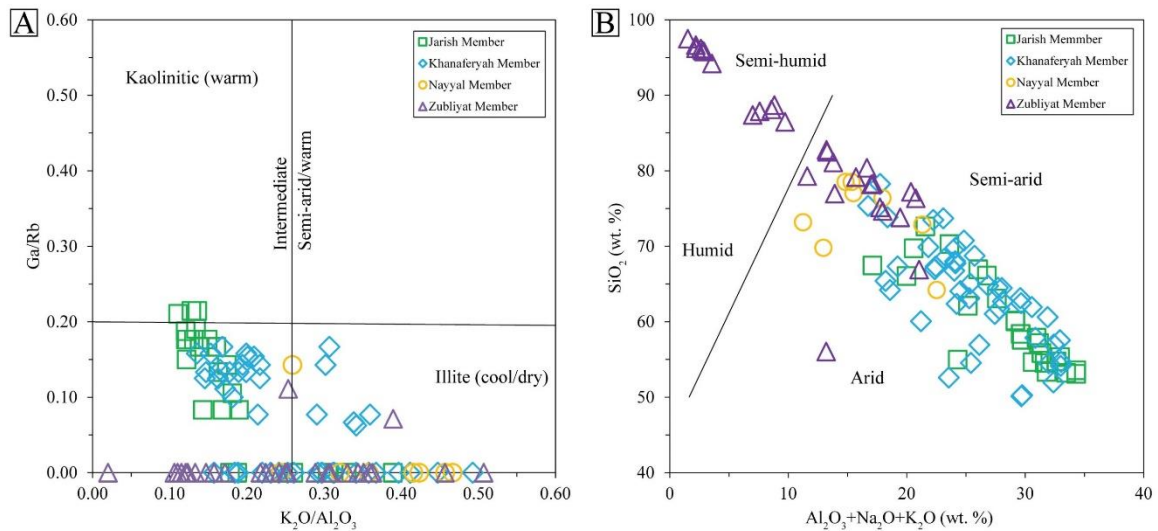


Figure 24: Plot of Ga/Rb against K₂O/Al₂O₃ & Plot of SiO₂ (wt. %) against Al₂O₃+Na₂O+K₂O (wt. %)

Geochemical proxies for weathering, and hence climate, allow inferences to be made of the paleoclimatic conditions under which the Sharawra Formation was deposited. To assess the climatic conditions involved in the deposition, Figure 9 (A), which plots the Ga/Rb ratio against K₂O/Al₂O₃ ratio, is used. Here, the majority of the samples from the Sharawra Formation plot within the semi-arid to intermediate climatic field, which suggests that the

formation was deposited under transitional climatic conditions. Such characteristics are present among the Nayyal and Zubliyat Members, namely the semi-aridity, where weathering was moderate and the rainfall was limited.

Additional insight is given over the climatic conditions provided by Figure 9 (B), which plots SiO_2 vs. $\text{Al}_2\text{O}_3 + \text{Na}_2\text{O} + \text{K}_2\text{O}$. Zubliyat Member plots in a region where the other members indicate slightly higher rainfall and weathering during their deposition. Depositional in a more dynamic climate phase with higher rainfall and sand mobilization is reflected by the increased influx of sand from continental sources, such as in the Zubliyat Member.

4.4 Sediment Maturity and Weathering Intensity

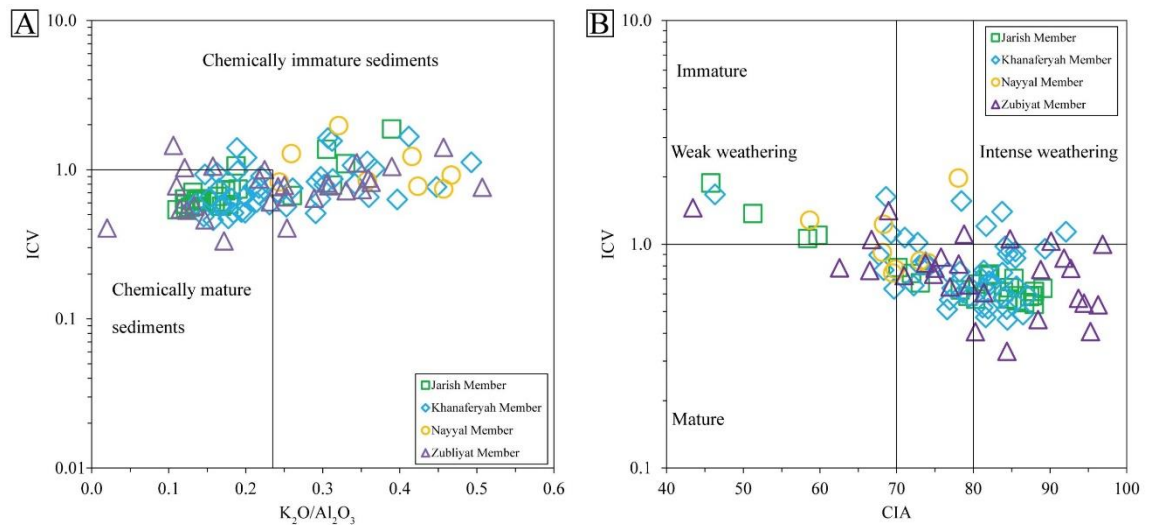


Figure 25: Plot of ICV vs. $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ & Plot of ICV vs. CIA

The ICV (Index of Chemical Variability) vs. $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ plots in Figure 10 (A) provide information on the maturity of the sediments. Chemical results indicate that, by and large, most of the samples from the Sharawra Formation are chemically immature, possessing

high proportions of feldspar and other unstable minerals. This is a feature of such sediments that are not greatly weathered and which are as yet immature in their chemical maturing.

For example, Figure 10 (B) shows that the sediments have degrees of weathering, the Khanafriyah Member being part of the region of weak weathering, while other members have stronger degrees of weathering. This more humid climatic condition is also indicated by the highest degree of weathering exhibited in the Zubliyat Member. Given the varying degrees of weathering across the members, the Sharawra Formation experienced both dry and wet periods rather more humid climatic conditions during deposition.

4.5 Provenance Discrimination

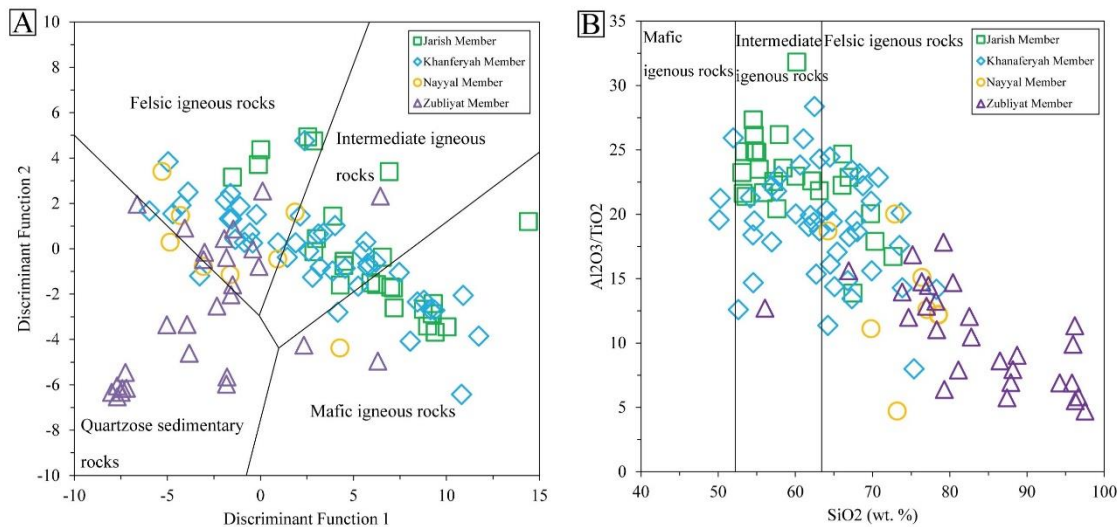


Figure 26: Provenance discrimination plot & Al₂O₃/TiO₂ ratio versus SiO₂ (wt. %) plot

Figures 11 (A) and 11 (B) of the provenance discrimination plots further clarify the source rocks of the Sharawra Formation. In Figure 11A, the discriminant function plot indicates that most of the Sharawra Formation sediments are of felsic igneous rock type, but there is also mixing of quartzose sedimentary rocks contributing to the Zubliyat Member. The

presence of a mixture also indicates that the Zubliyat Member contains some recycled and older sedimentary rocks.

Figure 11 (B), which shows $\text{Al}_2\text{O}_3/\text{TiO}_2$ and SiO_2 further confirm this, where the Zubliyat Member is more mixed in provenance than the majority of the Sharawra sediments. These thus indicate that in addition to primary igneous rocks as suggested elsewhere (Sakitova et al, 2011), the Zubliyat sediments were also eroded and redeposited from older sediments that had been reworked and reworked during more dynamic depositional events.

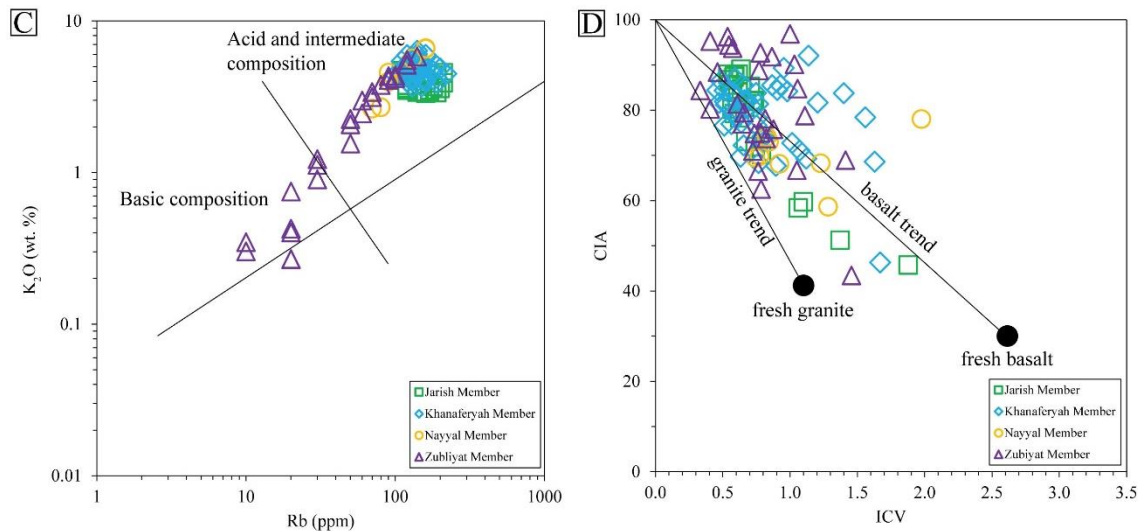


Figure 27: Provenance Rb (ppm) & ICV

In Figure 12, the researcher focused on Asheeft et al. (1982), tectonic discrimination, and chemical composition of the Sharawra sediments using $\text{K}_2\text{O}/\text{Na}_2\text{O}$ vs. Rb and C/A vs. CIA plots. In addition, these figures provide further insight into the chemical and tectonic setting of the sediments.

C: K_2O vs. Rb plot of figure 12 differentiates the acidic and intermediate composition. Sharawra sediments are mainly located in the acidic, intermediate composition zone, and are strongly leucoxenitic. Thus, it agrees with the results from Figure 6, which shows

a dominant felsic igneous source, whereby the Sharawra Formation has been sourced mainly from continental blocks, preferably, granitic rocks.

Figure 12 (D) provides an understanding of the trends of weathering across the formation with the CIA vs. C/A plot. Sharawra samples here mainly plot on the granite trend and thus are indicative of a source from granitic rocks that were moderately weathered. They are relatively mature, but some chemical weathering is present, as is typical of the weathering conditions suggested by the previous two figures. The data indicates a granitic source main, but with some contribution from basaltic sources in some places, as suggested by the slightly increasing trend towards the basaltic.

Both felsic igneous and basaltic sources in mixed proportions are further confirmed in the Sharawra Formation, with some sediments displaying chemical weathering.

4.6 Implications for Reservoir Quality

Significant implications of the provenance analysis on the reservoir quality of the Sharawra Formation are provided. The provenance of the formation appears to vary significantly from feldspar rich sandstones in the Nayyal Member and quartz rich sandstones in the Zubliyat Member, indicating that it may also have varying degrees of heterogeneity in terms of porosity and permeability. Given the higher feldspar content in the Nayyal Member, unstable minerals may undergo a diagenetic alteration, thereby reducing the reservoir quality. On the other hand, the more mature Zubliyat Member with higher quartz content, but less diagenetic alteration, may provide the better potential in reservoir terms.

4.7 Synthesis of Provenance Data

The provenance data that are presented in this chapter serve as a source of information for reconstructing the depositional history of the Sharawra Formation and its hydrocarbon potential. Igneous felsic rocks, as well as recycled sedimentary sources, make up the predominant sediment sources of the sediment. The formation was deposited at a passive margin shelf, in semi-arid to intermediate climatic conditions, subject to variations in climate during formation. The model of notational provenance shows some sandstone variation, feldspar-rich and quartz-rich, that is representative of a more dynamic depositional environment.

CHAPTER 5

DIAGENESIS

5.1 Introduction

Diagenesis is the physical, chemical, and biological change in sediments that takes place after deposition and during burial, culminating in loose sediments being turned into sedimentary rock. Significant changes to the petrophysical properties of siliciclastic reservoirs include porosity, permeability, mineralogy, and framework. The integrated interpretation of diagenetic processes affecting the Sharawra Formation in northwest Saudi Arabia based on petrographic thin section analysis, SEM imagery, XRD results, elemental mapping, point counting data, and porosity–permeability measurement is presented in this chapter. The analysis is over four members of the formation (Jarish, Khanafriyah, Nayya,l and Zubliyat).

5.2 Early Diagenetic Features

5.2.1 Mechanical Compaction

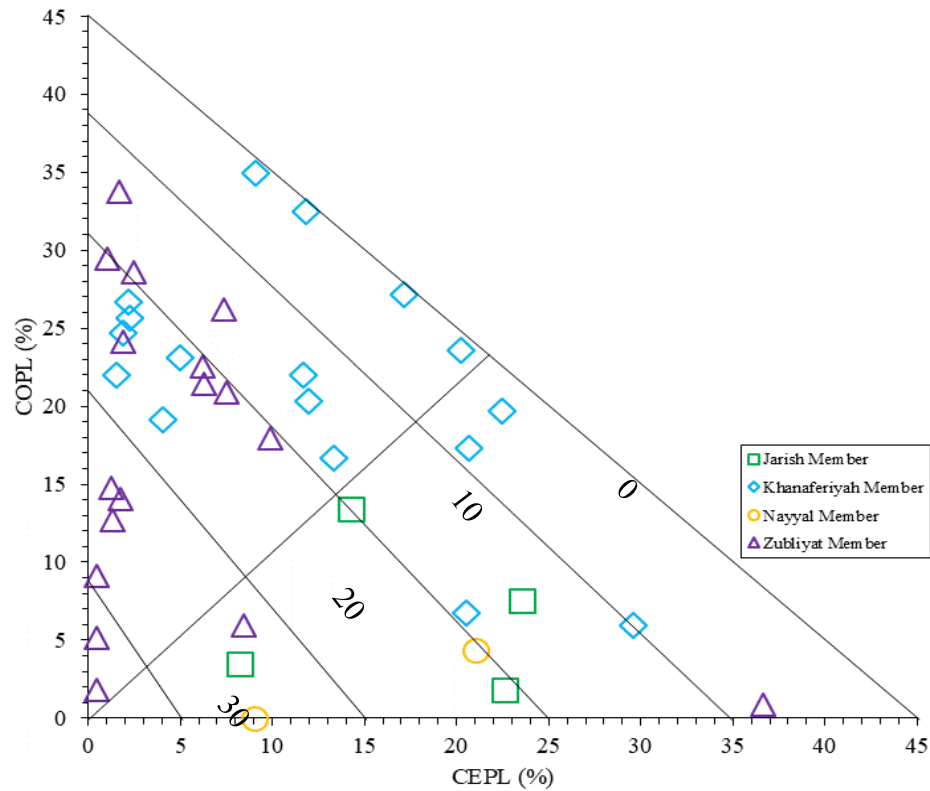


Figure 28: Compaction vs. Cementation plot

The earliest and most effective process of reducing porosity in the Sharawra Formation is mechanical compaction. Shallow to moderate burial is accomplished by rearranging grains, ductile component deformation, and pressure solution at grain contacts. Compactional porosity loss (COPL) and cementational porosity loss (CEPL) were quantified by using petrographic point counting and the Lundegard (1992) approach. As is shown in Figure 13, more than 70% of samples are found to reside within the compaction-dominated domain wherein porosity loss through mechanical grain rearrangement exceeds cementation effects. For instance, COPL(Compactional

Porosity Loss) values of Zubliyat samples vary 25–35%, and CEPL (Cementational Porosity Loss) is usually less than 5–8%. As in Khanafriyah, analogous trends are exhibited in these rocks, which provide support to the contention that these rocks were subject to intensive burial compaction and precipitation of cement. Relatively high intergranular porosity is preserved in some Zubliyat samples even with this compaction, due to the late development of cementing clays and the coarse grain size, respectively.

5.2.2 Grain-Coating and Pore-Lining Clays

Nayyal

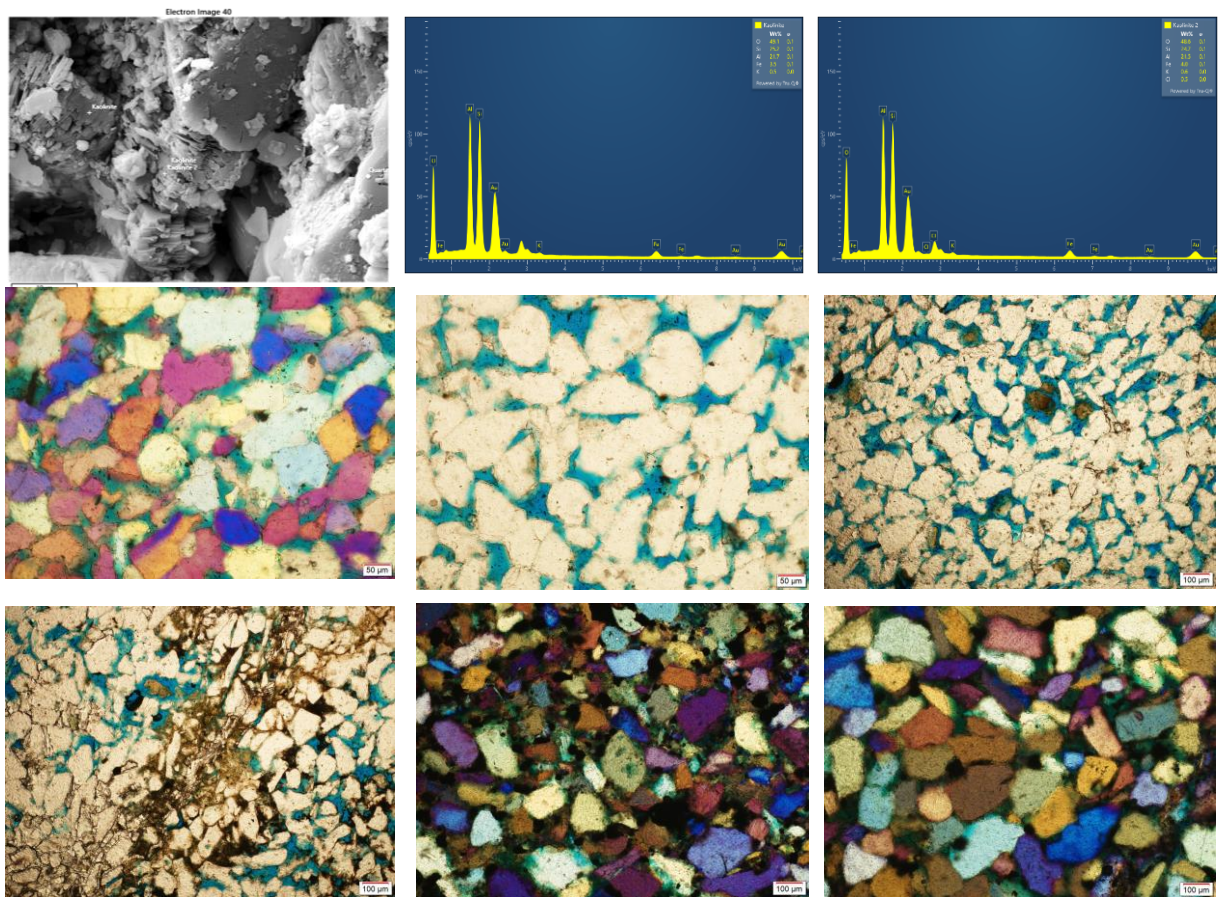


Figure 29: Petrographic and SEM images of the Nayyal Member showing textural and diagenetic features under plane-polarized light (PPL), cross-polarized light (XPL), and scanning electron microscopy (SEM).

Zubliyat

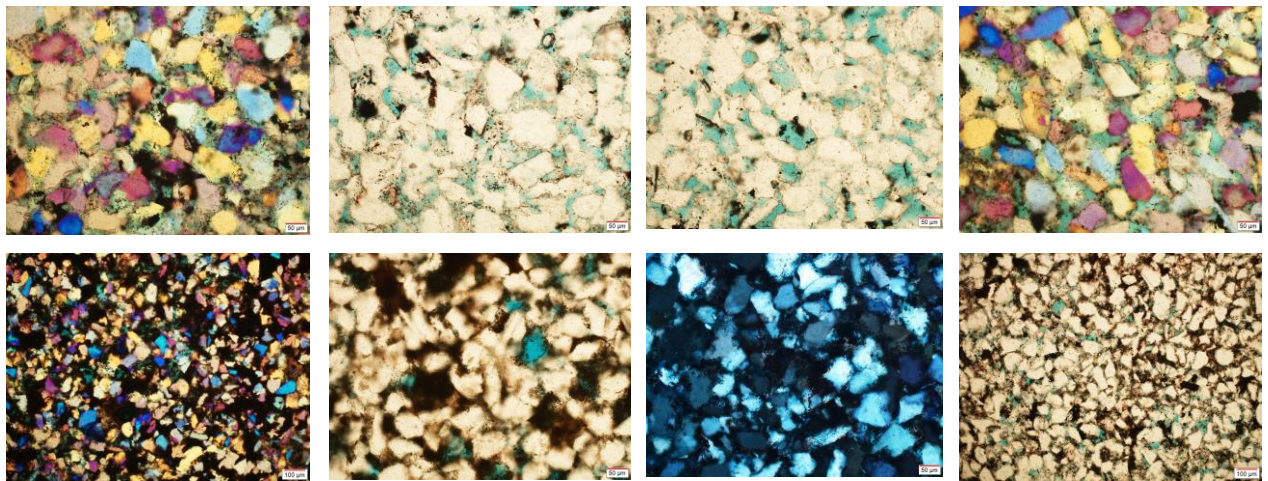
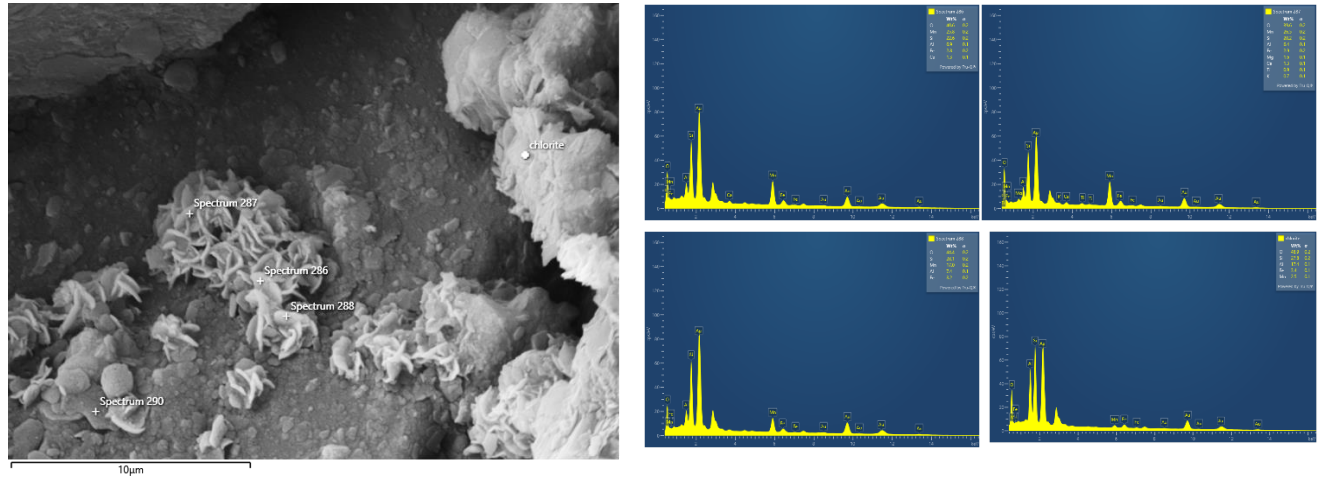


Figure 30: Petrographic and SEM images of the Zubliyat Member showing textural and diagenetic features under scanning electron microscopy (SEM) and polarized light (PPL and XPL).

Petrographic and SEM images of the Zubliyat Member (Figure 30) show that it is coarsely grain sandstone, with subrounded quartz grains of various sorting. The detailed grain surface is observed under SEM, which shows authigenic clay and possibly feldspar alteration, and early diagenetic processes like clay cementation and feldspar dissolution. Quartz exhibits very high mineralogical maturity, well indicated by the strong birefringence establishing quartz in the thin section photomicrographs, viewed both under plane-polarized light (PPL) and cross-polarized light (XPL). Through inspection of the polished thin section, visible intergranular porosity was found with some of the pore spaces

occluded by early calcite cementation. The texture of the samples in the photomicrographs is due to mineral composition and diagenetic overprint, which results in the color of the patterns. Such features are consistent with the interpretation that the depositional environment was high-energy shoreface or deltaic in configuration and that significant early diagenetic alteration has occurred during burial.

5.2.3 Authigenic Kaolinite

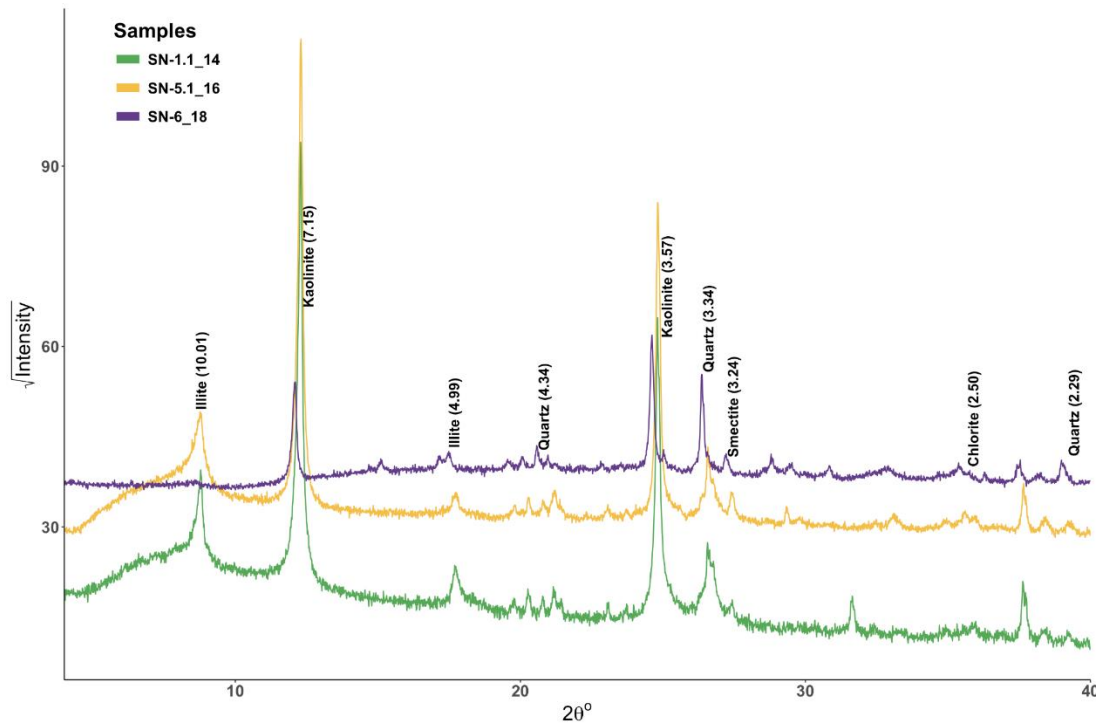


Figure 31: XRD clay-fraction pattern Nayyal Member

On the authigenic phase side, kaolinite is mainly formed from the alteration of feldspars in meteoric water environments of acidic pH. As XRD data confirms its dominance in the Nayyal and Jarish Members with strong peaks at 3.57Å and 7.15Å (Figure 31), this mineral may be termed wobbleite. The kaolinite in thin sections (Figure 14) and in SEM imagery is in the form of vermicular, platy aggregates that fill intergranular and intragranular pores. It is an early-stage clay mineral that has grown under low salinity, oxidizing conditions, and greatly reduces the permeability because it occupies the pore space. Furthermore, however, kaolinite is associated with preserved microporosity between stacked plates in some intervals, such as in Nayyal. The low permeability observed in the Jarish member is explained by the fact that the member is also rich in kaolinite (higher abundance) compared with the other two members.

5.3 Burial Diagenetic Features

5.3.1 Mineral Distribution and Diagenetic Features in the Samples

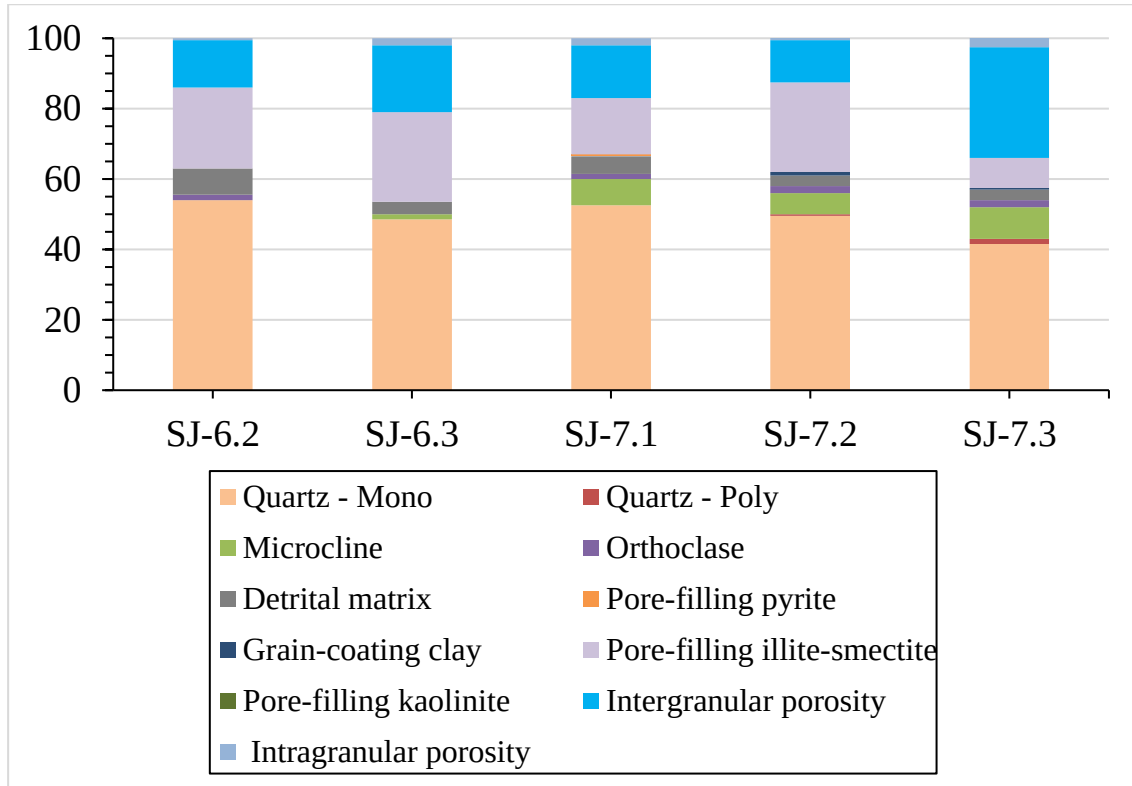


Figure 32: Jarish- Compositional Histogram

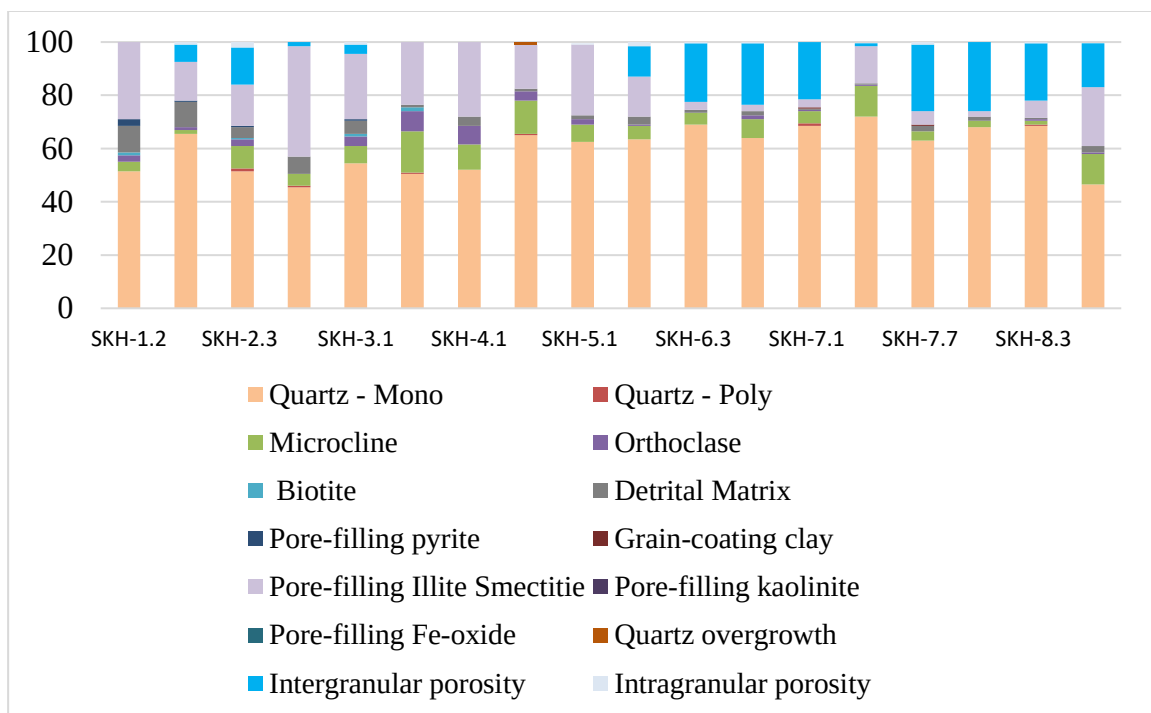


Figure 33: Khanafriyah Compositional Histogram

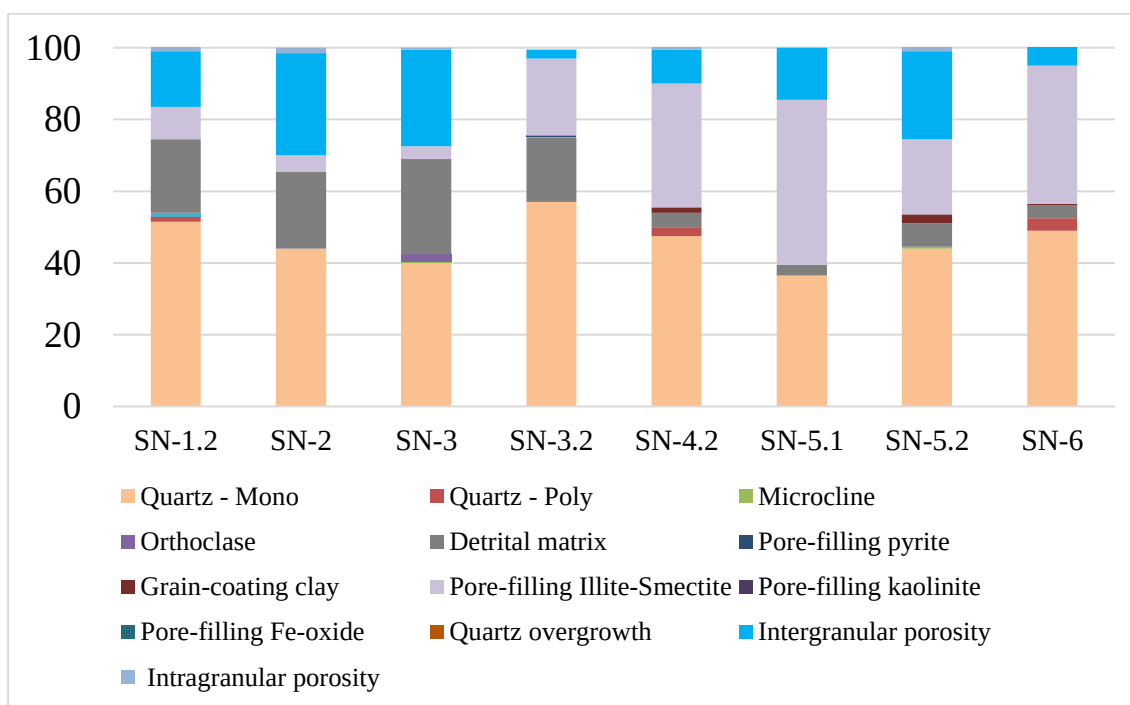


Figure 34: Nayyal Compositional Histogram

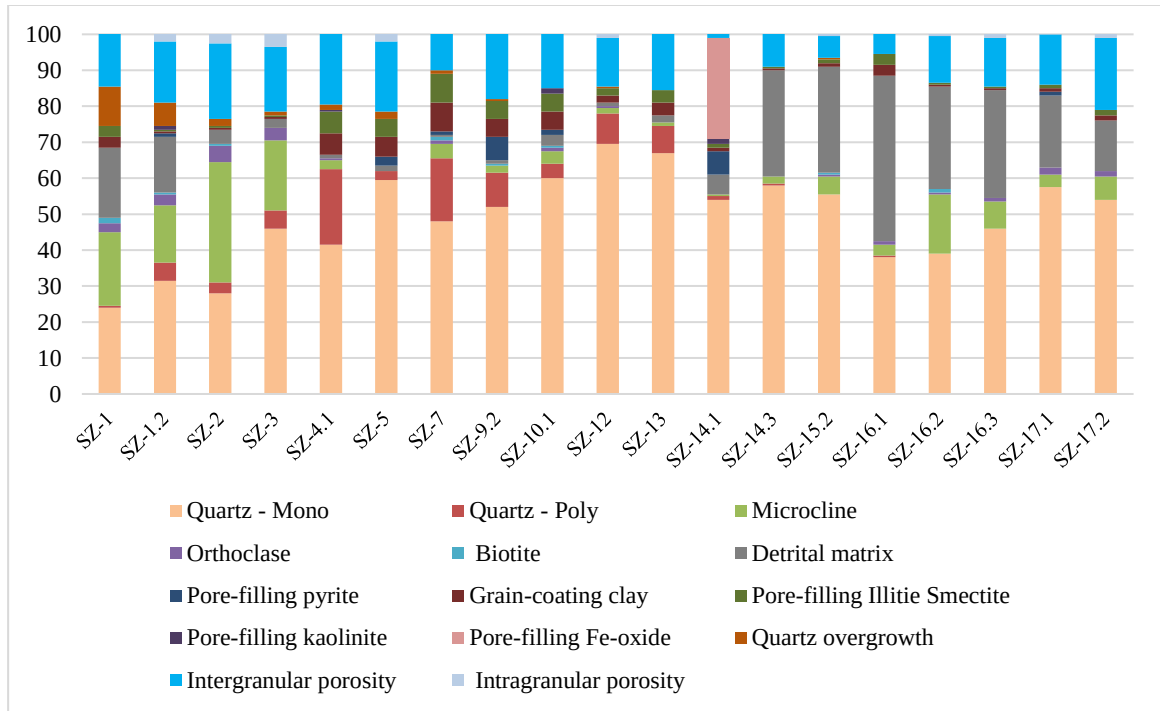


Figure 35: Zubliyat Compositional Histogram

Quartz overgrowths are generally regarded as occurring by silica precipitation during burial diagenesis and would usually form optically continuous rims around detrital quartz grains; however, no quartz overgrowths were observed in the studied samples of the Sharawra Formation. Even in the cleaner, well-sorted sandstones of the Zubliyat and Nayyal Members, in which such features are commonly found, point count analysis (Figures 35 and 34) showed their absence. Probably, early diagenetic grain coating clays (kaolinite, Illite, etc.) are present, which block silica-rich fluids from actually reaching quartz grain surfaces, thus preventing overgrowths. Thus, the development of syntaxial quartz overgrowth was suppressed. In the Jarish and Khanafriyah Members (Figures 32 and 33), high clay content and pervasive grain coatings inhibited quartz cementation even more, as is the case in the same inhibition mechanism (Figures 32 and 33).

5.3.2 Illite and Illite-Smectite

Illite and mixed-layer illite-smectite show well-defined burial diagenetic products and are generally formed through smectite to illite transformation at increasing temperature and potassium activity. Basal spacings shift from 10 Å to 9.6 Å, as indicated by XRD patterns, particularly for Zubliyat samples. SEM imaging (Figure 15) shows the presence of fibrous and hairlike morphologies inside the intergranular space. The presence of these minerals decreases both porosity and permeability by occluding pore throats. Zubliyat, as well as other parts of Nayyal, evidence this progressive burial and elevated thermal regimes, as well as their abundance in deeper stratigraphic intervals.

5.3.3 Chlorite Cement

Chlorite cement is a fill or coat phase of pore fill or grain coating cement and develops in Fe-Mg rich reducing conditions. As shown in SEM images (Figure 15), the chlorite in Zubliyat samples appears as rosette-like and flaky aggregates. Chlorite, however, may be sealing pore spaces, but in the case of grain coating chlorite alone, development of quartz overgrowth may be inhibited, maintaining primary porosity. Throughout the lower part of the Zubliyat Member, permeability values are more than 1000 mD even though the samples contain chlorite, an important diagenetic phase due to its dual role of occluding pores while precluding further silica cementation.

5.3.4 Calcite Cementation

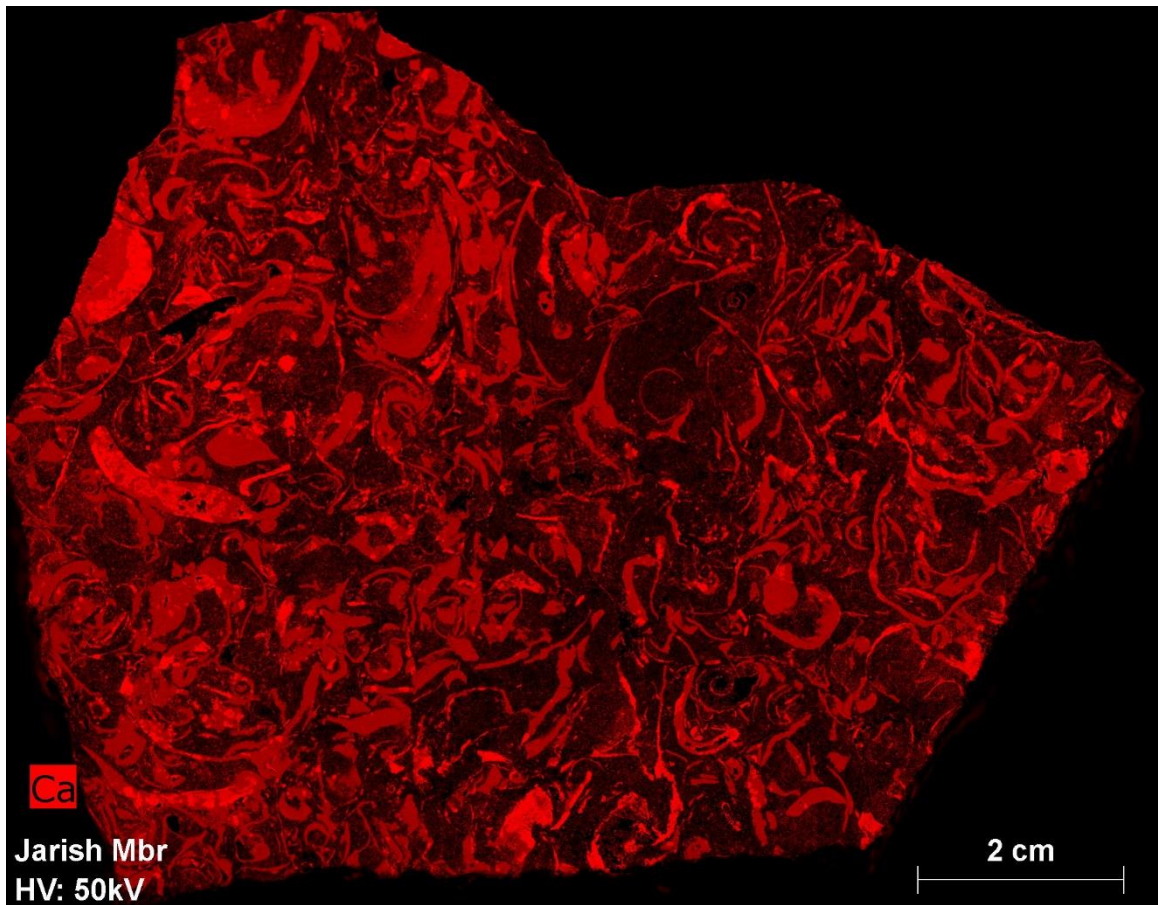


Figure 36: EDS calcium (Ca) elemental map of the Jarish Member

Figure 21 illustrating a dense concentration of calcium associated with micrite and bioclast-supported textures. The widespread Ca distribution, shown in red fluorescence, reflects pervasive early calcite cementation, likely of marine origin. This pattern supports petrographic evidence for early diagenetic stabilization and explains the significant reduction in primary porosity observed in this fine-grained, carbonate-rich unit.

5.4 Sandstone Classification and Compositional Maturity

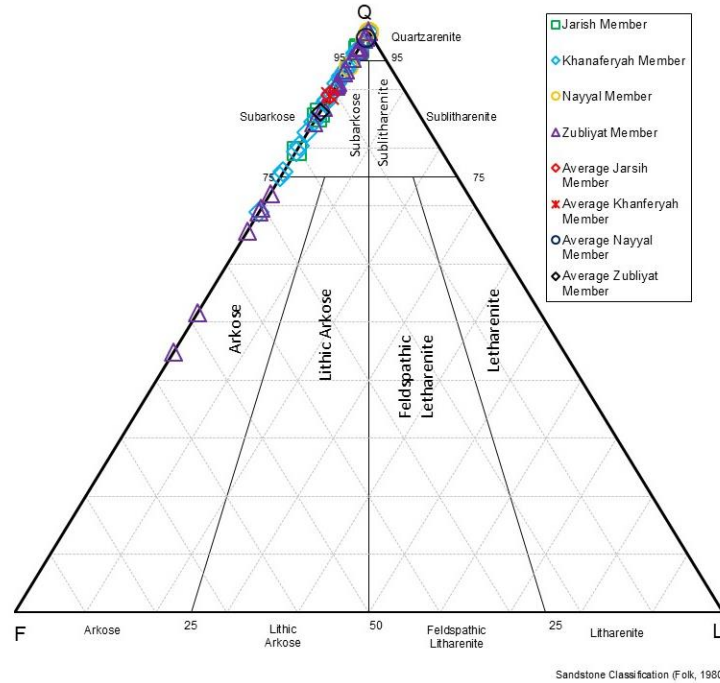


Figure 37: Sandstone classification of the Sharawra Formation based on Folk's (1980) QFL scheme.

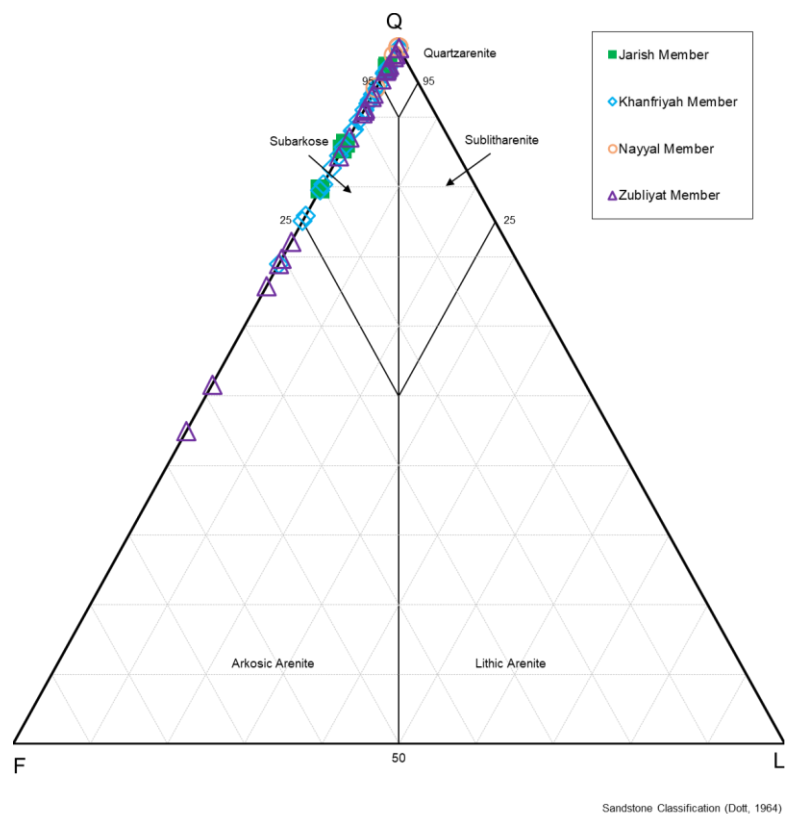


Figure 38: Simplified ternary compositional triangle showing the distribution of framework grain components in Sharawra Formation samples.

Applying point count petrographic data from the Sharawra Formation to Folk's (1980) QFL (Quartz-Feldspar-Lithics) ternary diagram, these data were plotted to evaluate compositional maturity and provenance trends. Finally, Figure 28 shows the classification results with increasing sandstone types from arkosic and subarkosic compositions to quartz arenite across the four members. In Fig. 29, we also include a simplified compositional triangle to give an easily visualized (if slightly biased) perspective on the relative distribution and clustering of the samples according to framework grain proportion, Member-by-Member Breakdown:

- It is the most compositionally mature unit among all members known in the Zubliyat. Over 70 percent of its samples plot on a firm quartz arenite field with an

average of more than 90 percent quartz and negligible feldspar or lithic fragments. For example, this implies prolonged sediment recycling and extensive weathering and is probably under humid, tectonically stable conditions. A few of these data points fall into the subarkose or arkose fields, indicating either local variability and variance or secondary feldspar influx. The excellent reservoir quality of the Zubliyat sandstones relates to their mineralogical purity (as discussed in Chapters 5.4 and 6).

- **Nayyal Member:** The quartz content is typically between 85–95% and the samples predominantly plot within the subarkose to quartz arenite transition zone. Feldspars are more abundant here than in Zubliyat and have slightly lower degrees of compositional maturity and reworking. However, despite the overly good precipitation of salt minerals, the overall mineralogy is clean and this is evidenced through the relatively good preserved intergranular porosity and moderate permeability in the member. XRD data suggest that feldspar alteration occurs during early diagenesis and is coincident with the increase in kaolinite content.
- This unit is more compositionally diverse than the Khanafriyah Member. Many samples lie in the arkose and subarkose fields with feldspar contents (15–25%) and occasional lithic fragments, and several are rhyolitic. XRD and thin section data have confirmed the presence of both orthoclase and plagioclase. The age and composition of these compositions, therefore, appear to be more proximal, less weathered, and possibly with granitic and volcanic input. In soils that had undergone feldspars alteration and burial, clay authigenesis (kaolinite, smectite, illite) was most important; that is where the feldspar content was highest. Therefore,

Khanafriyah sandstones have low permeability and variable porosities, as explained above.

- QFL terms could not be assigned to as many samples due to the micritic and fine-grained nature of this member. Nevertheless, data are available that locate it near the subarkosic domain with moderate feldspar and high matrix. This relates to the lack of sediment reworking and dominance of low energy depositional environments (e.g. shallow marine, lagoon). Furthermore, early calcite cementation (Figure 21) was so common in particular samples as to reduce porosity and obscure the presence of primary detrital framework components.

5.5 Impact of Diagenesis on Reservoir Quality

5.5.1 Porosity and Permeability Relationships

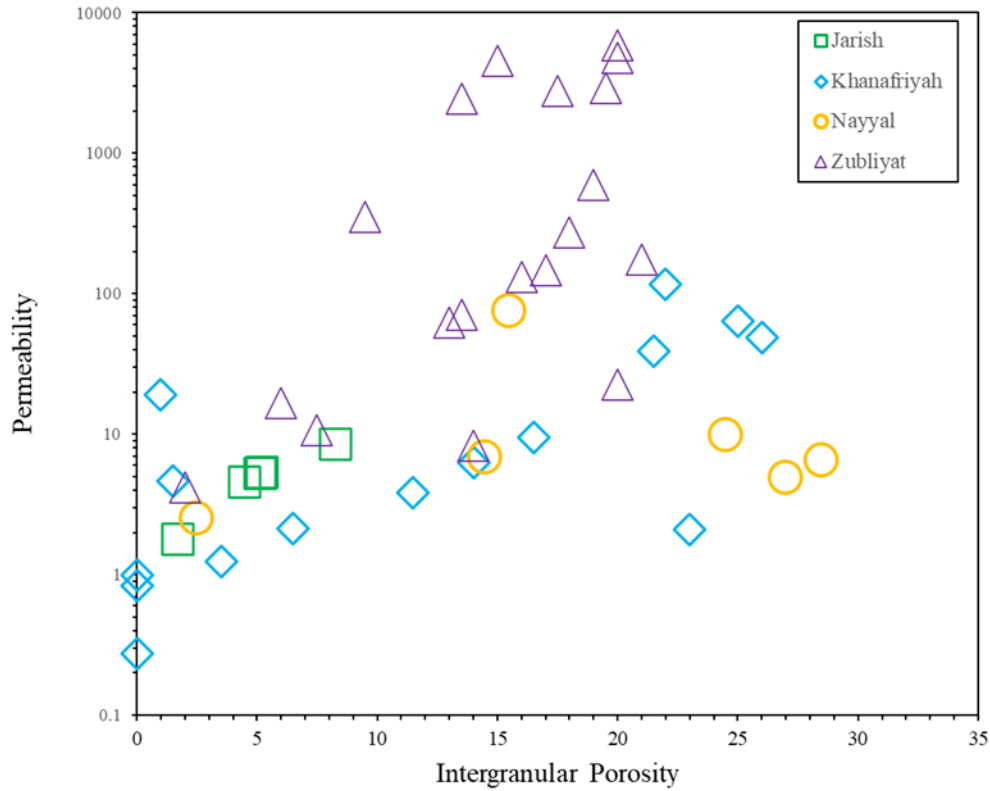


Figure 39: Intergranular porosity vs. permeability plot for the Jarish, Khanafriyah, and other Sharawra Formation samples, illustrating the variation in reservoir quality.

Distinct differences in reservoir quality for formation members are shown in Figure 37. Zubliyat samples are located at a point in the high porosity, high permeability domain, whereas Jarish and Khanafriyah samples are found within the low performance quadrant. One of the most crucial reservoir properties is porosity and permeability, the relationship of which can be strongly positive at the Sharawra Formation (Figure 37). In the Zubliyat Member, the values of porosity lie in the range of 18%~30%, and the corresponding values of permeability are often higher than 1000 mD. This is attributed to its coarse grain size, excellent sorting, and minimal cementation. Samples from both

the Jarish and Khanafriyah Members are commonly low porosity (< 5%) and permeability (< 10 mD), resulting from micritic cementation, high matrix content, and intense compaction. Comparison with Nayyal Member is made, with porosities of 10–25% and permeability between 10 and 250 mD; however, the porosities are influenced by cementation due to kaolinite and partial grain dissolution.

5.5.2 Effect of Grain Size

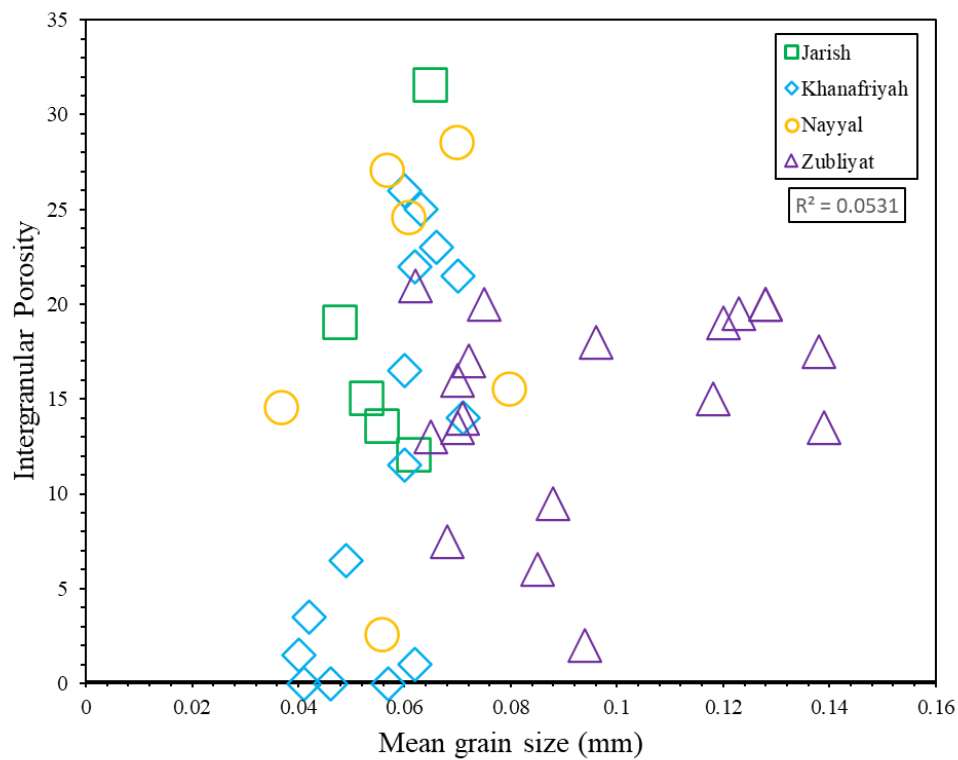


Figure 40: Plot of intergranular porosity versus mean grain size (mm) for samples from the Sharawra Formation, including the Jarish and Khanafriyah Members

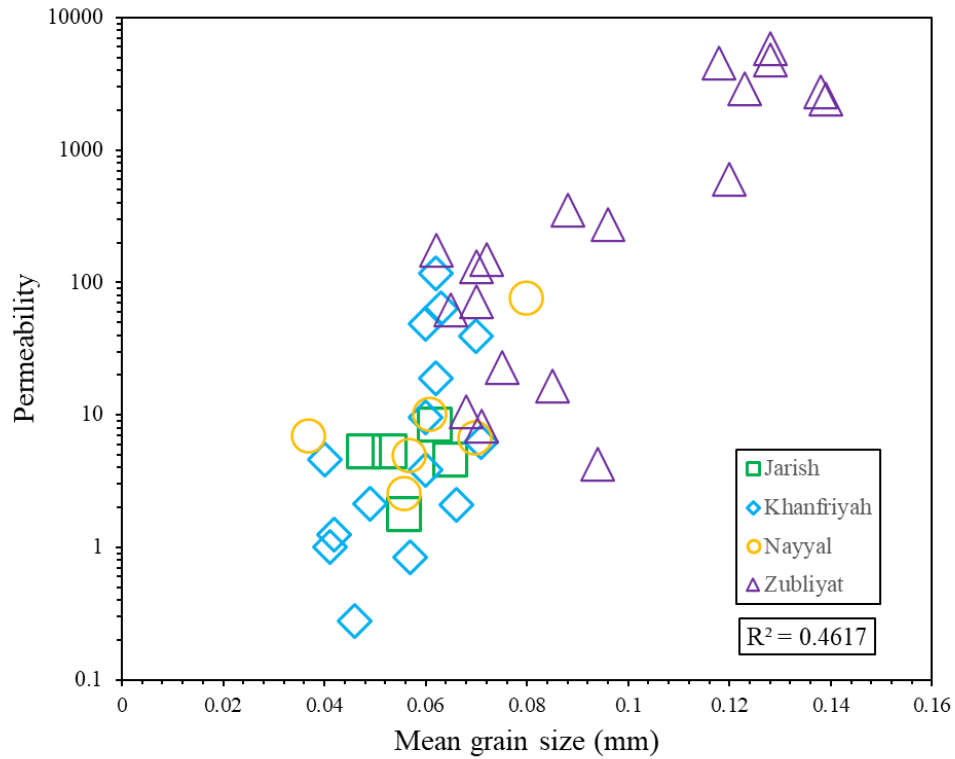


Figure 41: Plot of permeability versus mean grain size (mm) for samples from the Sharawra Formation, including the Jarish and Khanafriyah Members.

The relationship between intergranular porosity and mean grain size for samples from the Sharawra Formation, including samples of Jarish and Khanafriyah Members, is shown in Figure 38. Near-zero correlation ($R^2 = 0.0531$) between the points implies that original textural controls on porosity have been significantly overprinted by diagenetic processes, including compaction and cementation. Adversely, Figure 39 shows that grain size has a strong positive correlation with permeability ($R^2 = 0.7267$), showing that grain size is the major impacting parameter on permeability. The samples from the Zubliyat Member that have coarser grains (0.10–0.14 mm) have very high permeability values, exceeding 800 to 2000 mD. However, in comparison, the permeability values of the finest-grained Jarish and Khanafriyah samples (<0.063 mm)

are usually less than 10 mD. The grain sizes of the Nayyal Member are intermediate, with grain sizes of 0.06–0.09 mm and corresponding moderate permeability values from 10 to 250 mD. These observations imply that grain size is a primary control on reservoir flow capacity, particularly when diagenetic alteration is minor.

5.5.3 Role of Sorting and Matrix

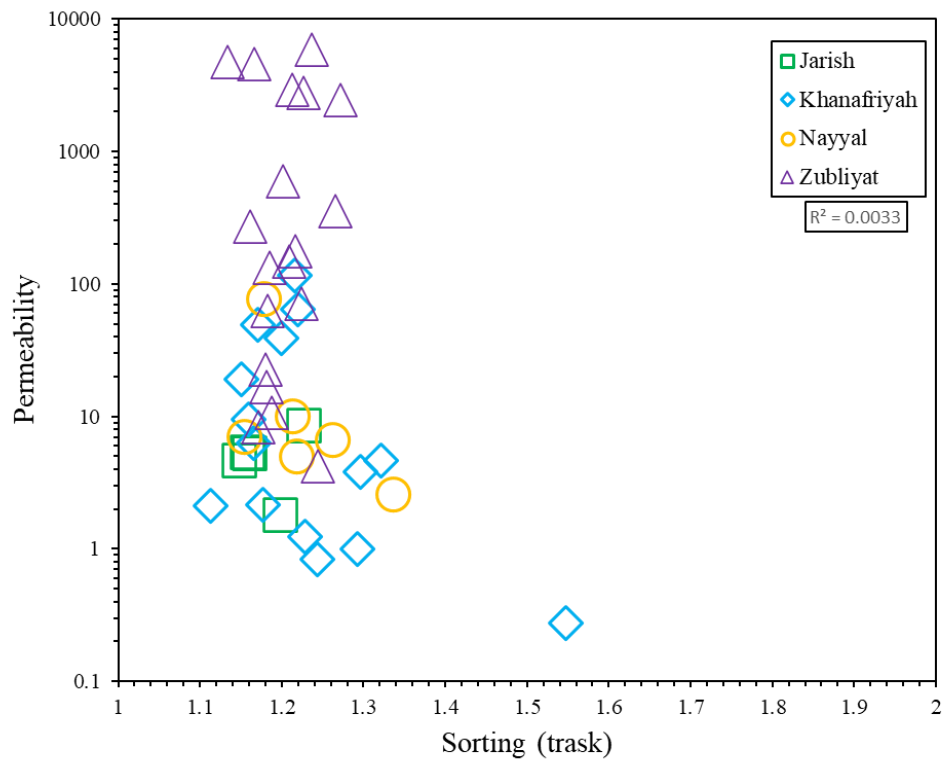


Figure 42: Plot of permeability versus Trask sorting coefficient for samples from the Sharawra Formation, including the Jarish and Khanafriyah Members.

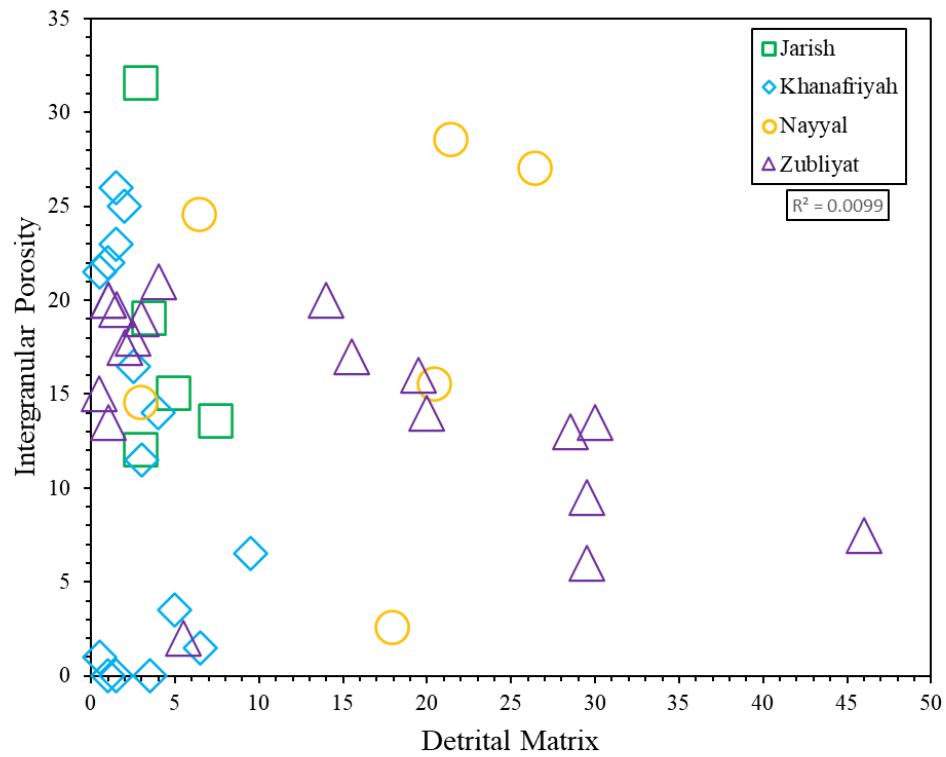


Figure 43: Plot of intergranular porosity versus detrital matrix content (%) for samples from the Sharawra Formation, including the Jarish and Khanafriyah Members.

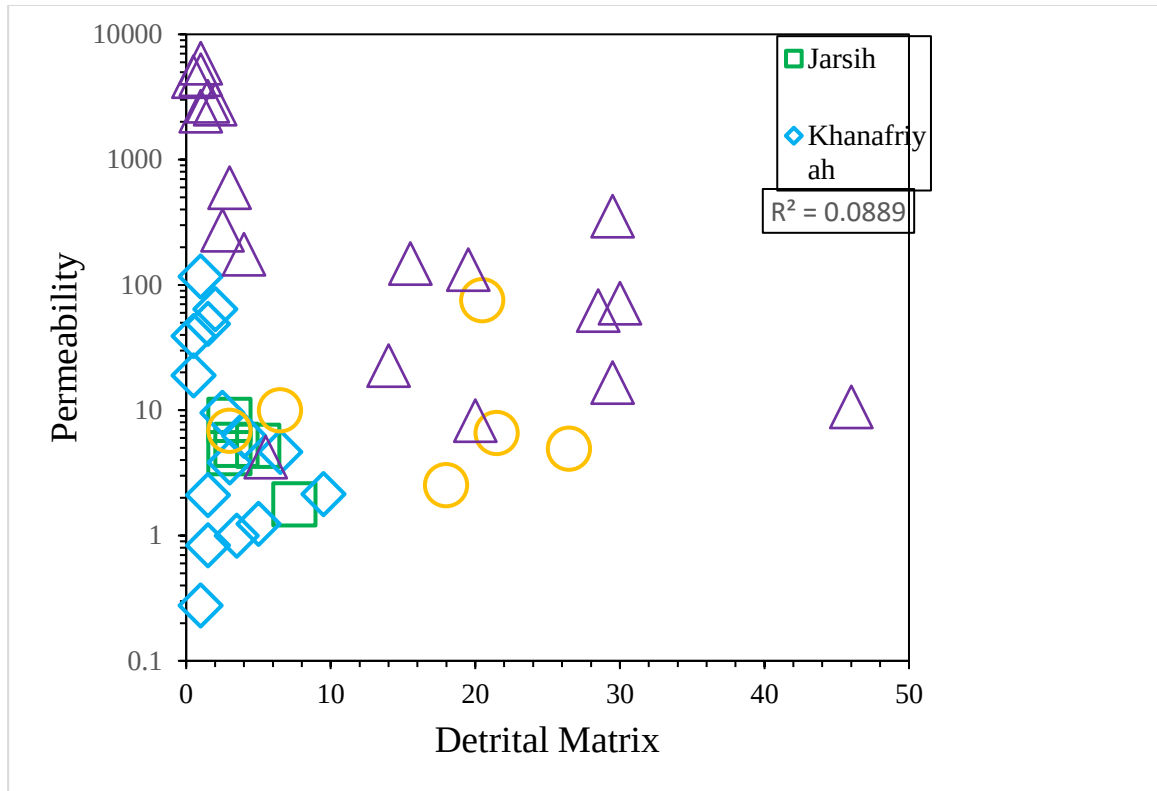


Figure 44: Plot of permeability versus detrital matrix content (%) for samples from the Sharawra Formation, including the Jarish and Khanafriyah Members.

The relation of permeability to the Trask sorting coefficient is shown in Figure 40 for samples of the Sharawra Formation, including the Jarish and Khanafriyah Members. With a statistical correlation of modest value ($R^2 = 0.068$), the data indicate that for cleaner sandstones, sorting has a significant effect on permeability. Better sorting (Trask values of ~ 1.2), particularly from the Zubliyat and Nayyal Members, are found to have much higher permeability values (>500 mD), which suggests more porous and interconnected pore space and an indication of better reservoir quality. Permeability of poorly sorted samples (Trask >1.5) typical of the Khanafriyah Member is reduced by inefficient grain packing and by constriction of pore throats.

Figures 41 and 42 present intergranular porosity and permeability vs. detrital matrix content. Although weak in statistical correlation ($R^2 < 0.01$), there is a consistent inverse trend in that higher matrix content tends to be associated with lower porosity and permeability in all members. Matrix ranges from less than 5 per cent in the Zubliyat Member to more than 25 per cent in the Jarish and Khanafriyah Members. It is suggested that diagenetic alteration of the matrix to pore blocking clays and fines occluded pore throats, hindering fluid flow, reduced the observed reservoir quality. Although low R^2 values with both quantitative variables do not reflect a strong relationship, the trend points to the devastating effect of matrix abundance on effective porosity and permeability

CHAPTER 6

GEOCHEMICAL BOUNDARIES BETWEEN MEMBERS

6.1 Introduction

The studied siliciclastic parts of sedimentary formations are important geochemical characteristics for showing the provenance, environment of deposition, and post depositional conditions. Transitions between the members, Jarish, Khanafriyah, Nayyal, and Zubliyat, defined in the Sharawra Formation, are not only on lithologic and textural levels but also for the bulk mineralogy, clay mineral assemblages, elemental composition, and grain size levels. These differences define discrete geochemical boundaries that indicate changes in sediment supply and depositional and diagenetic regimes. Thus, in this chapter, bulk and clay XRD analyses and SEM-EDS elemental maps and granulometry are synthesized to define these boundaries and to infer their diagenetic implications.

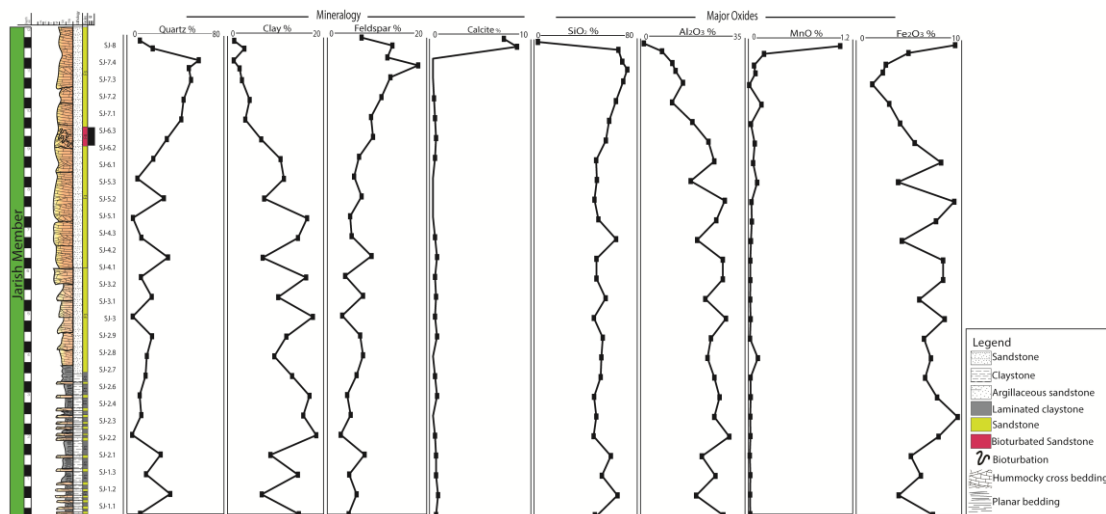


Figure 37: Integrated lithological, mineralogical, and geochemical profile of the Jarish Member showing vertical variations in sedimentary facies, mineral content, and major oxide concentrations.

Jarish Member

- **Major Oxides:** Shows moderate SiO_2 and relatively elevated Al_2O_3 and Fe_2O_3 levels, indicating the presence of clay minerals and possibly weathered feldspathic material.
- **Mineralogy (XRD):** Dominated by quartz and kaolinite/illite, with minor feldspars.
- **Interpretation:** Suggests a moderately mature siliciclastic system, likely deposited in a nearshore to inner shelf setting. Geochemically transitional, indicating some exposure to weathering and mild reworking.
- **Boundary Character:** Gradational geochemical transition upward into Khanafriyah, marked by decreasing Al_2O_3 and increasing SiO_2 .

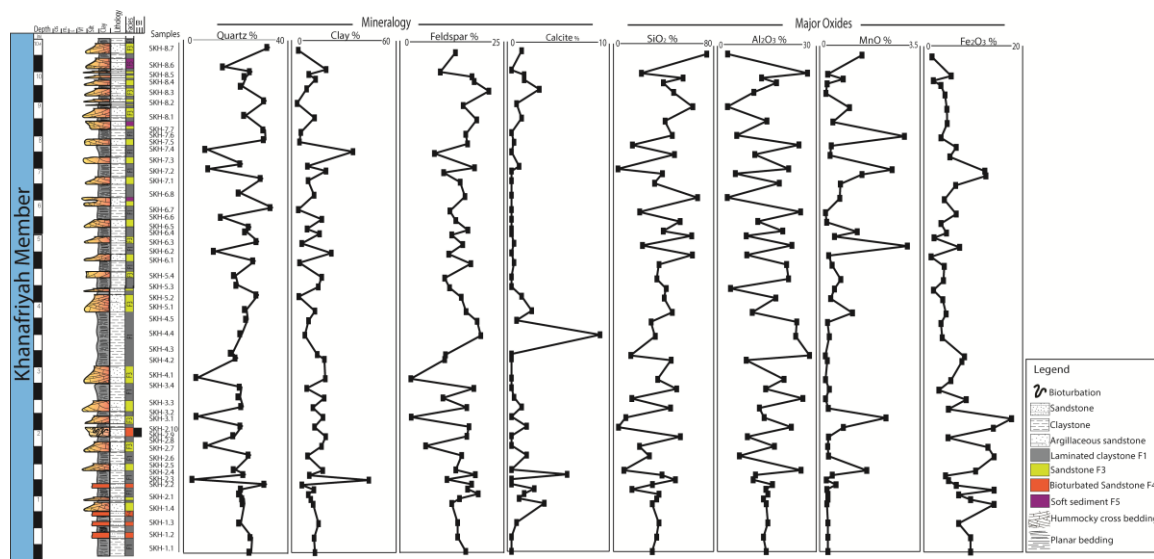


Figure 38: Integrated lithological, mineralogical, and geochemical profile of the Khanafriyah Member showing vertical variation in facies, mineral composition, and major oxide content.

Khanafriyah Member

- **Major Oxides:** High SiO_2 and slight increase in K_2O ; drop in Fe_2O_3 and Al_2O_3 .
- **Mineralogy:** Dominantly quartz with increased feldspar (orthoclase/plagioclase) and minor chlorite.
- **Interpretation:** More quartz-rich, tidally influenced or reworked sands with a clearer signal of chemical maturity.
- **Boundary Character:** Geochemically sharp upward shift marked by a notable rise in clay minerals and Fe_2O_3 heading into the Nayyal member.

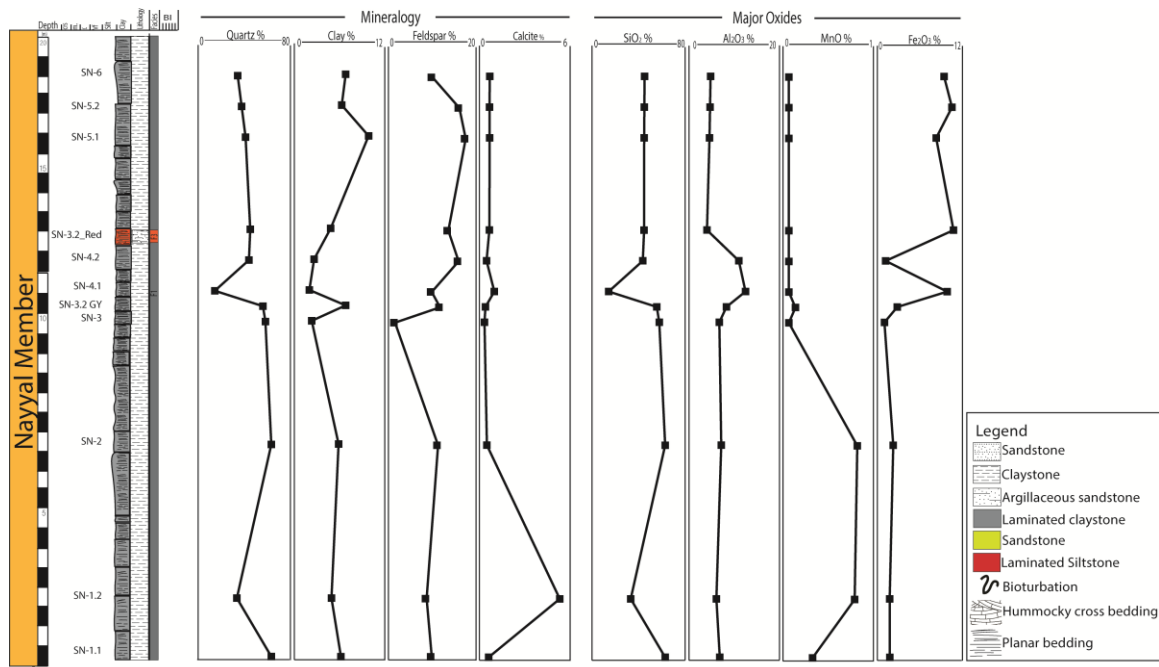


Figure 39: Integrated lithological, mineralogical, and geochemical profile of the Nayyal Member showing vertical variation in facies, mineral content, and major oxides.

Nayyal Member

- **Major Oxides:** Elevated Al_2O_3 , Fe_2O_3 , and TiO_2 ; low SiO_2 .
- **Mineralogy:** Rich in clay minerals (illite, chlorite), with low quartz content.
- **Interpretation:** **Low-energy offshore deposition** with high detrital clay input—chemically less mature and fine-grained.

- **Boundary Character:** Strong geochemical shift upward— SiO_2 increases, while clay-related oxides decrease sharply into Zubliyat.

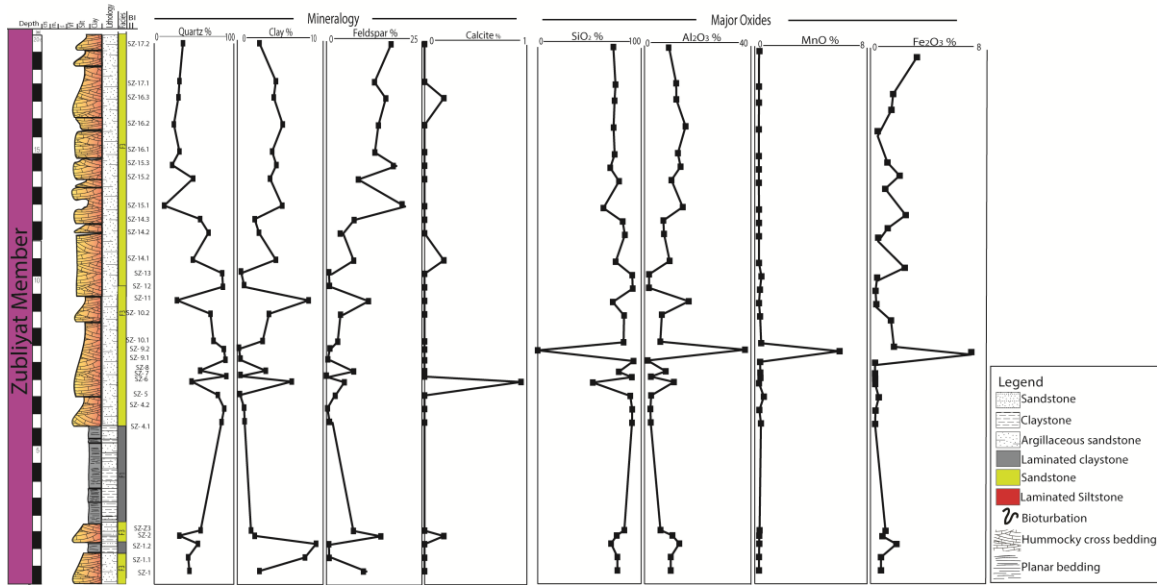


Figure 40: Integrated lithological, mineralogical, and geochemical profile of the Zubliyat Member showing vertical distribution of facies, mineralogy, and major oxides.

Zubliyat Member

- **Major Oxides:** High SiO_2 and K_2O ; low Fe_2O_3 and Al_2O_3 .
- **Mineralogy:** Quartz-rich with feldspar and muscovite; minor clays.
- **Interpretation:** High-energy, progradational setting, like delta front or shallow marine. The chemical signature reflects reworked, clean sands.
- **Boundary Character:** Distinct geochemical boundary from Nayyal—indicative of a major **environmental and energy shift**.

6.2 Bulk XRD Mineralogy

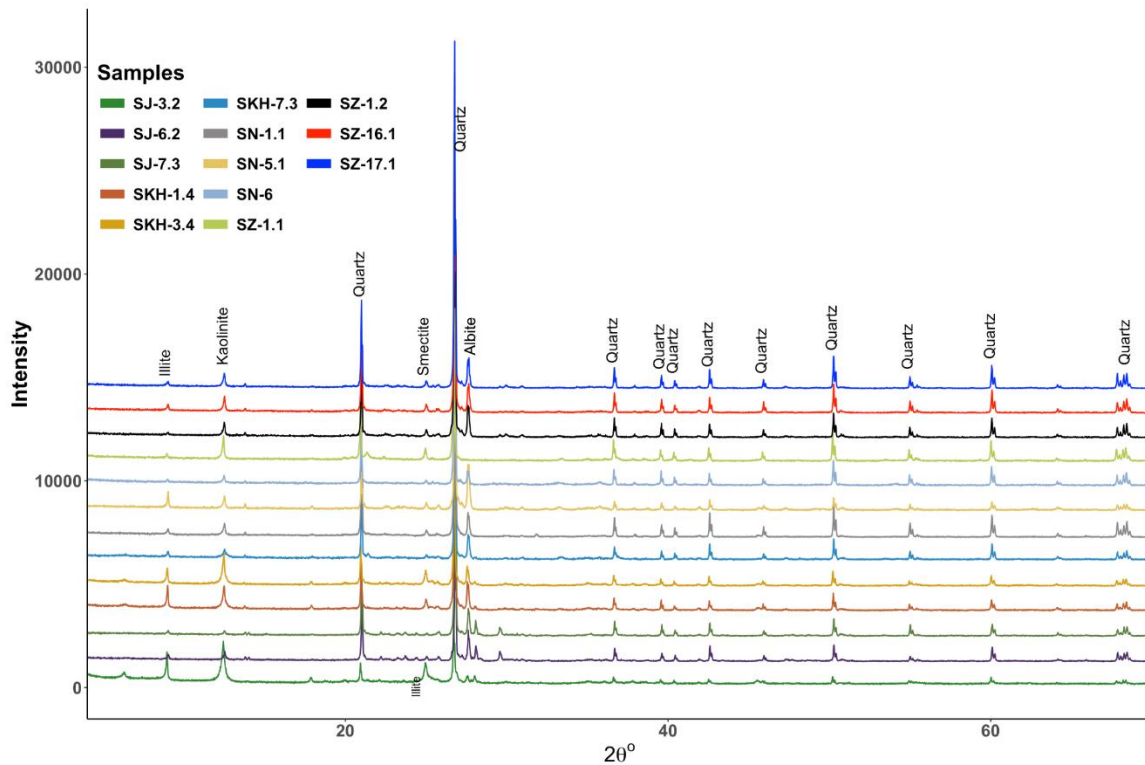


Figure 41: Bulk XRD pattern of the minerals from representative samples of the studied Shararwra Silurian Rocks

Bulk XRD results (Figure 49) confirm that quartz is always the most prominent mineral in the composition, various samples (over 60%) and samples (over 40%) and that it is consistently always there and does not vary significantly either in or out of pyrite ores. Nevertheless, they all reveal special mineralogical fingerprints over the baseline.

- Many samples display high quartz, higher than 70%, therefore, this represents high compositional maturity. Relative to these sandstone units, minor but significant quantities of feldspar (orthoclase and microcline) and clay minerals (illite-smectite) show both a granitic provenance burial-related diagenesis.

- Quartz remains dominant, although the content of kaolinite is higher than in other members, and there are traces of illite and chlorite. The pattern of alteration represents feldspar alteration by meteoric influence and mild burial diagenesis.
- Khanafriyah Member: Feldspar peaks are relatively higher than other members with an increase in clay content, especially smectite and illite. This mineralogical makeup is due to the mixed source and limited weathering reflected in an early diagenetic cementation phase.
- Jarish Member: Highly calcite, quartz and kaolinite. The coexistence of carbonate lends support to marine influence or the biogenic flux. Sharp calcite peaks are observed in XRD results, which differentiate it from overlying units.

6.3 Clay Mineralogy (Clay Fraction XRD)

XRD analysis of clay fraction provides additional resolution of mineralogical evolution and the imprint of diagenesis. Therefore, the patterns (Figures 31-33 and 16) reflect variability in the burial depth, sediment provenance, fluid interaction.

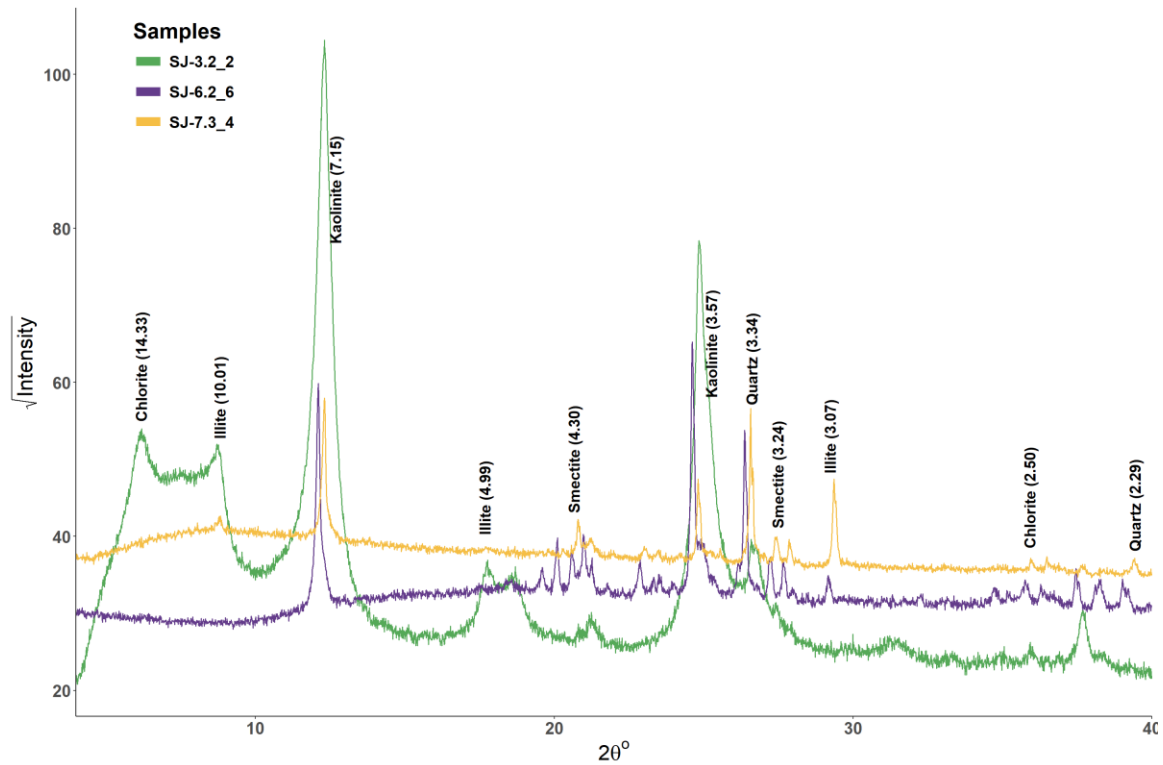


Figure 42: XRD patterns of the clay fraction Jarish Member

Jarish Member (Figure 50): strong kaolinite peaks at $7.15\text{\AA}$, $3.57\text{\AA}$, minor illite at about $10\text{\AA}$. Critical data showing the dominance of kaolinite confirm that weathering and feldspar alteration occurred under a doubly acid, meteoric environment, which is characteristic of shallow burial settings.

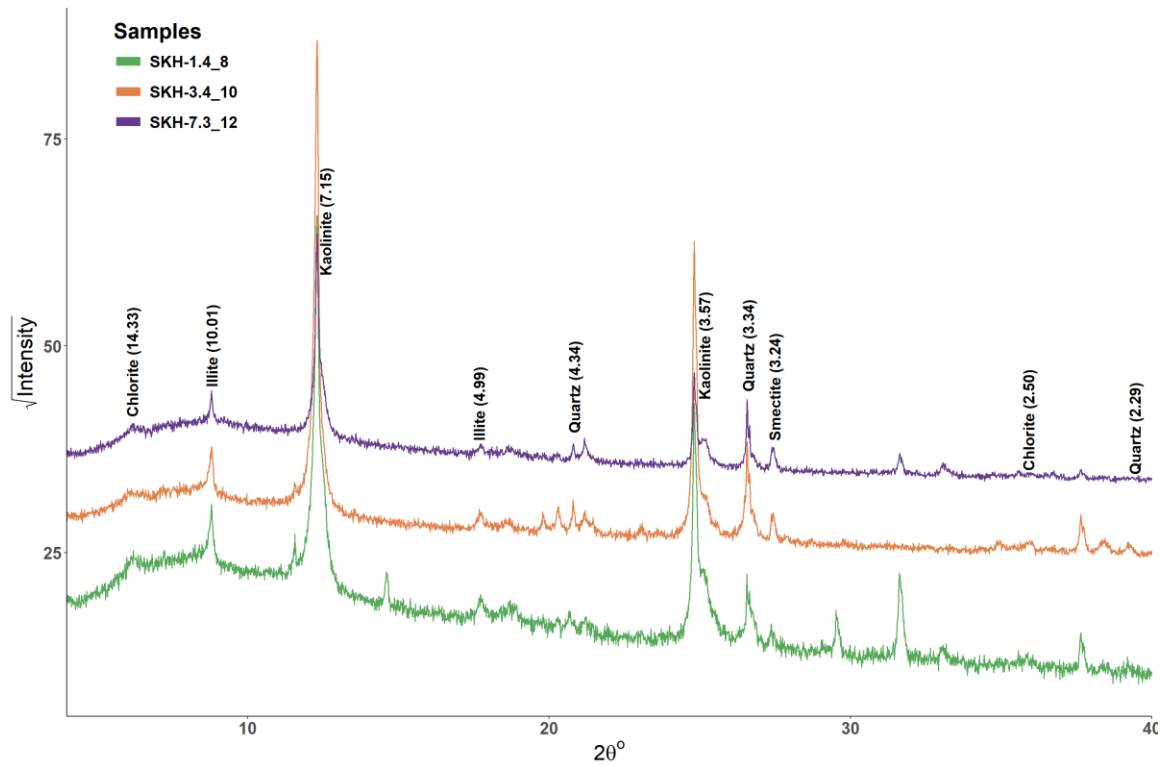


Figure 43: XRD patterns of the clay fraction Khanafriyah Member

Khanafriyah Member (Figure 51): Clay assemblage is a mixture of kaolinite, smectite and illite. The presence of smectite (with peaks near 14–15 Å) implies lower thermal maturity and early diagenetic conditions. Thus, this mineralogical mixture allows for a transitional depositional regime and progressive burial, Nayyal Member (Figure 31): Slightly kaolinitic, with consistent illite, and some trace chlorite. Again, feldspar breakdown in acidic waters gives rise to the kaolinite signature. Fe-Mg enrichment during late eodiagenesis is indicated by chlorite.

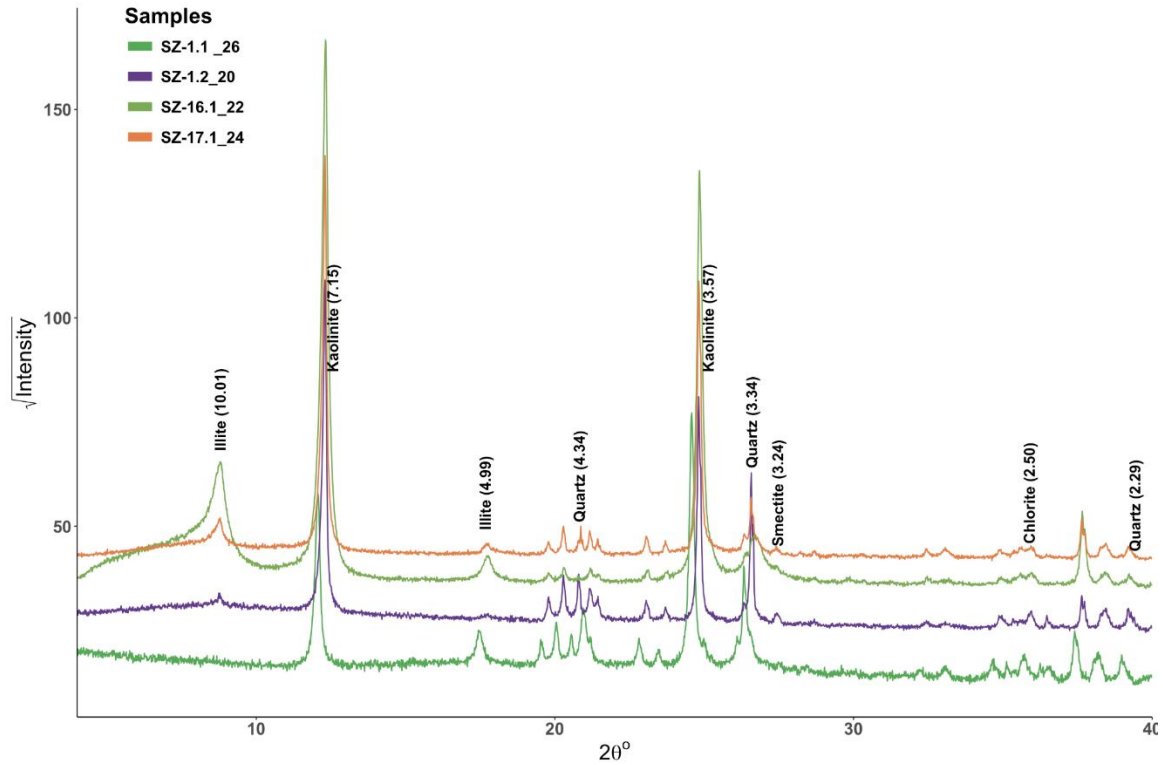


Figure 44: XRD patterns of the clay fraction Khanafriyah Member

Figure 52, Zubliyat Member (showing the most complex clay mineralogy with smectite, illite, and chlorite). Development of smectite peaks vertically within the member, indicating deeper burial and progression of illitization. Such a trend at elevated thermal maturity correlates with coarser grain texture, resulting in better reservoir performance.

6.4 Grain Size and Geochemical Transitions

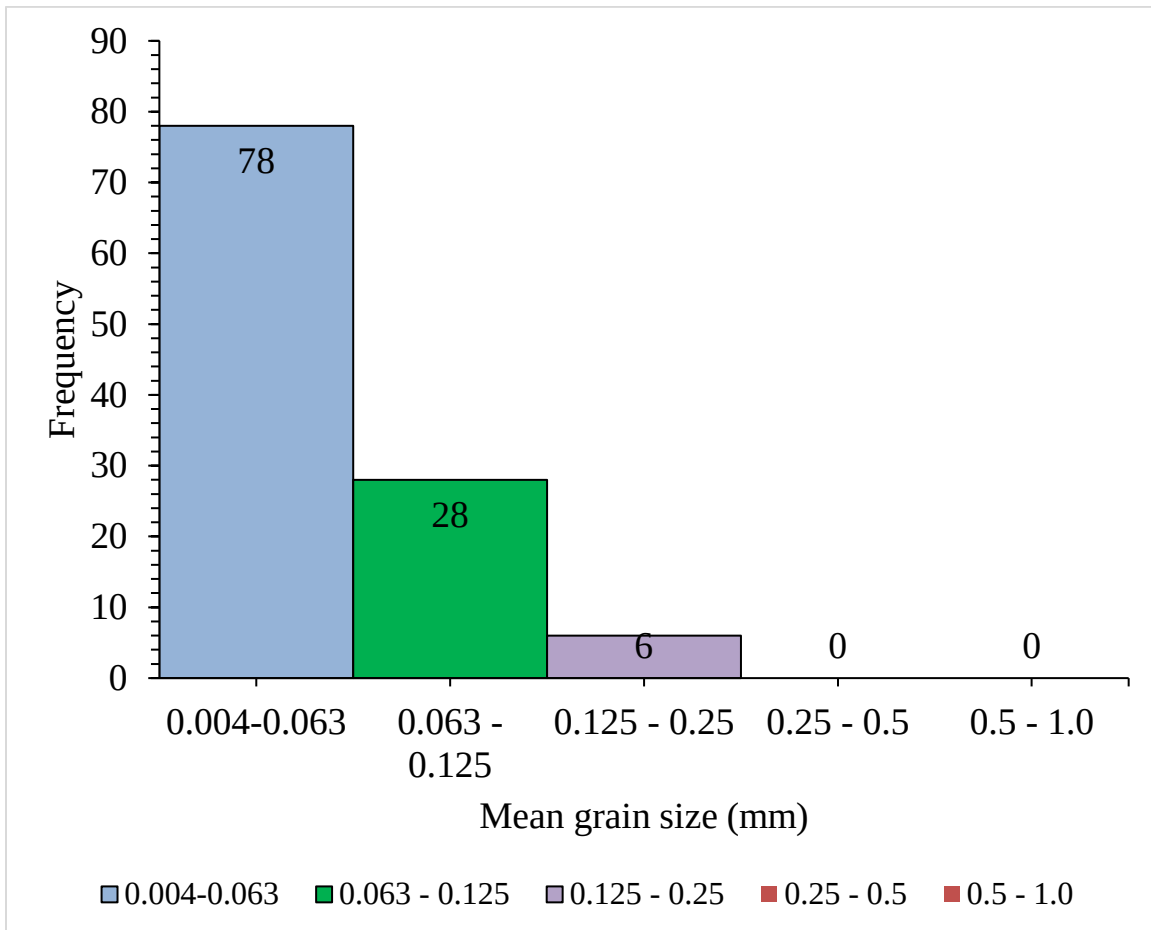


Figure 45: Grain size distribution histogram for each member

The geochemical contrasts and grain size distributions (Figure 53) help in stratigraphic interpretation, from clay Jarish to fine and coarse grain Zubliyat Member.

- Jarisch Member: More than 78% of the grains are described as clay size (<0.004 mm), with 28% falling in the very fine sand range (0.063-0.125 mm). Its high matrix and carbonate content, along with these results, indicate a very low energy depositional environment with a high mud influx.

- Both members of Khanafriyah & Nayyal show a moderate grain size range of 0.06 to 0.10 mm and moderate sorting. These members are a transition from clay-rich to more arenaceous facies, an increase in depositional energy, and a decrease of chemical cementation.
- Zubliyat member: To the coarsest grains in the formation, between 0.128 and 0.140 mm. They are clearer and correspond to a more open, perhaps fluvia, or deltaic marine environment. In XRD, the textural maturity is well alike in the low matrix and strong quartz signature.

CHAPTER 7

CONCLUSION AND RECOMMENDATION

7.1 Conclusions

This study demonstrates that the evolution of Sandstones of the Silurian Sharawra Formation in northwest Saudi Arabia is controlled by sediment provenance, mineralogical composition, and diagenetic alterations, all of which combined determine the development of the reservoir quality. The analysis undertaken using the major oxide discrimination diagram for provenance determination (Roser and Korsch, 1988) indicates that the Jarish and Khanafriyah members have intermediate to felsic igneous sources with an addition of felsic igneous rocks to the Nayyal member. On the contrary, the Zubliyat member has a recycled sedimentary signature sourced from felsic igneous rocks. Diverse tectonic and erosional processes controlled the complex depositional environment thus produced by these variations.

Regardless of the reconstruction, these diagrams exhibit the Sharawra Formation deposited in an area of passive margin tectonics. In addition, provenance analyses indicate that the depositional condition changed from semi-arid to intermediate climate (transitional state between warm humid and cool dry setting) that led to the sediment characteristics as well as subsequent diagenetic evolution.

Diagenetic processes have become important reservoir quality determinants. Mechanical compaction is quantified to have lost approximately 25–35 % in porosity and an additional 5–8 % early cementation loss in the Zubliyat member. In this regard, the porosity of Zubliyat members lies in the range of 18–30 % and permeability values exceeding 1000

mD. On the other hand, the Jarish and the Khanafriyah members with fine grain sizes and overprinting due to the diagenetic have low porosity (<5%) and low permeability (<10 mD). The intermediate-grain size Nayyal member has moderate reservoir properties (porosities from 10-25% and permeability in the range of 10 to 250 mD). Therefore, the most promising reservoir units within the formation comprise the Zubliyat and Nayyal members, and the Jarish and Khanafriyah members are the less promising ones.

In terms of the overall, this study points out the key for deciphering the interplay between sediment provenance, depositional environment, and diagenetic alterations, which require an integrated multidisciplinary approach. The results of the quantitative and qualitative investigations formed a robust framework for reservoir quality prediction on the scales of hydrocarbon exploration and management of deposits similar to those under study.

7.2 Recommendations

Based on the study findings, the author suggests the following:

- **Target Reservoir Units for Further Exploration:**
 - The Zubliyat and Nayyal members should be prioritized for future reservoir characterization in modern hydrocarbon exploration projects, given their demonstrated superior reservoir quality.
- **Conduct Comprehensive Petrophysical and Core Analyses:**
 - Further detailed petrophysical studies, including core sampling, laboratory analysis, and flow testing, may be undertaken to validate and refine porosity, permeability, and saturation models.

- Advanced techniques, such as CT scanning and NMR, may be employed to better understand pore networks and fluid flow behavior, thereby optimizing development strategies.
- **Leverage Outcrop Studies as Educational Platforms:**
 - The Silurian Sharawra outcrops may serve as natural laboratories for field training in reservoir characterization and sedimentary facies identification.
 - It is recommended that field workshops and training programs be organized to enhance geoscientists' practical skills in integrating geological, geochemical, and petrophysical data.
- **Promote Interdisciplinary Research Initiatives:**
 - Collaboration between sedimentologists, structural geologists, and geochemists may be encouraged to integrate diverse datasets, leading to more robust predictive models.
 - Joint projects combining field observations with laboratory experiments and numerical simulations are suggested to better elucidate the interplay between sediment deposition, tectonic processes, and diagenetic alterations.
- **Integrate Data for Enhanced Reservoir Modeling:**
 - It is suggested that comprehensive reservoir models be developed that integrate geological, petrophysical, and geochemical data to improve prediction accuracy.

- Utilizing integrated 3D seismic interpretation and reservoir simulation tools may help map spatial variations in reservoir properties and diagenetic overprinting, thereby reducing uncertainty in reservoir performance assessments.

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