

**Spatial variations in the pore system of
the burrow fillings and their impact on
the reservoir quality – A case study from
Hanifa Formation**

BY

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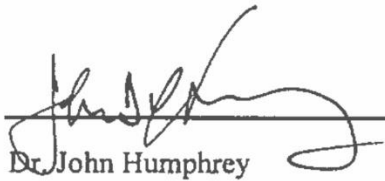
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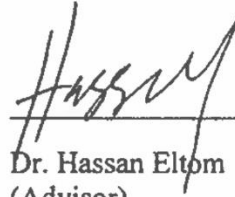

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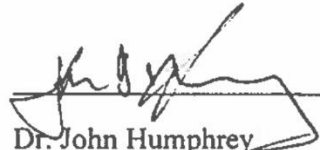


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To my beloved Family

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LIST OF ABBREVIATIONS

CT	:	Computer Tomography
BF	:	Burrow Fillings
TOC	:	Total Organic Carbon
TBN	:	<i>Thalassinoides</i> Burrow Networks
BI	:	Burrow Intensity
MPS	:	Multipoint Statistics
HRM	:	Host Rock Matrix
BP	:	Burrow Percentage
SEM	:	Scanning Electron Microscopy
μ-CT	:	Micro Computer Tomography
Max	:	Maximum
Mini	:	Minimum
StDev	:	Standard Deviation
scmpp	:	Slightly compacted mud-poor packstone
scg	:	Slightly compacted grainstone
hcmpp	:	Highly compacted mud-poor packstone

hcg	:	Highly compacted grainstone
mcmrp	:	Moderately compacted mud-rich packstone
mcmpp	:	Moderately compacted mud-poor packstone
mcg	:	Moderately compacted grainstone

ABSTRACT

Full Name : Ahmed Adel Refaat Mohamed

Thesis Title : Spatial variations in the pore system of the burrow fillings and their impact on the reservoir quality – A case study from Hanifa Formation

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Over the last few decades, significant advancement has been made in understanding petrophysical parameters in carbonate hydrocarbon reservoirs and aquifers affected by bioturbation. Previous research has investigated the effects of burrows in terms of morphology, connectivity, intensity, filling, and the dimensions of shafts and tunnels on the reservoir quality. However, the influence of pore system variations within burrow fillings on storage capacity and fluid flow remains understudied. This research addresses this gap by analyzing burrow fillings from five bioturbated intervals in the upper Hanifa Formation, central Saudi Arabia, using field observations, petrographic analysis, porosity and permeability measurements, high-resolution CT scanning, digital rock modeling, permeability simulations, and backstripping techniques. The studied interval consists of five extensively burrowed intervals. These were classified based on burrowing style into bio-retextured intervals (2 and 3) and pipe-framework burrows (1, 4, and 5). Bio-retextured intervals exhibited smaller grain sizes (355–402 μm) and lower porosity (1.64–2.71%), while pipe-framework intervals had larger grains (514–766 μm) and higher porosity (4–7.75%). Mud content and dolomitization were identified as key factors controlling porosity evolution in the burrow fillings. Dolomitization preserved porosity in mud-rich packstones by resisting compaction, while compaction degraded porosity in mud-poor packstones with lower dolomite content. Grain-supported burrow fillings generally showed limited improvement in porosity post-compaction, while less compacted, open-fabric grainstones achieved up to 20% porosity and >5000 mD permeability. Even with >10% mud content, connected pore networks in open-fabric burrow fillings maintained permeability (>1000 mD). The study highlights the dynamic evolution of porosity and permeability within bioturbated strata. Initially low-quality, mud-rich packstones can improve through

dolomitization and dissolution, while initially high-quality, mud-poor packstones may degrade due to compaction. The pore system predominantly comprises isolated pores with vertical variations in volume, surface area, and equivalent diameter. By integrating digital rock modeling and backstripping techniques, this research provides a comprehensive framework for quantifying and predicting porosity and permeability evolution in bioturbated reservoirs. These insights are critical for understanding reservoir performance and fluid flow in systems where direct permeability measurements are challenging.

Keywords: Carbonate; Bioturbation; Pore System Variations; Burrow fillings; Hanifa Formation.

ملخص الرسالة

الاسم الكامل: أحمد عادل رفعت محمد

عنوان الرسالة: الاختلافات المكانية في نظام مسام حشوات الجحور وتأثيرها على جودة الخزان – دراسة حالة من تكوين حنيفة

التخصص: جيولوجيا

تاريخ الدرجة العلمية: نوفمبر 2024

على مدى العقود القليلة الماضية، تم تحقيق تقدم كبير في فهم المعايير البتروفيزيائية في مكامن النفط والخزانات الجوفية الكربونية المتأثرة بالاضطرابات البيولوجية. وقد تناولت الدراسات السابقة تأثيرات التجاويف الجحورية (الأحافير الأثرية) من حيث الشكل، الاتصال، الكثافة، تكوين الحشوات، والأبعاد على جودة الخزان. ومع ذلك، فإن تأثير التغيرات في نظام المسام حشوات هذه التجاويف على سعة التخزين وتدفق السوائل غير مدروس بشكل كافٍ. تسعى هذه الدراسة إلى سد هذه الفجوة من خلال تحليل حشوات الحفريات الأثرية في خمسة طبقات متأثرة بعمليات التخلخل الحيوي ضمن تكوين حنيفة العلوي في وسط المملكة العربية السعودية، باستخدام ملاحظات الحقل، وتحليل الصخور البتروغرافي، وقياسات المسامية والنفاذية، وتقنيات التصوير المقطعي عالي الدقة، ونمذجة الصخور الرقمية، ومحاكاة النفاذية، وتحليل التراجع الزمني. تم تصنيف الطبقات المدروسة، التي تتضمن خمسة طبقات مخلخله حيويًا بشكل مكثف، وفقًا لأنماط التخلخل الحيوي إلى طبقات معاد تشكيلها حيويًا (2 و 3) وطبقات ذات إطار أنبوبي (1، 4، و 5). أظهرت الطبقات المعاد تشكيلها بيولوجيًا حبيبات أصغر حجمًا (355–402 ميكرومتر) ومسامية أقل (1.64–2.71%)، بينما أظهرت الطبقات ذات الإطار الأنبوبي حبيبات أكبر حجمًا (514–766 ميكرومتر) ومسامية أعلى (4–7.75%). وتم تحديد محتوى الطين وعملية الدلمته كعوامل رئيسية تتحكم في تطور المسامية داخل حشوات الحفريات الأثرية. حيث حافظت عملية الدلمته على المسامية في الحشوات الغنية بالطين من خلال مقاومتها للانضغاط، بينما أدى الانضغاط إلى تدهور المسامية في الحشوات الفقيرة بالطين ذات المحتوى الأقل من الدولوميت. أظهرت حشوات الحفريات الأثرية ذات الرواسب خشنة الحبيبات تحسنًا محدودًا في المسامية بعد الانضغاط، بينما حققت الحشوات ذات النسيج المفتوح وغير المضغوطة ما يصل إلى 20% من المسامية ونفاذية تجاوزت 5000 ملي دارسي. وحتى مع محتوى طيني يزيد عن 10%، حافظت المسامية المتصلة في الحشوات ذات النسيج المفتوح على نفاذية كبيرة (>1000 ملي دارسي). تسلط الدراسة الضوء على التطور الديناميكي للمسامية والنفاذية داخل الطبقات المتخلخله حيويًا. يمكن أن تتحسن الحجارة الحشوات الغنية بالطين ذات الجودة المنخفضة مبدئيًا من خلال عمليات الدلمته والذوبان، في حين قد تتدهور الحشوات الفقيرة بالطين ذات الجودة العالية مبدئيًا بسبب الانضغاط. يتألف نظام المسام بشكل أساسي من مسام معزولة مع تباينات رأسية في الحجم، ومساحة السطح، والقطر. من خلال دمج تقنيات نمذجة الصخور الرقمية وتحليل التراجع

الزماني، تقدم هذه الدراسة إطاراً شاملاً لتحديد وقياس تطور المسامية والنفاذية في مكامن النفط وخزانات المياه ذات الصخور المتخلخلة حيويًا. وتعد هذه النتائج أساسية لفهم أداء المكامن وتدفق السوائل في الأنظمة التي يصعب فيها قياس النفاذية بشكل مباشر.

الكلمات المفتاحية: كربونات، الاضطراب البيولوجي، تغيرات نظام المسام، حشوات الجحور، تكوين حنيفة.

CHAPTER 1

INTRODUCTION

1.1 Bioturbated Carbonate Reservoirs

Burrowed strata occur in many parts of the world encompassing significant hydrocarbon reserves and aquifers (e.g., Gingras et al., 1999; 2004a; 2012; Cunningham, 2004; Cunningham et al., 2009; 2012; Hovikoski et al., 2007; Volkenborn et al., 2007; Tonkin et al., 2010; Baniak et al., 2013; 2014; 2015; La Croix et al., 2013). Therefore, the comprehension of the petrophysical parameters of these strata has expanded greatly during the last two decades. The term “bioturbation” describes the way that biological activity modifies deposits and soils (Richter, 1936). It can take place either during the depositional processes or following the lithification of deposits, leading to changes in the physical properties of the rock substrate through the mixing of sediment and redistribution of grains, resulting in the formation of new structures. Such modifications could involve compaction, emplacement (biodeposition), sorting (biostratification), and sediment removal (bioerosion) (Taylor et al., 2003). Furthermore, burrowing organisms have the ability to alter the geochemical signatures of sediments through the combination of organic matter that they produce (Pemberton and Gingras, 2005; Gingras et al., 2009).

Most bioturbated strata exhibit variations in their porosity and permeability properties in comparison to the nearby unbioturbated host matrix as a result of these alterations to the

sediment (Baniak et al., 2022). Burrow fillings (BF) and their interconnections are the primary factors controlling the quality of reservoir in burrowed strata (e.g., Gingras et al., 1999; Pemberton and Gingras, 2005; La Croix et al., 2012; Baniak et al., 2013, 2014, 2015; Eltom et al., 2019). Formerly, it was considered that bioturbation reduced reservoir quality (Grier and Marschall, 1992). However, contemporary investigations have revealed that bioturbation may also improve reservoir quality, particularly in terms of permeability, to different levels (Dawson, 1978; Gingras et al., 2004a; Pemberton and Gingras, 2005; Cunningham et al., 2009; Gordon et al., 2010; Ben-Awuah and Eswaran, 2015; Friesen et al., 2017; Quaye et al., 2019; Eltom et al., 2019).

1.2 *Glossifungites* Ichnofacies

Seilacher (1978) formulated the term *Glossifungites* ichnofacies to describe the burrows dug up into firm or unlithified substrates. Consequently, this ichnofacies could be used to interpret the occurrence of firm ground conditions which is also known as substrate-controlled ichnofacies (Seilacher, 1978). Although this ichnofacies is highly associated with muddy substrates, some studies documented its occurrence in incipiently cemented sandy substrates (Pemberton and MacEachern, 1995; Pemberton et al., 2004). The existence of *Glossifungites* ichnofacies is prevailing throughout different temporal and spatial scales with exhumation that may occur in a variety of environments encompassing terrestrial, shallow-water, and deep-marine settings (Abdel-Fattah et al., 2016).

Glossifungites ichnofacies consist mainly of both vertical and subvertical burrows (Knaust, 2017). Three recurrent and typically distinctive features are present in *Glossifungites* ichnofacies: (1) they exhibit locally scratch-marked and unlined margins and sharp walls showing how cohesive the substrate was during burrows excavation, (2) they reflect that

they functioned as dwellings and were occupied until after the omission depositional event because they are passively filled, and (3) extensive occurrence of colonization in a substrate that remained stable for long time allowing substantial growth of organisms that are responsible for trace marks represented by expansion of structures.

One ichnotaxon that usually forms *Glossifungites* ichnofacies is *Thalassinoides*. This ichnotaxon is characterized by a boxwork pattern with vertical shafts and horizontal mazes. Furthermore, T and Y shapes with elongated tubes and cross-sections of circular to elliptical shafts are displayed in the transfer sections of rocks that bear *Thalassinoides*. Bulbous sections with an inconsistent size and shape that are much larger than the shaft cross-sections are generated by the burrows at the junctions of these shafts. Additionally, these burrows are characterized by Passive filling inside walls that are locally scratched and marked, as well as sharp unlined (Eltom et al., 2021).

1.3 Stratigraphy and Sedimentology of Hanifa Formation

The Shaqra group, which is of Jurassic age, comprises seven units in Saudi Arabia, the fourth of which is the Hanifa Formation (Fig. 1A, El-Sorogy et al., 2018). The Hanifa formation's type section is defined at Jabal Al-Abakkayn in Wadi Hanifa, positioned in central Saudi Arabia (Fig. 1C, Powers et al., 1966). In the study area, the Hawtah and Ulayyah members make up the Hanifa Formation (Fig. 1A). The base of the Hawtah Member consists of soft calcareous shale interval that unconformably overlies the limestone of the Tuwaiq Mountain Formation. This interval passes up to strata composed of mudstone and skeletal carbonates, and it is equivalent to a key source rock interval in

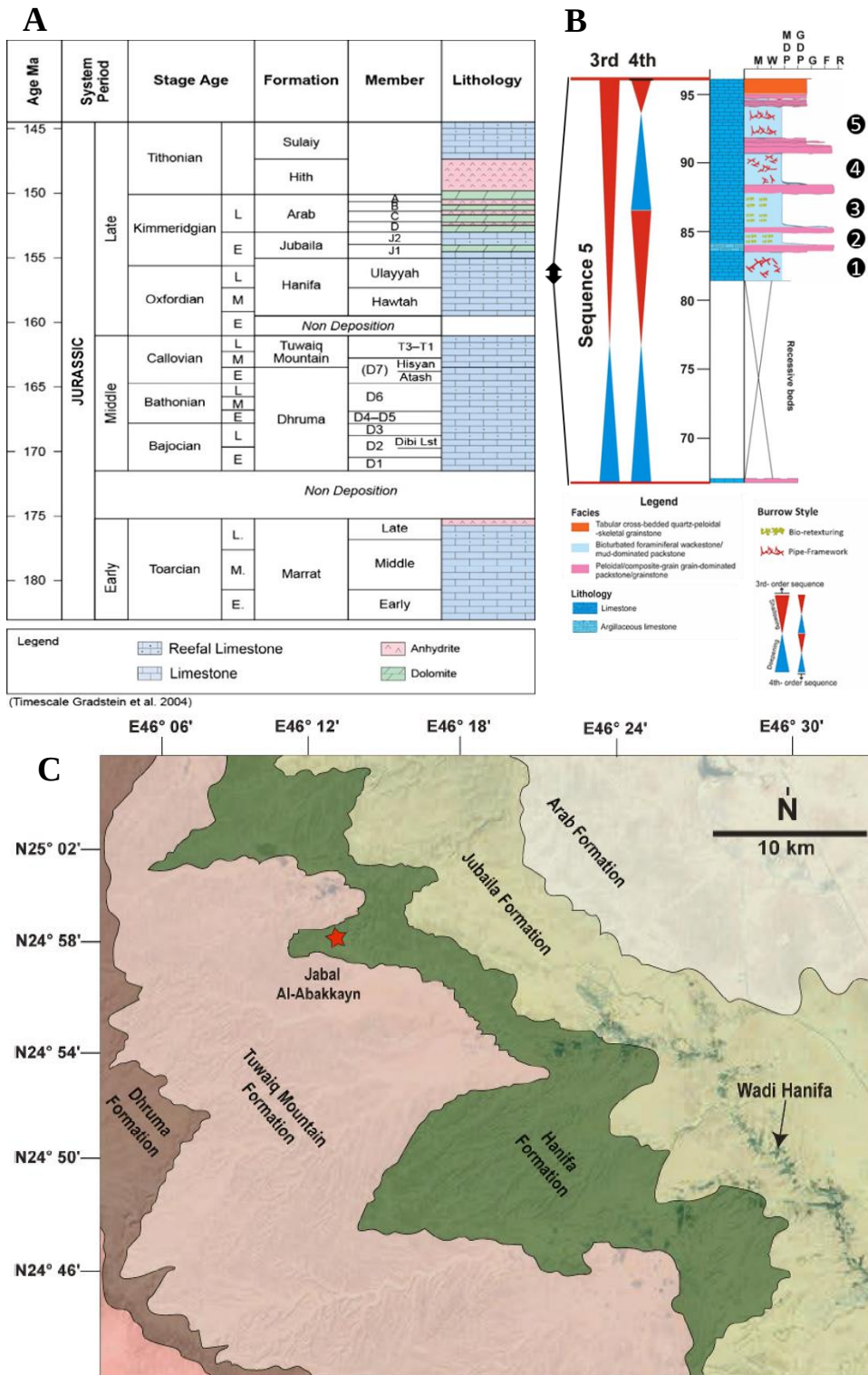


Figure 1. (A) A generalized stratigraphic column of the Jurassic succession in Saudi Arabia (after El-Asmar et al., 2015). (B) Measured section at Jabel Al-Abakkayn showing sequence stratigraphy of the Hanifa Formation and the five studied intervals (Modified from Fallatah and Kerans, 2018; Syahputra et al., 2022). (C) A geologic map of central Saudi Arabia illustrates the location of the study area (Jabel Al-Abakkayn, Red star) where the intervals were studied (modified from Syahputra et al. (2022)).

the petroleum system of the Arabian Platform. Organic matter with total organic carbon content (TOC) in the subsurface strata equivalent to Hawtah Member fluctuates between 1% and can reach 14% in some oil fields, as reported by (Droste, 1990; Carrigan et al., 1995).

The Ulayyah Member corresponds to strata similar to the hydrocarbon reservoir in the Hanifa Reservoir in eastern Saudi Arabia (Droste, 1990; Carrigan et al., 1995). This reservoir is predominantly characterized by basin-margin grainstone facies, which are juxtaposed with source rock rich in organic matter within the Tuwaiq Mountain Formation. As a result, it represents a significant permeable reservoir for hydrocarbon in the Middle East, which is sealed effectively by the muddy limestones of the Jubaila Formation. At the top, the Hanifa Formation also has a disconformity contact with the Jubaila Formation above it (Powers et al., 1966; ap Gwilym Hughes, 2004).

Fallatah and Kerans (2018) found that the Hanifa Formation in central Saudi Arabia is made up of five major third-order sequences, which are ordered from the base to the top (sequences 1 to 5). There are two fourth-order sequences within each of these third-order sequences. At Jabal Al-Abakkayn, sequence 1 is pinched out while the other four sequences (sequences 2 to 5) are observable. This study targets the five bioturbated intervals of the Ulayyah Member founding within sequence 5 (Fig. 1B). These intervals are located above a significant regional marker bed of the Hanifa Formation and represent a part of the bioturbated foraminiferal wackestone/mud-dominated packstone strata (Fallatah and Kerans, 2018).

1.4 The Hanifa Formation Bioturbated Strata

This study targeted the intervals affected by bioturbation, particularly, in the uppermost part of Ulayyah member that was caused by marine fauna (Fig. 1B). *Cruziana* ichnofacies represent the whole trace fossils found in these strata (El-hedeny., 2012). *Thalassinoides* burrow networks (TBN) that penetrate a firm substrate of carbonate strata dominated by mud are the most prevalent trace fossils (El-hedeny., 2012, Eltom et al., 2018). Some of the burrows remain partly or fully open at the outcrop scale, creating tubes or vugs with diameters ranging between 0.4 and 3.0 cm, either connected or unconnected. Related to the grain sizes of the burrow fillings, they can be either coarse or fine. The burrows within the grain-dominated units were predominantly filled with fine sediments, but they can also be present in mud-dominated units. In the same manner, coarse grain fillings are more frequent in the mud-dominated units and they can occur in the grain-dominated units (Salih et al., 2021).

1.5 Petroleum System

The Oxfordian-Kimmeridgian aged Hanifa Formation, which is part of the Jurassic succession, is a significant unit in Saudi Arabia. It contains economically significant conventional hydrocarbon deposits within several oilfields and shows potential as an unconventional source rocks in lower portions of the Arabian Platform (Alsharhan and Magara, 1994). It is economically important because it serves as a source, reservoir, and seal in the subsurface (Kompanik et al., 1993; Al-Khalifah and Makkawi, 2002). Previous research has identified certain intervals in both outcrops and subsurface reservoirs of the

Hanifa Formation as bioturbated (Al Ibrahim et al., 2017; Fallatah and Kerans, 2018; Eltom et al., 2019).

1.6 The research motivation and objectives

Previous research has investigated the impact of burrow attributes in terms of intensity, morphology, size, filling, and connectivity and reported laboratory measurements to better understand strata with bioturbation within the Hanifa Formation, central Saudi Arabia, with a focus on the petrophysical properties and the role of bioturbation affecting the reservoir quality. However, quantitative and qualitative characterization of the carbonate pore system within the burrow fillings and its relationship to sedimentological and diagenetic processes are poorly understood. As a result, the main objectives of this study were to answer upon three questions:

1. How the pore system and porosity vary vertically within the burrow fillings and how they can be affected by the other factors involving sedimentological and diagenetic processes?
2. How the porosity and permeability within the burrow fillings of packstone fabric evolved over time?
3. Do spot permeability measurements always reflect the bulk permeability of bioturbated reservoirs?

1.7 The study area

The type section of the Hanifa Formation, which has a thickness of ~101m, is defined at Jabal Al-Abakkayn, near Riyadh City, positioned in central Saudi Arabia (Fig. 1C, Powers et al., 1966) where the Ulayyah Member of the Hanifa Formation is exposed (Fig. 2). To

achieve the objective of this study, we examined carbonate rocks that consist of *Thalassinoides* as *Glossifungites* ichnofacies found in the upper Hanifa Formation (Fig. 1B and Fig. 2). The rocks were previously described by Eltom and Hasiotis (2018) and subsequently investigated by many other studies (Eltom et al., 2021b; Eltom and Alqubalee, 2022; Syahputra et al., 2022).

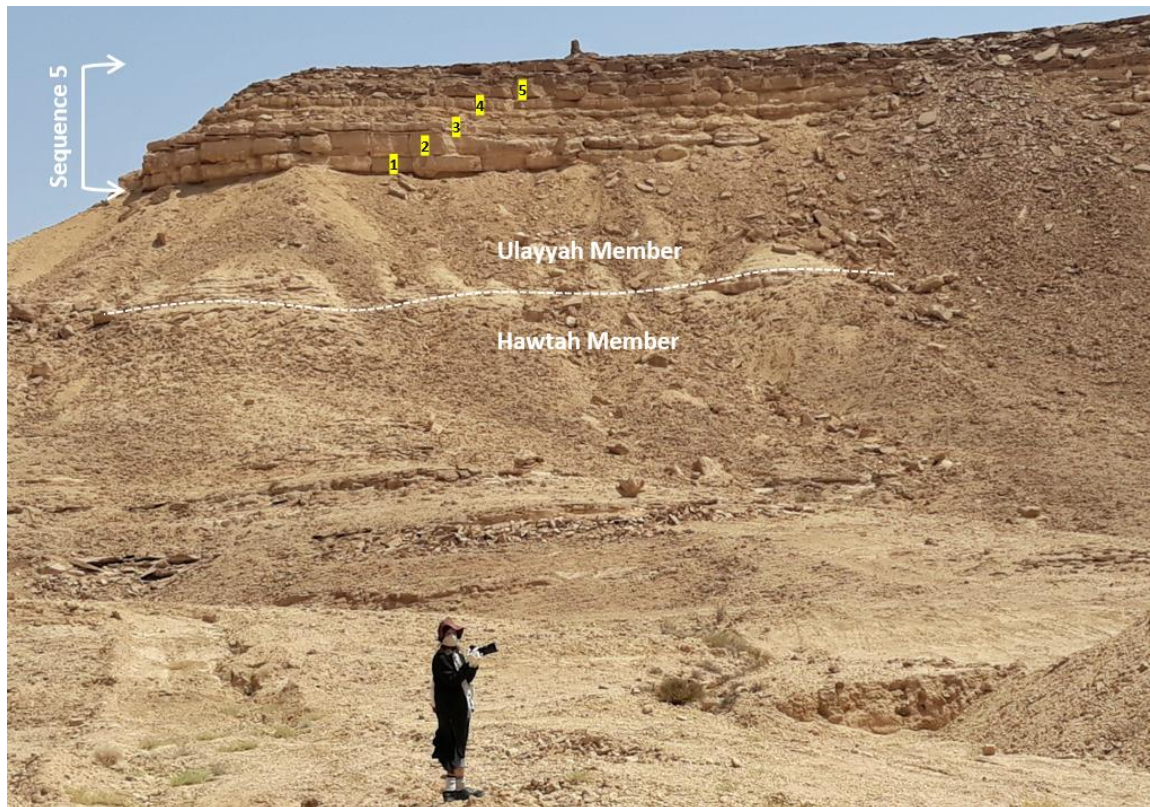


Figure 2. Photograph showing the studied five intervals located in sequence 5 in the Upper Hanifa Formation at Jabel Al-Abakkayn.

CHAPTER 2

Sedimentological and diagenetic controls on burrow fillings in the Upper Jurassic Hanifa Formation, central Saudi Arabia: Implications for porosity and pore system variation in bioturbated reservoirs

Abstract

Evaluating the petrophysical properties of bioturbated carbonate strata requires an understanding of the heterogeneity in rock texture within burrow fillings (BF). This study examines five bioturbated stratigraphic intervals in the upper Hanifa Formation, Saudi Arabia, focusing on burrowing style, depositional texture, diagenetic alterations, porosity, and pore system. The primary objective is to understand how the pore system and porosity vary vertically within the BF of these bioturbated intervals and how they can be affected by the other factors involving the burrowing style, the depositional texture, and the diagenetic alterations. Based on the burrowing style, the five bioturbated stratigraphic intervals can be classified into intervals with bio-retexturing fabric and intervals with pipe framework burrows due to burrowing, according to the results of field study, petrographic analysis, and medical CT scanning.

Data from petrographic investigation suggested that BF in intervals with a pipe framework burrowing (intervals 1, 4, and 5) likely deposited in similar environments exhibit prominent variations in grain size, with mean grain sizes of $766 \pm 752 \mu\text{m}$ for interval 1, $739 \pm 433 \mu\text{m}$ for interval 4, and $514 \pm 341 \mu\text{m}$ for interval 5. Porosity values from micro-CT scans show 7.15%, 4%, and 7.75%, respectively. In contrast, bio-retextured intervals (intervals

2 and 3) have smaller mean grain sizes of $355 \pm 206 \mu\text{m}$ and $402 \pm 148 \mu\text{m}$, with lower total porosity values of 1.64% and 2.71%, respectively.

The rock texture in the BF of the pipe framework was classified as either mud-rich packstone (interval 5) or mud-poor packstone (intervals 1 and 4) based on the mud content. Petrographic analysis suggested that dolomitization plays a crucial role in preserving porosity in mud-rich packstones by resisting compaction. In contrast, mud-poor packstones with lower dolomite content exhibit significant porosity reduction due to compaction. The findings contributed to our understanding of how porosity in packstones within BF evolved. Initially, mud-rich packstones with poor porosity and permeability might become more permeable due to preferential dolomitization and subsequent dissolution. On the other hand, compaction may cause the higher porosity and permeability values of initially good-quality mud-poor packstones to degrade in quality. When it comes to bioturbated strata, where direct measurements of permeability are difficult, understanding these processes is essential for predicting reservoir performance and fluid flow. Finally, the pore system of the BF predominantly consists of isolated pores with vertical variation in volumes, surface areas, and equivalent diameters.

Keywords:

Burrow fillings; Burrowing style; Rock texture; Diagenetic alterations; Pore system.

2.1 Introduction

Carbonate rocks are characterized by their significant storage and flow capacities, making them important not only for containing substantial hydrocarbon reserves and extensive water aquifers but also for serving as reservoirs for the disposal of carbon dioxide and

waste materials (Merritt, 1986; Alsharhan and Nairn, 1993; Lucia et al., 2003; Cantrell et al., 2004; Cunningham et al., 2004; Cunningham et al., 2006; Lindsay et al., 2006; Cunningham et al., 2009; Goldscheider et al., 2010; Cunningham and Sukop, 2012; Cantrell et al., 2014). However, the heterogeneous texture of carbonate rocks poses challenges in their characterization and modeling (Moore, 1989; Cantrell and Hagerty, 2003; Lucia et al., 2003; Chekani and Kharrat, 2009; Moore and Wade, 2013). This heterogeneity impacts the accuracy of predictions related to their porosity and permeability and, consequently, their capacity to store and transmit fluids. Understanding these complexities is crucial for optimizing the exploitation and management of natural resources.

Bioturbation (Bromley, 2012), a process defined as biological activity during and after sedimentation, plays an important role in controlling carbonate rock heterogeneity. These activities can significantly alter sediments through mechanisms such as pack filling, sorting, and compaction (Buatois et al., 1999; Pemberton and Gingras, 2005; Buatois et al., 2020). Numerous previous studies have documented bioturbation as a process that enhances porosity and permeability in sedimentary strata, particularly when burrows, such as those associated with *Glossifungites* ichnofacies, are present (Gingras et al., 1999; MacEachern et al., 2007; Gingras et al., 2012; Eltom and Hasiotis, 2019; Baniak et al., 2022).

The presence of *Glossifungites* ichnofacies within carbonate rocks serves as an indicator of surface-constrained discrete heterogeneities (Pemberton and Gingras, 2005). *Glossifungites* ichnofacies represents a surface of omission and is characterized by burrows that are excavated into firm or compacted substrates within mud-dominated strata, which

are subsequently passively filled with coarser-grained sediments (Gingras et al., 1999; MacEachern et al., 2007; Gingras et al., 2012; Eltom and Hasiotis, 2019; Baniak et al., 2022). In scenarios where the burrows that make up the *Glossifungites* ichnofacies are typically interconnected and extensive, they can form pathways for permeability within the otherwise less permeable host rock matrix (La Croix et al., 2012; Eltom et al., 2019; Eltom and Goldstein, 2021; Eltom and Goldstein, 2023b; Eltom and Goldstein, 2023a). This is due to the passive fillings and permeable nature of the burrow fillings, which facilitate fluid flow through the rock, significantly altering its overall permeability characteristics.

Petrophysical properties in carbonate strata, under these conditions, are influenced by two levels of rock heterogeneity. The first, a larger-scale level, dictates the characteristics of the burrow network, including burrow intensity, morphology, connectivity, and the dimensions of shafts and tunnels. The second, a more granular level, relates to the attributes of the burrow fillings, such as texture, grain size distribution, degree of sorting, and the pore system. While numerous studies have explored the first level of heterogeneity, focusing on how burrow intensity and connectivity affect the petrophysical properties within bioturbated strata, the impact of the characteristics of burrow fillings in terms of sedimentological and diagenetic factors on these properties has received comparatively less attention, especially in scenarios where burrows significantly influence rock heterogeneity in carbonate rocks.

Despite the recognition of bioturbation as a significant process influencing reservoir quality, the controls on the evolution of porosity within the burrow fillings remain inadequately studied. This gap in understanding limits our ability to accurately assess porosity and pore system variations within bioturbated carbonate strata, potentially leading

to shortcomings in reservoir evaluation. Accurate evaluation of fluid flow behavior in bioturbated strata critically depends on understanding the heterogeneity of burrow fillings, as the evolution of porosity within these fillings can significantly alter permeability over time, ultimately impacting reservoir performance and influencing exploration and production strategies in carbonate reservoirs.

In this context, the objective of this study was to examine the *Glossifungites* ichnofacies and *Thalassinoides* burrow fillings found in the Upper Jurassic Hanifa Formation (Fig. 1B and Fig. 2), employing an integrated approach that combines petrographic and CT scanning analysis with digital rock physics modeling. This approach aims to understand how porosity and pore system evolve and vary in these burrow fillings and how they can be controlled by the sedimentological and diagenetic processes. Our findings provide a conceptual framework for understanding these processes.

2.2 Geological background

2.2.1 Study area

The type section of the Hanifa Formation, which has a thickness of ~101m, is defined at Jabal Al-Abakkayn, near Riyadh City, positioned in central Saudi Arabia (Fig. 1C, Powers et al., 1966) where the Ulayyah Member of the Hanifa Formation is exposed (Fig. 2). To achieve the objective of this study, we examined carbonate rocks that consist of *Thalassinoides* as *Glossifungites* ichnofacies found in the upper Hanifa Formation (Fig. 1B and Fig. 2). The rocks were previously described by Eltom and Hasiotis (2018) and subsequently investigated by many other studies (Eltom et al., 2021b; Eltom and Alqubalee, 2022; Syahputra et al., 2022).

During the Late Jurassic, the Arabian Plate was represented as an intrashelf basin located in an equatorial position in the northeastern part of Gondwanaland (Fig. 3). The study area situated on the western flank of this basin and located near the paleo-shoreline of the Tethys Ocean (ap Gwilym Hughes, 2004; ap Gwilym Hughes et al., 2008; Fallatah and Kerans, 2018). Sharland et al. (2001) classified the Late Jurassic succession of the Arabian plate as strata deposited in a passive margin environment with shallow marine conditions (Fig. 3).

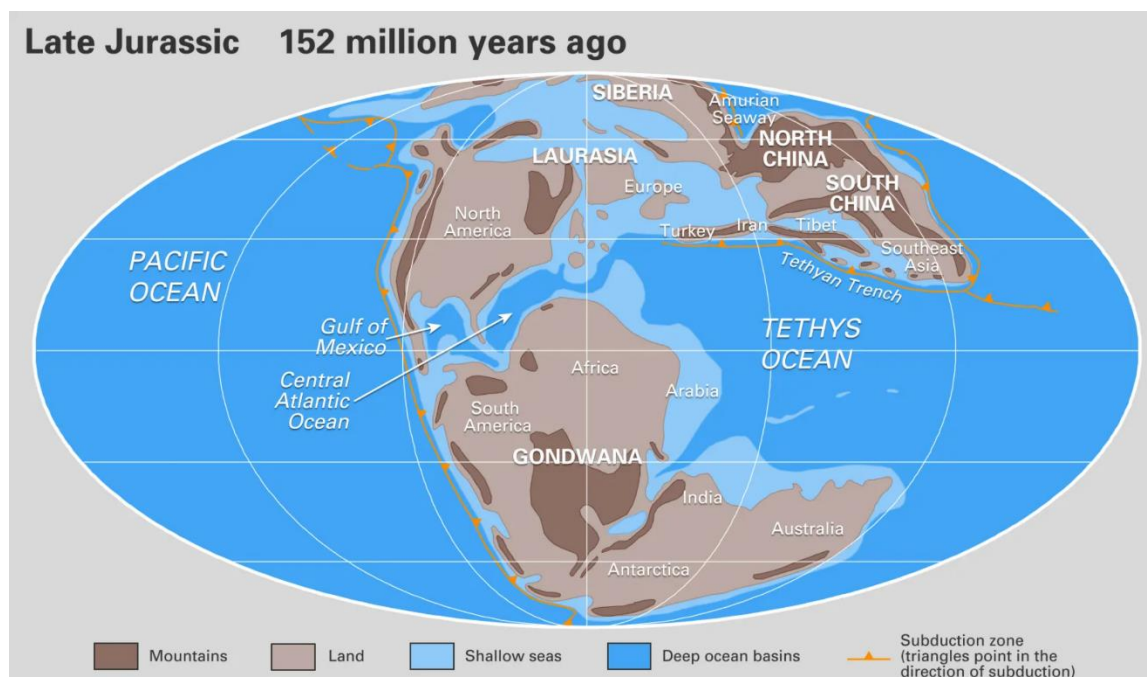


Figure 3. Paleogeographic map from the late Jurassic period displaying the Arabian Plate at an equatorial position facing the western Tethys Ocean and covered by shallow waters (modified from Scotese, 2002, <https://www.britannica.com/science/Jurassic-Period>).

2.2.2 Sedimentology and Stratigraphy

In the study area (Fig. 1C), the Hawtah and Ulayyah members make up the Hanifa Formation (Fig. 1A). The base of the Hawtah Member consists of soft calcareous shale interval that unconformably overlies the limestone of the Tuwaiq Mountain Formation. This interval passes up to strata composed of mudstone and skeletal carbonates, and it is

equivalent to a key source rock interval in the petroleum system of the Arabian Platform. Organic matter with total organic carbon content (TOC) in the subsurface strata equivalent to Hawtah Member fluctuates between 1% and can reach 14% in some oil fields, as reported by (Droste, 1990; Carrigan et al., 1995).

The Ulayyah Member corresponds to strata similar to the hydrocarbon reservoir in the Hanifa Reservoir in eastern Saudi Arabia (Droste, 1990; Carrigan et al., 1995). This reservoir is predominantly characterized by basin-margin grainstone facies, which are juxtaposed with source rock rich in organic matter within the Tuwaiq Mountain Formation. As a result, it represents a significant permeable reservoir for hydrocarbon in the Middle East, which is sealed effectively by the muddy limestones of the Jubaila Formation. At the top, the Hanifa Formation also has a disconformity contact with the Jubaila Formation above it (Powers et al., 1966; ap Gwilym Hughes, 2004).

Fallatah and Kerans (2018) found that the Hanifa Formation in central Saudi Arabia is made up of five major third-order sequences, which are ordered from the base to the top (sequences 1 to 5). There are two fourth-order sequences within each of these third-order sequences. At Jabal Al-Abakkayn, sequence 1 is pinched out while the other four sequences (sequences 2 to 5) are observable. This study targeted the bioturbated intervals of the Ulayyah Member founding within sequence 5 (Fig. 1B and Fig. 2). These intervals are located above a significant regional marker bed of the Hanifa Formation and represent a part of the bioturbated foraminiferal wackestone/mud-dominated packstone strata (Fallatah and Kerans, 2018).

2.2.3 The main objective of this study compared to the previous works

Previous research has investigated the impact of burrow attributes in terms of intensity, morphology, size, filling, and connectivity and reported laboratory measurements to better understand strata with bioturbation within the Hanifa Formation, central Saudi Arabia, with a focus on the petrophysical properties and the role of bioturbation affecting the reservoir quality. Eltom and Hasiotis (2019) used outcrop data and 3D geocellular facies-based models to investigate the spatial and temporal variations in *Thalassinoides* burrow networks (TBN) and their influence on the lateral and vertical distribution of flow pathways, providing insights into reservoir quality. After that, Salih et al. (2021) examined the controlling factors in terms of burrow intensity (BI), size of the burrow fillings (coarse or fine grains), and mineralogy on the petrophysical and acoustic properties of bioturbated carbonates of the Hanifa Formation.

The findings of these investigations highlighted the concerns that the Hanifa Formation contains an overlooked bioturbated reservoir. In further studies, Eltom et al. (2021a) employed a combination of petrophysical, petrographic, and ichnological investigations along with multipoint statistics (MPS) modeling to demonstrate how *Thalassinoides*, which possess passive fillings of grain-dominated carbonate, can enhance the petrophysical properties in host rock matrix with mud-dominated texture. Following this, Eltom and Alqubalee (2022) investigated the quantitative variability in the burrow percentages estimated from 2D views by utilizing different methodologies, such as a medical-CT scanner and various software, including PetrelTM 2019 and Fiji ImageJ to quantitatively understand how 2D views underestimate and overestimate the actual burrow percentage of the *Thalassinoides*. El-Husseiny et al. (2022a) characterized seventy-seven core plugs

using laboratory methods such as petrophysical measurements of velocity, porosity, and permeability, petrography, and CT scanning to investigate the impact of the burrow fillings (BF) and the intensity of bioturbation (BI) on the elastic velocity.

More recently, Eltom and Goldstein (2023) utilized a data-driven approach obtained from a medical CT scanner conducted on only a core with a diameter of ~18.5 cm extracted from *Thalassinoides*-bearing strata to determine the appropriate dimensions of the subsamples (representative elementary volume) of the core to represent the vertical connectivity and the burrow percentages (BP) which may control the petrophysical properties in such facies. To improve knowledge of how *Thalassinoides* affect petrophysical properties, Eltom et al., 2023 employed an integration of petrographic analysis, petrophysical measurements, computer tomographic (CT) scanning, and high-resolution imaging with scanning electron microscopy (SEM) to study the spatial complexity of burrow attributes in terms of burrow intensity and burrowing style and determine how they can control the spatial variability of petrophysical properties.

The impact of *Thalassinoides* on the reservoir quality of bioturbated strata in the Hanifa Formation has been greatly highlighted by these previous investigations. However, these studies faced limitations in evaluating the pore system, porosity, and permeability. Regarding the pore system within the burrow fillings, they overlooked the vertical variation in the pore-size distribution regarding pore volumes, areas, and equivalent diameters, particularly in stratigraphically separated bioturbated intervals. Moreover, the influence of the sedimentological processes (e.g., burrowing style, rock texture, mud content, grain-size distribution, and grain percentage) and diagenetic alterations (e.g., dolomitization,

compaction, dissolution, and cementation) on the vertical variation of the pore system within the burrow fillings has received less attention.

The porosity of the burrow fillings in the previous works was visually estimated from the thin-sections ignoring the heterogeneity in the pore structure. This limitation can be addressed by utilizing the digital rock modeling to visualize the pore network in 3D enabling a more accurate estimation of porosity and better assessment of vertical variations within the . Concerning bulk permeability, spot permeability measurements for the burrow fillings and host rock matrix cannot take into consideration isolated or poorly connected pore systems. While spot measurements can be beneficial for localized permeability analysis, they often fail to capture the true complexity of the reservoir.

To address these gaps, this study employs an integrated approach that combines petrographic and CT scanning analysis with digital rock physics modeling to quantitatively and qualitatively characterize the vertical variation in carbonate pore system and the porosity within the burrow fillings as well as their relationship to sedimentological and diagenetic processes. This comprehensive methodology not only enhances the accuracy of pore system characterization in the Hanifa Formation but can also be applied to other bioturbated carbonate reservoirs.

2.3 Materials and Methods

2.3.1 Fieldwork and Sampling

Fieldwork in the study area has been made to examine the depositional texture, the burrowing style, the thickness of studied intervals, and the stratigraphic patterns, as well as to collect samples. Five boulder-sized samples, labeled from bottom to top as intervals 1

through 5, were collected from the bioturbated strata in the uppermost part of Hanifa Formation at Jabal Al-Abakkayn (Fig. 1B and Fig. 2). These samples range in length from 29 cm to 76 cm. They were slabbed and cored to systematically extract plug samples based on the required laboratory analysis. Plugs with a diameter of 3.81 cm were cut every 10 cm, yielding a total of 28 core plugs from these slabs. Each sample comprises parts of the burrow fillings and the host rock matrix. Petrographic analysis and digital rock physics modeling are conducted on these samples. A 9.65 cm diameter cores that penetrated the entire stratum were cut for medical CT scanning to image the morphology and the burrowing style of the *Thalassinoides* burrow networks in the studied intervals.

2.3.2 Petrographic analysis

Thin-sections were obtained from the 3.8-cm plugs and prepared to standard dimensions (27 × 46 mm). Each thin-section includes parts of both the burrow fillings and the host rock matrix and was prepared to characterize depositional textures, diagenetic features, pore types, and biocomponents. To highlight the pores and delineate the geometry of the pore spaces, the sections were stained with blue-dyed epoxy. For analysis, these sections were imaged using an AxioScan system in the King Fahd University of Petroleum & Minerals (KFUPM) laboratory. The obtained images were processed and analyzed using ZEISS ZEN 3.8 software. In these images, the carbonate pore systems of both burrow fillings and host rock matrix were classified using the Choquette and Pray, (1970) scheme. The ZEISS ZEN 3.8 software was utilized to measure the major and minor axes of the allochems, allowing for the calculation of their size, sorting, and aspect ratios (α) which can be correlated with geological processes. In addition to the AxioScan image analysis performed by ZEISS ZEN 3.8 software, the thin-sections were examined under a conventional light

microscope in order to identify the overall paragenetic sequence in the burrow fillings. Cross-cutting relationships and superposition were used to identify the timing of each diagenetic event.

2.3.3 Medical-CT scanning

The medical-CT scanner instrument of Toshiba Alexion TSX-032A was utilized to acquire medical-CT scan data with a 1 mm resolution. These data were processed by using OsiriX software. The processed CT scans were transformed into SEG-Y files using PerGeos software, allowing Petrel™ 2020 software to manipulate the files as seismic cubes. The burrow networks in the CT scans of the cores were extracted using Petrel™ 2020 software, allowing for the observation of variations in their morphology and burrowing style. The CT scanner and the software utilized for processing and interpreting CT data are located in KFUPM.

2.3.4 Micro-CT scanning

Based on the petrographic analysis, five samples (each from a distinct interval) were chosen for subsampling to apply further high-resolution imaging techniques (micro-CT scanning). Subsampling involved cutting thumbnail-sized samples from the burrow fillings, although the host rock matrix may also be present in these samples (Fig. 4A). These smaller samples were micro-CT scanned using a Versa XRM-5002D scanner (located at KFUPM) with a 9 µm voxel resolution to yield 2D micro-CT slices. The micro-CT scanner utilized a polychromatic conical X-ray beam, produced by microfocused X-rays, to generate images of the samples using a circular trajectory with 1601 projections. To achieve optimal X-ray intensity flux, the scan voltage was set at 140 kV, with a power

of 10 W, and an exposure time ranging from one to four seconds. Digital software (Avizo) was then used to process and analyze the data that was acquired from the micro-CT scanner for each sample (Fig. 4B).

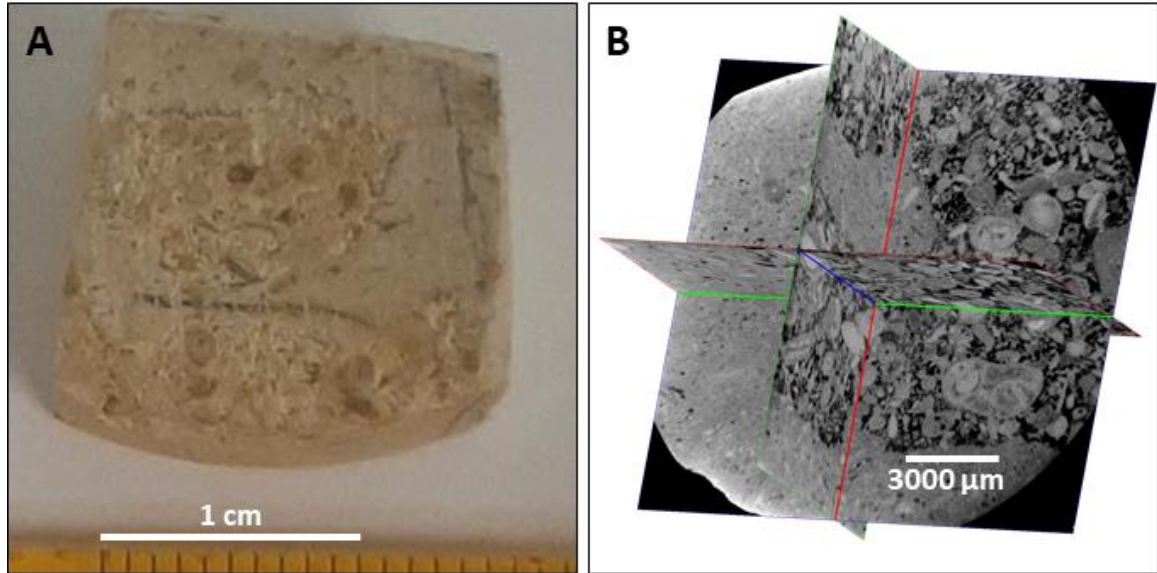


Figure 4. (A) Photograph of the thumbnail-sized sample preparing for micro-CT scanning. (B) Screen capture of the sample in Avizo software with imaging resolution of 9 microns displaying the HRM and the BF.

2.3.5 Digital rock physics modeling

A. Extract Subvolume and Advanced Image Processing

To analyze the image data acquired from the μ -CT scanner, Avizo software was employed for processing. Cubes with the same number of voxels in the vertical (Z) and the horizontal (X and Y) directions were extracted within the burrow fillings from each sample using the Extract Subvolume module in Avizo to be representative for them since the main objective was to study the pore system inside the burrow fillings (Fig. 5A). The number of voxels differed from sample to sample depending on the dimensions of each sample. Following the cubes extraction and prior to the segmentation process, digital image filter was applied for controlling noise, smoothing, contrast or artifacts reduction, and feature enhancement

that can help further segmentation. For better segmentation of pores and estimation of porosity, the Non-Local Means filter found in Avizo, which is well-known for efficiently preserving edges and handling noisy data, was applied from the Filter Sandbox module (Fig. 5B).

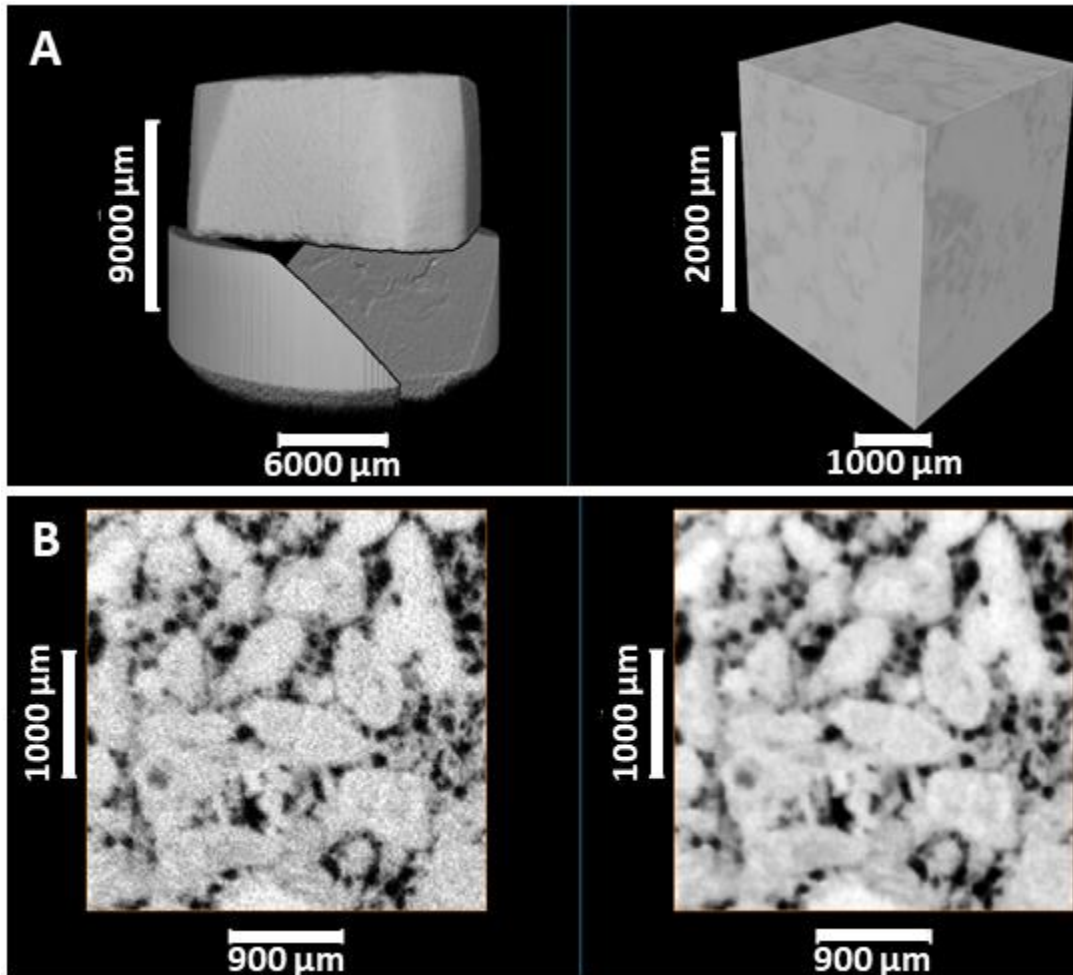


Figure 5. (A) Screen capture of the samples obtained from the micro-CT scanner (left side) and cubic Sub-volume extraction inside the burrow fillings (right side). (B) Screen capture displaying the smoothing of data by utilizing the Non-Local Means filter.

B. Segmentation

Utilizing the Edit New Label Field in the Image Segmentation module in Avizo, each sample was segmented into some materials indicated by different colors depending on the

density (Fig. 6). To accurately identify the pores within the samples, the thresholding segmentation tool was employed. Additionally, the Top-Hat tool was utilized to identify tiny and intraparticle pores within the grains that were not picked by the previous tool. Following the pores segmentation, the value of the thresholding segmentation tool was adjusted to label the matrix. The grains were the last material to be segmented. Once the three structures were segmented, using the Volume Fraction module in Avizo to measure their volumes was straightforward. Specifically, the pores volume will represent the total porosity within each sample (Fig. 7A).

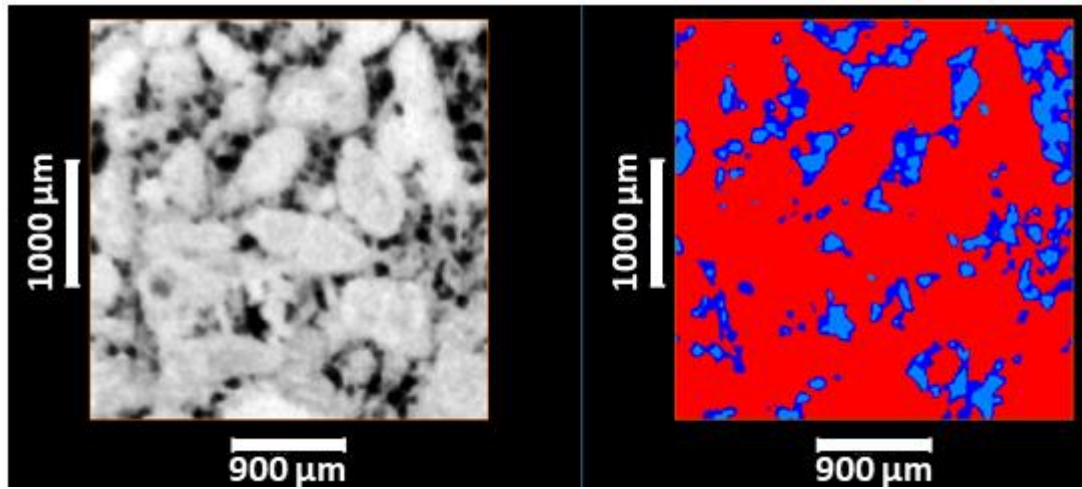


Figure 6. Screen capture showing the segmentation process separating the burrow fillings into three materials (red for grains, dark blue for matrix, and light blue for pore spaces).

C. Pore Network Modeling (PNM)

Axis Connectivity module in Avizo was utilized to measure the connectivity in X, Y, and Z-directions. This newly created object enables effective labeling of the connected pores within the pore system of the burrow fillings (Fig. 7B). Consequently, the Volume Fraction module was used to quantify the volumes of both total and connected pores within each model. Conversely, the isolated pores (Fig. 7C) were delineated by employing the Subtract Image module in Avizo to subtract the connected pores from the total pores. Finally, the

connected and isolated pores within the burrow fillings were visualized in the three dimensions (3D), providing insights into their spatial distribution and connectivity (Fig. 7B and C).

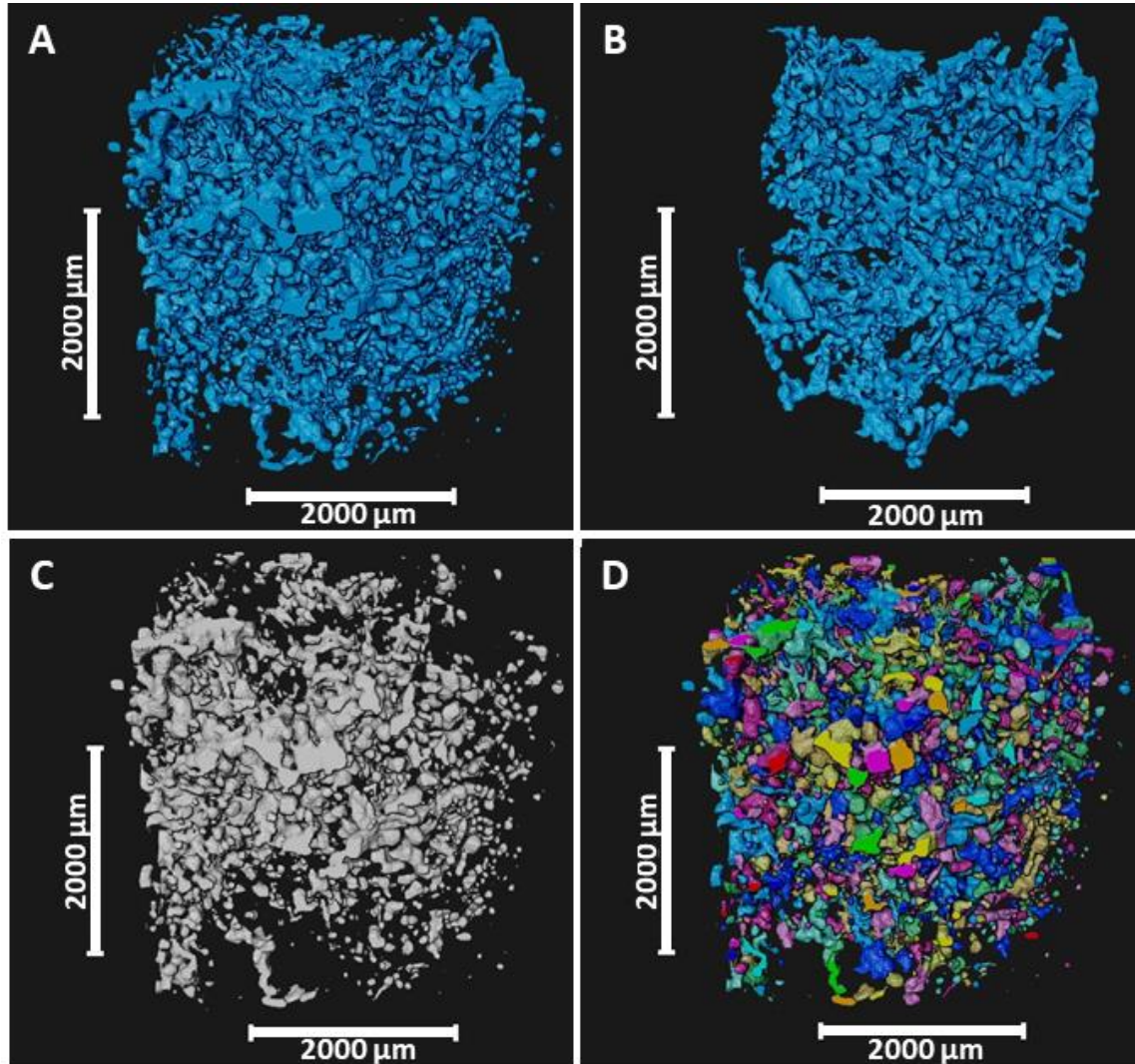


Figure 7. Screen captures for the pore system resulted from the segmentation process. (A) Total porosity, (B) Connected porosity, (C) Isolated porosity, and (D) the Labeling analysis of the pore spaces within each sample.

D. Quantitative analysis (statistical measurements)

Some of the pores resulted from the segmentation process appeared to be touching each other, but ideally, they should be separated for proper analysis. Thresholding cannot avoid

this type of output despite the acquisition data being filtered before segmentation. Consequently, the Separate Objects module in Avizo software was used to separate the connected pores to enable thorough analysis. Subsequently, the resulted object was utilized to extract comprehensive numerical and statistical information. By applying the Label Analysis module in Avizo Software, it became straightforward to measure the pore volumes, areas, equivalent diameters, sphericity, anisotropy, elongation, flatness, etc., individually for each separated pore (Fig. 7D). This approach served as a systematic approach to analyze the pores identified within each model, ensuring accurate characterization and enabling insightful comparisons between the samples.

2.4 Results

2.4.1 Burrowing style and Rock texture

The burrowing style varies across the five intervals of sequence 5 and significantly impacts the rock texture of the bioturbated units in the Hanifa Formation (Fig. 1B). In intervals 1, 4, and 5 of the sequence, the burrows create a pipe framework burrowing style with distinct burrow fillings and host rock matrix areas within the rocks (Fig. 8A, B, and C). Boxwork patterns of *Thalassinoides* that are organized as vertical shafts and horizontal mazes and are passively filled with coarse carbonate materials such as skeletal fragments, oncoids, and peloids characterize these intervals (Fig. 8A, B, and C). The boxwork networks of the pipe framework are very distinct in the CT scans with distinct density contrast between burrow fillings and host rock matrix (Fig. 8A and B). *Thalassinoides* burrow networks in the intervals with pipe framework burrowing style are characterized by features such as unlined tubes and scratch marks with sharp sides (Fig. 8C).

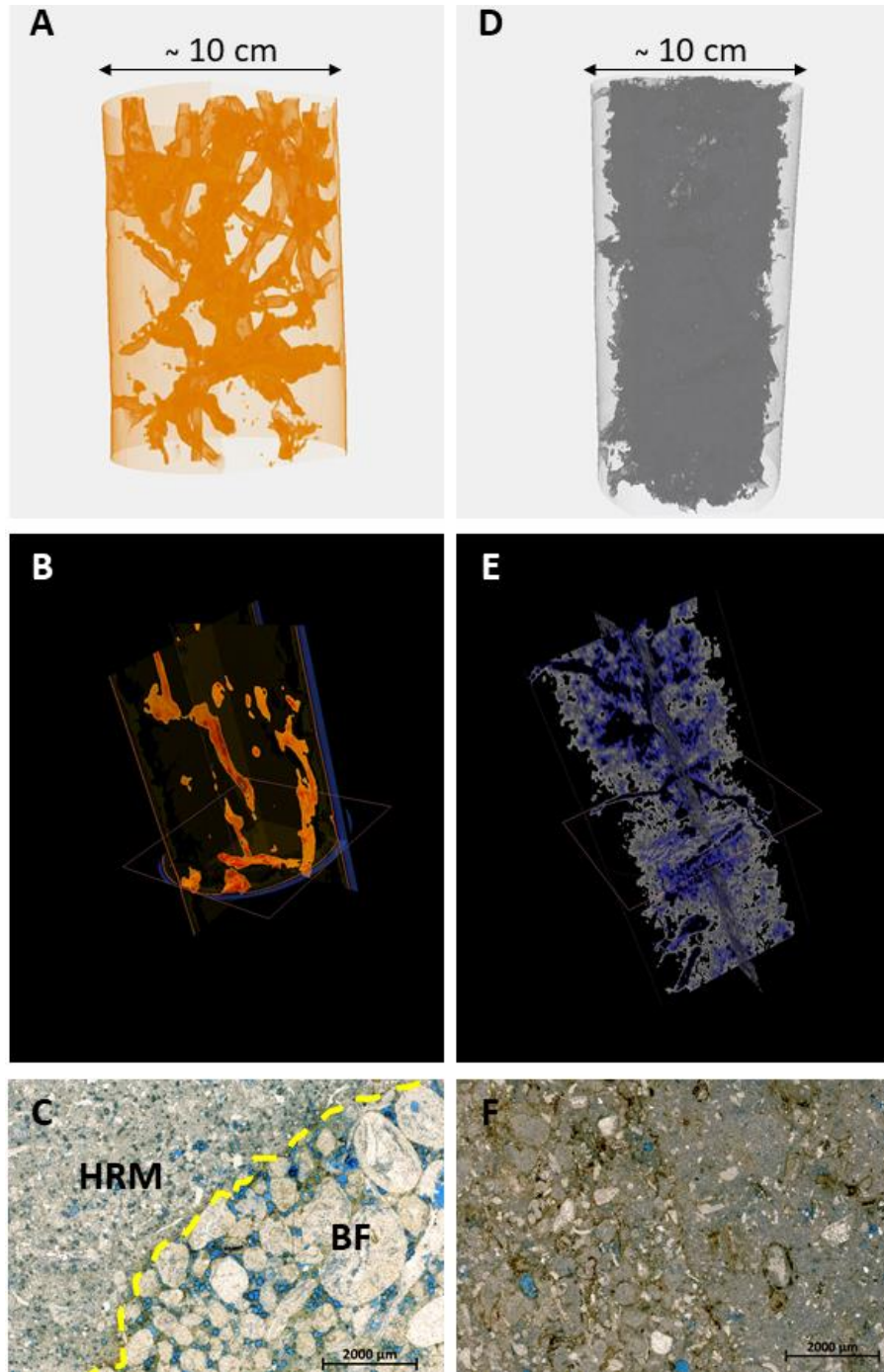


Figure 8. Burrowing styles found within the studied intervals. (A, B, and C) The pipe framework burrowing style obtained from medical CT scans of cores, ortho view of the CT scans, and thin-section photomicrograph, respectively. Note: the yellowed dashed line represents the boundary between the HRM and the BF displaying scratch-marks with sharp sides. (D, E, and F) The bio-retexturing burrowing style obtained from medical CT scans of cores, ortho view of the CT scans, and thin-section photomicrograph, respectively.

Conversely, in intervals 2 and 3 of sequence 5 (Fig. 1B), the burrows lead to bio-retexturing of the carbonate strata, resulting in a homogenization of the burrow fillings and host rock matrix where the boundaries of the burrows are not distinct (Fig. 8D, E, and F). Within these intervals, the burrows mixed relatively coarser materials such as skeletal grains, coated grains, and peloids with the mud-dominated host rock matrix (Fig. 8F). These coarser materials are displayed within the host rock matrix with random orientation, co-existing with grain compactions and burrow deformation (Fig. 9B and C). As a result, the burrows do not reflect clear morphology and are not distinct from the matrix in CT scans or thin-section photomicrographs (Fig. 8D, E, and F).

In the pipe framework burrowing style (intervals 1, 4, and 5), the rock texture of the host rock matrix is distinct from the burrow fillings in terms of mud content, grain size, grain type, and overall rock texture. As previously described by (Syahputra et al., 2022), the host rock matrix consists mainly of a wackestone texture or, in some circumstances, a fused peloidal packstone texture, characterized by abundant spiculitic molds and scattered skeletal grains (Fig. 9A, D, and E). Conversely, the burrow fillings exhibit a grain-dominated texture (mainly packstone), with a matrix that partially fills the interparticle pores. The carbonate grains in the burrow fillings include skeletal fragments, coated grains, and peloids (Fig. 9A, D, and E).

Regarding the proportions of muddy matrix, there was a clear relationship between the mud content and the burrowing style. As outlined in Table 1, the bio-retexturing intervals exhibited the largest mud content with values of 22.3% and 21% in intervals 2 and 3, respectively. In contrast, the burrow fillings within the pipe framework intervals characterized by grain-dominated texture (Fig. 9A, D, and E) showed significantly low

mud content compared to the bio-retexturing intervals. The proportions of muddy matrix in these intervals were 9.36%, 3.29%, and 12.54% corresponding to intervals 1, 4, and 5, respectively.

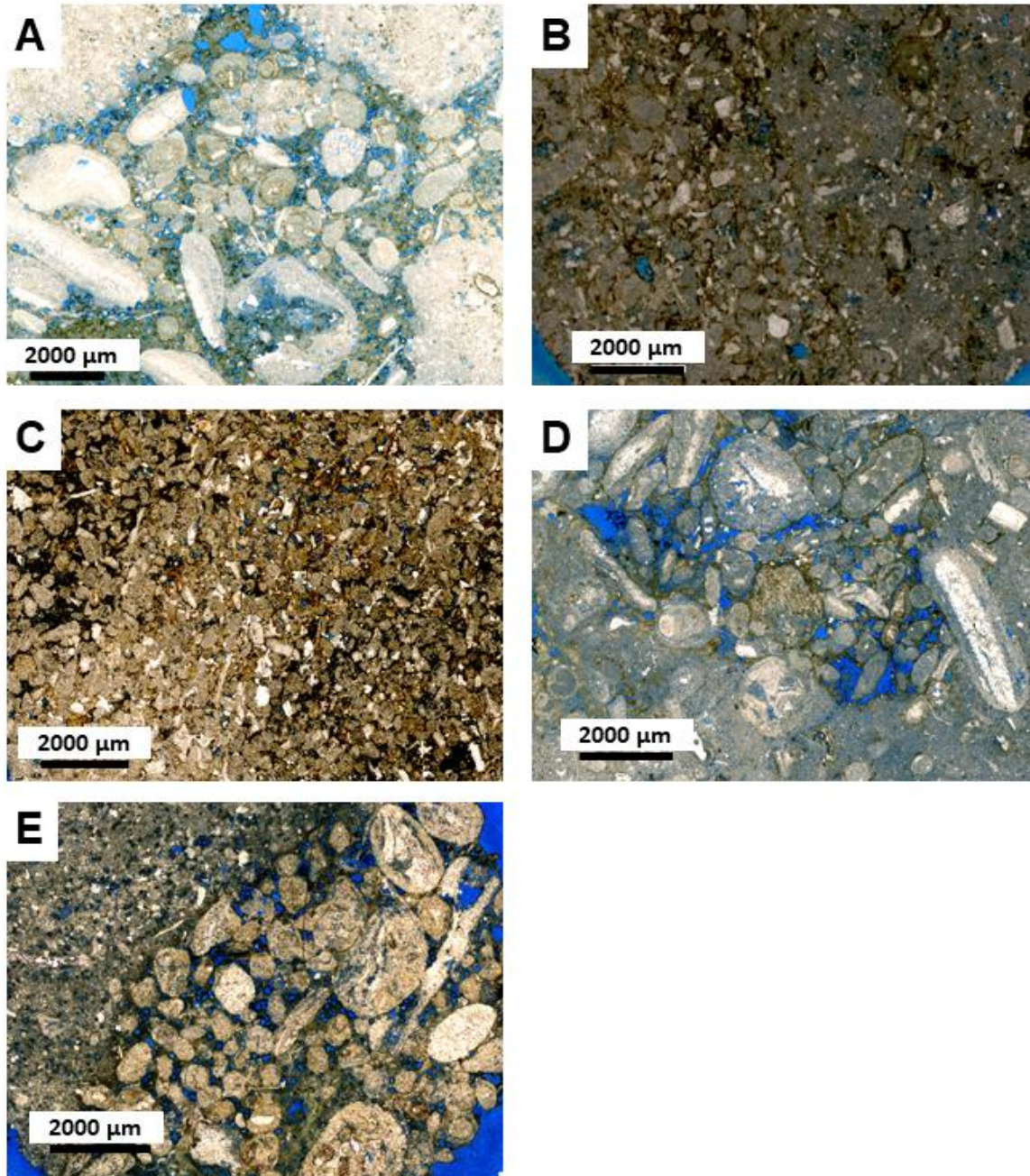


Figure 9. Thin-section photomicrographs showing rock texture for intervals 1-5. (A, D, F) Thin-section photomicrographs showing the mud-dominated host rock matrix and the burrow fillings with grain-dominated texture within pipe framework burrowing style. (B, C) bio-retexturing burrowing style in intervals 2 and 3.

Table 1. Percentages of the three components inside the BF resulted from the segmentation process in Avizo software within the five intervals.

	Interval 1	Interval 2	Interval 3	Interval 4	Interval 5
Grains (%)	83.49	76.06	76.29	92.71	79.71
Matrix (%)	9.36	22.30	21.00	3.29	12.54
Total Porosity (%)	7.15	1.64	2.71	4.00	7.75

2.4.2 Grain size, percentage, and aspect ratio (α)

Although the constituents of the burrow fillings (peloids, skeletal grains, and coated grains) are generally the same and there is a subtle difference in their relative abundance, their grain size varies vertically from one unit to another within the five intervals of the Upper Hanifa Formation, as shown in (Fig. 9, Table 2). For example, the grain size, measured by the long axis of the grains in the burrow fillings (Fig. 10A and B), exhibits notable variations. The highest mean and standard deviation values are observed in interval 1 ($766 \pm 752 \mu\text{m}$) and interval 4 ($739 \pm 433 \mu\text{m}$) indicating that they are the largest and poorly sorted grains (Table 2, Fig. 9A and D). Interval 5 (Fig. 9E) displays intermediate grain sizes with mean and standard deviation values of $514 \pm 341 \mu\text{m}$ (Table 2).

The smallest mean of grain size occurs in intervals 2 and 3 (Table 2, Fig. 9B and C), where the major axis of the grains is significantly lower ($355 \pm 206 \mu\text{m}$) in interval 2 and ($402 \pm 148 \mu\text{m}$) in interval 3. Thus, no continuous vertical trends (increasing or decreasing) can be depicted for grain size distribution, indicated by the major axis of the grains, across these five intervals. If the data are grouped based on burrowing style, there is a distinct

Table 2. Descriptive statistics of grain-size distribution within the five intervals.

		Max	Mini	Mean	Median	STDEV
Long Axis (μm)	Interval 1	5385	108	766	612	752
	Interval 2	1754	68	355	306	206
	Interval 3	1103	134	402	382	148
	Interval 4	2976	95	739	625	433
	Interval 5	2588	116	514	466	341
Short Axis (μm)	Interval 1	1703	53	445	389	319
	Interval 2	739	51	213	175	121
	Interval 3	628	80	242	228	90
	Interval 4	1397	35	446	417	207
	Interval 5	927	51	295	274	147
Aspect Ratio (α)	Interval 1	1.00	0.20	0.65	0.64	0.18
	Interval 2	0.99	0.16	0.62	0.63	0.16
	Interval 3	1.00	0.17	0.62	0.63	0.16
	Interval 4	0.99	0.18	0.65	0.65	0.17
	Interval 5	0.99	0.15	0.62	0.63	0.17

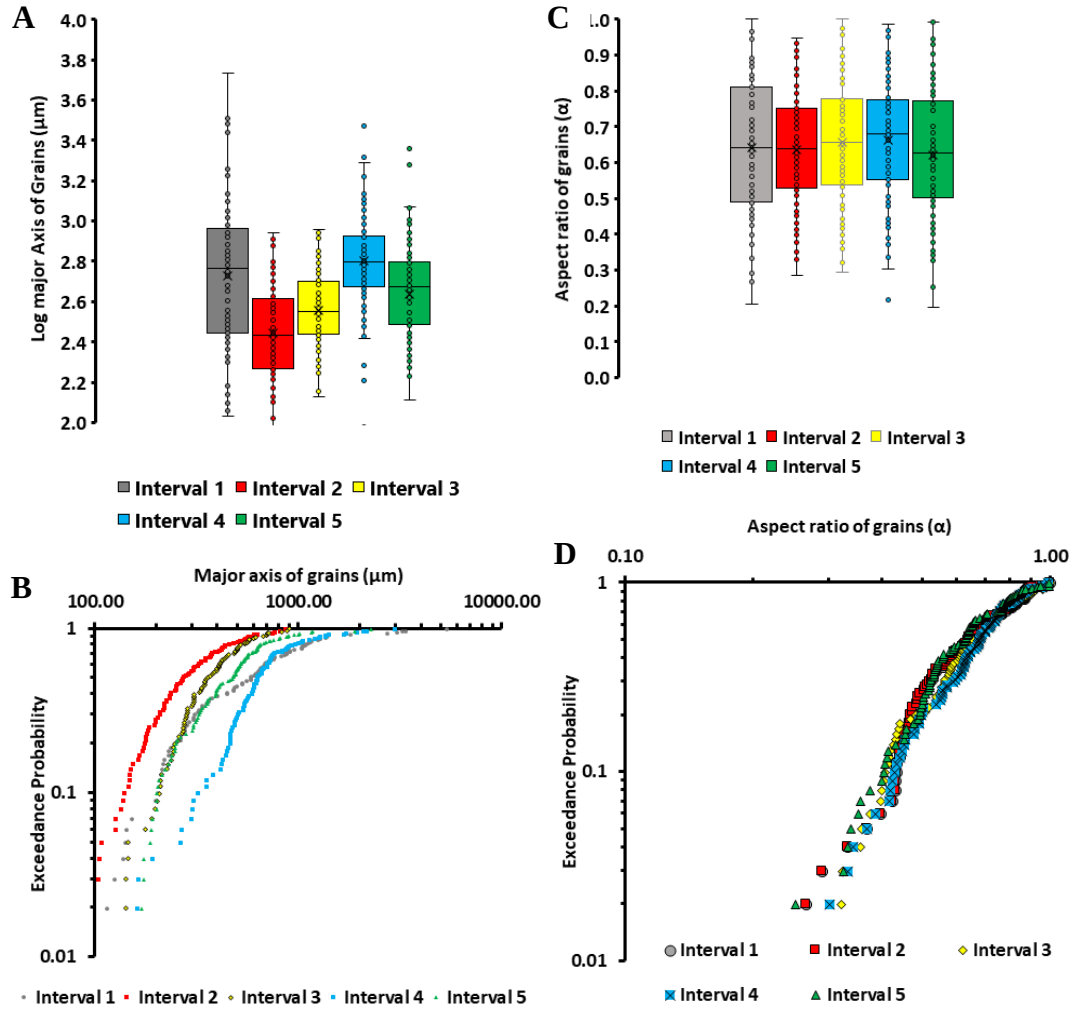


Figure 10. (A) Box-and-Whisker plots of the major axis of grains within the BF in logarithmic scale. (B) Exceedance probability graphical plots of the major axis of grains within the BF. (C and D) Exceedance probability and Box-and-Whisker plots of the aspect ratio of the first 100 grains from the five intervals. Note the data point in the exceedance probability plot cluster tightly which was confirmed with the Box-and-Whisker plot (no significant difference was observed).

decrease in mean grain size upward in the intervals containing pipe framework burrowing style (intervals 1, 4, and 5) (Table 2, Fig. 10A and B). Conversely, in the intervals dominated by bio-texturing fabric, there is a subtle increase in grain size when moving vertically from interval 2 to interval 3 (Table 2, Fig. 10A and B).

Graphical plots of exceedance probability and Box-and-Whisker plots (Fig. 10A and B) of the major axis of the largest 100 grains from the five intervals support the conclusions drawn from the statistical parameters. In the exceedance probability plots, interval 2 consistently shows the lowest exceedance probability of the long axis compared to other intervals, while interval 4 consistently exhibits the highest (Fig. 10B). At larger grain sizes, there is overlap between the data points representing intervals 4 and 1 (Fig. 10B). The Box-and-Whisker plots of the major axis of the grains display a similar pattern to the exceedance probability plots, but they notably highlight the outliers in grain size (Fig. 10A).

The aspect ratio of the grains, used as a proxy for grain shape, does not vary significantly across the five intervals. As shown in (Table 2), Intervals 1 and 4 have similar mean aspect ratios of 0.65, with only slight differences in their standard deviations (0.18 and 0.17, respectively). The other three intervals—2, 3, and 5—display nearly identical aspect ratios of 0.62 and similarly close standard deviations (approximately 0.16). Thus, as a proxy for shape, the aspect ratio shows no substantial variability among the five intervals.

Graphical plots of exceedance probability and Box-and-Whisker (Fig. 10C and D) of the aspect ratio of the first 100 grains from the five intervals also support the conclusions drawn from the statistical parameters. In the exceedance probability plots, the data are tightly grouped, showing minimal variation (Fig. 10D). The Box-and-Whisker plots of the aspect ratios demonstrate generally similar ranges and means across the five intervals (Fig. 10C).

Data from micro-CT scans allowed to segment the burrow fillings into three components: pores, matrix, and grains (Fig. 6, Table 1). The proportions of grains, determined from the segmentation process, varied vertically with no trend. The bio-retexturing intervals showed

almost the same percentages (76.06% in interval 2) and (76.29% in interval 3) which were small values compared to the pipe-framework intervals as shown in (Table 1). On the other hand, the proportions of 83.49%, 92.71%, and 79.71% are found within the pipe-framework intervals (intervals 1, 4, and 5), respectively (Table 1).

2.4.3 Diagenetic alterations in the BF

Compaction, subsequent dissolution, preferential dolomitization of the muddy matrix, and cementation were the major diagenetic alterations seen in the burrow fillings of the pipe framework burrows (Fig. 11). Interval 1 shows the least compacted sediments. With few grains in contact, the carbonate grains in this interval form an open fabric. Where the carbonate grains are not in touch, the spaces between the grains are dominated by molds of dissolved dolomite rhombs found in the matrix between the grains (Fig. 11A). The molds can occasionally be deformed at the grain-to-grain contact. On the other hand, a portion of the dolomite rhombs appeared cloudy when they were undissolved. Calcite cements are not prominent in this interval, but when present, they are found within the intraparticle pores of the grains.

The most intense compaction existed in interval 4, where pore space is significantly reduced (Fig. 11B). Evidence of compaction included grain penetration, grain-to-grain contact, pressure solution, and microstylolitization. In this interval, neither the dolomite rhomb molds nor the dolomitic matrix are prevalent. Interparticle pores, however, were preserved. Cementation occurs in these interparticle pores and within the intraparticle pores of the carbonate grains. Interval 5 shows moderate compaction, with some grain-to-grain contact and pressure solution (Fig. 11C). Moldic rhombs are substantial, and their

abundance exceeds that of the dolomite matrix. Similar to interval 1, interparticle pores are not well preserved in this interval and calcite cement existed in the intraparticle pores.

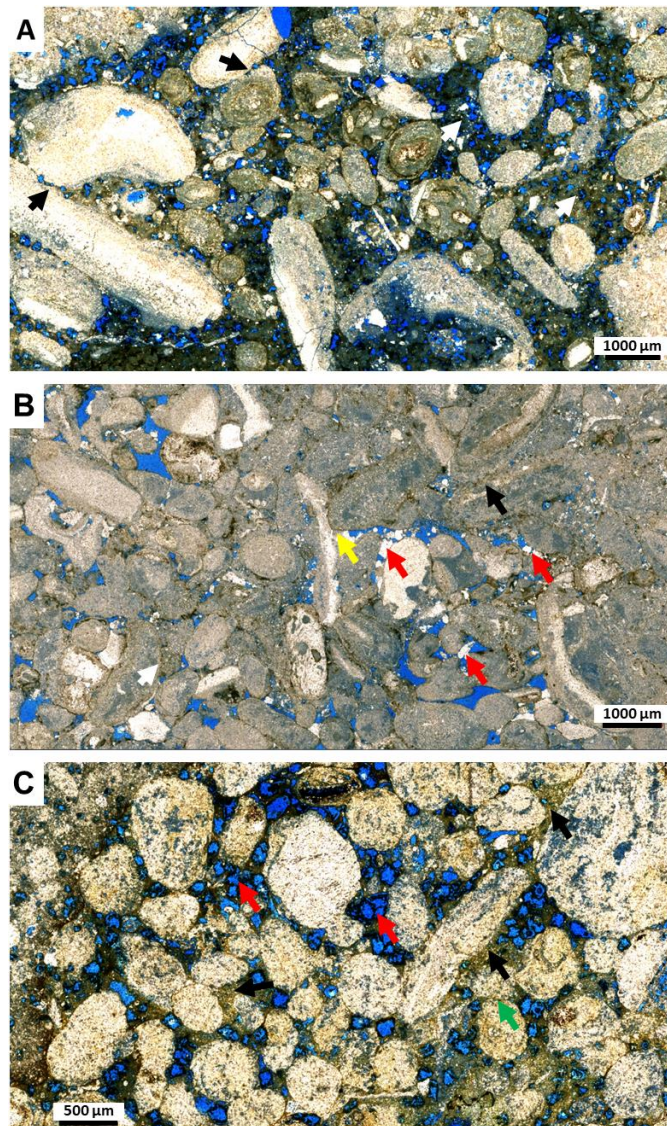


Figure 11. Thin-section photomicrographs showing the diagenetic modifications in the BF within the intervals with pipe framework (intervals 1, 4, and 5). (A) BF in interval 1 with floating grains resulted in an open fabric with rhombohedral pores occurring at the grain-to-grain contact (black arrows). Abundant dissolved dolomite rhombs can be observed in the dolomitic matrix (white arrows). (B) BF in interval 4 showing highly-compacted rock texture with calcite cement (red arrows). Compaction evidence includes grain-to-grain contact with pressure solution (black arrow) and grain penetration (yellow arrow). (C) BF in interval 5 with less compact fabric compared to interval 4. Note the abundant dissolved dolomite rhombs in the dolomitic matrix (red arrows).

In the bio-retextured intervals (intervals 2 and 3), high compaction is observed (Fig. 12). This compaction affected both the mud and grains equally. Features such as grain-to-grain contact, pressure solution, grain penetration, and microstylolitization are all evident in intervals 2 and 3. Dolomitization is not as predominant as in intervals 1, 4, and 5, which exhibit a pipe-framework burrowing style. The interparticle pore spaces are either filled with mud or reduced by compaction, leaving very minimal interparticle porosity. When present, dolomite rhombs are scattered and dissolved. Additionally, intraparticle porosity is observed in some skeletal grains.

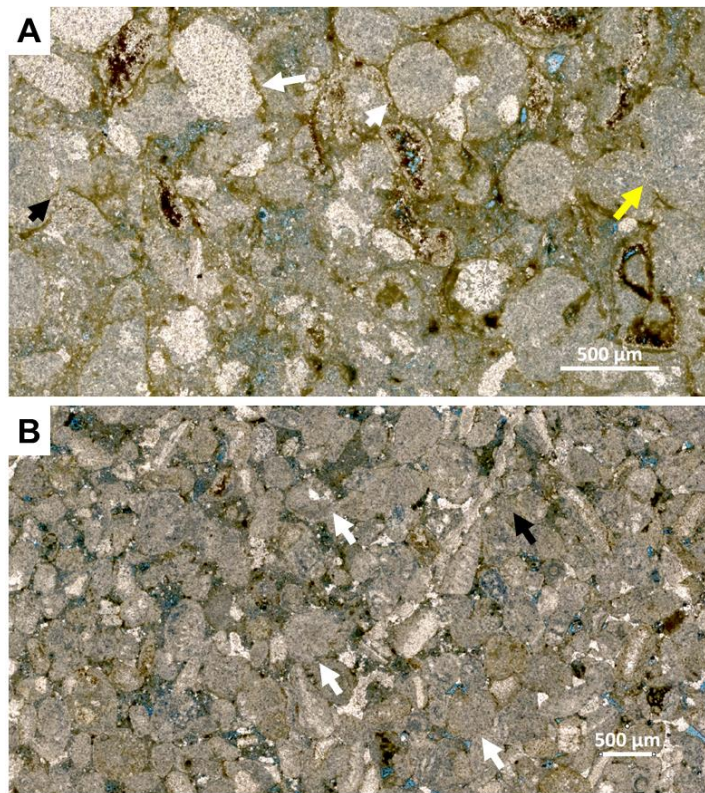


Figure 12. Thin-section photomicrographs showing the diagenetic modifications in the interval with bio-retexturing [(A) interval 2 and (B) interval 3]. Note the compacted rock fabric with grain-to-grain contact and pressure solution (white arrows), grain penetration (yellow arrows).

2.4.4 Porosity

As shown in (Table 1, Fig. 13A), the total porosity values of the burrow fillings, estimated from the segmentation process, varied vertically across the five intervals of sequence 5 without any observable trend. However, they can still be grouped based on the burrowing style of the five intervals. The bio-retexturing intervals had the smallest percentages of total porosity, with values of 1.64% and 2.71% in intervals 2 and 3, respectively. In contrast, the pipe-framework intervals had relatively larger proportions, with values of 7.15%, 4%, and 7.75% in intervals 1, 4, and 5, respectively.

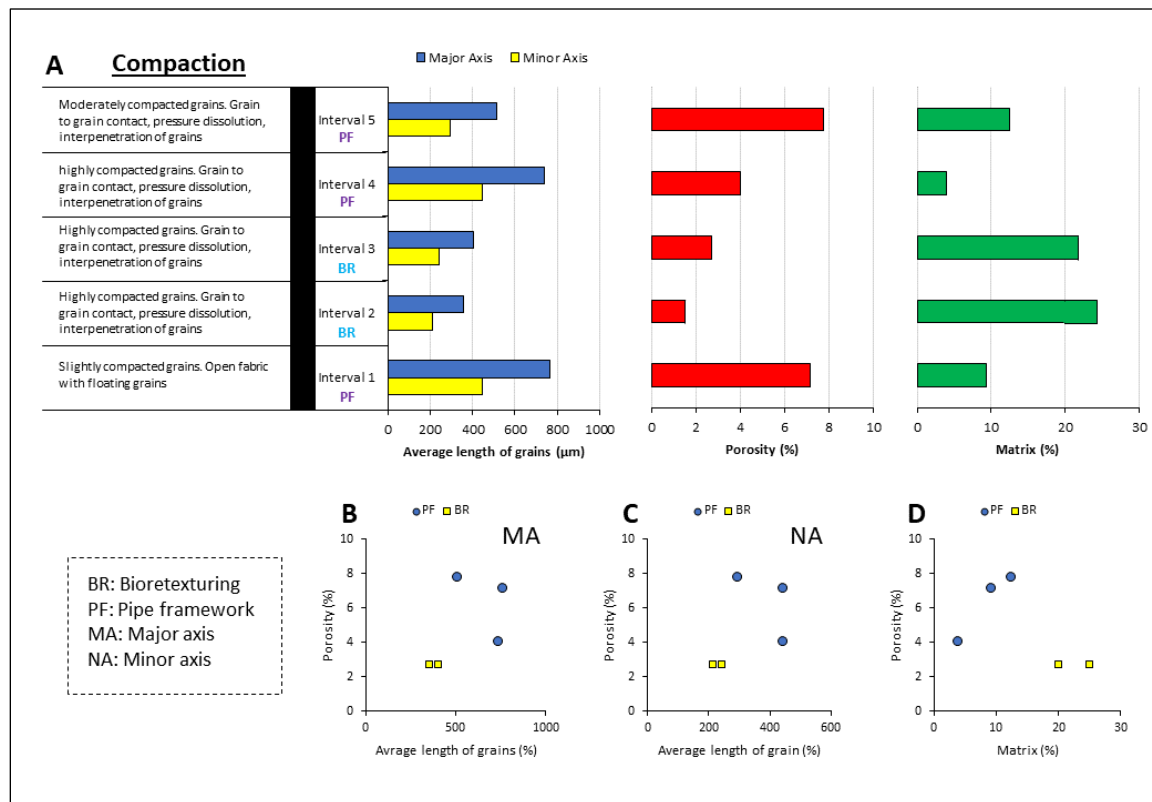


Figure 13. (A) Bar diagrams showing the relationship among compaction, grain size, porosity, and dolomitic matrix. (B, C, and D) Cross plots showing the relationship of porosity with grain size (represented by the major and minor axes of grains) and mud matrix.

When comparing the porosity values to the burrowing style, patterns of compaction, grain size, and matrix percentage in the five bioturbated intervals, the data reveal interesting trends (Fig. 13A, B, C, and D). Porosity values are relatively high in intervals with the pipe framework burrowing styles. In these intervals (1, 4, and 5), porosity is low in intervals where compaction is high and mud matrix percentage is low (interval 4). Interestingly, porosity is relatively high in intervals where the matrix percentage is high and compaction is low (intervals 1 and 5). There is no direct correlation between grain size and porosity; however, there is a clear correlation between porosity, compaction, and matrix percentage. The higher the matrix percentage, the lower the degree of compaction, the higher the porosity value.

2.4.5 Pore system

The pore system of the studied intervals is predominantly composed of isolated pores (Fig. 14). These pores were characterized by their attributes: pore volumes, areas, and equivalent diameters (Table 3, Fig. 14). The trends on the relative abundance of these attributes followed the trend of grain size distribution. For example, the largest mean pore volume is found in interval 4 ($0.0062 \pm 0.0118 \text{ mm}^3$), followed by interval 1 ($0.0059 \pm 0.0036 \text{ mm}^3$) and then interval 5 ($0.0023 \pm 0.0029 \text{ mm}^3$) (Fig. 15A, Table 3). Intervals 3 and 2 show remarkably smaller mean pore volumes, with values of ($0.0008 \pm 0.0010 \text{ mm}^3$) and ($0.0015 \pm 0.0023 \text{ mm}^3$), respectively (Fig. 15A, Table 3). The same trend existed within the values of the surface area and the equivalent diameter (Fig. 15B and C, Table 3).

Graphical plots of exceedance probability and Box-and-Whisker plots of the pore volumes, areas, and equivalent diameters of the largest 1000 pores from the five intervals support the conclusions drawn from the statistical parameters (Fig. 15D, E, and F).

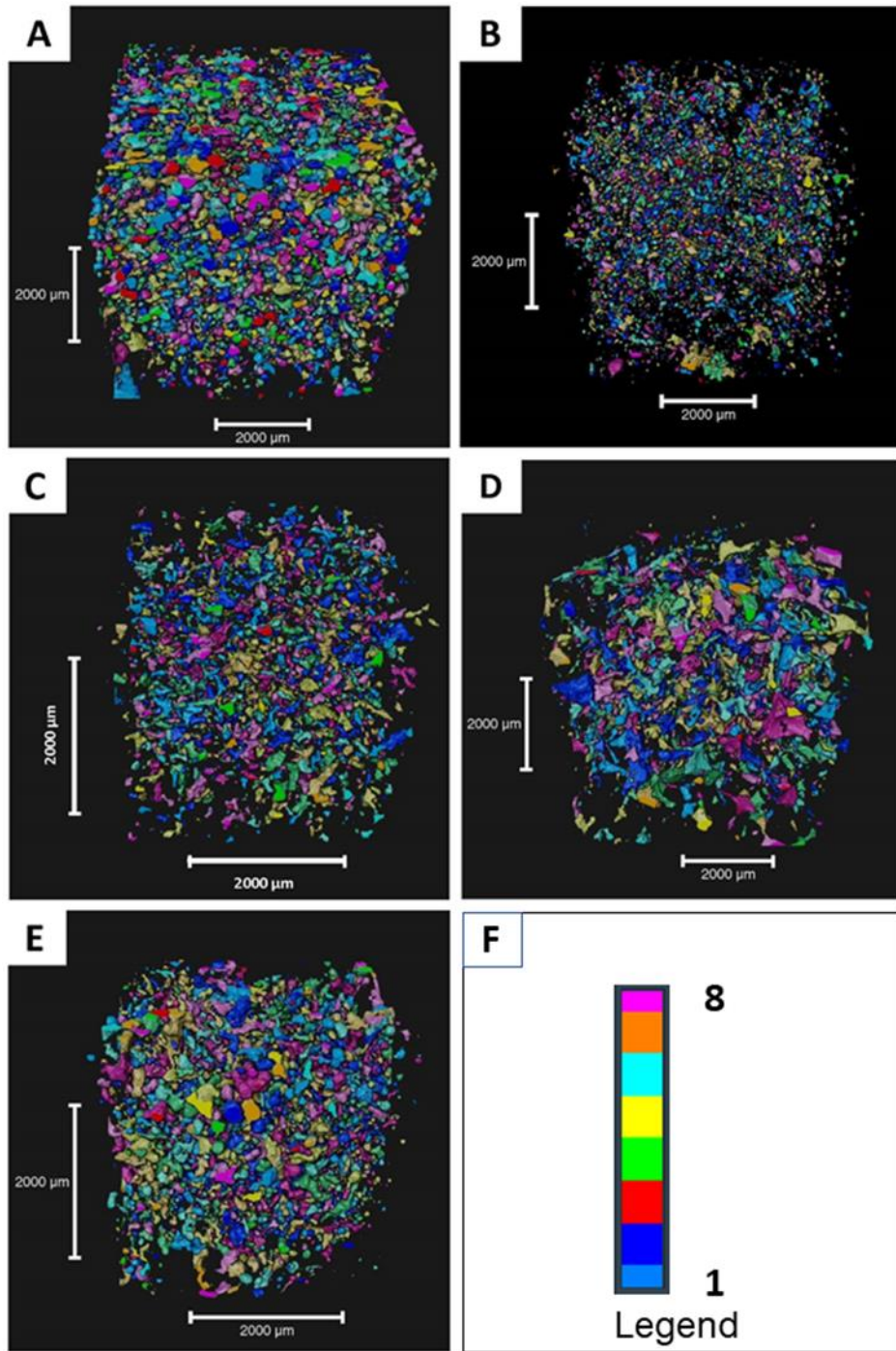


Figure 14. Screen capture showing the labeling analysis of only the pore spaces within intervals 1-5 after filtering out the rock grains and muddy matrix. Each pore space with different volume, area, or equivalent diameter is assigned a unique color. Note that the pores in all intervals are substantially isolated. Despite being isolated, the pore volumes in interval 4 (D) are the largest, followed by intervals 1 (A) and 5 (E). The pores in the intervals with bio-retexturing (B and C) have significantly smaller pore volumes. (F) The legend of the colors outlined in the captures.

Table 3. Descriptive statistics of pore-size distribution (volume, surface area, and equivalent diameter) within the five intervals.

		Mean	Mini	Max	Median	StDev
Volume (mm³)	Interval 1	0.0059	0.0030	0.0373	0.0047	0.0036
	Interval 2	0.0015	0.0004	0.0256	0.0009	0.0023
	Interval 3	0.0008	0.0001	0.0076	0.0005	0.0010
	Interval 4	0.0062	0.0002	0.1340	0.0020	0.0118
	Interval 5	0.0023	0.0005	0.0405	0.0014	0.0029
Area (mm²)	Interval 1	0.2303	0.1362	1.0518	0.1955	0.1084
	Interval 2	0.0869	0.0335	0.8384	0.0583	0.0860
	Interval 3	0.0578	0.0141	0.3779	0.0406	0.0520
	Interval 4	0.2082	0.0234	2.2502	0.1132	0.2596
	Interval 5	0.1153	0.0360	1.0587	0.0827	0.0988
Equivalent Diameter (mm)	Interval 1	0.2182	0.1781	0.4146	0.2077	0.0363
	Interval 2	0.1302	0.0936	0.3654	0.1177	0.0394
	Interval 3	0.1043	0.0621	0.2438	0.0970	0.0348
	Interval 4	0.1825	0.0770	0.6350	0.1563	0.0918
	Interval 5	0.1501	0.0964	0.4261	0.1388	0.0458

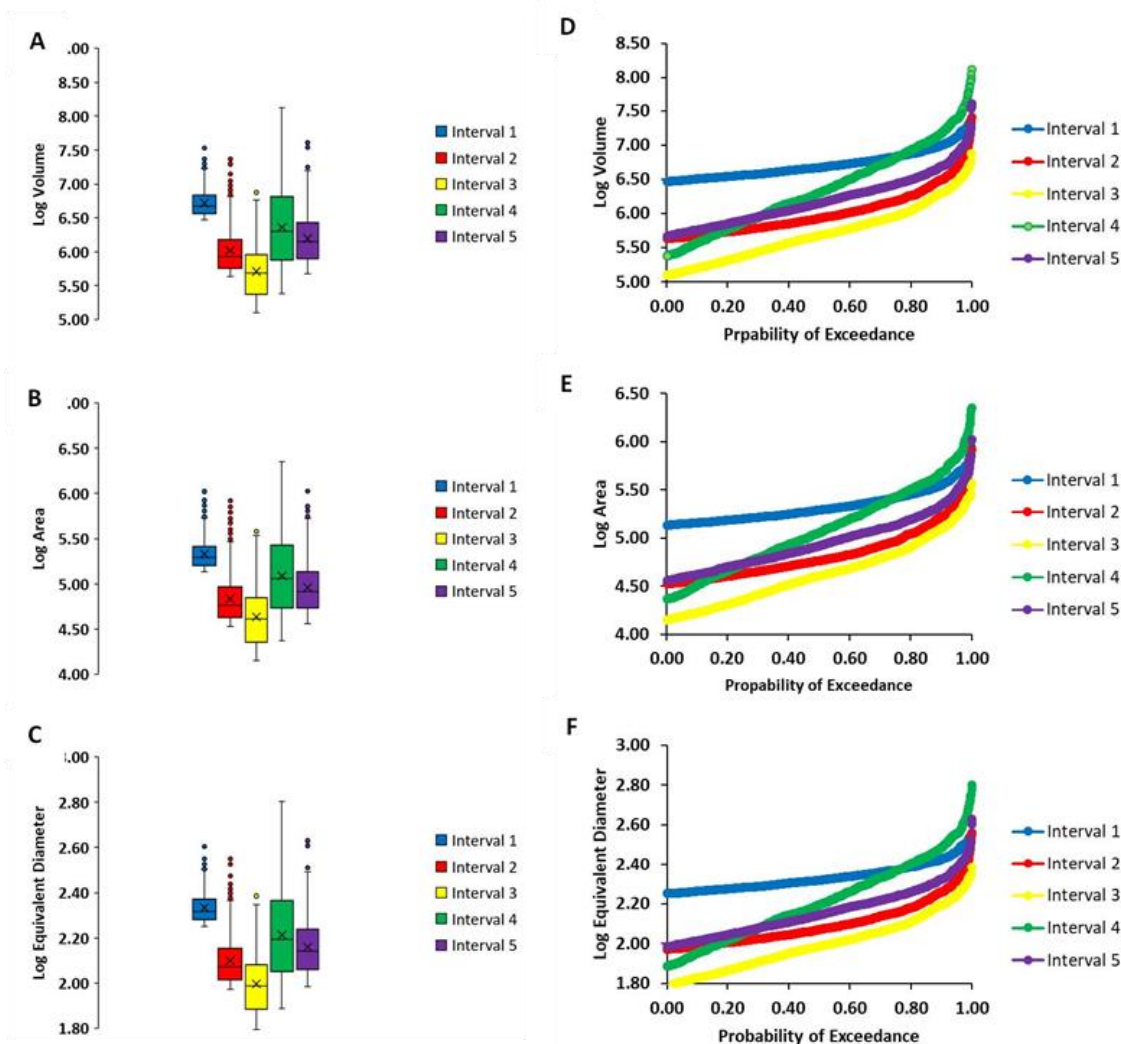


Figure 15. Box-and-Whisker plots showing the pore-size distribution [pore volume (A), pore area (B), and pore equivalent diameter (C)] inside the BF. Exceedance probability graphical plots of the pore-size distribution [pore volume (D), pore area (E), and pore equivalent diameter (F)] inside the BF.

In the exceedance probability plots, interval 3 consistently shows the lowest exceedance probability compared to other intervals. At larger pores, there is overlap between the data points representing intervals 4 and 1. Additionally, it is observed from the curve of interval 4 that it has high variation in pore sizes as it can contain values less than these of the bio-retexturing intervals at the smaller pores and then high values at the larger pores. Finally,

the curves of exceedance probability graphical plots indicating the occurrence of two pore systems within the burrow fillings in each interval.

2.5 Discussion

To understand the impact of rock texture heterogeneity within the burrow fillings on the porosity and the pore system of bioturbated strata, this study documents and analyzes results from five bioturbated stratigraphic units in the upper Hanifa Formation. The investigation focuses on three critical components of the burrow fillings rock texture. First are the burrowing style and depositional texture within the burrow fillings, which influence grain size distribution and shape, fundamental for understanding the initial rock framework. Second, major diagenetic modifications significantly alter the original characteristics of the depositional texture within the burrow fillings. Third, the porosity and pore system, which are the overall results of the collective impact of depositional and diagenetic processes. The collective investigation of these components provides comprehensive insights into how rock heterogeneity within the burrow fillings affects the overall reservoir quality of bioturbated carbonate rocks.

2.5.1 Burrowing style and Sedimentary environment

The pipe framework burrows are interpreted as *Glossifungites* ichnofacies, consisting of a *Thalassinoides* burrow network. Several previous studies on the bioturbated strata of the Hanifa Formation have documented evidence of *Glossifungites* ichnofacies in the studied strata (Eltom et al., 2018; Eltom and Hasiotis, 2019; Syahputra et al., 2022). Among these evidences are passive fillings, unlined tubes, scratch marks, and sharp sides of the burrows (Fig. 8C, 9A, D, and E). Such burrow characteristics indicate that at the time of burrowing,

the carbonate strata had a cohesive nature and the rate of sedimentation was slow (Pemberton and Gingras, 2005; Abdel-Fattah et al., 2016; Syahputra et al., 2022). In this sense, *Glossifungites* ichnofacies represent surface of omission in which *Thalassinoides* shafts and tunnels remain open until they are filled by sediments from the subsequent flooding event (Pemberton and Gingras, 2005; MacEachern et al., 2007; Abdel-Fattah et al., 2016).

Thus, the development of the *Glossifungites* ichnofacies in the Hanifa Formation suggests deposition in two chronologically different environments (Eltom et al., 2021a; Syahputra et al., 2022). Firstly, the host rock matrix was deposited in a low-energy environment, as indicated by the presence of a muddy texture and the absence of sedimentary structures that would indicate agitation (Syahputra et al., 2022). Secondly, the burrow fillings accumulated in a high-energy environment, evidenced by coarse and well-rounded carbonate grains within a grain-dominated texture (Syahputra et al., 2022).

The bio-retexturing burrowing style (Fig 8F, 9B and C), which dominated the middle intervals of sequence 5 (intervals 2 and 3), can be interpreted as a product of mixing the mud-dominated host rock matrix with the transported grain-dominated sediments producing a new texture that did not reflect their depositional controls (Burchette and Wright, 1992; Tonkin et al., 2010). The explanation of this process can be described as follows: at the time of the initial flooding of the transported coarse carbonate grains, the host rock matrix was still soft and these conditions were suitable for animals to move easily through the matrix and mix it with such transported coarse-grained sediments causing these materials to be randomly oriented and co-existed with grains compaction resulting in burrow deformation.

As mentioned above, *Glossifungites* ichnofacies (as expressed by pipe framework) could be formed in two deposition periods, with the filling stage of burrows occurring after the consolidation and burrowing of the host rock matrix substrate (Pemberton and Gingras, 2005). The results showed that the constituents of the burrow fillings (which accumulate in the filling stage) of the *Glossifungites* ichnofacies are generally the same (peloids, skeletal grains, and coated grains) (Fig. 9A, D, and E) and probably have similar shapes (no variation in aspect ratio, Table 2, Fig. 10C and D). However, there is a distinct variation in the size of these components (Fig. 10A and B, Table 2), particularly when the five intervals are grouped based on the style of burrowing. Among the intervals with a pipe framework (Intervals 1, 4, and 5), there is only a subtle variation in grain size between intervals 1 and 4 and a remarkable difference in interval 5. Intervals with bio-retexturing (intervals 2 and 3) exhibit a distinct difference in grain size compared to intervals 1, 4, and 5. Factors that can control such variation include energy conditions, proximity to the source, biological activity, and sediment supply, as noted by many studies (Wilson, 1997; Flügel and Munnecke, 2010).

In the context of the Hanifa Formation at outcrop, projecting these processes in the interpreted environment of deposition to understand the variation of the grain size in the burrow fillings is challenging due to the controversial interpretations of the environment of deposition of the Hanifa Formation in the literature. While many authors suggest that the argillaceous mudstone in sequence 5 of the Hanifa Formation was deposited in an open-marine, outer ramp setting below storm wave base and the bioturbated strata above as middle to outer ramp (ap Gwilym Hughes et al., 2008; Fallatah and Kerans, 2018), others propose a restricted environment of deposition for the argillaceous mudstone and lagoonal

setting for the bioturbated strata above (Al-Mojel et al., 2020). Based on these two different interpretations of the environment of deposition, the grain size variation of the burrow fillings can be interpreted in two different ways.

The first possible scenario adopting an open marine setting suggests that the *Glossifungites* ichnofacies deposited initially in the middle to outer ramps in an open marine setting as consolidated and burrowed substrate that, followed by a flooding stage, brought the coarse sediments to fill the open burrows (Fallatah and Kerans, 2018; Syahputra et al., 2022). In such cases, the coarse sediments of the fillings are likely to be accumulated in a high-energy setting above the wave base and then transported down the slope to the location of the open burrows. Fallatah and Kerans (2018) suggested that such transportation took place as tempestite as a result of storm events. Although such a scenario has not been documented in the literature for the subsurface Hanifa Formation, there is an excellent example from the Arab-D reservoir (strata above the Hanifa Formation) that showed extensive *Glossifungites* ichnofacies in the middle ramp setting (Lindsay et al., 2006).

The similarity in the aspect ratio of the carbonate grains in the burrow fillings (Fig. 10C and D, Table 2) suggests a similar source of these transported sediments, while the higher and uniform aspect ratio indicates a longer distance of transportation in high-energy settings. This is because grains transported over long distances in high-energy environments tend to become more rounded and uniform in shape due to continuous abrasion and sorting (Ginsburg, 1956; Wilson and Wilson, 1975; Flügel and Munnecke, 2010). The large portion of well-rounded grains in the burrow fillings of the pipe framework further confirms deposition under high-energy conditions.

In the case of sequence 5 of the Hanifa Formation, bio-retexturing likely occurred in an environment distal to the pipe framework where the host rock matrix substrate was not consolidated, resulting in smaller sediment sizes towards the basin becoming mixed with this unconsolidated substrate. The three intervals with pipe framework (intervals 1, 4, and 5) are likely to be deposited in a nearly similar depositional environment. As Ginsburg (1956) pointed out, major differences in the environment of deposition produce sediments with markedly different grain sizes and constituent compositions, while small and gradual changes in the environment result in less distinctive variations in carbonate constituents.

The second possible scenario adopts a lagoonal setting for the bioturbated strata of sequence 5 in the upper Hanifa Formation (Al-Mojel et al., 2020). In such a setting, *Glossifungites* Ichnofacies could be deposited in the lagoon interior where consolidated sediments form firmground (Frey and Seilacher, 1980). As pointed out by many authors (Bromley, 2012), *Glossifungites* ichnofacies prefer settings with substrates subjected to dewatering. On carbonate ramps, such settings are found in shallow subtidal and intertidal to supratidal environments, such as lagoons, beaches, and shoals (Pemberton and Frey, 1984).

In such a case, the coarse carbonate sediments in the burrow fillings could be transported from the barrier reefal setting of the inner ramp or shoal deposits (Knaust, 2009). This process may resemble the distribution of reef sand aprons on isolated platforms, where the sand aprons are largely composed of debris that is shed from shelf-margin reefs towards the lagoon (Rankey, 2016). These reef sand aprons are characterized by their composition of bioclastic debris and skeletal fragments, similar to the composition of the burrow fillings in sequence 5 of the upper Hanifa Formation, which are transported and deposited by wave

and current action. The burrow fillings characteristics in this scenario, therefore, depend on how the sand aprons form (Rankey, 2016).

In summary, the three intervals with pipe framework (intervals 1, 4, and 5) are likely deposited in similar depositional environments without significant differences in grain size and shape. Consequently, grain size distribution appears to have a minor impact on the variation in porosity of the burrow fillings of these intervals (Fig. 13A, B, and C).

2.5.2 Diagenetic modifications and Porosity evolution

Based on the observation of cores and thin-sections, the alterations that occurred in the host rock matrix were underwent into six evolutionary stages: burrow generation, Passive infill, near-surface meteoric diagenesis, matrix dolomitization, compaction, and rhombohedral pores formation resulting from the dissolution of the dolomite rhombs (Fig. 16). The first stage improved the reservoir quality by creating open burrows within the host rock matrix that significantly increased the porosity and permeability. However, the subsequent four stages declined the petrophysical properties within the burrows compared to the first stage. In contrast, during the final stage, these properties enhanced once again by the dissolution restoring some of the porosity and permeability lost during the earlier stages. Overall, the burrow fillings had good reservoir quality compared to the host rock matrix.

It is evident from the cross-cutting relationship that dolomitization took place prior to compaction. The existence of molds and compacted dolomite rhombs provides evidence for this claim (Fig. 11). Dolomitization likely occurred preferentially in the muddy matrix between the grains of the burrow fillings. Consequently, there will be two types of burrow fillings within the pipe framework intervals based on the muddy matrix content. The first

type, mud-rich packstone, contains grains and an abundant precursor muddy matrix (matrix percentage >10% and grain percentage ~80%, Table 1) such as interval 5. The other type, like intervals 1 and 4, contains grains with a minimal precursor muddy matrix (matrix percentage <10%, Table 1); this is what we call mud-poor packstone. These terms were adapted from (Alsuwaidi et al., 2020) who suggested that they should be used instead of the terms "mud-dominated" and "grain-dominated" packstones because packstone has, by definition (Dunham, 1962), a grain-supported limestone texture and to be compatible with the Lucia classification.

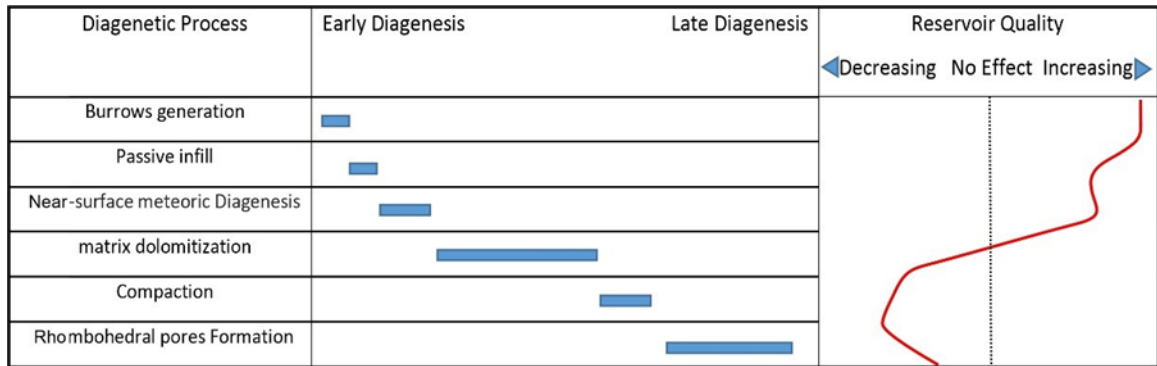


Figure 16. The six stages causing the modifications of HRM and their impact on the reservoir quality.

These packstones may have had a grainstone texture originally, but the addition of the mud matrix altered them, making them either mud-rich or mud-poor (Alsuwaidi et al., 2020). A variety of sources, such as the mechanical deformation of peloids and bioturbation, can originate the mud matrix found in packstones (Dunham, 1962). Alternatively, as the water energy that first carried the coarse carbonate particles to the burrow network diminished, the mud could have been introduced. According to Alsuwaidi et al. (2020), in this scenario, the mud penetrated through the porous and permeable precursor grainstone texture of the

burrow fillings. Thus, this process caused the transformation of grainstone into packstone, either mud-rich or mud-poor.

Because the coarse-grain carbonate sediments in the burrow fillings are much more stable than the mud matrix, they remained undolomitized and dolomitization only preferentially affected the mud matrix. The main reason is that the muddy part or micrite is favored for dolomitization because of the high surface area that provides numerous active sites for nucleation (Sibley and Gregg, 1987; Sadooni and Al Awadi, 2009). Such preferential dolomitization of the muddy matrix was described from different carbonates in the world (Teoh and Laya, 2021; Morad et al., 2023). Compaction affected two distinct packstone scenarios when it occurred afterward. The first scenario exhibited packstone with a dolomitized matrix and was rich in mud that resisted compaction and helped to preserve the interparticle space. However, the second scenario, including packstone with low dolomite content (mud-poor), experienced a substantial reduction in interparticle porosity as a result of compaction.

Dolomite rhombs in the muddy matrix dissolved at the later diagenetic stage (after compaction), creating pore spaces in the interparticle area and rhomb molds. Because some of the dolomite rhombs in the dolomitized muddy matrix were not entirely dissolved, these molds are not totally connected. This might be attributed to the variation in dolomite crystal composition, where the presence of highly soluble inclusions at the crystal core may promote selective dissolution of the cores while the more stable rims were preserved, resulting in the development of “hollow dolomites” (Jones, 2007; James and Jones, 2015). The correlation between porosity value and the mud matrix (Fig. 13) and the isolated nature of the pore in the segmented micro-CT scan (Fig. 14) confirm this observation.

The paragenetic sequence of the modification of burrow fillings was not observed in the bio-retextured intervals (intervals 2 and 3) simply because there were no interparticle pores nor grainstone texture developed for this type of rock texture. The major modification of the rocks in these two intervals is compaction, which impacted the mud and grains equally. No dolomitized matrix is observed; only scattered dolomite rhombs are present. Thus, the impact of the dissolution process is low within these intervals as they contain few dolomite rhombs.

This complex interplay of dolomitization, compaction, and subsequent dissolution significantly influences porosity evolution in the burrow fillings and eventually the reservoir quality. In mud-rich packstones, the dolomitized matrix helps to preserve porosity by resisting compaction, while in mud-poor packstones, the low dolomite content leads to reduced porosity due to the low resistance to compaction (Fig. 13). The partial dissolution of dolomite rhombs further modifies the porosity by creating molds that enhance connectivity, although imperfectly. Cementation occurred in the interparticle and intraparticle pore systems but did not substantially reduce the porosity.

2.5.3 Implications and limitations of this study

The results of this study demonstrate that integrating petrographic, CT scanning, and digital rock physics modeling can effectively assess spatial variations in the pore system and rock texture of burrow fillings and their impact on reservoir quality. This approach is particularly valuable for understanding porosity evolution and pore system complexity. Gaining insights into these aspects is essential for predicting fluid flow in these complex bioturbated strata. This understanding is especially important given the challenges

associated with measuring permeability in these rocks due to the absence of appropriately sized samples for laboratory measurements.

One significant insight from this study is the evolution of porosity in the packstone within the burrow fillings. Initially, the packstone in the burrow fillings may have started as a mud-rich packstone, which would be of poor reservoir quality due to its very low porosity and high mud content. However, with dolomitization occurring preferentially in the muddy matrix of this packstone, compaction would not severely reduce the pore space between grains. Subsequent dissolution of the dolomitized matrix could transform the poor-quality mud-rich packstone into a mud-poor packstone with moldic rhombohedral pores of dolomite in the interparticle pore space. With continuous dissolution of the dolomite, the burrow fillings with this type of packstone may become extremely permeable.

Conversely, the packstone in the burrow fillings that started as a mud-poor packstone might initially have been of good reservoir quality with highly connected interparticle pores. However, due to compaction, these interparticle pores can be significantly reduced. Since there was not much dolomitized mud to resist compaction, the reduction in porosity could be substantial. Thus, a packstone that initially had good reservoir quality might, over time, become a poor-quality reservoir packstone due to compaction.

Understanding these scenarios is essential for predicting the reservoir quality of bioturbated strata. By recognizing the impact of dolomitization, compaction, and subsequent dissolution processes on the pore system, geologists and reservoir engineers can better predict fluid flow behavior and reservoir performance in bioturbated strata. This knowledge is particularly valuable in fields where direct measurement of permeability is

challenging, and it underscores the importance of integrating multiple analytical approaches to achieve comprehensive reservoir characterization.

2.6 Conclusion

This study integrates petrographic analysis and CT scanning with digital rock physics modeling of samples collected from bioturbated intervals in the upper Hanifa Formation, central Saudi Arabia, to assess how porosity evolves in burrow fillings of *Glossifungites* ichnofacies. The key findings are:

- The burrowing style and depositional texture significantly influence grain size distribution and shape, providing a basis for understanding the initial depositional rock framework.
- Diagenetic modifications, including dolomitization, compaction, and dissolution, play a crucial role in altering the original characteristics of the depositional texture, impacting porosity and pore system.
- Intervals with a pipe framework burrowing style (intervals 1, 4, and 5) likely deposited in similar depositional environments exhibit minor variations in grain size and have higher porosity compared to bio-retextured intervals (intervals 2 and 3).
- The porosity and pore system in burrow fillings are predominantly composed of isolated pores, with variations in pore volume, surface area, and equivalent diameter across the intervals.
- Dolomitization in mud-rich packstones helps preserve porosity by resisting compaction, while mud-poor packstones with lower dolomite content exhibit significant porosity reduction due to compaction. Subsequent dissolution of dolomite

creates new porosity in the interparticle space of the burrow fillings. Continuous dissolution may change the initial deposited poor reservoir packstone to a highly porous packstone.

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CHAPTER 3

Modeling porosity and permeability evolution of burrow fillings with packstone fabric in the Upper Jurassic Hanifa Formation, central Saudi Arabia: A diagenetic backstripping study

Abstract

Understanding the development and characteristics of burrow fillings is crucial for predicting porosity, permeability, and fluid flow behavior in bioturbated carbonate reservoirs. Advanced imaging, digital rock modeling, and backstripping techniques offer valuable insights into this development. In this study, we examined the BF in the bioturbated strata of the Upper Jurassic Hanifa Formation (central Saudi Arabia) to understand how sedimentological and diagenetic processes—such as compaction, dolomitization, and dissolution—influence porosity and permeability over time.

Backstripping results provide significant insights into the evolution of porosity and permeability within packstone BF of the studied strata. We found that compacted, grain-supported BF exhibit limited improvement in porosity and permeability post-compaction. In contrast, less compacted intervals with open fabric BF can achieve up to 20% porosity and >5000 mD permeability in their grainstone versions. Notably, even with over 10% mud content, open fabric BF maintained substantial permeability (>1000 mD) due to a connected pore network. Moreover, these BF have the potential to recover porosity and

permeability after complete pore network occlusion by the mud matrix through diagenetic processes like preferential dolomitization of the mud matrix and subsequent dissolution. The findings underscore the dynamic evolution of porosity in packstones within BF of bioturbated strata. Initially, mud-rich packstones with low porosity and permeability can transform into more permeable packstones through dolomitization and dissolution. Conversely, initially high-quality, mud-poor packstones with high porosity and permeability may degrade due to compaction. The quantification of porosity and permeability using digital rock modeling and backstripping techniques provides an objective and comprehensive understanding of these evolving properties, highlighting key phases and processes affecting reservoir quality. The approach of integrating digital rock modeling and backstripping technique enhances the ability to predict subsurface storage and flow capacity in bioturbated strata.

Keywords:

Burrow fillings; Bioturbated carbonate reservoirs; Digital rock modeling; Hanifa Formation; Saudi Arabia.

3.1 Introduction

Burrows filled with packstone (Dunham, 1962) in carbonate strata are commonly observed in substrate-controlled ichnofacies like *Glossifungites* (Pemberton and Gingras, 2005; Knaust, 2009, 2014; Bromley, 2012; Liu et al., 2019; Eltom et al., 2021a, 2021c; Niu et al., 2022). When these burrowed strata reach a certain percentage of 12%, they can form a connected network of grain-dominated fillings, which can become fluid flow passageways if the grain-supported fillings have preserved porosity (Gingras et al., 2004, 2012; La Croix

et al., 2008, 2012; Baniak et al., 2013, 2015; Eltom and Hasiotis, 2019; Eltom and Goldstein, 2021). The efficacy of such a network depends largely on the characteristics of the grain-dominated fillings such as grain size and shape, pore system, and mud content which can be quite complex.

Packstone is a grain-dominated carbonate class that contains a mud matrix and is characterized by grain-supported rock fabric, where sand-sized grains maintain interparticle contacts (Dunham, 1962). Dunham (1962) noted that grain-support is typical of sediments deposited in agitated waters, while the presence of mud indicates deposition in quieter waters. This contrast has led many researchers to propose different models to explain the coexistence of mud and grains in packstone rocks (Burchette and Wright, 1992; Alsuwaidi et al., 2020). These models highlight that the texture of packstones evolves over time through multiple stages, leading to simultaneous changes in porosity and permeability and variations in reservoir quality where bioturbators can introduce carbonate mud resulting in alteration of grainstones into packstones (Alsuwaidi et al., 2020). Burrow fillings with packstone texture are expected to exhibit similar texture and flow properties changes over time.

Understanding the development and characteristics of packstone-filled burrows is crucial for predicting fluid flow behavior in bioturbated carbonate reservoirs. The interconnected nature of these burrows (Gingras et al., 2004, 2012; La Croix et al., 2008, 2012; Baniak et al., 2022; Eltom and Alqubalee, 2022; Eltom and Goldstein, 2023), along with the evolving texture and porosity of packstones, influences the overall permeability and flow capacity of these reservoirs. As packstones evolve, their ability to serve as fluid conduits can change, affecting their performance in subsurface geological settings (Lucia, 1995; Lucia et al.,

2001, 2003). Therefore, a comprehensive understanding of this evolution is essential for accurate reservoir characterization and effective resource management.

The objective of this study is to conduct a backstripping diagenetic, porosity, and permeability modeling study on the packstone burrow fillings of *Glossifungites* ichnofacies in the Upper Jurassic Hanifa Formation of central Saudi Arabia (Fig. 1B and Fig. 2) which represent deposition on extensive shallow marine system in southern margin of the Tethys Ocean (Fig. 17, Powers et al., 1966). The aim is to understand how the porosity and permeability of these fillings evolve over time with changes in packstone texture. To achieve this, the study integrates petrographic analysis with digital rock modeling, including micro-CT scanning on samples from the fillings, followed by pore network modeling and permeability simulation.

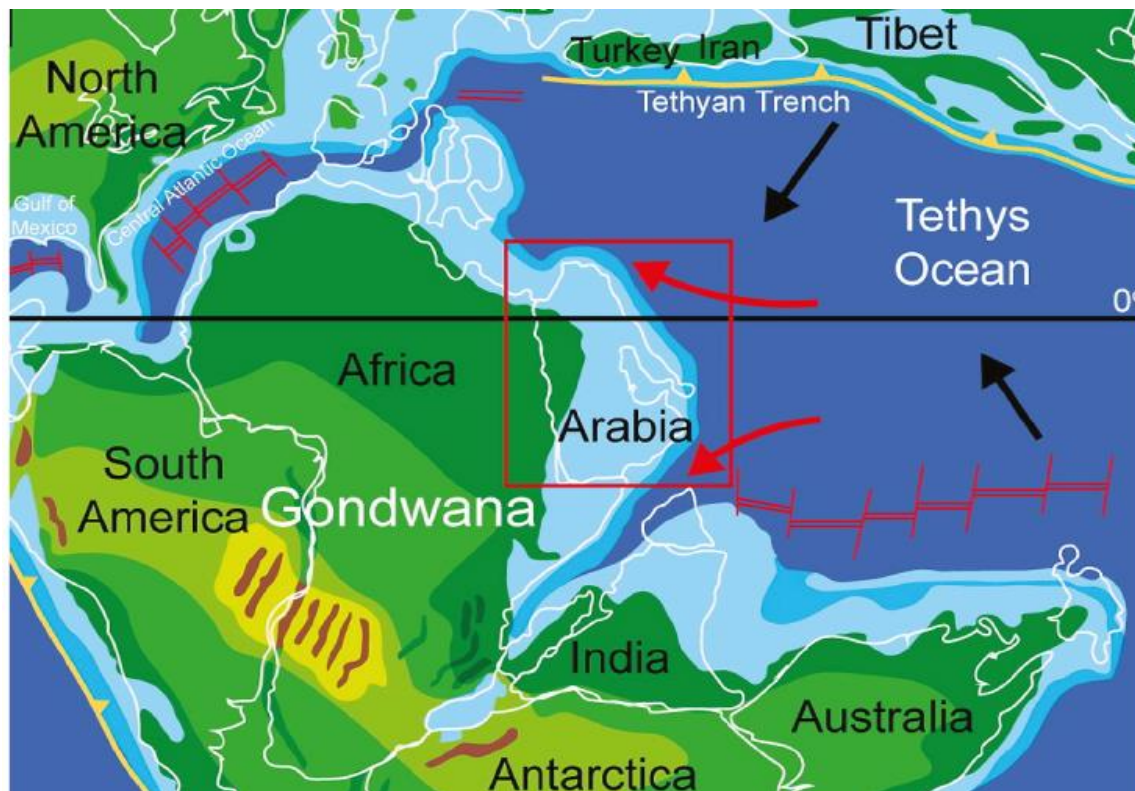


Figure 17. Paleogeographic map showing the Arabian Plate facing the western Tethys Ocean and covered by shallow-water seas at an equatorial position during late Jurassic (modified from Scotese, 2002).

3.2 Study area and Geological background

3.2.1 Study area

The study was conducted using samples from strata characterized by extensive *Thalassinoides*, which exist as *Glossifungites* Ichnofacies in the Upper Jurassic Hanifa Formation at Jabal Al-Abakkayn, near Riyadh, Saudi Arabia (Fig. 1C). The location and geological context are detailed in previous studies (Eltom et al., 2021a, 2021b, 2022; Eltom and Alqubalee, 2022). Detailed information on the stratigraphy, age of the Hanifa Formations and *Glossifungites* Ichnofacies is in the following section.

3.2.2 Stratigraphy of the Hanifa Formation

At Jabal Al-Abakkayn, the Hanifa Formation lies above the Tuwaiq Mountain Formation and beneath the Jubaila Formation (Fig. 1A). The Hanifa Formation is divided into two members: the Hawtah and Ulayyah members (Fig. 1A, Powers et al., 1966). Both members feature a recessive interval at the base and a resistive interval at the top. The focus of this study is on the uppermost Hanifa Formation, specifically the upper part of the Ulayyah Member (Fig. 1B and Fig. 2), which is characterized by extensive bioturbated beds.

Powers et al. (1966) identified Jabal Al-Abakkayn (Fig. 1C) as a reference section for the Hanifa Formation. Building on their work, Fallatah and Kerans (2018), Eltom et al. (2018), and Elzain et al. (2020) measured a 114-m stratigraphic section at Jabal Al-Abakkayn, documenting the key lithofacies, beds, bed sets, and sequence stratigraphy features (Fig. 18). According to this measured section, the Hanifa Formation consists of four sequences, with the uppermost sequence (Fig. 2) containing the studied strata (Fallatah and Kerans, 2018). These strata (Fig. 1B and 2) are characterized by burrowed, mud-dominated deposits

that include foraminifera, brachiopods, echinoid spines and plates, and occasional quartz grains (Fallatah and Kerans, 2018).

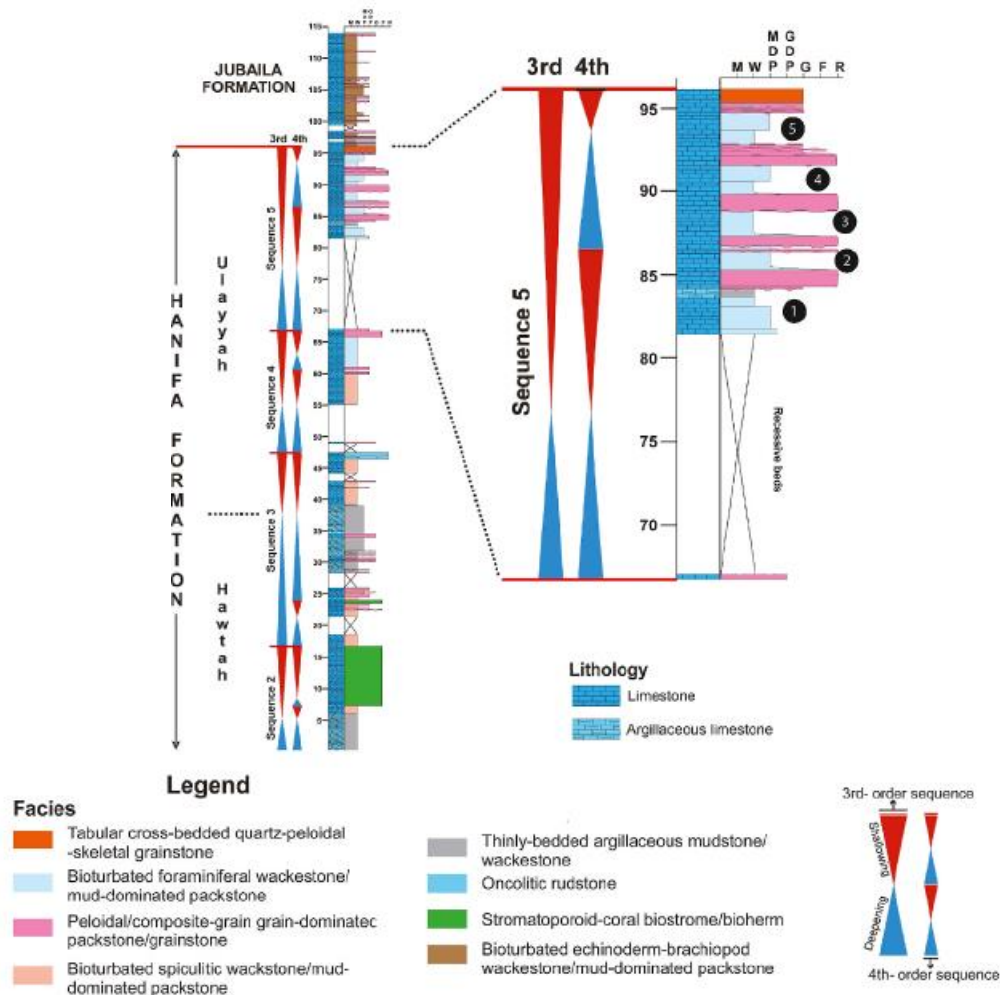


Figure 18. Measured section at Jabel Al-Abakkayn showing sequence stratigraphy of the Hanifa Formation and the five studied intervals (Modified from Fallatah and Kerans, 2018; Syahputra et al., 2022).

3.2.3 Age of the Hanifa Formation

Early studies on the Jurassic succession in Saudi Arabia suggested that the Hanifa Formation contained strata from the Early Kimmeridgian (Powers et al., 1966). However, more detailed research by Enay et al. (1987) and Fischer et al. (2001) proposed a revised

age: A Middle Oxfordian age for the Hawtah Member, a Late Oxfordian age for the lower part of the Ulayyah Member, and an Early Kimmeridgian age for the uppermost portion of the Ulayyah Member, where the *Glossifungites* Ichnofacies interval is found in Jabal Al-Abakkayn.

Hughes et al. (2008) further refined the age of the Hanifa Formation by analyzing nannofossils, microfossils, and macrofossils from outcrops and subsurface wells in central and eastern Saudi Arabia. Based on these fossils and previous studies (Powers et al., 1966; Enay et al., 1987; Fischer et al., 2001; Hughes et al., 2008) suggested that the basal section of the Hanifa Formation (lower Hawtah Member) dates to the Early Oxfordian. The middle and upper sections of the Hawtah Member are dated to the Middle Oxfordian, while the lower portion of the Ulayyah Member is assigned to the Late Oxfordian. The uppermost part of the Hanifa Formation (upper Ulayyah Member, our studied interval) is assigned an Early Kimmeridgian age.

3.2.4 *Glossifungites* Ichnofacies in the Hanifa Formation

This study builds on the foundational work of Eltom et al. (2017), Eltom et al. (2021a, 2021b), Eltom and Alqubalee (2022), Eltom et al. (2022), and Syahputra et al. (2022), which examined the *Glossifungites* Ichnofacies in the upper Hanifa Formation. These previous investigations provided significant insights into the characteristics and implications of these ichnofacies for the reservoir quality of carbonate systems of the Hanifa Formation. Notably, these previous studies identified five bioturbated intervals in the upper Hanifa Formation, which were categorized based on burrowing style: three intervals with *Thalassinoides* as a pipe framework and two intervals with bio-retextured fabric due to burrowing (Fig. 19).

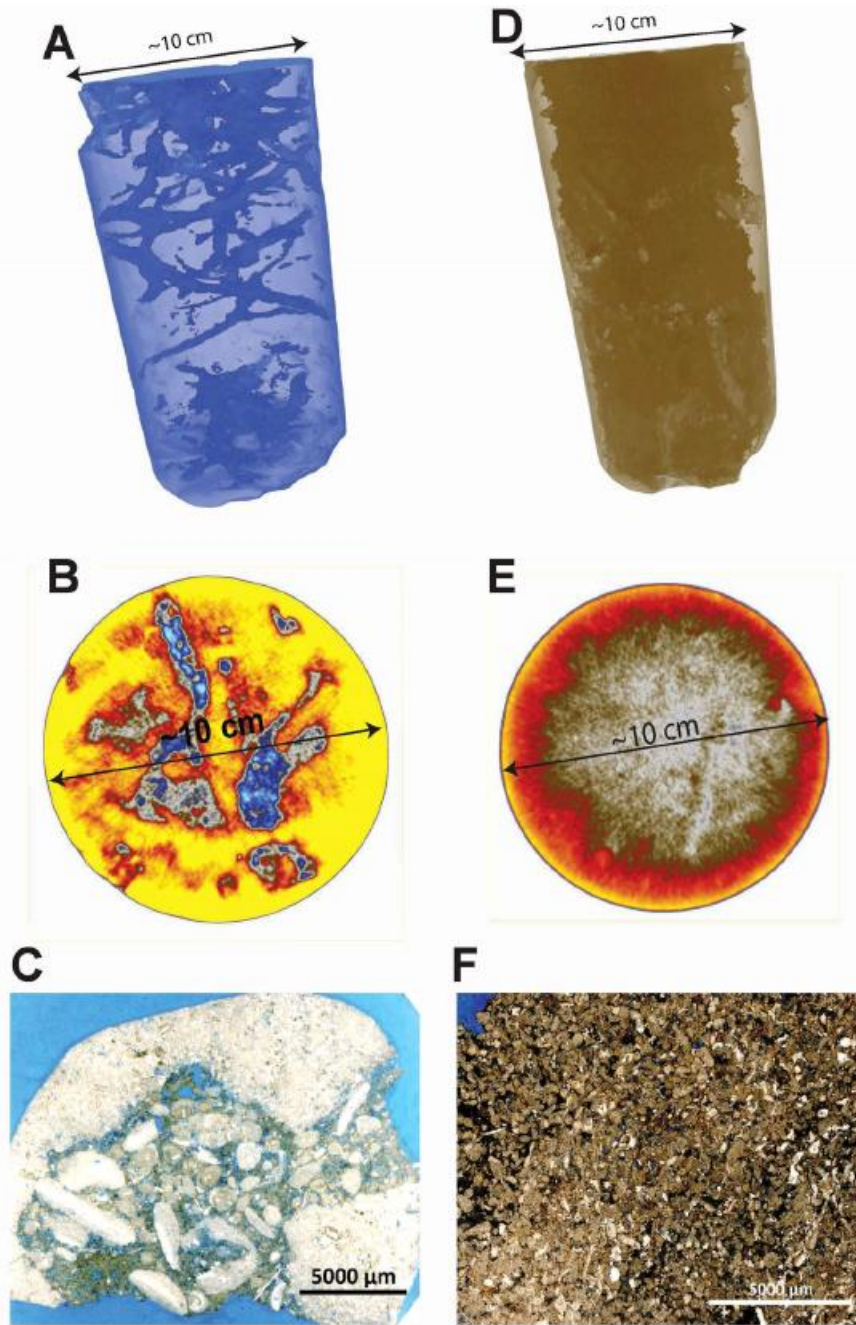


Figure 19. Burrowing styles found within the studied intervals. (A, B, and C) The pipe framework burrowing style obtained from medical CT scans of cores, 2D slice view of the CT scans, and thin-section photomicrograph, respectively. (D, E, and F) The bioretecturing burrowing style obtained from medical CT scans of cores, 2D slice view of the CT scans, and thin-section photomicrograph, respectively.

In the intervals where burrows exhibit pipe framework (Fig. 19A and B), the host rock matrix predominantly consisted of wackestones or fused peloidal packstones, while the BF exhibited a grain-supported texture, primarily packstones (Fig. 19C). In contrast, intervals where burrowing resulted in bio-retextured rock fabric show no distinct burrow framework (Fig. 19D–F). This study focuses on the *Glossifungites* Ichnofacies intervals with pipe framework burrows, as these provide valuable examples where burrows can act as permeability pathways, enhancing the flow capacity of carbonate rocks. Building on previous work, the use of backstripping techniques and digital rock modeling offers intriguing insights into how porosity and permeability evolve over time in these *Glossifungites* Ichnofacies.

3.3 Methodology

3.3.1 Sampling and Imaging

Three boulder-sized samples were collected from three stratigraphic intervals (interval-1, interval-4, and interval-5) characterized by pipe framework burrowing style (Fig. 1B and Fig. 2). The samples were slabbed to investigate the burrow morphology and their fillings. CT scans were performed using a medical CT scanner to examine the burrows in three-dimensions (Fig. 19A and D). Subsamples were taken from the slabbed boulder samples by extracting 1.5-inch diameter plugs every 10 cm, resulting in 18 total samples from the three slabs (Fig. 20A and B).

Thin-sections were prepared to standard dimensions (27 ×46 mm) for each core plug sample and scanned using the AxioScan system and then inspected by utilizing ZEISS ZEN 3.8 software. They used to characterize the depositional texture and the pore system within the BF. The thin-sections were also studied using a traditional light microscope in addition

to the analysis of the AxioScan images by ZEISS ZEN 3.8 ware to determine the overall diagenetic features in the BF. The timing of each diagenetic event was determined based on cross-cutting relationships and superposition.

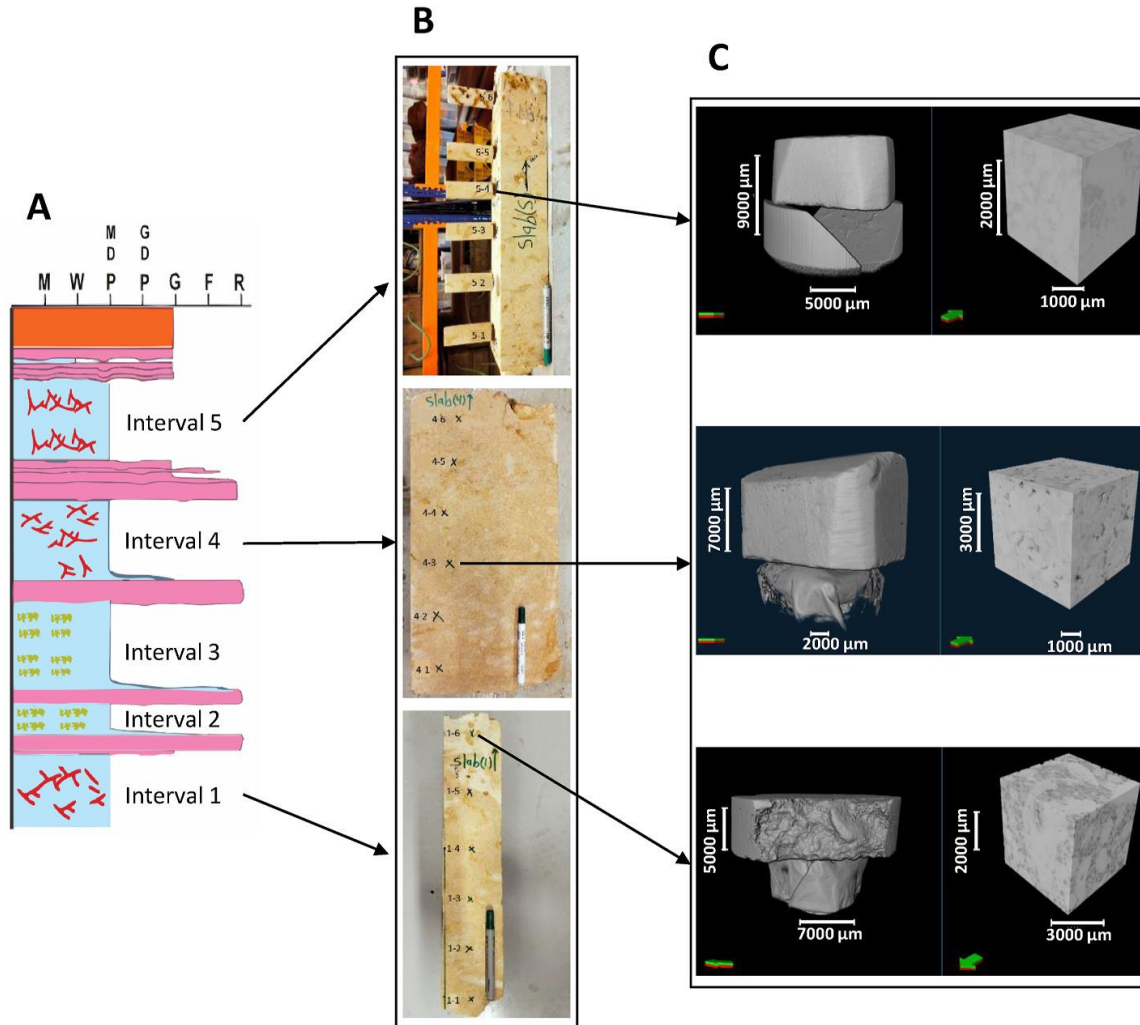


Figure 20. (A) Measured stratigraphic section of the uppermost part of Hanifa Formation at Jabel Al-Abakkayn showing the bioturbated strata and the location of the samples (Modified from Fallatah and Kerans, 2018; Syahputra et al., 2022). (B) Photographs of the slabbed boulder-size samples collected from the studied intervals. (C) Images of the subsamples obtained from micro-CT scanner (left side) and cubic Sub-volume extraction inside the burrow fillings (right side).

Subsequently, three separated samples (each sample from different slab) were selected for further high-resolution imaging using the Versa XRM-500 μ -CT scanner with a 9 μ m voxel

resolution to obtain these high-resolution images. This selection was based on the investigations from the thin-sections. The data from the μ -CT scanner were processed and analyzed using Avizo software (Fig. 20C).

To focus on the pore system inside the burrow filling, the Extract Subvolume module was used to extract cubes with the nearly same volume but slightly different numbers of slices in the X, Y, and Z directions within the burrow filling. The number of cube slices varied from one sample to another according to the sample dimensions. Before segmentation, digital image filters were applied to control contrast, and smoothness, reduce noise or artifacts, and enhance features for better segmentation. The Non-Local Means filter from the Filter Sandbox module was used for maintaining edges and handling noisy data. Parameters such as Spatial Standard Deviation, Intensity Standard Deviation, Search Window, and Local Neighborhood Ports were set at 2, 0.2, 10, and 3, respectively, to effectively define micro and macro pores.

In the Image Segmentation module, the 'Edit New Label Field' function allowed each sample to be segmented into different materials, identified by unique colors. The thresholding segmentation tool accurately detected pores, and the Top-Hat tool identified smaller and intraparticle pores within the grains. After segmenting the pores, the tool settings were adjusted to label the matrix, and lastly, the grains. Once all three materials were segmented, measuring their volumes using the Volume Fraction module became straightforward. The measured pore volume provided an assessment of the total porosity of each sample.

3.3.2 Backstripping technique of packstones

The BF was dominated by allochems (>80%) and smaller amounts of pores and matrix (utilized to classify the BF into mud-poor packstones, mud-rich-packstones, or grainstones). These allochems range from: slightly compacted, moderately compacted, and highly compacted. Backstripping techniques were used to explore how adding or subtracting matrix from the BF at these different compaction stages affects porosity and permeability.

Three μ -CT scanned samples were used as the basis for modeling (Fig. 21), creating five distinct models for each sample. Model 1 represents the current state of the BF, progressing to Model 5, which represents the grainstone texture. In total, 15 digital models were developed to represent seven stages of compaction and varying mud matrix content within the BF, reflecting distinct textures and grain-supported fabric types. Pore network modeling was conducted using Avizo software to determine the connectivity and the percentage of pore networks in each model.

Permeability simulations were conducted on each of the 15 digital rock models, simulating permeability in three directions (x, y, and z), yielding 45 permeability values. Using Avizo software's Absolute Permeability Experiment Simulation module, fluid flow was simulated through the identified pore networks. Simulation parameters were set as follows: data output from the Axis Connectivity module, pore space at 1 as the two other materials of the sample took value of 0, directions at X, Y, and Z, input pressure at 130,000 Pa, output pressure at 100,000 Pa, and fluid viscosity at 0.001 Pa s. These settings helped quantify absolute permeability in micrometers squared and darcy across the three directions.

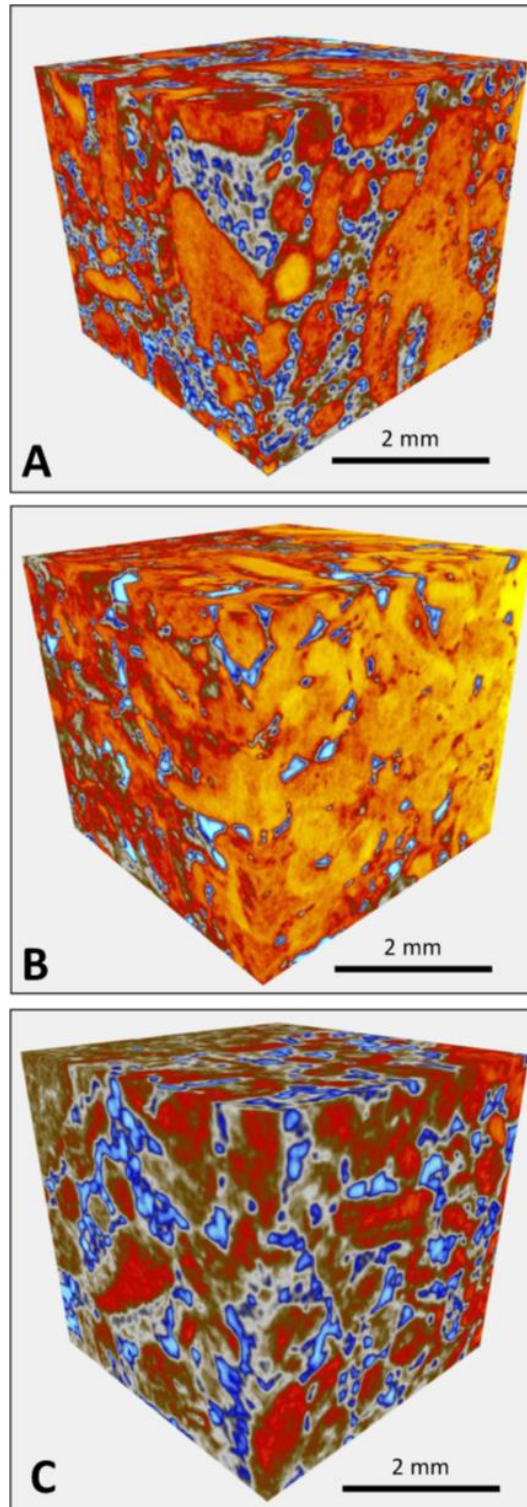


Figure 21. Screen captures showing the μ -CT scans of the cubes collected from samples in interval 1 (A), interval 4 (B), and interval 5 (C). The rock components within these cubes are distinguishable based on density contrast: the carbonate allochems appear reddish, the mud matrix is whitish, and the pores are blue.

We also obtained outputs for velocity and pressure for each direction. Using the Magnitude module, we computed scalar magnitudes from the velocity data, and the Illuminated Streamlines module visualized the permeable pathways in all three directions for each model, enhancing our understanding of fluid transport mechanisms and characterizing the porous materials.

3.4 Results

3.4.1 Characteristics of the digital rock samples

The digital rock analysis and thin-sections revealed that the BF in the three studied intervals exhibit a grain-dominated texture (Fig. 21). These textures are composed of allochems, mud, and pores, distinguishable by their different CT scan densities, allowing for clear segmentation in the digital samples (Fig. 21). This segmentation and subsequent numerical data collection enabled precise quantification of these components (Table 4).

The allochems percentage in the BF varies significantly across the three intervals. Interval 4 has the highest grain proportion at 92.71%, interval 1 has 83.49%, and interval 5 has the lowest at 79.71% (Table 4, Fig. 21). This variation corresponds with the compaction levels of the samples, with Interval 4 showing the highest compaction and Interval 1 showing a more open fabric texture with minimal grain-to-grain contact. Interval 5 represents an intermediate stage (Fig. 21).

These data indicate that the BF in the three intervals are poorly sorted, featuring a mixture of very large and smaller grains. The large grains are elongated and often packed in a preferential orientation, although the exact orientation relative to the bedding planes remains unclear (Fig. 21).

Table 4. Data from the 15 digital models of the three studied intervals showing the texture type, percentages of total porosity, connected porosity, isolated porosity, matrix, and grains, as well as the values of absolute permeability in the X, Y, and Z directions.

Interval No.	Model No.	Porosity (%)	Connected porosity (%)	Isolated porosity (%)	Matrix (%)	Grains (%)	Kx (mD)	Ky (mD)	Kz (mD)	Texture
1	1	7.15	N/A	7.15	9.36	83.49	N/A	N/A	N/A	scmpp
	2	8.46	N/A	8.46	8.05		N/A	N/A	N/A	scmpp
	3	10.3	N/A	10.3	6.21		N/A	N/A	N/A	scmpp
	4	12.9	N/A	12.9	3.61		N/A	N/A	N/A	scmpp
	5	16.51	13.1	3.41	N/A		17640	18170	1660	scg
4	1	4	N/A	4	3.29	92.71	N/A	N/A	N/A	hcmp
	2	4.57	N/A	4.57	2.72		N/A	N/A	N/A	hcmp
	3	5.26	N/A	5.26	2.03		N/A	N/A	N/A	hcmp
	4	6.11	N/A	6.11	1.18		N/A	N/A	N/A	hcmp
	5	7.29	5.33	1.96	N/A		5950	4700	3720	hcg
5	1	7.75	N/A	7.75	12.54	79.71	N/A	N/A	N/A	mcmrp
	2	10.02	6.9	3.12	10.27		800	720	1470	mcmrp
	3	12.8	11.2	1.6	7.49		1440	6700	1890	mcmp
	4	16.18	15.19	0.99	4.11		6080	11940	4600	mcmp
	5	20.29	19.78	0.51	N/A		16320	20150	10440	mcg

The total segmented pores in the digital samples are either connected or isolated, with varying porosity percentages (7.15% in interval 1, 4% in interval 4, and 7.75% in interval 5; (Table 4, Fig. 21). Mud content also varies with interval 1, 4, and 5 (9.36%, 3.29%, and 12.54%, respectively; (Table 4, Fig. 21). The distinct densities of allochems, pores, and mud make them easily identifiable, displaying allochems (reddish), connected pores (blue), and mud matrix (whitish) in Fig. 21.

3.4.2 Diagenetic modifications in the BF

The major diagenetic modifications that were observed in the BF included compaction, preferential dolomitization of mud matrix, and substantial dissolution (Figs. 22 and 23). Interval 1 and 5 shows low to moderate compaction (Fig. 22). The allochems in the BF of these two intervals form an open fabric with few grains in contact (Fig. 22A). The mud matrix between the allochems in the BF (Fig. 22B) contains molds of dissolved dolomite rhombs, and where the allochems are not in contact, these molds dominate the spaces between allochems (Fig. 22B). In some cases, the molds are deformed at grain-to-grain contacts (Fig. 22C and D). Some of the dolomite rhombs remain undissolved and exhibit a cloudy appearance (Fig. 22B).

Interval 4 has the most intensive compaction in BF, with substantially reduced pore space (Fig. 23). Evidence of compaction includes grain-to-grain contact (Fig. 23B), grain penetration (Fig. 23B), pressure solution (Fig. 23C), and microstylolitization (Fig. 23C). The molds of dolomite rhombs and the dolomitic matrix are not dominant in this interval. Instead, interparticle pores are preserved but substantially reduced by compaction (Fig. 23).

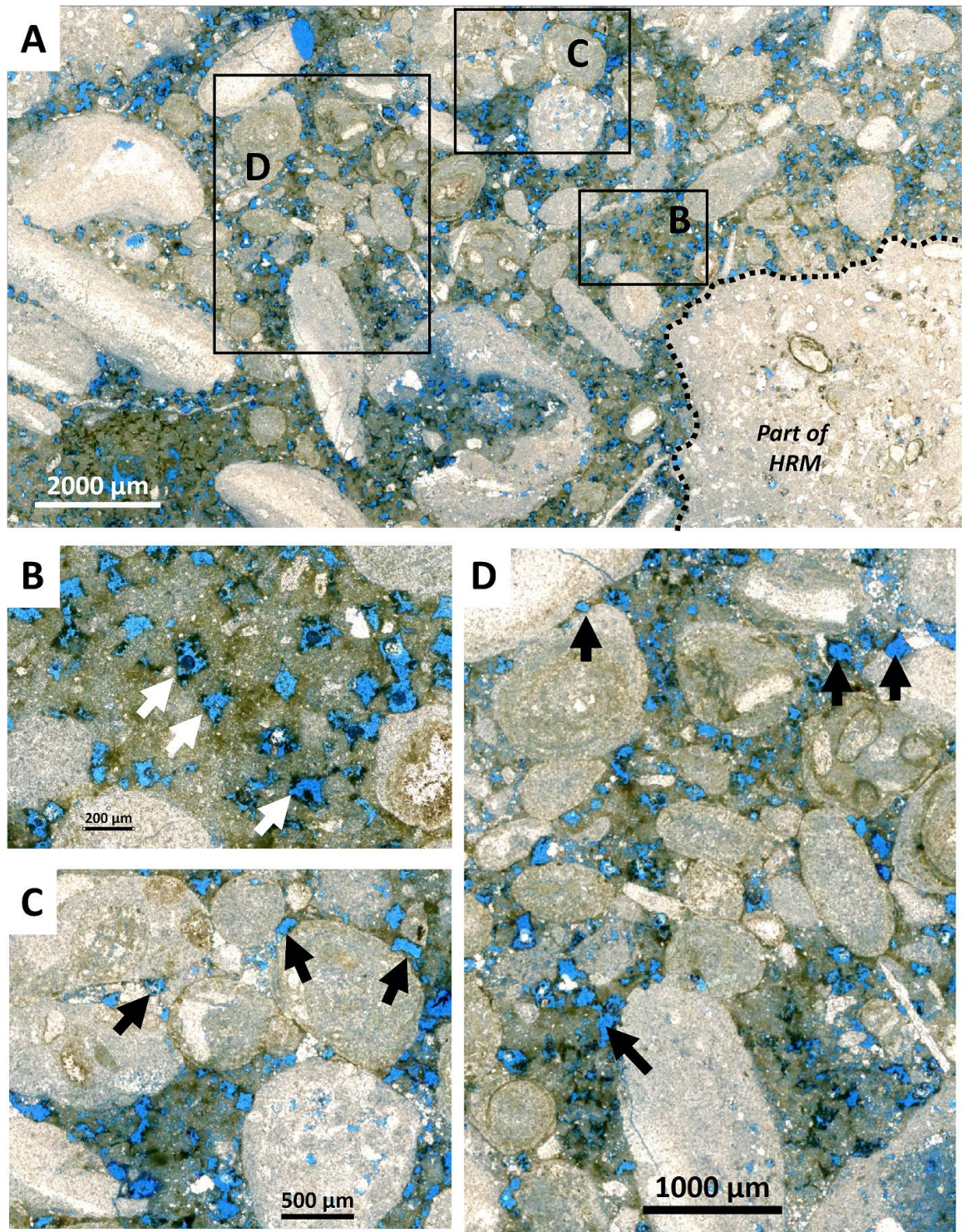


Figure 22. Thin-section photomicrographs of interval 1. (A) Photomicrograph showing the open fabric (slightly compacted) texture of mud-poor packstone fillings in interval 1. (B) Magnified photomicrograph of a thin-section highlighting the dolomitized mud matrix with dissolved dolomite rhombs (white arrows). (C and D) Magnified photomicrographs showing compacted dolomite crystals and molds (black arrows).

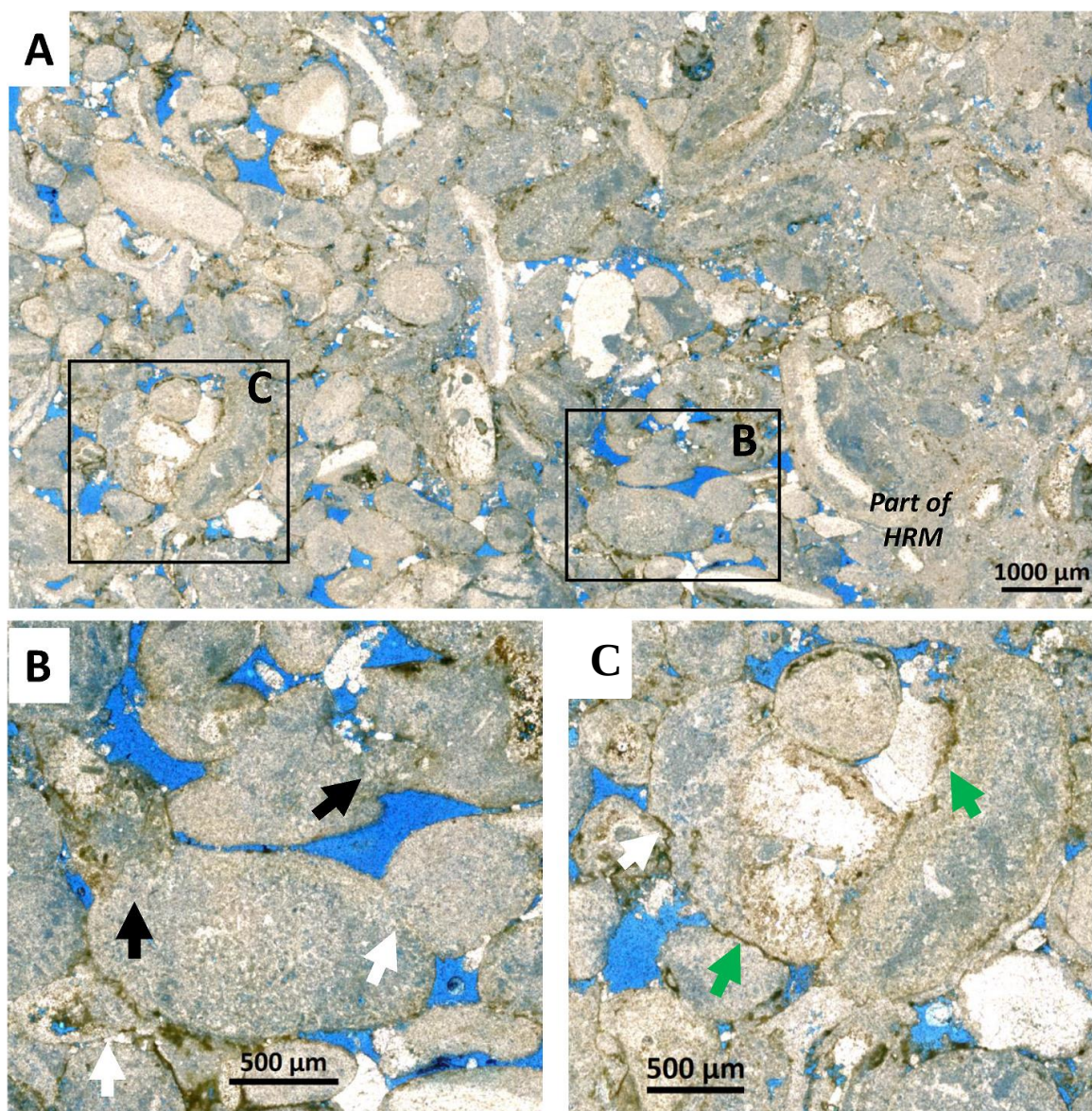


Figure 23. Thin-section photomicrographs of interval 4. (A) Photomicrograph showing the compacted texture of mud-poor packstone fillings in interval 4. (B and C) Magnified photomicrographs highlighting features of compaction, including grain-to-grain contact (white arrow), grain penetration (black arrows), and pressure solution (green arrows).

3.4.3 Porosity and permeability in the digital rock models

Five digital models of the BF were constructed for each of the three μ -CT scanned samples from the pipe framework intervals (Fig. 24-26). Model 1 for each interval represents the current state of the BF, while Model 5 represents the grainstone texture. Models 2 to 4

represent intermediate stages with varying percentages of the matrix found in the current state (Fig. 24-26). With progressing from Model 1 to Model 5, the pore volume fraction increases while the mud matrix volume decreases. Ultimately, in Model 5, each sample includes only pores and grains, reflecting the grainstone state during deposition before mud matrix introduction (Fig. 24-26).

These processes resulted in the construction of 15 digital models (Table 4), capturing unique cases of different textures in the BF with grain-supported fabric ranging from mud-rich packstone, mud-poor packstone to grainstone. The identified fabric types include slightly, moderately, and highly compacted mud-rich and mud-poor packstone and grainstone (Table 4). The rock components, pore system characteristics, total segmented porosity, and simulated permeability for these cases are discussed in the following sections.

3.4.4 Mud-rich packstone scenarios

The mud-rich packstone scenario occurred when the BF had over 10% mud content (Table 4), seen in moderately compacted interval 5 models (Fig. 24). Among the 15 digital models of μ -CT scanned, only two reflected this scenario: model 5–1 (Fig. 24A and B) and model 5–2 (Fig. 24C and D). Segmented porosity values of these models were 7.75% and 10.02%, with mud contents of 12.54% and 10.27%, respectively. Model 5-1 had exclusively isolated pores (Fig. 24B), resulting in zero simulated permeability, while model 5-2 showed some connected pores (Fig. 24D) with simulated permeabilities of 800 mD, 720 mD, and 1470 mD in the X, Y, and Z directions, respectively (Table 4).

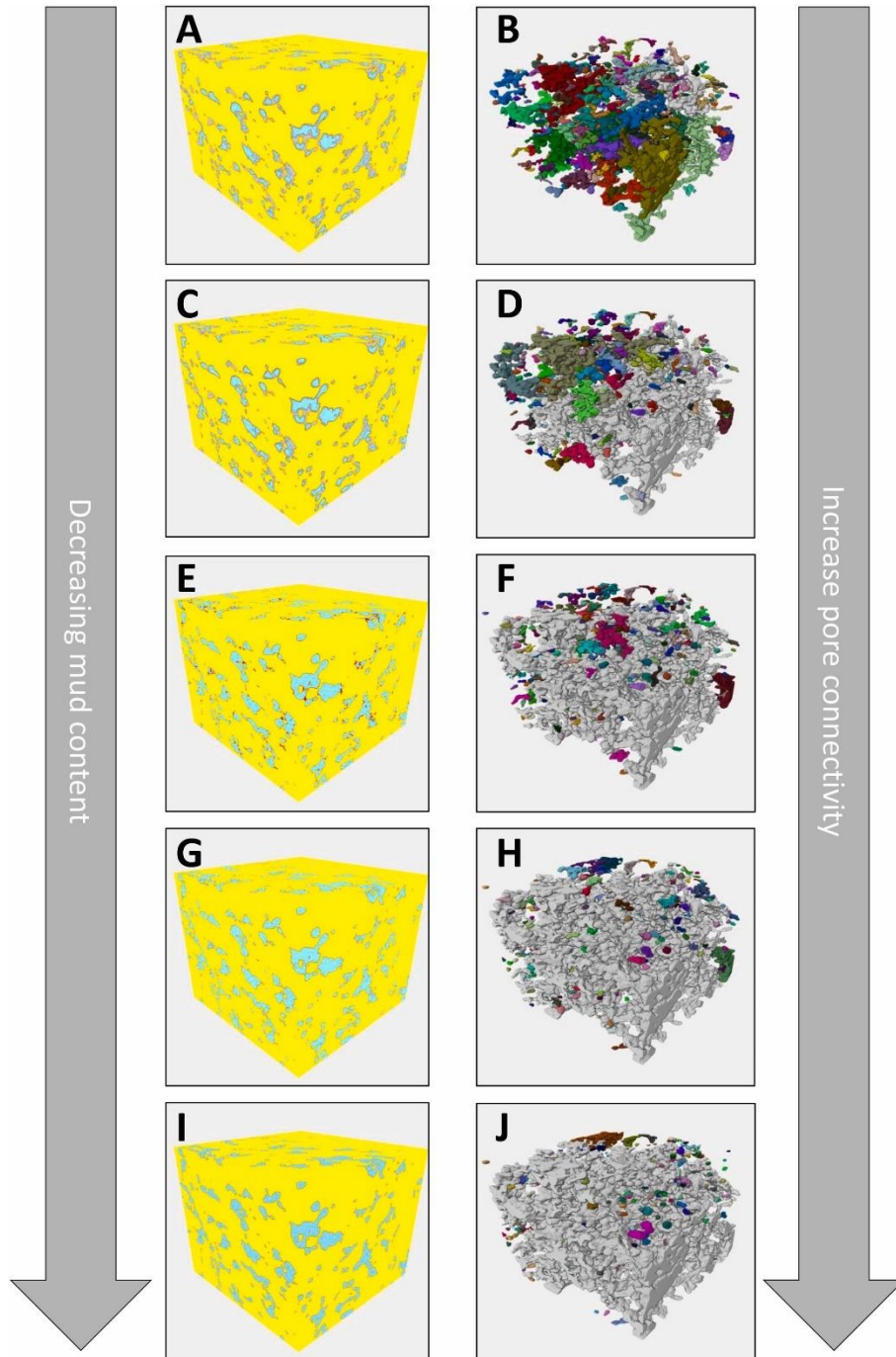


Figure 24. Screenshots from the 5 digital models of interval 5 (each cube side length is ~ 2.5 mm). These screenshots are displayed as pairs: on the left, segmented cubes showing allochems (yellow), pores (cyan), and mud matrix (purple); on the right, pore models with allochems and mud filtered out. In the pore models, different colors represent different pore volumes, with the largest volume always indicated by light gray. Note that as mud content decreases, the volume of the largest pore increases.

Porosity and permeability deterioration of grain-supported BF is greatest when mud content exceeds 10%, (Table 4). Model 5–1 (Fig. 24A and B) demonstrates this with zero simulated permeability, while model 5–2 (Fig. 24C and D), despite being mud-rich, exhibited connected pores and relatively higher permeability, likely due to its borderline mud content between mud-poor and mud-rich packstone (Table 4).

3.4.5 Mud-poor packstone scenarios

Most digital models of the BF followed the mud-poor packstone scenario, with less than 10% mud content (Table 4, Fig. 24-26). Examples include models 5–3 (Fig. 24E and F), 5–4 (Fig. 24G and H), 4–1 to 4–4 (Fig. 25A - H), and 1-1 to 1–4 (Fig. 26A–H), categorized by their compaction levels: open fabric, moderately compacted, and highly compacted (Table 4). Moderately compacted models (5–3 and 5–4, Fig. 24E–H) exhibited connected pores and higher porosity and permeability (Table 4). Model 5-3 had 7.49% mud content, 11.2% connected porosity, and 1.6% isolated porosity, with simulated permeability of 1440 mD, 6700 mD, and 1890 mD in the X, Y, and Z directions, respectively (Table 4). Model 5-4 had 4.11% mud content, 15.19% connected porosity, and 0.99% isolated porosity, with simulated permeability of 6080 mD, 11940 mD, and 4600 mD in the X, Y, and Z directions, respectively (Table 4).

Open fabric models (1-1 to 1–4, Fig. 26A–H) had porosities ranging from 7.15% to 12.9%, with mud contents from 9.36% to 3.61% (Table 4). These models exhibited isolated pores (Fig. 26A-H) with zero simulated permeability. Highly compacted models (4–1 to 4-4, Fig. 25A–H) had porosities from 4% to 6.11% and mud contents from 3.29% to 1.18% (Table 4). These models also showed isolated pores with zero simulated permeability (Fig. 25A-H).

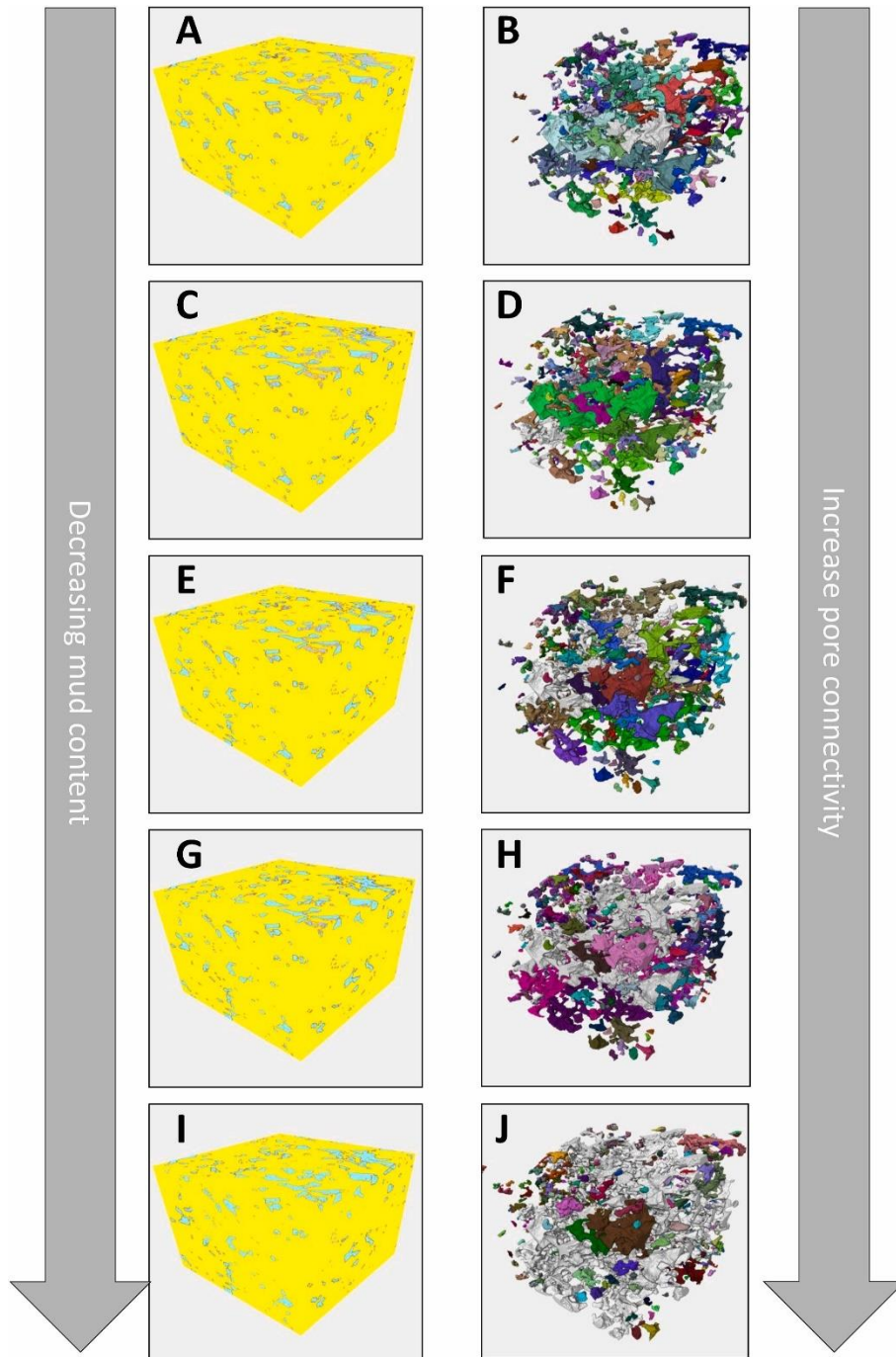


Figure 25. Screenshots from the 5 digital models of interval 4 (each cube side length is ~2.5 mm). These screenshots are displayed as pairs: on the left, segmented cubes showing allochems (yellow), pores (cyan), and mud matrix (purple); on the right, pore models with allochems and mud filtered out. In the pore models, different colors represent different pore volumes, with the largest volume always indicated by light gray. Note that as mud content decreases, the volume of the largest pore increases.

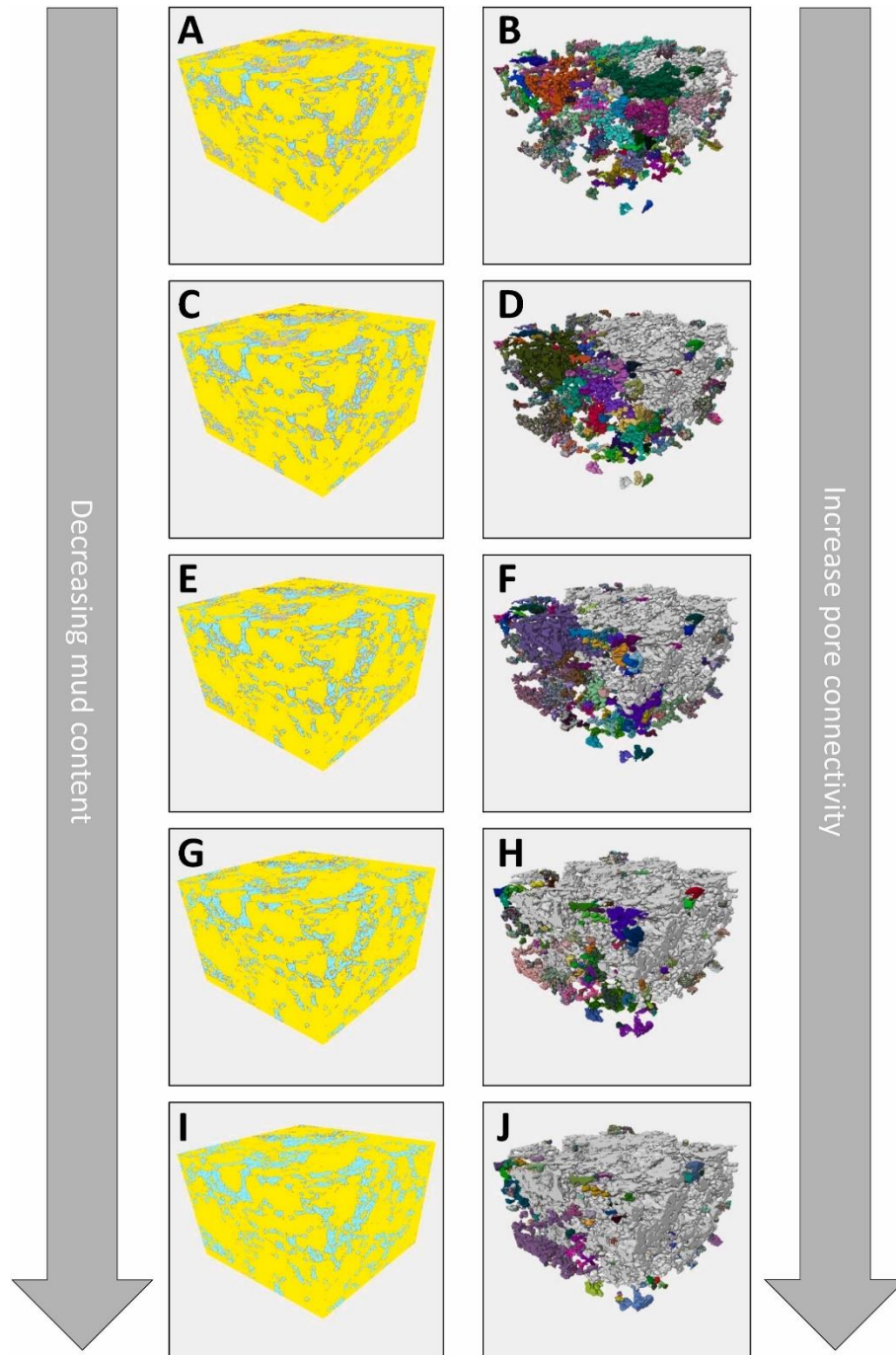


Figure 26. Screenshots from the 5 digital models of interval 1 (each cube side length is ~ 2.5 mm). These screenshots are displayed as pairs: on the left, segmented cubes showing allochems (yellow), pores (cyan), and mud matrix (purple); on the right, pore models with allochems and mud filtered out. In the pore models, different colors represent different pore volumes, with the largest volume always indicated by light gray. Note that as mud content decreases, the volume of the largest pore increases.

3.4.6 Grainstone scenarios

Grainstone scenarios consisting only of grains and pores across three models: moderately compacted (model 5-5, Fig. 24I and J), open fabric (model 1-5, Fig. 26I and J), and highly compacted (model 4-5, Fig. 25I and J). All these models showed connected pore networks. The moderately compacted grainstone (model 5-5, Fig. 24I and J) exhibited 20.29% total porosity (19.78% connected, 0.51% isolated) with simulated permeability of 16320 mD, 20150 mD, and 10440 mD in the X, Y, and Z directions, respectively. The slightly compacted grainstone model (model 1-5, Fig. 26I and J) had 16.51% total porosity (13.1% connected, 3.41% isolated) with simulated permeability of 17640 mD, 18170 mD, and 1660 mD in the X, Y, and Z directions. The highly compacted grainstone model (model 4-5, Fig. 25I and J) had 7.29% total porosity (5.33% connected, 1.96% isolated) with simulated permeability of 5950 mD, 4700 mD, and 3720 mD. All the grainstone models (models 1-5, 4-5 and 5-5) have connected pores. These results indicate that grainstones with open fabric exhibit substantially higher permeability compared to those with compacted fabric. Understanding the degree of compaction and fabric type is crucial in evaluating reservoir quality, as it directly influences fluid flow and hydrocarbon recovery potential.

3.5 Discussion

This study focuses on understanding the depositional and diagenetic evolution of packstone BF within the *Glossifungites* ichnofacies in the Upper Jurassic Hanifa Formation and its impact on reservoir permeability and porosity. By integrating petrography, micro-CT scanning, and digital rock modeling, we aimed to map the temporal changes in these burrow systems using backstripping techniques. The objective is to develop a detailed

digital rock models that can help to predict how these textural changes influence porosity and permeability. The study has broader implications, offering a conceptual understanding of porosity and permeability evolution in BF over time, which may be applicable to similar bioturbated reservoirs elsewhere.

3.5.1 Origin of packstone in the BF

Digital samples suggest two types of BF. One type, such as interval 5 (Fig. 21C, Table 4), with ~80% allochems and an abundant precursor muddy matrix (now dolomized); we refer to this as mud-rich packstone. The other type, like intervals 1 and 4 (Fig. 21A and B–Table 4), contains allochems with a minimal precursor muddy matrix (matrix percentage <10%, Table 4); we refer to this as mud-poor packstone. These naming are adopted from (Alsuwaidi et al., 2020) who modified Lucia classes of packstone: grain-dominated and mud-dominated packstones.

The original texture of these packstones (whether mud-rich or mud-poor) might have been a grainstone texture that was later modified by the addition of the mud matrix (Alsuwaidi et al., 2020). The mud matrix in the packstone can originate from various sources, including bioturbation and the mechanical deformation of peloids (Dunham, 1962). Alternatively, the mud could have been added after the water energy, which initially transported the coarse carbonate sediments to the burrow network, decreased. When water energy of the depositional environment waned, it becomes favorable for the deposition of the mud. In this scenario, the mud infiltrated through the porous and permeable precursor grainstone texture of the BF (Alsuwaidi et al., 2020) changing the grainstone to packstone. Thus, the mud matrix in the packstone texture of the BF might have different origin than the coarse carbonate sediments.

3.5.2 Impact of dolomitization on compaction

Based on the cross-cutting relationship (Fig. 22), it is evident that dolomitization in the BF occurred before compaction. The evidence for this interpretation includes the presence of compacted dolomite rhombs and deformed crystal molds between the carbonate allochems (Fig. 22C and D). Interestingly, the carbonate allochems are not dolomitized suggesting that when dolomitization occurred in the BF, it preferentially dolomitized the mud matrix (Fig. 22B), leaving the carbonate allochems undolomitized because they are much more stable than the mud matrix. Thus, the higher the amount of mud in the packstone, the higher the dolomite content.

When compaction happened afterward, it impacted two different scenarios of packstones. One scenario involved mud-rich packstone with a dolomitized matrix (Fig. 22), while the other involved mud-poor packstone with interparticle porosity and low dolomite content (Fig. 23). In the mud-rich packstone (Fig. 22), the dolomitized muddy matrix resisted compaction, preserving the interparticle area (Fig. 22B). On the other hand, the mud-poor packstone (Fig. 23), having a low content of dolomitized matrix, experienced substantial reduction in interparticle porosity due to compaction (Fig. 23).

Following compaction (in later diagenetic stage), the dissolution of dolomite rhombs within the muddy matrix occurred, creating molds of rhombs (Fig. 22B). This dissolution generated porosity in the interparticle area (Figs. 21–23). However, because not all of the dolomite rhombs in the dolomitized muddy matrix were dissolved, these molds are not perfectly connected (Fig. 21A).

3.5.3 Impact of compaction on porosity and permeability

The samples studied here are collected from three distinct stratigraphic intervals (Fig. 20). These intervals are both spatially and temporally distinct, even though they share common characteristics in rock texture. There are subtle but important differences among the samples in terms of the proportions of allochems, mud (dolomite), and cements (Fig. 21, Table 4). Such variations are expected given their spatial and temporal separation and are considered primary controls on the initial rock texture (as discussed above).

These textural differences subsequently influenced the way compaction impacted each interval. Although the three intervals are separated by only a few meters, suggesting they were likely subjected to similar compaction forces, the effects of compaction varied due to their differing initial textures. Essentially, the same cause—compaction—produced different effects—porosity reduction—across the stratigraphic intervals. For instance, BF with a higher initial mud content (and consequently more dolomite, Fig. 21A and C) were better able to resist compaction. In contrast, BF with less mud content (and consequently less or no dolomite, Fig. 21B) became more compacted under the same forces. When muddy matrix dissolved, it created substantial amount of interparticle porosity (Fig. 21A–C).

The results of digital rock modeling helped understand the evolution of porosity in packstones within the BF of the *Glossifungites* Ichnofacies of the Hanifa Formation. Initially mud-rich packstones BF with low porosity and permeability can transform into more permeable packstones through dolomitization and subsequent dissolution (Fig. 21A and C). Conversely, initially good-quality mud-poor packstones BF with high porosity and permeability may degrade in quality due to compaction (Fig. 21B). Understanding these

processes is crucial for predicting fluid flow and reservoir performance in bioturbated strata, especially where direct permeability measurements are challenging.

3.5.4 Backstripping the BF

The preceding discussion offers a conceptual framework for understanding how the rock texture of the current stage of the BF may have evolved over time. However, this naturally leads to an important question: What additional value can backstripping contribute to this understanding? This question is particularly significant because traditional petrographic investigations alone can often provide such a foundational conceptual understanding. Yet, the answer lies in the unique advantages that backstripping and digital sample analysis bring to the table.

Backstripping, coupled with digital samples (Figs. 24–26), allows for a precise and quantitative assessment of the evolution of porosity and permeability within the BF (Table 4). While traditional methods might suggest possible trends and patterns, backstripping can accurately measure the extent to which porosity and permeability have been reduced or enhanced across such trends and patterns (Table 4). Digital models provided 3D visualization of pore network which is not easy capture using traditional methods (Figs. 24–26). This quantitative approach transforms a conceptual hypothesis into a more objective and verifiable understanding, offering a deeper insight into the complex interplay of depositional and diagenetic processes that shape the porosity and permeability of the BF through time.

By integrating backstripping with digital sample analysis, it becomes possible to not only visualize but also quantify permeability evolution in the BF (Table 4, Figs. 24–26). For example, there are three grainstone versions of the burrow filling in the studied samples:

highly compacted, moderately compacted, and slightly compacted (Figs. 24–26). The digital samples of these three versions indicate a substantial reduction in permeability due to compaction alone, with a reduction amount of approximately four times (Table 4).

Moreover, the quantification of permeability in the digital samples provides a clearer and more detailed picture of how permeability is impacted by mud content as the digital samples evolve from grainstone to mud-poor packstone to mud-rich packstone (Figs. 24–26). This is particularly evident in the case of interval 5 (Fig. 24), where the simulated vertical permeability changes from 10,440 mD in the grainstone version to 1890 mD in the mud-poor version, eventually reaching zero or no flow in the mud-rich packstone version (Table 4).

Such precise quantification is beyond the capabilities of traditional petrographic analysis, underscoring the added value of integrating digital methods and backstripping in understanding permeability evolution in the BF of bioturbated strata. By applying the insights from the results of digital rock modeling, geologists and reservoir engineers can better predict the behavior of bioturbated strata, leading to more accurate reservoir assessments and more effective resource management strategies.

3.6 Conclusion

Backstripping of the digital rock samples from the BF of the Upper Jurassic Hanifa Formation quantified the evolution of porosity and permeability due to sedimentological and diagenetic processes. Two major factors influencing the initially deposited grainstone in the BF are the addition or removal of the mud matrix and the compaction of grains. The results suggest the following points:

- Compacted grain-dominated BF have limited potential for improving porosity and permeability after compaction. In contrast, open fabric BF exhibit significantly higher porosity and permeability, which can be attributed to the later-stage dissolution of the dolomitized mud matrix. For instance, highly compacted mud-poor packstone BF show only 6.11% porosity and zero permeability, while slightly compacted mud-poor packstone has 12.80% porosity and 6700 mD permeability.
- High porosity and permeability in open fabric BF: Models of open fabric BF (slightly compacted, interval 5) show high porosity (20.29%) and permeability (5531.51 mD) in the grainstone scenario. Even mud-rich packstone scenarios with open fabric BF exhibit considerable permeability, with up to 10% mud content showing connected pores and simulated permeabilities of 800 mD, 720 mD, and 1470 mD in the X, Y, and Z directions. This suggest that in slightly compacted BF fabric even mud-rich packstone could make permeable passageways in the burrow network.
- Porosity and permeability recovery potential in open fabric BF: Open fabric BF can recover porosity and permeability even after complete pore occlusion by the mud matrix, potentially through preferential dolomitization and subsequent dissolution.
- Comprehensive understanding through backstripping: Backstripping digital rock models provided a comprehensive understanding of the dynamic evolution of porosity and permeability over geological time scales (with data driven conclusions). This methodology identified key phases of significant changes and critical thresholds where porosity and permeability deteriorate, enhancing the

ability to forecast subsurface reservoir quality and make informed decisions in storage and flow capacity of bioturbated reservoirs.

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CHAPTER 4

On the limitations of spot permeability measurements to quantify bulk permeability of bioturbated reservoirs: Insights from digital rock physics

Abstract

This study critically examines the limitations of spot permeability measurements in accurately determining bulk permeability in bioturbated reservoirs, using insights gained from digital rock physics modeling. Bioturbated reservoirs, characterized by burrows that create a dual-porosity system, present significant permeability contrasts between the coarse-grained burrow fillings and the fine-grained host rock matrix. These rock components often exhibit permeability variations over several orders of magnitude, complicating the task of assessing bulk permeability. Through an integrated workflow combining spot permeability measurements, micro-CT scanning, pore network modeling, and permeability simulations on samples from the upper Hanifa Formation in Saudi Arabia, we aimed to evaluate the accuracy of spot permeability data in capturing bulk flow behavior. Our findings reveal that spot permeability measurements, while providing useful localized permeability estimates, can misrepresent the true bulk permeability due to their inability to account for isolated or poorly connected pore systems. Notably, the contrast between CT scan data and spot permeability measurements presents a key challenge: while spot measurements suggested higher permeability in burrow fillings, the CT scan data showed isolated pore systems with limited connectivity, leading to no

measurable flow in permeability simulations. These contrasting results underscore the complexity of using localized measurements to infer bulk reservoir properties. Thus, a comprehensive approach, integrating spot permeability with high-resolution imaging and digital simulations, is essential for more reliable permeability estimations in bioturbated reservoirs.

Keywords:

Limitations; Spot permeability; Pore network modeling; Permeability simulation; Pore system.

4.1 Introduction

The term "bioturbated reservoir" refers to reservoirs in sedimentary strata that their sediments reworked by organisms, enhancing their storage and flow capacity (Pemberton and Frey, 1984; Meadows and Tait, 1989; Green et al., 1992; Zenger, 1992; Gingras et al., 2004; Pemberton and Gingras, 2005). These reservoirs typically have two pore systems: burrow pores and host rock matrix pores, with burrows being trace fossils from bioturbation. Burrows may be filled with coarse sediments or remain partially or fully open, leading to varied permeability contrasts between burrow pores and the surrounding matrix (Pemberton and Gingras, 2005; Tonkin et al., 2010; Cunningham and Sukop, 2012; Gingras et al., 2012; Baniak et al., 2013). In many circumstances the permeability contrast in bioturbated reservoirs is high, ranging from one order of magnitude with compact burrow fills to over three orders of magnitude with coarse-grained fillings or partially open burrows (Baniak et al., 2013; Baniak et al., 2014b; Baniak et al., 2015; Rodríguez-Tovar and Dorador, 2015; Golab et al., 2017a; Golab et al., 2017b; Eltom et al., 2021; Baniak et

al., 2022). This results in a complex porosity system controlled by the amount and morphology of the burrows, reflecting complex organism behaviors.

The inherited heterogeneous porosity system of bioturbated reservoirs poses a challenge in quantifying their bulk permeability, which is crucial for evaluating their flow capacity (Knaust, 2014; Knaust et al., 2020). Bulk permeability is defined here as the permeability of a homogeneous sample in which the fluid flow is uniform under the same pressure and boundary conditions (Baniak et al., 2013). This challenge becomes evident when defining a representative elementary volume (REV) for laboratory measurements (La Croix et al., 2017; Baniak et al., 2022; Eltom et al., 2023a). Previous studies have indicated that determining the REV of bioturbated strata is difficult because it must encompass the full morphology of the burrows that control porosity and permeability (La Croix et al., 2017; Baniak et al., 2022). These burrows are often much larger than the standard laboratory sample size, complicating the accurate definition of the REV (Eltom and Goldstein, 2021; Eltom and Goldstein, 2023b; Eltom and Goldstein, 2023a).

Pioneering studies addressed this challenge and proposed solutions using spot permeability measurements to estimate bulk permeability (Gingras et al., 2012; Baniak et al., 2013; Baniak et al., 2014b; Baniak et al., 2022). They analyzed the contrast between the permeability of burrow fillings and the rock matrix (measured by spot permeability measurement), defining two fluid flow media: dual-permeability fluid flow media (D-PermFFM) and dual-porosity fluid flow media (D-PorFFM). In D-PermFFM, the permeability contrast between burrow fillings and the host rock matrix is about three orders of magnitude, while in D-PorFFM, the contrast is about one order of magnitude. Bulk permeability in burrowed reservoirs is influenced by the type of fluid flow media and the

burrow percentage (BP). In D-PermFFM, the geometric mean of spot permeability is suitable for BP ranges from 25% to 65%, and the arithmetic mean for BP ranges from 65% to 80%. In D-PorFFM, the geometric mean is suitable for BP ranges from 10% to 50%, and the harmonic mean for BP ranges from 50% to 80%.

However, this solution has a significant limitation. It assumes that spot permeability accurately measures the permeability of the burrow fillings. Beyond sample preparation, such as ensuring a smooth surface and perfect contact of the measurement probe with the sample surface, there is the issue of localized diffusion of gas during measurement in isolated pores. This diffusion may show substantial permeability that is much localized. Such permeability does not reflect the true permeability of the burrow fillings because it comes from isolated pores. Including such measurements in the calculation of bulk permeability as proposed by previous studies will likely result in an accurate estimation of bulk permeability.

To highlight this issue with data and documented examples, the objective of this study is to integrate spot permeability measurements with digital pore network modeling and permeability simulation to answer an important question: do spot permeability measurements always reflect the bulk permeability of bioturbated reservoirs? Using samples from the upper Hanifa Formation in central Saudi Arabia (Fig. 27), the study highlights significant limitations of spot permeability measurements and aims to raise awareness among researchers working on bioturbated strata using this method.

4.2 Workflow

To address the question of this study, we applied an integrated workflow consisting of five steps: 1) measure spot permeability; 2) collect a micro sample from the measurement locations; 3) perform CT scans on the micro sample; 4) conduct pore network modeling; 5) simulate permeability and compare the simulated results with the spot permeability measurements. Details of this workflow are provided in the following section.

4.2.1 Samples

The samples used to apply this workflow comes from well-studied bioturbated strata in the upper Hanifa Formation (Fig. 27), which features *Thalassinoides* in *Glossifungites* ichnofacies (Eltom and Hasiotis, 2019; Eltom et al., 2019; Eltom et al., 2021; El-Husseiny et al., 2022; Eltom and Alqubalee, 2022; Eltom et al., 2022; Eltom and Goldstein, 2023b; Eltom and Goldstein, 2023a; Eltom et al., 2023b). As described in previous studies, these strata have *Thalassinoides* as the dominant burrow, with burrow percentages ranging from approximately 10% to 40%. *Thalassinoides* is passively filled with coarse-grained carbonate sediments in a host rock matrix of mud-dominated carbonate. As a result, spot permeability data from these previous works documented relatively higher permeability in the burrow fillings (ranging from 6.0 mD to 628.9 mD) compared to the host rock matrix (ranging from 0.1 mD to 5.4 mD) (Eltom et al., 2021, 2022).

The bioturbated strata of the upper Hanifa Formation include five intervals (numbered from bottom to top as 1 to 5, Fig. 27B). Two intervals are characterized by bio-retexturing due to bioturbation (intervals 2 and 3, with a homogenized texture where burrow morphology is hardly distinguishable), whereas three intervals are characterized by pipe framework

burrows in which *Thalassinoides* is very distinct (Fig. 27B). The workflow of this study was performed on samples from the interval 5.

A Boulder-size sample was collected from interval 5 (Fig. 27C), slabbed, and systematically subsampled to extract six 1.5-inch-diameter core plugs every 10 cm (Fig. 27D). From each plug samples thin-section was prepared for petrographic investigation. Furthermore, smaller sample (approximately 5 mm by 5 mm) was selected for very high resolution (9-micron) micro-CT scanning from four samples of these (Fig. 27E). These different scales of samples and measurements provide data that help answer the research questions of this study.

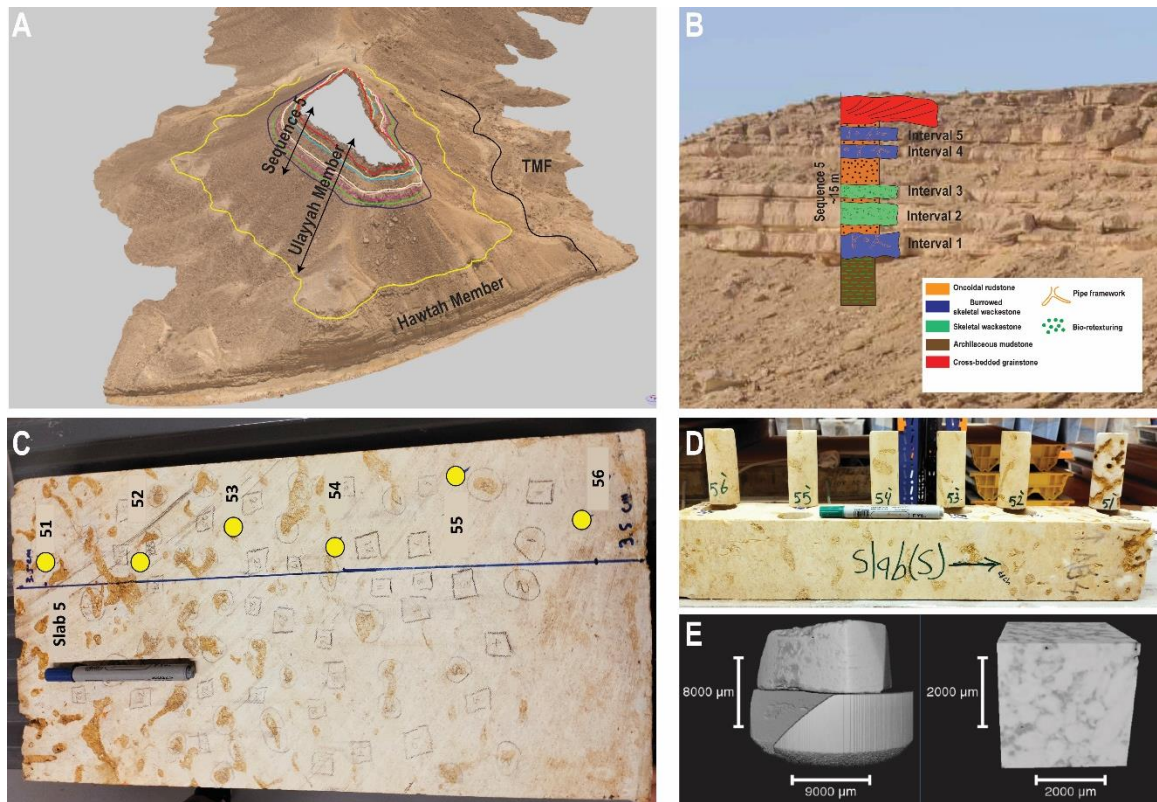


Figure 27. Photographs of the collected samples from the Upper Hanifa Formation. A) 3D photogrammetry of Jabal Al-Abakkayn. B) Photograph of the Upper Hanifa Formation with a measured section showing five burrowed intervals. C) Photograph of the Slabbed sample from Interval 5, indicating the locations of the 1.5-inch core plugs. D) Photograph showing six 1.5-inch core plug samples. E) Screenshot of the microsample extracted from the burrow fillings, which was micro-CT scanned.

4.2.2 Spot permeability measurements

Permeability measurements were taken on the flat surfaces of the slabbed boulder-size sample (Fig. 27C), which included both the matrix and the passive fillings of the *Thalassinoides*. A total of 32 measurements were taken from each of these rock components, resulting in a total of 64 spot permeability measurements. Each of these 64 measurements has a unique location on the sample's surface, identified by local X and Y coordinates on the boulder sample surface, which features a rectangular surface with dimensions of 20 cm by 30 cm. Descriptive statistics of each dataset were performed using Microsoft Excel.

These measurements were performed using the AutoScan system (New England Research, 2016), which employs a steady-state gas injection method (Nitrogen gas is used for the measurement) capable of measuring permeabilities ranging from 0.01 mD to 3.00 D (Fig. 28). The spot permeability measurement employs a probe that uses gas flow through a rock sample (Fig. 28A). A mobile probe is placed at different locations on the sample surface, allowing gas to flow through it (Fig. 28B). Permeability is automatically measured and recorded as gas continues to flow until a steady state is reached. The final permeability reading, taken at steady state, is considered the true permeability of the sample at that specific location. The probe has an internal diameter of 4.00 mm (Fig. 28C), with the difference accounted for by a rubber pad that ensures a tight seal to prevent gas leakage. Sufficient pressure is applied to maintain this seal.

To calculate the average permeability from the spot permeability measurements, three methods were used: (1) arithmetic, (2) harmonic, and (3) geometric averages (Gingras et al., 2012; Baniak et al., 2013; Baniak et al., 2014a). By integrating BP and using the fluid

flow media definitions from Baniak et al. (2013), the bulk permeability of the samples was estimated. This estimated permeability was then compared with the simulated permeability from the rock physics model for validation purposes.

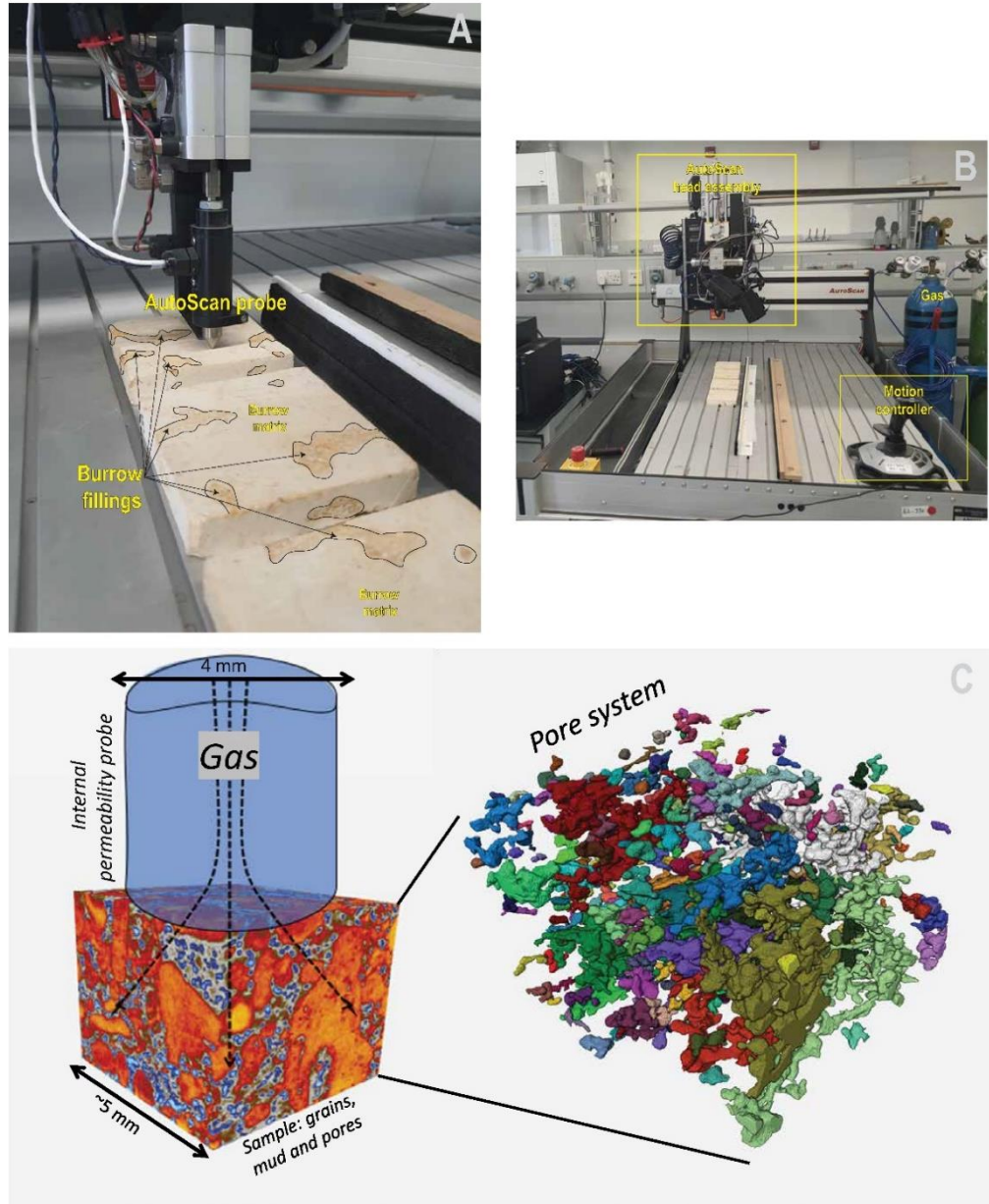


Figure 28. (A and B) AutoScan system with detailed descriptions of its major components used for measuring spot permeability. (C) Schematic illustrating the permeability probe of the AutoScan positioned on the extracted sample from the burrow fillings. The colored volume in C represents the pore system, where each color indicates a distinct, isolated pore volume. These isolated volumes suggest no flow in the samples spot.

4.2.3 Permeability simulation

The permeability simulation involves the final two steps of the workflow, which include performing pore network modeling on the micro CT scans of samples extracted from the burrow fillings and subsequently running permeability simulations on these pore network models (Fig. 29). The pore network modeling was carried out using Aviso software. This process begins with segmenting the micro CT scans (Fig. 29A) into three components: grains, pores, and mud matrix (Fig. 29B). The segmentation process allows for both quantitative and qualitative characterization of the pore network within the burrow fillings (Fig. 29C). Crucially, it also enables further segmentation of the CT scans into pores and matrix (include both grains and mud), a step essential for permeability simulation.

In the permeability simulation (Fig. 29D), absolute permeability was calculated using Aviso software on three CT scans. Fluid flow was simulated through the identified pore networks with the following parameters: data output from the Axis Connectivity module, pore space set to 1, directions along X, Y, and Z, input pressure at 130,000 Pa, output pressure at 100,000 Pa, and fluid viscosity at 0.001 Pa.s. These settings allowed us to quantify absolute permeability in micrometers squared and darcy across the three directions. Additionally, we obtained velocity and pressure outputs for each direction. The Magnitude module was used to compute scalar magnitudes from the velocity data, and the Illuminated Streamlines module visualized the permeable pathways in all three directions for each model.

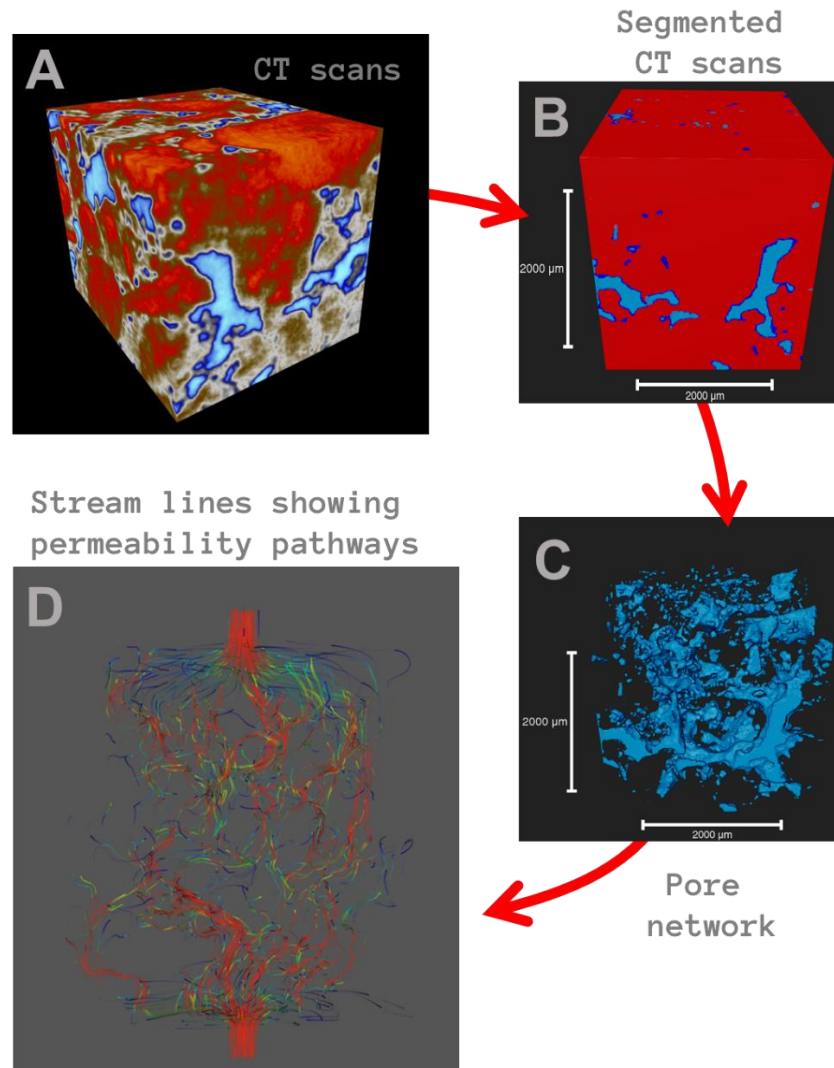


Figure 29. Screenshot showing the workflow of permeability simulation. (A) CT scan of the sample extracted from the burrow fillings, with different colors representing various rock texture components: reddish tones indicate grains, white and grey indicate the mud matrix, and blue illustrates pores. (B) Segmented volume showing two components: pores and matrix (including both mud matrix and grains). (C) Extracted pore volume. (D) Streamlines of fluid flow illustrating permeability pathways. Note that in the stream lines the warmer colors, such as red or orange, typically represent higher permeability, while cooler colors, like blue or green, indicate lower permeability.

4.3 Results

4.3.1 Estimating bulk permeability from spot permeability

The results of permeability measurements are documented in Table 5. The descriptive statistics of these measurements are provided in Table 6. Fig. 30 shows a bar diagram of the spot permeability of the burrow fillings and host rock matrix, ranked from largest to smallest. These data demonstrate substantial variability in the spot permeability of the burrow fillings, which ranges from 2.65 mD to 796.30 mD (arithmetic mean value = 87.27 ± 170.24 mD). In contrast, the host rock matrix shows less variability in spot permeability, with an arithmetic mean value of 1.42 ± 0.79 mD and a range from 0.26 mD to 4.73 mD. These data suggest a D-PorFFM system in the slabbed samples, as the difference between the mean value of the spot permeability of the burrow fillings and the mean value of the spot permeability of the host rock matrix is within one order of magnitude.

The 64 permeability measurements from both the burrow fillings and the host rock matrix produced different types of average values. The arithmetic mean was 44.34 mD, the geometric mean was 5.99 mD, and the harmonic mean was 2.02 mD. When looking at the burrow fillings alone, the arithmetic mean was 87.27 mD, the geometric mean was 28.53 mD, and the harmonic mean was 13.33 mD (Fig. 31). The boulder sample has a BP of approximately 15%, and the fluid flow within the slabbed sample is interpreted as a D-PorFFM system. According to the method by Baniak et al. (2013), the bulk permeability is best represented by the geometric mean of the spot permeability, which in this case is 5.99 mD.

Table 5. Permeability data measured using AutoScan system.

Rank of measurement	Permeability of the host rock matrix (mD)	Permeability of the burrow fillings (mD)
1	4.73	796.30
2	2.98	430.21
3	2.20	406.82
4	1.83	330.69
5	1.80	121.71
6	1.78	112.55
7	1.76	67.84
8	1.68	51.03
9	1.55	49.84
10	1.50	44.85
11	1.49	34.56
12	1.46	32.90
13	1.45	32.09
14	1.37	31.64
15	1.33	28.02
16	1.31	25.07
17	1.26	22.63
18	1.24	21.73
19	1.22	20.84
20	1.13	19.90
21	1.13	18.30
22	1.12	17.26
23	1.04	13.24
24	1.04	12.84
25	1.04	10.16
26	0.95	9.70
27	0.93	8.52
28	0.84	7.15
29	0.78	4.94
30	0.65	3.66
31	0.56	3.00
32	0.26	2.65

Table 6. Statistical parameters of the spot permeability measurements.

Statistics	Host rock matrix	Burrow fillings
No. of points	32	32
Minimum	0.26	2.65
Maximum	4.73	796.3
1st Quartile	1.04	12.17
Median	1.29	23.85
3rd Quartile	1.58	50.14
Mean	1.42	87.27
Variance (n-1)	0.62	28980.07
Standard deviation (n-1)	0.79	170.24

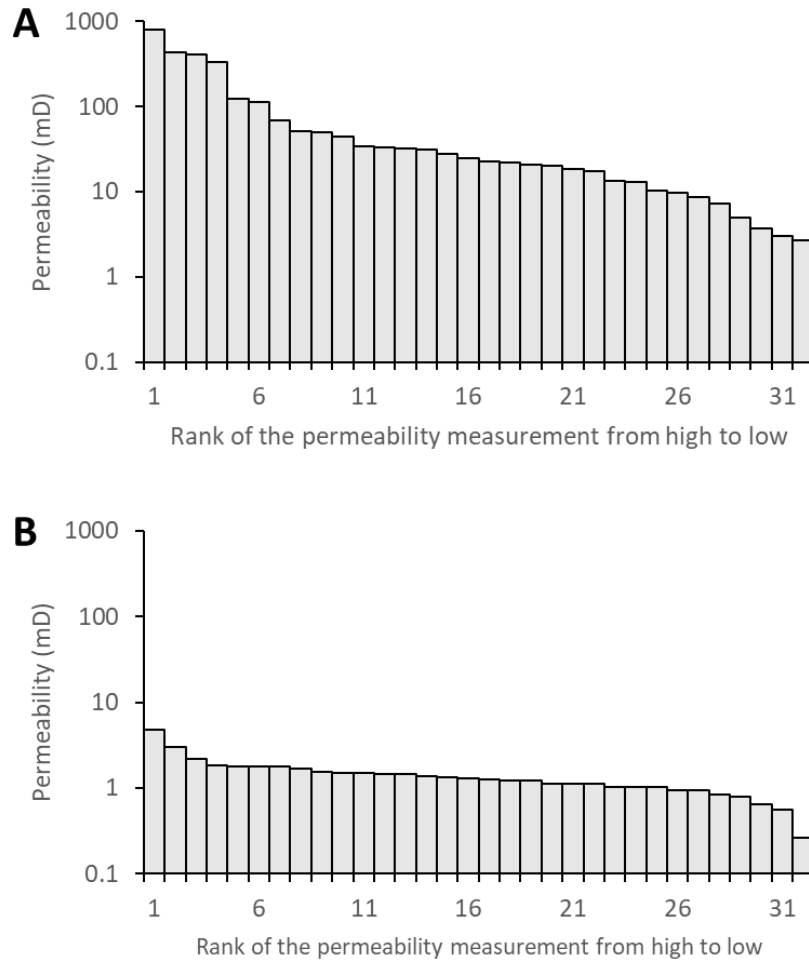


Figure 30. Bar diagram showing spot permeability measurement results in the burrow fillings (A) and the burrow matrix (B), with the data ranked from high to low along the x-axis. Note that permeability in the y-axis is in logarithmic scale.

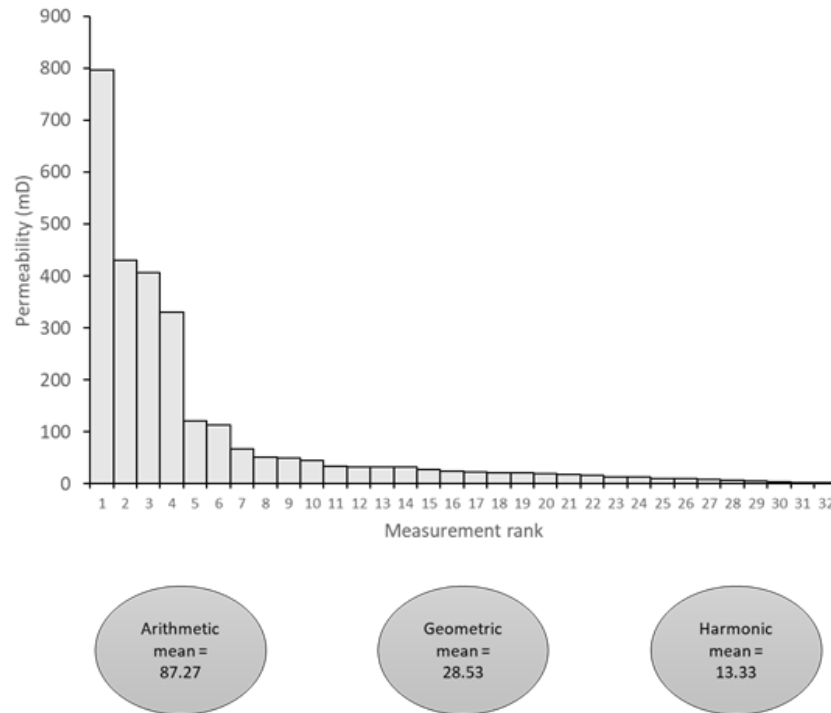


Figure 31. Bar diagram showing spot permeability measurement results in the burrow fillings, along with the calculated average permeability using three methods: arithmetic, geometric, and harmonic. Note that the permeability on the y-axis is displayed in a normal scale.

4.3.2 Rock composition and Pore system

Rock sample examination (Fig. 32A) and petrographic analysis (Fig. 32B) has highlighted the textural differences between the host rock matrix and the burrow fills, which appear to be the main factors influencing permeability variations in the bioturbated strata studied. The host rock matrix is mainly composed of mud with dispersed skeletal fragments, foraminifera, and sponge spicules (Fig. 32B). The foraminifera identified include benthic types. Skeletal remains are composed of echinoid pieces and costate brachiopods, with sponge spicules found in both monaxon and tetraxon forms. Additionally, bryozoan fragments are present. The pore system in the host rock matrix is predominantly moldic, with poor connectivity between pores.

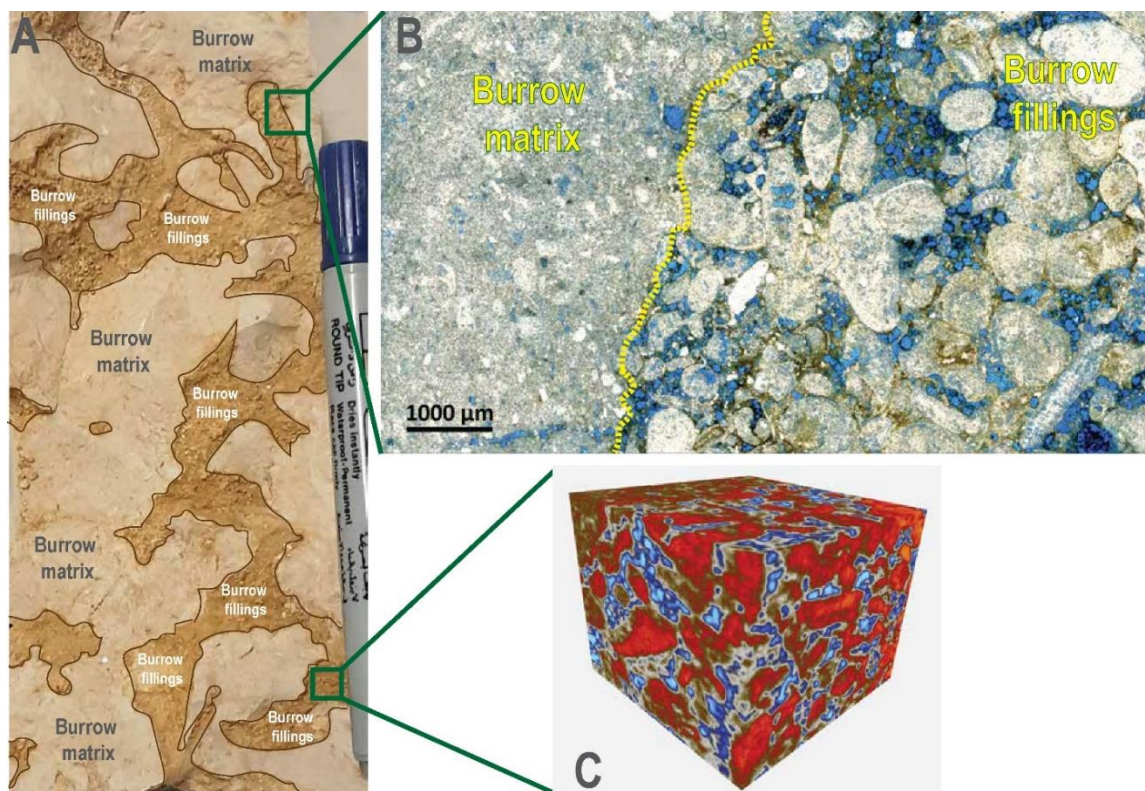


Figure 32. (A) Photograph, (B) thin-section photomicrograph, and (C) screenshot (~2.5 mm each side) of the studied rocks highlighting the textural differences between the host rock matrix and the burrow fills. Note the coarser-grained texture in the burrow fills compared to the finer-grained burrow matrix.

Conversely, the passive fillings are made up of carbonate grains, a mud matrix, and pores (Fig. 32B). The carbonate grains comprise skeletal fragments, coated grains, and peloids that are well-rounded and well-sorted. While most carbonate grains are less than 0.5 mm in size, a notable number exceed 2 mm. Occasionally, *Cladocoropsis* fragments are found within the *Thalassinoides* fills. The burrow matrix and fillings also contain benthic foraminifera. The mud matrix content ranges from 4% to 15%, while porosity in the burrow fillings varies from 5% to 10%.

Results of micro-CT scanning provided high-resolution 3D images of the burrow fillings at micron-scale resolution. This scanning technique allowed for the visualization and

quantification of the different components within the burrow fillings. The data supported the petrographic analysis, confirming that the burrow fillings contain three distinct components: grains, a mud matrix, and pores, each with distinct densities visible in the CT scan (Fig. 32B, C). An important piece of information obtained from the CT scan was the 3D visualization of the pore system within the burrow fillings, offering a detailed look at the spatial distribution and connectivity of the pores.

Segmentation of the CT scan (Figs. 32C, 33) into the three components provided data to quantify them. In the burrow fillings from the collected sample at interval 5, grains comprise 79.71% of the total rock volume, while the mud matrix and pores account for 7.75% and 12.54%, respectively.

4.3.3 Permeability simulation

Permeability simulation was performed on the segmented CT scan of the burrow fillings, which was divided into two binary components: the grains and mud matrix as one component (referred to as the matrix), and the pores as the other component (referred to as porosity) (Fig. 33). As expected, given the isolated nature of the pores in the burrow fillings, the simulation indicated no flow across the samples in all three directions (x, y, z), with no stream lines, suggesting zero permeability in these directions.

A substantial change occurred when the mud matrix volume was added to the pore system volume instead of being grouped with the grains (Fig. 34). In this case, the burrow fillings consisted of interparticle pores and grains, mimicking the grainstone version of the burrow fillings (Fig. 34A). Pore volume in this case is nearly 100% connected (Fig. 34B). When we repeated the simulation of the burrow filling cube of sample 5-1, streamlines connected

the opposite sides in the x, y, and z directions (Fig. 34C), and the simulated permeability was 16,320 mD, 20,150 mD, and 10,440 mD in these three directions, respectively.

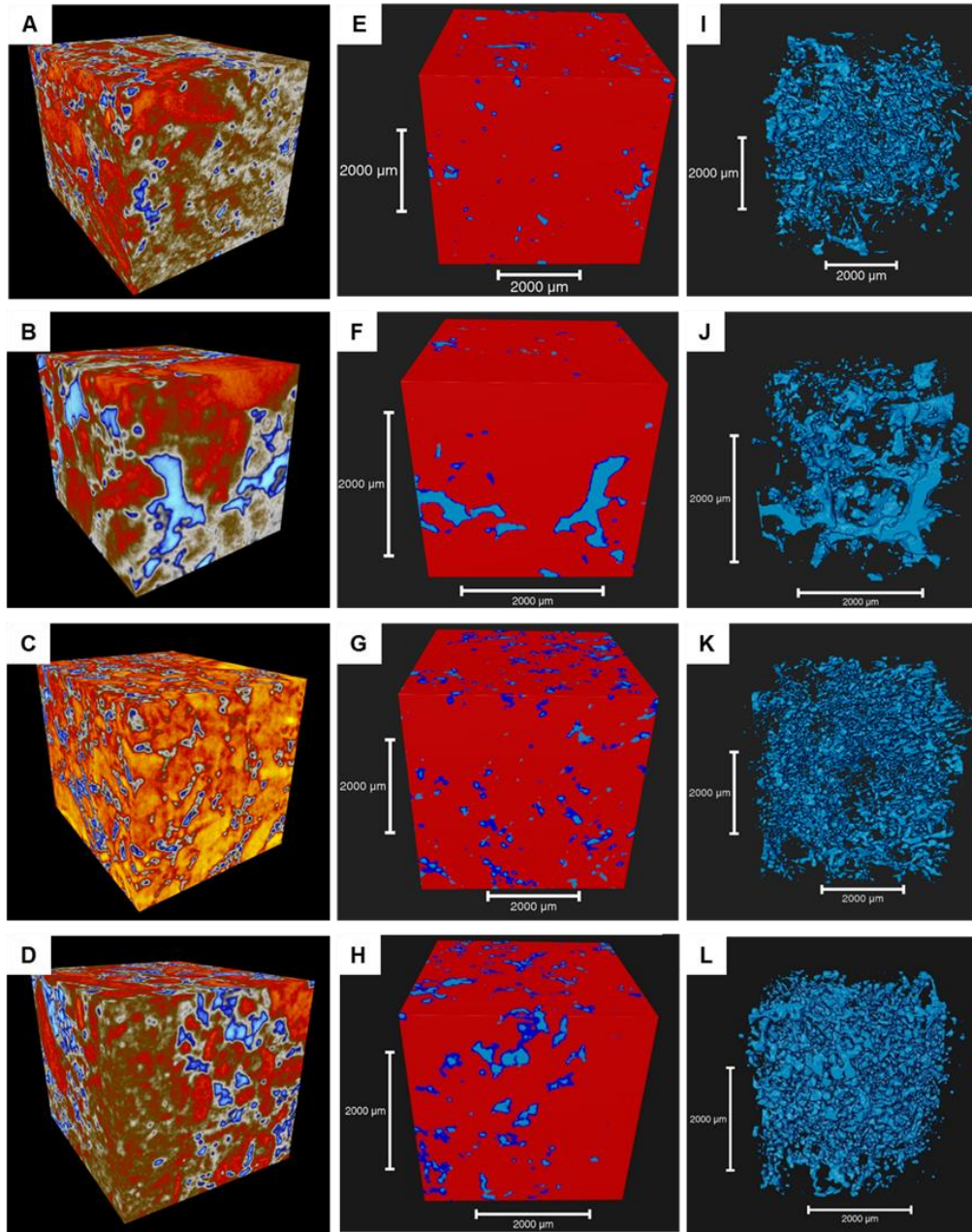


Figure 33. Screen captures of the CT scans (A-D), segmented CT scans (E-H), and pore network models (I-L) for micro samples extracted from burrow fillings 1-4, respectively. Each row in the figure includes three panels illustrating the same sample. Note that the pore network analysis indicates the absence of pore connectivity in all four samples.

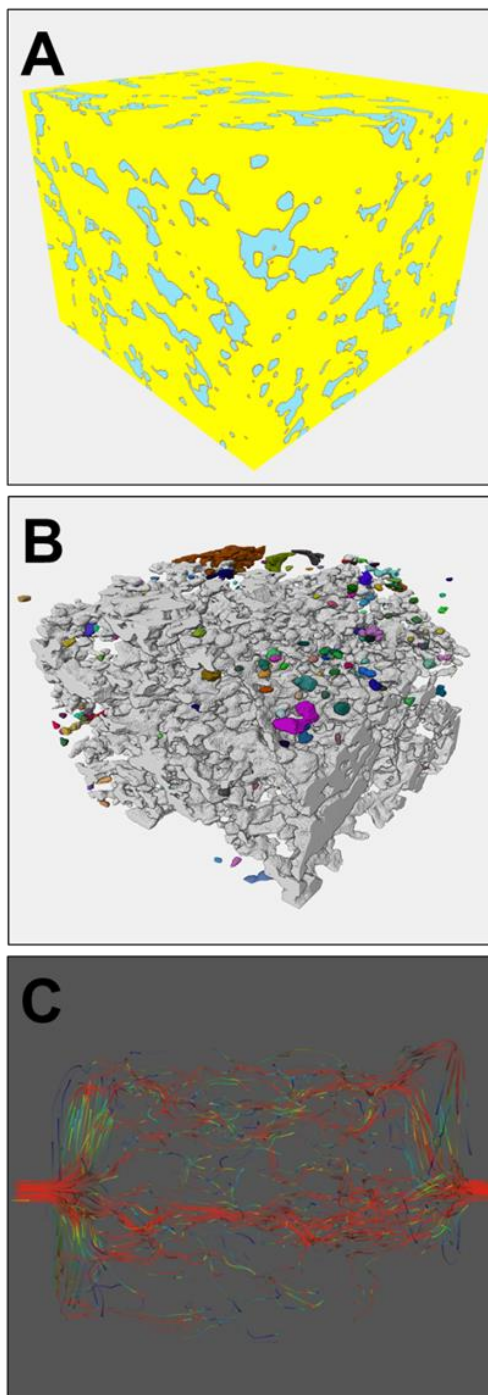


Figure 34. (A) Screen captures of segmented CT scans of sample 5-1 showing two components: the grains and the pore system after adding the mud matrix to the pore system, mimicking the grainstone version of the sample. (B) Screen capture of the pore system after filtering out the grains. (C) Streamlines of fluid flow in the grainstone version of sample 5-1, illustrating permeability pathways. Note that in the streamlines, warmer colors, such as red or orange, typically represent higher permeability, while cooler colors, like blue or green, indicate lower permeability.

4.4 Discussion

The main objective of this study was to address the question: do spot permeability measurements always reflect the bulk permeability of bioturbated reservoirs? To achieve this, we conducted spot permeability measurements (Figs. 30, 31), petrographic analysis (Fig. 32B), and digital rock modeling (Figs. 33, 34) on samples of bioturbated strata from the Hanifa Formation in central Saudi Arabia. While spot permeability and petrographic analysis suggest that the strata are permeable (Figs. 30, 31), the digital rock models provide a different perspective.

The spot measurements indicated substantially high permeability of burrow fillings compared to the host rock matrix (Figs. 30, 31). This variability suggests that burrow fillings, with their relatively higher permeability, could dominate fluid flow in bioturbated strata, thereby significantly enhancing the overall permeability of the formation. The calculated bulk permeability based on spot permeability using the geometric mean provided a more conservative estimate, aligning with previous contribution of the host rock matrix and the low value of the BP (Figs. 30, 31).

Petrographic analysis (Fig. 32B) explained the difference in spot permeability between the burrow fillings and host rock matrix. The host rock matrix, dominated by mud and characterized by isolated moldic pores, showed poor connectivity and, consequently, lower permeability. In contrast, the burrow fillings, rich in carbonate grains and with better-sorted peloids, suggested higher permeability due to their more connected pore systems.

Micro-CT scanning provided further insights (Figs. 33, 34), confirming the distinct densities and components within the burrow fillings. The 3D visualization of the pore system revealed a predominance of isolated pores (Fig. 33), which initially suggested low

permeability due to poor connectivity. This finding appeared to contradict the implications of the petrographic analysis and spot permeability measurements. The permeability simulations added another layer of complexity. When the burrow fillings were segmented into binary components (matrix and porosity), the simulations indicated no flow across the samples, suggesting zero permeability (Fig. 33). This result was consistent with the isolated nature of the pores observed in the CT scans.

However, a substantial change was observed when the mud matrix was included in the pore volume, mimicking a grainstone-like structure (Fig. 34). Under these conditions, the simulations showed significant permeability in all directions, with streamlines connecting opposite sides of the sample. This dramatic shift highlighted the importance of pore connectivity and spatial arrangement in determining permeability.

These findings present two contrasting views on permeability in bioturbated reservoirs. On one hand, spot permeability measurements and petrographic analysis suggest that burrow fillings enhance overall permeability due to their higher individual permeabilities and better pore connectivity. On the other hand, digital rock models indicate that permeability can be highly variable and dependent on the specific configuration of the pore system.

This contradiction underscores the complexity of predicting bulk permeability in bioturbated reservoirs. It suggests that while spot measurements provide valuable information about local permeability variations, they may not always accurately reflect the bulk permeability of the entire reservoir. Therefore, a comprehensive approach that integrates multiple methods, including petrographic analysis, spot measurements, and

digital modeling, is essential for a more accurate assessment of permeability in such heterogeneous systems.

4.5 Conclusion

This study highlights the significant limitations of spot permeability measurements in quantifying bulk permeability in bioturbated reservoirs. The complex and heterogeneous pore system of these reservoirs, characterized by high permeability contrasts between burrow fills and the host rock matrix, poses challenges in accurately assessing bulk permeability. Our analysis, integrating spot permeability measurements with digital rock physics, shows that while spot measurements provide valuable insight into local permeability variations, they often fail to capture the overall flow dynamics due to poor pore connectivity. The use of digital rock modeling and permeability simulations revealed that the arrangement and connectivity of pores are critical to determining bulk permeability. These findings underscore the necessity of a multi-faceted approach, combining spot permeability measurements with advanced modeling techniques, to obtain more accurate estimates of bulk permeability in such complex reservoirs.

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CHAPTER 5

CONCLUSION

This study integrates petrographic analysis, CT scanning, and digital rock physics modeling to examine the porosity evolution in bioturbated intervals of the upper Hanifa Formation, central Saudi Arabia, particularly in relation to *Glossifungites* ichnofacies. Key findings reveal that burrowing style and depositional texture are pivotal in influencing grain size distribution and shape, forming the foundation of the initial depositional framework. Diagenetic alterations, such as dolomitization, compaction, and dissolution, substantially modify the original rock characteristics, impacting the porosity and pore system. Intervals with a pipe-framework burrowing style exhibit higher porosity compared to bio-retextured intervals, while mud-rich packstones that undergo dolomitization retain porosity by resisting compaction. In contrast, mud-poor packstones exhibit significant porosity loss due to compaction, though subsequent dolomite dissolution can increase interparticle porosity, potentially transforming initially poor reservoirs into highly porous ones.

Backstripping of digital rock samples quantified the effects of sedimentological and diagenetic processes on porosity and permeability, highlighting two major influences on grainstone: the addition/removal of mud matrix and grain compaction. Compacted grain-dominated BF have limited potential for porosity and permeability recovery, whereas open fabric BF exhibit significantly enhanced porosity and permeability due to late-stage dolomite dissolution. For example, models of open fabric BF reveal high porosity and

permeability (20.29% and 5531.51 mD, respectively) in the grainstone scenario. Even mud-rich packstone with open fabric BF can form permeable pathways within the burrow network. This study also shows that open fabric BF can recover permeability through preferential dolomitization and dissolution, with backstripping models providing insights into the dynamic evolution of porosity and permeability over geological time, thereby enhancing predictions of reservoir quality.

Additionally, the study addresses the limitations of spot permeability measurements in accurately assessing bulk permeability in bioturbated reservoirs. Due to high permeability contrasts between burrow fills and host matrix, spot measurements may fail to capture overall flow dynamics. By integrating spot measurements with digital rock modeling and permeability simulations, the study highlights that pore arrangement and connectivity are critical to bulk permeability. This comprehensive approach underscores the need for advanced modeling techniques combined with spot measurements to achieve accurate bulk permeability estimates in such heterogeneous reservoirs.

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