

An Integrated Study to Characterize and Model Strata with Biogenically Influenced Flow Media in the Aruma Formation, Central Saudi Arabia

BY

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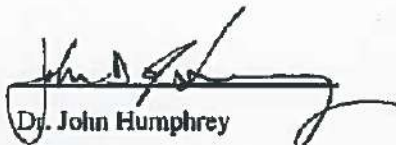
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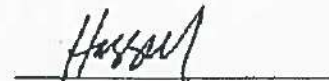
This thesis, written by **Nabil Ali Ali Saraih** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **DOCTOR OF PHILOSOPHY IN GEOLOGY**

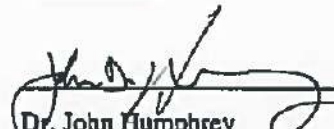

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This thesis is humbly dedicated to the memory of my father, who passed when I was a child. His hope to see me in a good place has been a guiding star in my journey.

To my mother, whose endless prayers and pride have been my steadfast support and encouragement. Her faith in me has been the bedrock of my journey.

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Contents

ACKNOWLEDGMENTS.....	V
LIST OF TABLES.....	XI
LIST OF FIGURES	XII
ABSTRACT	XIX
ملخص الرسالة.....	XXI
1 CHAPTER 1 INRODUCATION	1
1.1. INTRODUCTION	1
1.1.1. Problem statement.....	2
1.1.2. Objectives.....	4
1.2. STUDY AREA AND GEOLOGICAL BACKGROUND OF THE ARUMA FORMATION	4
1.2.1. Contacts, lithology and Stratigraphy.....	4
1.2.2. Age	7
1.2.3. Paleogeography setting of the Aruma Formation	9
1.2.4. Study Area	9
1.3. METHODS.....	10
1.3.1. Sedimentological, ichnologic, and stratigraphic description	10
1.3.2. Burrow morphology.....	11
CHAPTER 2 BIOTURBATED STRATA IN THE UPPER CRETACEOUS ARUMA FORMATION, CENTRAL SAUDI ARABIA: AN ANALOG FOR AQUIFERS AND HYDROCARBON RESERVOIRS WITH LARGE BURROWS.....	12

ABSTRACT	12
2.1. INTRODUCTION	13
2.2. GEOLOGICAL BACKGROUND.....	15
2.3. METHODS.....	17
2.4. RESULTS	18
2.4.1. Sedimentology and stratigraphy	18
2.4.2. Biogenically influenced fluid flow media in the Khanasir Member of the Aruma Formation...	26
2.5. DISCUSSION	35
2.5.1. Depositional Environment	35
2.5.2. Impact of the <i>Thalassinoides</i> on fluid flow and storage capacity	37
2.5.3. Implications	39
2.5.4. Future Considerations.....	45
2.6. CONCLUSIONS.....	46
CHAPTER 3 CONTROLS ON FRACTURE PROPAGATION IN BIOTURBATED CARBONATE ROCKS: INSIGHTS FROM THE ARUMA FORMATION, CENTRAL SAUDI ARABIA.....	48
ABSTRACT	48
3.1. INTRODUCTION	49
3.2. GEOLOGICAL BACKGROUND.....	51
3.2.1. Stratigraphy.....	51
3.2.2. Lithological Units	53
3.2.3. Study area	55

3.3. METHODOLOGY	56
3.4. RESULTS	58
3.4.1. Fracture System at Outcrop Scale and CT-scan Scale	58
3.4.2. Fracture System at Microscopic Scale	67
3.5. DISCUSSION	70
3.5.1. Impact of Bioturbation on the Fracture Characteristics	72
3.5.2. Conceptual model.....	85
3.5.3. Implications	86
3.6. CONCLUSIONS.....	89
 CHAPTER 4 CHARACTERIZING THE ATTRIBUTES OF LARGE BURROWS IN THE UPPER CRETACEOUS ARUMA FORMATION: INSIGHTS FROM GROUND PENETRATING RADAR	 91
ABSTRACT	91
4.1. INTRODUCTION	92
4.2. GEOLOGICAL SETTING AND STUDY AREA	94
4.3. METHODOLOGY	97
4.3.1. Characterization of burrow attributes	97
4.3.2. GPR data acquisition.....	98
4.3.3. 3D block construction	101
4.4. RESULTS AND DISCUSSION	103
4.4.1. Burrow morphology.....	103
4.4.2. Burrow diameter	105
4.4.3. Burrow percentage	106

4.4.4. Comparative analysis of burrow attributes	110
4.4.5. Advantages of GPR in studying trace fossils	115
4.4.6. Implications	116
4.5. CONCLUSIONS.....	116
CHAPTER 5 CONCLUSIONS.....	118
CONCLUSIONS.....	118
REFERENCES	120
VITAE.....	144

LIST OF TABLES

Table 2.1: The XRD and XRF results of the host rock matrix and burrow filling of the Khanasir Member. Note that samples from 1 to 23 represents the analysis of the host rock matrix of biologically influenced fluid flow media 1 (BIFM1) (unit 1 and subunit 2B), samples from 24-26 represent the composition of the host rock matrix of subunit 2A, samples from 27 to 29 represent the composition of the burrow filling of subunit 2A, and samples from 30 to 36 represent the composition of the host rock matrix of unit 3.	37
Table 2.2: Porosity and permeability measurements of 28 cores of the biologically influenced fluid flow media 1 and 3 (BIFM1 and 3) matrix, as well as the burrow fills and matrix of BIFM2, and unit 3 which is referred to as NO-BIFM since it does not exhibit the same bioturbation as the underlining units 1 and 2.....	38
Table 4. 1: The results of ANOVA with post hoc and Bonferroni correction to evaluate the burrow percentage difference across X, Y, and Z-axis of the Ct-scan and GPR data.	109

LIST OF FIGURES

Figure 1.1: The Aruma Formation lithostratigraphic section from the Al Kharj section (Philip et al., 2002).	6
Figure 1.2: Correlation between the Aruma Formation outcrops (reference).	8
Figure 2.1: Location, stratigraphy, and sedimentology of the Aruma Formation. (A) Outcrop distribution of the Aruma Formation and study area (red square). (B) Stratigraphy and lithology of the Aruma formation (after Philip et al., 2002), red square shows focus of the this study.....	15
Figure 2.2: Measured section of the Aruma Formation in the study area showing three distinct stratigraphic units.	19
Figure 2.3: Outcrop photographs and image analysis showing open burrows in unit 1. (A) Ubiquitous open burrows in unit 1. Burrow size can reach up to 7.5 cm in diameter. (B) Close up view of the burrows showing open shafts and percentage. (C) Example of an image analysis to show the burrow percentage of 41%.	21
Figure 2.4: Results of representative XRD analyses of the matrix and burrow fillings of the Khanasir Member (unit 1 to unit 3). (A) Matrix of unit 1. (B) Burrow filling of unit 1 and subunit 2B. (C) Matrix of subunit 2A (D) Burrow filling of subunit 2A (E) Lower interval of unit 3. (F) Upper interval of unit 3.21.	22
Figure 2.5: Outcrop photographs showing (A) Circular burrow cross sections. (B) Elliptical burrow cross section. (C) Cross section of solution-enlarged elliptical burrow. (D) Oblique shaft intersecting the lower tunnel. (E) Rhizolith. (F) Laminated crust. The yellow arrow points to the features in the figure captions.	24
Figure 2.6: Rendering of the same core sample with varying views of a vertical and horizontal slice. (A-F) CT scan data show diagnostic criteria for <i>Thalassinoides</i> including: vertical (yellow arrow) and horizontal (white arrow) tunnel; angles of shaft connection (blue arrow); intersections between shafts and tunnels (green arrow); and boxwork of the <i>Thalassinoides</i> (white box). The burrows could be partially filled with sediment, as shown in fig. B, or the infill has been partially exhumed, as shown in fig. C. The core diameter is 10-inch.....	25
Figure 2.7: Burrow diameter measurements of Units 1 and 2. (A) Burrow diameter in subunit 1A. (B) Burrow diameter in subunit 1B. (C) Burrow diameter in subunit 2A, vertical face. (D) Burrow diameter in subunit 2A, horizontal face. . (E) Average diameter in subunit 2A. (F) Burrow diameter in subunit 2B. Figure A, B, and F are super-K subunits. The burrow diameter in subunit 1A is slightly higher than the other subunits. Fig. 7A and 7B represent BIFM1; Fig. 7C-E represent BIFM2; and Fig. 7F represents BIFM1.....	27

- Figure 2.8:** Outcrop photographs showing karst features in the Khanasir Member. Features include: (A) sinkholes with collapse boulders; (B) sinkholes with collapse breccia. (C) caves (white arrow). (D) sinking streams. In the Khanasir Member, these karst features offer flow pathways in addition to the burrows, and reflect modification of the burrows during subaerial exposure and karstification.28
- Figure 2.9:** Thin section images of faunal content in unit 1A. (A-D) Dasycladacean green algae (E-F) Planktonic foraminifera (G) Large benthic foraminifera (H) Miliolids (I) Rotalina (I-J) Planktonic foraminifera (K) Bryozoans (L) Transverse section of gastropod. The scale bar (green rectangular) is 200 millimicron.29
- Figure 2.10:** Thin section images of faunal content in unit 1B. (A) Large benthic foraminifera (B) Miliolids (C-D) Rotalina (E-H) Planktonic Foraminifera (I-J) Dasycladacean green algal (K) Echinoderms (L) Bryozoans. The scale bar (green rectangular) is 200 millimicron.30
- Figure 2.11:** Outcrop photographs of unit 2B and image analysis. (A) Field photo showing relation between units 2A and 2B; (B) vertical face of unit 2B; (C) image analysis of Plane C showing the burrow percentage; (D) top of horizontal face in unit 2B showing large and open burrows; (E) image analysis of Plane D showing the burrow percentage.33
- Figure 2.12:** Thin section images of benthic and large benthic foraminifera in unit 2B. (A) Benthic foraminifera (B-C) Large benthic foraminifera. The scale bar (green rectangular) is 500 millimicron.34
- Figure 2.13:** Photographs of a slabbed surface and thin section images of both burrow filling and host rock matrix from unit 2A. (A) Slabbed surface which exhibits both the burrow fills and the matrix; the white color is burrow filling and the gray color is host rock matrix. (B) Elemental maps for the same slabbed surface shows the variation in chemical composition, where the green color (red arrow) represents the matrix, and blue color (yellow arrow) indicates the burrow. (C) Thin section showing micritic burrow filling (upper section) and dolomite matrix (lower section). Note that most of the dolomitization occurred in the host rock matrix, whereas the dolomitization did not fully dolomitize the burrow fillings, except for a few isolated dolomite crystals. (D) Thin section of nodular limestone (burrow filling) containing dasycladacean algae (red arrow), planktonic foraminifera (yellow arrow). (E) Dolomitized matrix. (F) Close up view of the dolomite which shows zonation (red arrow points to clay minerals).34
- Figure 2.14:** Outcrop photographs of unit 2A and image analysis. (A) Cross section view of the nodular limestone (burrow filling) and dolomite (matrix). (B) Bedding plane view of the nodular limestone (burrow filling) and dolomite (matrix) with noticeable decrease of burrow-matrix ratio (B/M) compared to Fig. 2.14D. (C) Vertical cross section view of the nodular limestone (burrow filling) and dolomite (matrix) with a noticeable increase of B/M compared with Fig. 2.14F. (D) Bedding plane view of the nodular limestone (burrow filling) and dolomite (matrix) with noticeable

increase of B/M compared to Fig. 2.14B (red arrow points to the matrix). (E) Image analysis of plane E shows an example of the burrow percentage of subunit 2A. (F) Vertical cross section view of the nodular limestone (burrow filling) and dolomite (matrix) with a noticeable decrease of B/M compared to Fig. 14C (black arrow points to the burrow filling). (G) Image analysis of plane G shows an example of the burrow percentage of subunit 2A. Variation in B/M is related to the bioturbation percentage and compaction.40

Figure 2.15: Screen captures of the CT scan data of: (A) Irregular-shaped sample, where the orange color represents the matrix, and blue color indicates the burrow; and (B-C) rectangular-shaped sample. The CT scan results show diagnostic criteria for the *Thalassinoides* including: vertical shafts (yellow arrow) and horizontal tunnels (white arrow); and boxwork of the *Thalassinoides* (white box).41

Figure 2.16: Outcrop photographs showing karst features in the Khanasir Member in subunit 2A. Features include (A) Caves; (B) Sinkhole; and (C) Discontinuous semi-vertical solution-enlarged fractures (yellow arrows). In subunit 2A, these karst features and fractures are features of fluid flow pathways.42

Figure 2.17: Thin section images from the upper unit of the Khanasir Member (unit 3). (A) Dolomite crystals showing zonation. (B) Thin section photomicrograph showing dolomite with high porosity (blue epoxy). (C) Ostracods. (D) Dasycladacean algae. (E-F) Benthic Foraminifera. The scale bar (green rectangular) is 200 millimicron.43

Figure 2.18: Nonfabric and fabric selective porosity of the rock matrix of unit 1 and unit 2. (A1-A2) Channel porosity. (B1-B) Vug porosity. (C1-D2) Moldic porosity. (E1-E2) Shelter porosity. (F1-F2) Intercrystal porosity.44

Figure 3.1: Outcrop distribution and stratigraphy of the Aruma Formation (A) The exposed outcrops map of the Aruma Formation and the location of the study area (red square) (B) Stratigraphy of the Aruma formation; the red square points to the studied interval.52

Figure 3.2: Measured section of the Khanasir Member in the study area showing sedimentological characteristics, mineralogical composition, burrow percentage, and fracture classification.57

Figure 3.3: Unit 1 outcrop images depict bedding and vertical faces along with corresponding fracture analyses. (A, C, E, G) showcase various views of the outcrop. (B, D, F, H) provide fracture analyses for images A, C, E, and G, respectively. Notably, Figures 3A and 3G exhibit a higher density of fractures associated with elongated, irregularly shaped burrows affected by dissolution, in contrast to the more circular burrows seen in Figure 3C. Additionally, Figure 3E emphasizes the variability of fractures on the vertical plane, influenced by the orientation and morphology of the burrows. PL stands for Planar fractures, CO for Contorted fractures, and AN for Anastomosing fractures.60

- Figure 3.4:** Statistical analysis of fracture density, spacing, and length (A) Fracture density. (B) Fracture spacing. (C) Fracture length. 61
- Figure 3.5:** Fracture orientation and apparent dip for all the units. (A-B) Fracture orientation and apparent dip of unit 1. (C-D) Fracture orientation and dip of the lower part of subunit 2A. (E-F) Fracture orientation and apparent dip of the upper part of subunit 2A. (G-H) Fracture orientation and apparent dip of subunit 2B. (I-J) Fracture orientation and apparent dip of unit 3. 63
- Figure 3.6:** Outcrop and slabbed sample photographs displaying variations in fracture length and filling. (A) Outcrop photograph showcasing intense bioturbation and open fractures (blue arrow) and filled fractures (red arrow). (B) Outcrop photograph displaying a fracture (yellow arrow) exceeding a meter in length, in contrast to the typical fractures in this unit, which typically have an average of less than 5 cm. (C) Photograph of a core, which exhibits small fracture propagation between the burrow pores (blue arrow). (D) Slabbed surface of a filled fracture (green arrow), filled with pedogenic material. 64
- Figure 3.7:** Outcrop and core samples from Subunit 2A provide insight into the scale of fractures. (A) Reveals a large-scale fracture intersecting Subunits 2A and 2B. (B) Shows a small-scale fracture affecting both the burrow fillings and the host matrix in Subunit 2A. (C) Offers a detailed view of very small-scale fractures; note the fractures within the burrow fillings (indicated by red arrows) and at the contacts between burrow fillings and the host rock matrix (indicated by a blue arrow). (D-E) Core samples illustrate fractures predominantly within the burrow fillings, noting that the gray color represents the matrix and the white color represents the burrow fillings. (H) A core sample exhibits fractures at the interface between burrow fillings and the host rock matrix. 67
- Figure 3.8:** (A) An outcrop photograph of Subunit 2A displaying the variability of fracture density in relation to the brittleness (B) and ductility (D) of both the burrow fillings (BF) and the host rock matrix (M), as well as the burrow percentage. Notably, areas with a higher percentage of burrows tend to have increased fracture densities, where the burrows show greater brittleness. (B) This is a fracture analysis of the photograph shown in Fig. 3.8A. 69
- Figure 3.9:** Fractures in the upper part of Subunit 2A. (A) Displays a photograph of the upper part of Subunit 2A. (B) A thin section from the lower part of Subunit 2A reveals a significantly higher concentration of palygorskite compared to the upper matrix of Subunit 2A, as shown in (D). (C) Offers a fracture analysis of the photograph in (A). (D) Presents a thin section from the upper part of Subunit 2A, highlighting a lower presence of palygorskite relative to the lower part, as depicted in (B). 71
- Figure 3.10:** Field sample and its CT scan result: (A) Irregular-shaped. sample showing fracture within the burrow fillings (white arrow), fracture on the interface between the host rock and the burrow filling (orange arrow), and the host rock matrix (red arrow). (B-D) Screen captures of the CT scan data showing the fractures from a sample of

subunit 2A. In the CT scan data, the yellow color indicates the matrix, while the blue represents the burrow fillings.	73
Figure 3.11: Outcrop photographs in subunit 2B, alongside corresponding fractures. (A, C) Photographs of subunit 2B. (B, D) Fracture analysis of the photographs in A, and C respectively.....	75
Figure 3.12: Outcrop photographs in unit 3 from bedding and vertical faces, alongside corresponding fracture traces. (A, C) Photographs from a horizontal face. (B, D) Fracture analysis of the photographs in A, respectively. (E_F) Photographs from a vertical face.	77
Figure 3.13: Thin section photomicrographs of the host rock matrix of unit 1 and subunit 2B reveal the rock textures and associated micro-fractures. (A) Wackestone with a planar [P] to sub-planar fracture. In all photomicrographs, the blue arrow indicates a partially filled fracture, and the green arrow highlights an open fracture. (B) A close-up view of the panel in Figure 12A, showing the partially filled fracture. (C) Fully filled planar fractures. In all photomicrographs, the red arrow points to fully mineralized fracture (D) Open contorted [C] fracture. (E) Fully and partially filled contorted fractures. (F) A close-up view of the panel in Figure 7E, demonstrating the partially filled contorted fracture in its vertical segment and partially filled in its horizontal segment. (G-H) Fully mineralized anastomosing fractures [A]. Note the branches of the fractures. (I-J) Fully mineralized planar fractures intersecting. It is important to note that fracture 1 is older than fracture 2. PL: Planar fractures, CO: Contorted fractures, AN: Anastomosing fractures.	78
Figure 3.14: Thin-section photomicrographs of the burrow fillings and the host rock matrix revealing the rock texture and associated micro-fractures of subunit 2A. (A) Burrow filling exhibiting a wackestone texture and fully mineralized contorted fractures. The red arrow points to fully mineralized fracture (B) Fully mineralized contorted-anastomosing fracture. Notably, this fracture appears as a contorted fracture [C] the yellow square and as an anastomosing fracture [A] in blue square, highlighting the complexity of this fracture. The red arrow points to fully mineralized fracture. (C) Open planar to sub-planar fractures in the partially dolomitized limestone burrow fillings. The green arrow points to an open fracture. (D) Open planar fractures in the dolomitized host rock matrix, resulting in the formation of fracture porosity. The green arrow points to an open fracture. PL: Planar fractures, CO: Contorted fractures, AN: Anastomosing fractures. PL: Planar fractures, CO: Contorted fractures, AN: Anastomosing fractures.	80
Figure 3.15: Thin section photomicrographs of unit 3. (A-B) Partially dolomitized limestone featuring open anastomosing fractures [A]. Yellow arrows point to the anastomosing fractures [A]. (C) Dolomite with mimetically replaced allochem. Observe the notable high porosity. AN: Anastomosing fractures.	81
Figure 3.16: Conceptual model of fracture formation. (A) Fractures that occur with an open burrow. (B) Fractures that occur in association with a filled burrow.....	84

- Figure 4.1:** Overview and detailed views of the Aruma Formation outcrops. (A) Map depicting the exposed outcrops of the Aruma Formation with the study area marked by a red square. Inset shows location (red square) of the detailed map. (B) Close-up photograph of Subunit 1A, where the GPR survey was carried out. Note that the burrows are mostly open. (C) Hand specimen from subunit 1A. This sample then analyzed using a medical CT.....95
- Figure 4.2:** Field sampling and challenges. (A) Hand specimen used for CT-scan, collected from Subunit 1A, shows open and partially filled burrows. (B) Field photograph depicting the attempt to obtain a core sample from Subunit 2A, this attempt failed due to the large burrow size and fracturing.....97
- Figure 4.3:** The wooden board utilized as a stable platform during the GPR survey to ensure consistent data recording.....98
- Figure 4.4:** Data processing filters applied to GPR survey (A) Raw data. (B) Subtracting average (dewow). (C) Background removal. (D) Energy decay (E) Bandpass butterworth. (F) Manual gain.....99
- Figure 4.5:** Comparison of raw and resampled GPR Data. (A) Raw GPR data, profile # 1, composed of 722 traces. (B) The same profile after resampling, updated number of traces is 101.....102
- Figure 4.6:** GPR data visualization for Subunit 1A. (A) A 2D slices from horizontal and vertical direction, highlighting vertical shafts (red arrows), horizontal tunnels (yellow arrows), oblique shafts (white arrow) and a range of burrow shapes such as U, V, and boxwork pattern (white square). (B) 3D cube of the GPR data showing the same features in the Fig. 4.6A. note that some areas were subjected to solution enlargement (red square). Some of these burrows form “circular” complete burrow systems (orange arrow). The grey color indicates the matrix while the blue/purple indicates the burrow.105
- Figure 4.7:** CT Scan captures of bioturbated samples from Subunit 1A .(A) CT scan snapshots of the hand specimen illustrating vertical burrow shafts (yellow arrows) and horizontal tunnels (white arrows). (B-C) CT images of the rectangular sample displaying burrows with circular to elliptical shapes. Blue color indicates the burrows, whereas orange color indicates the surrounding matrix.....108
- Figure 4.8:** Field photographs and analysis of Subunit 1A. (A, D) Showcasing varying field photographs from the vicinity of the GPR survey site. (B, E) Illustrate the analysis of burrow diameters corresponding to the photographs in A, D. (C, F) Displaying the percentage of burrows as observed in the field photographs A, D.....110
- Figure 4.9:** Box and whiskers plot of the burrow diameter measurements obtained from field photographs, CT scans, and GPR data.112
- Figure 4.10:** Cross-plots showing variations in burrow percentage, as derived from 2D slices (in different orientations: X, Y, and Z) of the CT –scan hand specimen sample and

2D slices from the GPR data. (A) The burrow percentage derived from GPR data, and it exhibits fluctuations around a mean value of approximately 18% (grey line), most values fall within the standard deviation, approximately 6.0% (green lines). The 2D slices on the X and Y-axis are arranged at 10 cm intervals, but the 2D slices on the Z-axis are arranged at 5 cm intervals, sequenced in descending order from the top to the bottom slice. (B) The burrow percentage is calculated from CT scan, and it exhibits fluctuations around a mean value of approximately 13% (grey line), most values fall within the standard deviation, approximately 5.0% (green lines). 113

Figure 4.11: Box and whiskers plot of the burrow percentage measurements obtained..... 114

ABSTRACT

Full Name : [Nabil Ali Ali Saraih]

Thesis Title : [An Integrated Study to Characterize and Model Strata with
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The Upper Cretaceous Khanasir Member of the Aruma Formation in central Saudi Arabia comprises bioturbated strata that can serve as analogs to carbonate reservoirs with large (up to 8-cm diameter) burrows. These strata offer valuable data that are difficult to obtain via conventional subsurface methods such as seismic, well logs, or cores, thus facilitating the exploration of poorly understood aspects of geo-energy storage and flow in such carbonate strata. This dissertation aimed to: 1) investigate the stratigraphic, ichnologic, and sedimentologic controls on burrow attributes (morphology, size, filling, and percentage); 2) explore how utilizing ground-penetrating radar (GPR) can provide high-resolution images to overcome the limitations associated with imaging and sampling large burrows; and 3) explore the impact of large burrows on the distribution and characteristics of natural fractures. A comprehensive approach combining field investigations, laboratory analyses (including petrography, geochemistry, petrophysical measurements, and CT scanning), field photograph analysis, and GPR surveys have been employed to achieve these objectives.

The results revealed three characteristics of burrows - either open, compacted and open, or filled with carbonate sediments. Each case represents unique fluid flow media with different

stratigraphic, ichnologic, and sedimentologic controls. Processed GPR data provide information on burrow attributes (mainly the morphology, size, and percentage) that cannot be obtained from CT scans or outcrop photographs, overcoming the limitation of the representation of the burrow attributes in 2D views and 3D laboratory volumes of rocks (hand specimens). Fracture characteristics were influenced by factors including burrow fillings, matrix mineralogy, and burrow percentage, underscoring the impact of bioturbation on fracture networks.

This research provides insight into how burrows with large diameters can influence storage and flow capacity of sedimentary strata. It also provides clues on what controls the distribution of such burrows and their impact, as well as how to overcome the limitation of imaging such large burrows using GPR surveys.

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التخصص : [جيولوجي]

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ينكشف عضو الخناصر (Khanasir Member) من تكوين العرمة (Aruma Formation), ذو العصر الطباشيري العلوي في وسط المملكة العربية السعودية, ويحتوي على طبقات مضطربة حيويًا (bioturbated strata), والتي تمثل نموذجًا ومثالًا للصخور الكربونية المضطربة حيويًا والتي تتميز بالثقوب الكبيرة (large burrow) المتواجدة تحت السطح والتي قد تصل اقطارها الى 8 سم. مثل هذه الطبقات توفر لنا معلومات لم يكن بالإمكان الحصول عليها من المعلومات تحت سطحية مثل الزلزالية (Seismic) واللباب الحفري (core plug) وتتيح لنا فرصة الإجابة واستكشاف بعض المواضيع التي لم تتناول بشكل كافٍ في مجال القدرات التخزينية والتدفقية لهذه الطبقات. هذه الرسالة تهدف الى: (1) دارسه تأثير الخصائص الطباقية (stratigraphic), الأثرية الحفرية (ichnological), والرسوبية على خصائص الثقوب (burrow attributes) مثل الشكل (morphology), الحجم (size), نوع الرواسب المملوءة داخل للثقوب (burrow fillings), ونسبة الثقوب (burrow percentage) في مثل هذه الطبقات المضطربة حيويًا; (2) استكشاف كيفية استخدام تقنية رادار الاختراق الأرضي (ground penetration radar) لتزودنا بمعلومات وصورة ذات دقة عالية للتغلب على الصعوبات والقيود المرتبطة بصعوبة التصوير المقطعي (computed tomography) واخذ عينات للثقوب الكبيرة; (3) استكشاف تأثير الثقوب الكبيرة على خصائص الكسور الطبيعية (natural fracture characterization) وتوزيعها. لتحقيق هذه الأهداف, تم عمل مزيج من الزيارات والملاحظات الحقلية والدراسات المختبرية (بما في ذلك البتروغرافيا, التقييمات الجيوكيميائية, قياسات الخواص الفيزيائية الصخرية, والتصوير بالأشعة المقطعية, تحليل الصور المؤخذة من المكشف الصخري, وعمل المسوحات باستخدام رادار الأرض الاختراقي .

اضطرت نتائج هذه الدراسة عن ثلاث خصائص للثقوب (burrow) - إما مفتوحة، ومضغوطة ومفتوحة، أو مملوءة برواسب الكربونات. وفي كل حالة، فهي تمثل وسط ذو خصائص فريدة من ناحية تدفق السوائل خلالها وتتميز كل حالة بعوامل طباقية وحفرية اثريه ورسوبية مختلفة تتحكم بها. بالنسبة للبيانات الناتجة من معالجة بيانات الرادار الأرضي الاختراقي لخصائص الثقوب مثل الشكل، الحجم، ونسبتها، قد قدمت نتائج صعب الحصول عليها من الأشعة المقطعية أو الصور الفوتوغرافية للكاشف الصخرية متغلبا على القيود والصعوبات في عرض شبكات الثقوب بشكل ثنائي الأبعاد أو عرض ثلاثي الأبعاد للثقوب بالعينات اليدوية بالمختبر. اما بالنسبة للكسور الطبيعية فان خصائصها تتأثر بعوامل مثل نوع الرواسب المملوءة داخل للثقوب (burrow fillings)، تكوين الصخور المستضيفة (matrix composition)، نسبة الثقوب (burrow percentage)، مؤكدا تأثير الاضطراب الحيوي (bioturbation) على خصائص الكسور. وبالتالي فان هذه الدراسة قدمت رؤية حول كيف يمكن أن تؤثر الثقوب ذات الأقطار الكبيرة على القدرة التخزينية والتدفقية. كما تقدم دلائل حول ما يتحكم في توزيع مثل هذه الثقوب، وبالتالي تأثيرها، وكيفية التغلب على القيود المتعلقة بتصوير مثل هذه الثقوب الكبيرة باستخدام المسوحات الأرضية الاختراقية.

CHAPTER 1

INRODUCATION

1.1. Introduction

Importance of burrowed carbonate strata as hydrocarbon reservoirs. Despite the focus on renewable energy as a new energy supply for the world, non-renewable resources such as oil, gas, and coal have played an important role in the global energy supply for centuries and might continue in the future. A large quantity of hydrocarbon reserves has been reported in carbonate strata (La Croix et al., 2012; Ray et al., 2014; Al-Kahtany et al., 2016). Halbouty, (1970) stated that carbonate reservoirs contain more than 40% of the oil reservoirs and a quarter of the gas reservoirs. Exploration and exploitation of hydrocarbon from these strata are challenging because of the inherited depositional and post-depositional complexity. Understanding such complexity of carbonate strata is essential to exploiting their hydrocarbon reserve.

Carbonate reservoirs can be broadly classified into three end members 1) bedded carbonate reservoirs, 2) fractured carbonate reservoirs, and 3) burrowed carbonate reservoirs. Although the bedded and fractured carbonate reservoirs received much attention in terms of characterization and modeling, burrowed reservoirs are less well addressed. Nevertheless, this type of carbonate strata holds large quantities of hydrocarbon and water reserves. A well-studied example of burrowed reservoirs was reported in the Wabamun Group in the Pine Creek gas field of central Alberta, Canada (Baniak et al., 2013). In this

reservoir, the fabric-selective dolomite that follows a predefined texture by *Thalassinoides* plays a significant role in porosity and permeability distribution and, ultimately, reservoir quality. Another example of burrowed reservoirs comprises the Viking Formation, Alberta, Canada (La Croix et al., 2017). In the Viking Formation, assemblages of burrows consisting of passive sand fill provide permeability pathways in less permeable laminated beds. A third example includes the Lower Cretaceous Lower Glen Rose Limestone strata in Texas, USA. In these strata, burrows provide a pathway for groundwater flow and facilitate groundwater transport between karstic features and major faults (Golab et al., 2017). These burrow networks could be the cause of a high super-permeability zone, such as those reported in the upper Jubaila Formation, central Saudi Arabia (Eltom et al., 2020), the Biscayne aquifer, south Florida, USA, and the Gullfaks Field, Norwegian North Sea (Knaust et al., 2020).

In all of these examples, the pore system has a textural contrast between burrows and the host rock matrix and was referred to as biogenically influenced flow media. In such flow media, burrows are more porous than the host rock matrix and provide permeability flow pathways upon connection (Baniak et al., 2013; La Croix et al., 2012, 2017; Dey & Sen, 2017; Eltom et al., 2019a; Eltom, 2020; Golab et al., 2017). The interaction between burrow attributes such as burrow size, filling, morphology and connectivity, and host rock matrix characteristics such as texture and composition generate complex reservoirs favorable for future exploration.

1.1.1. Problem statement

Although the concept that burrows improve reservoir quality of bioturbated (burrowed) reservoirs is fairly well understood, detailed ichnological characteristics, sedimentary

processes, and stratigraphic controls, and fracture propagation associated with biogenically influenced flow media with large burrows are less well-constrained. Nevertheless, such understanding is crucial to predicting the storage and flow capacity of sedimentary strata with biogenically influenced flow media, leading eventually to better management of their hydrocarbon reservoirs and water aquifers. This knowledge gap is critical, particularly in cases where burrows are large and entirely open or partially filled. In such cases, subsurface data like seismic, conventional reservoir cores, and well logs have limitations to capture the characteristics of such burrowed strata. In this context, understanding the sedimentary processes and stratigraphic controls associated with burrowed strata in the outcrop of the Aruma Formation in central Saudi Arabia is of particular interest for several reasons:

- Aruma Formation contains strata that represent an analog to the biogenically influenced flow media with large-size burrows that can make super permeability zones in the subsurface.
- These strata can provide data that are not limited to the boreholes' scale and allow recognition of sedimentary and stratigraphic patterns that are hard to observe from subsurface data alone.
- These burrowed strata are genetically related to other strata in the Aruma Formation, which can all be connected to a shallow marine depositional system and sea-level fluctuation.

Therefore, burrowed strata in the Aruma Formation exhibit broad patterns and trends in analogous biogenically influenced flow media with large burrow pores. This study will describe the sedimentological and stratigraphic patterns and burrow attributes of

burrowed strata in the Aruma Formation. The main aim of this research is to understand the sedimentological and stratigraphic controls on the biogenically influenced flow media that are similar to these strata. Ultimately, this study will provide geostatistical models to understand flow behavior and predict reservoir performance in fluid flow media with large pores. Moreover, this research will attempt to generate forward seismic models to better understand the seismic signature of similar reservoirs in the subsurface.

1.1.2. Objectives

This research aims to systematically accomplish the following objectives:

- Describe the diversity of burrows found within the Aruma Formation and how they vary stratigraphically.
- Discuss in a broad context, the sedimentological and stratigraphic controls on the biogenically influenced flow media.
- To investigate the influence of bioturbation on fracture development and propagation within the geological formations.
- To employ cutting-edge techniques, specifically Ground Penetrating Radar (GPR), to thoroughly analyze the attributes of burrows in the strata.

1.2. Study area and geological background of the Aruma Formation

1.2.1. Contacts, lithology and Stratigraphy

The Aruma Formation disconformably overlies the Wasia Formation and is disconformably overlain by the Umm er Radhuma Formation (Fig. 1. 1). The lower contact of the formation is distinguished by the presence of varicoloured clastic rock of the Wasia Formation, whereas the top contact is defined by the transition from dolomitic shale in the Aruma Formation to crystalline Lockhartia-bearing dolomite in the Umm er

Radhuma Formation (Philip et al., 2002). The formation comprises three members from bottom to top: the Khanasir, Hajajah, and Lina Shale members (Fig. 1.1) (Al-Husseini & Matthews, 2005; Al-Kahtany et al., 2016; Philip et al., 2002).

The Khanasir Member consists of one sequence that is further subdivided into three parasequences (Philip et al. 2002, 1a – 1c from bottom to top, see their Fig. 1.2). Parasequence 1a consists of beds of claystone, *Skolithos* sandstone, and burrowed chalky and fossiliferous wackestones (carbonate). Parasequence 1b contains dolomitic shale that is overlain by wackestone beds with Dasycladacean algae and chert nodules. Parasequences 1c consists of shale overlain by burrowed wackestone. Strata in the Khanasir Member is interpreted to have been deposited in a low-energy, protected carbonate platform environment.

The Hajajah Member is divided into two sequences (sequence 1- sequence 2 from bottom to top), which are further subdivided into ten parasequences (from bottom to top, 2a – 2D, 3a – 3f) (reference needed). Sequence 1 consists of varicoloured shale interbedded with limestone that is rich in corals, large Foraminifera, and Rudist. Parasequence 2a consists of shale and grades upward into floatstone, which is rich in biostromal rudist, chaetetid, and coral. Parasequence 2b consists of shale that gradually progresses into fine sand.

Parasequence 2c consists of green shales and contains iron oxide, fish fragments, and nodules in its lower part. Parasequence 2d comprises green shale, mudstone, and dolomitic packstones-grainstone. This parasequence is separated from the underlying parasequences by iron-stained hardground. Sequence 1 is interpreted to have been deposited as a result of sea level transgressions and regressions. An incised surface formed at the top of the SB1

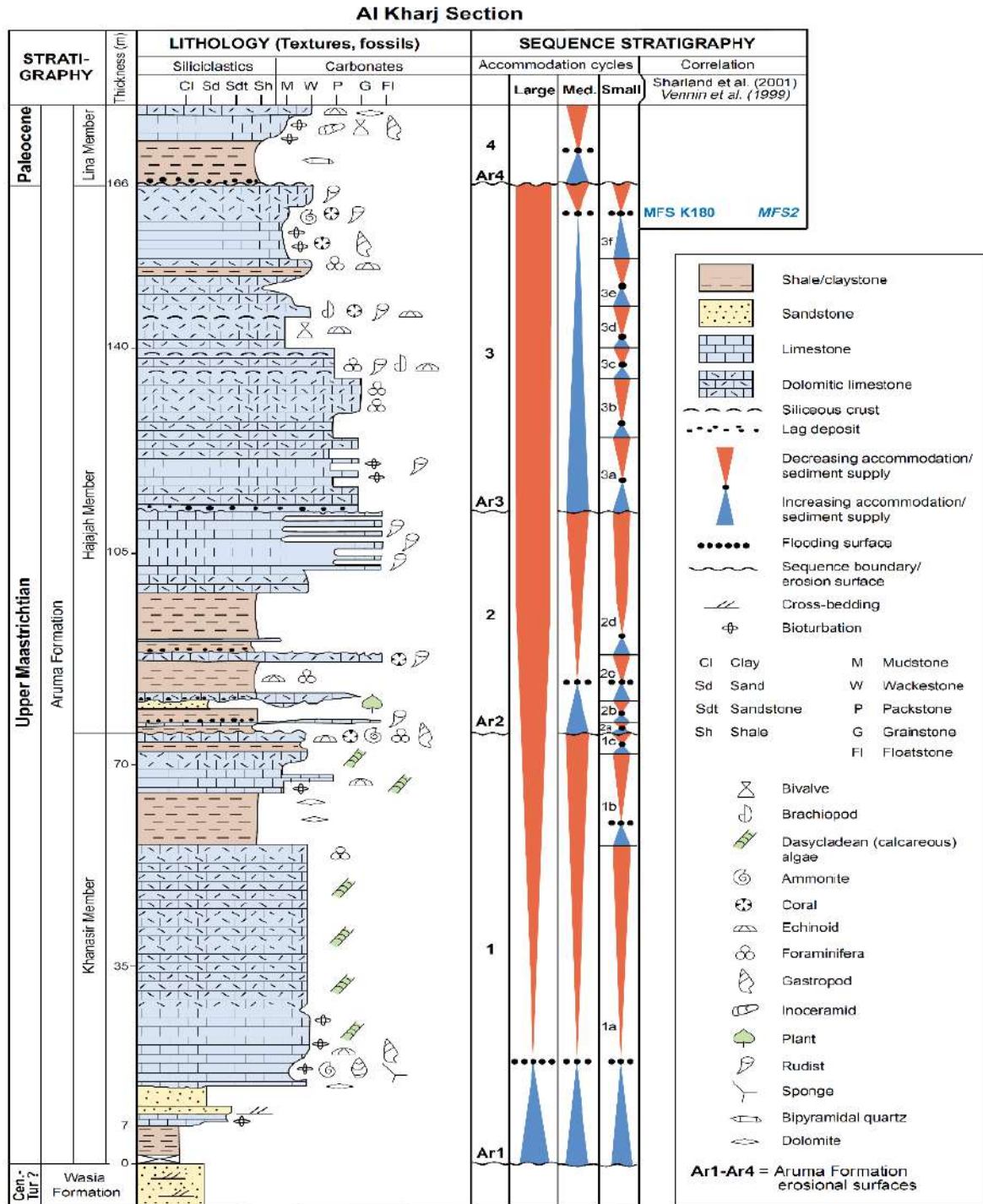


Figure 1.1: The Aruma Formation lithostratigraphic section from the Al Kharj section (Philip et al., 2002).

as a result of a significant drop in sea level.

The Hajajah Member also comprises six parasequences between sequences two and three. Parasequence 3a consists of bioturbated packstones and dolomitized grainstones. Parasequence 3b contains bioturbated wackestones and grainstone with large Foraminifera. Parasequences 3c and 3d are composed of poorly fossiliferous dolomitized wackestones-mudstones that are overlain by mudstones containing solitary echinoids, corals, and brachiopods. Parasequence 3e consists of wackestone which grades upwards to shales which are overlain by wackestone containing large Foraminifera. Parasequence 3f consists of bioturbated mudstones-wackestones and fossiliferous mudstones-wackestones at the top. Sequence 3 is interpreted to have been deposited in high-energy carbonate platform environments (parasequences 3a–3b), which then evolved into low-energy offshore environments (parasequences 3c–3f). There is a significant erosional surface between the top of the Hajajah Member and the Lina Shale, which resulted from a hiatus of several million years at the Cretaceous-Paleogene boundary (Thomas et al., 1999).

The Lina Shale Member consists of shale interbedded with subordinate dolomite. The lower and middle parts of the members are devoid of fossils, with the exception of a few plants, a few molluscs that are weakly preserved, and some coral (Thomas et al., 1999). The Lina shale Member is interpreted to have been deposited in a relatively open marine setting and at a deeper setting than the underlying members due to a decrease in accommodation space due to sea-level rise (Al-Kahtany et al., 2016).

1.2.2. Age

The Khanasir and Hajajah members have been assigned as Maastrichtian based on integrated biostratigraphical evidence, particularly from ammonites, large Foraminifera, nannoflora, and rudists (Philip et al., 2002; Hughes et al., 2020). However, based on

ostracod (El-Sorogy et al., 2016) and Solitary corals (Gameil et al., 2020), the Hajajah member was assigned to the Campanian. The Lina Shale Member is assigned as Paleocene (Philip et al., 2002), but can be extended to the Early Eocene based on evidence from marine vertebrates such as selachian, actinopterygian (Thomas et al., 1999). El-Nakhal & El-Naggar, (1994) noted in their chronostratigraphic review of the Aruma Formation that disagreements over the Aruma Formation's geological age might exist between different areas and sometimes within the same location, as well as in the surface and subsurface. (Note: you have two identical figures below, one overlain atop the other).

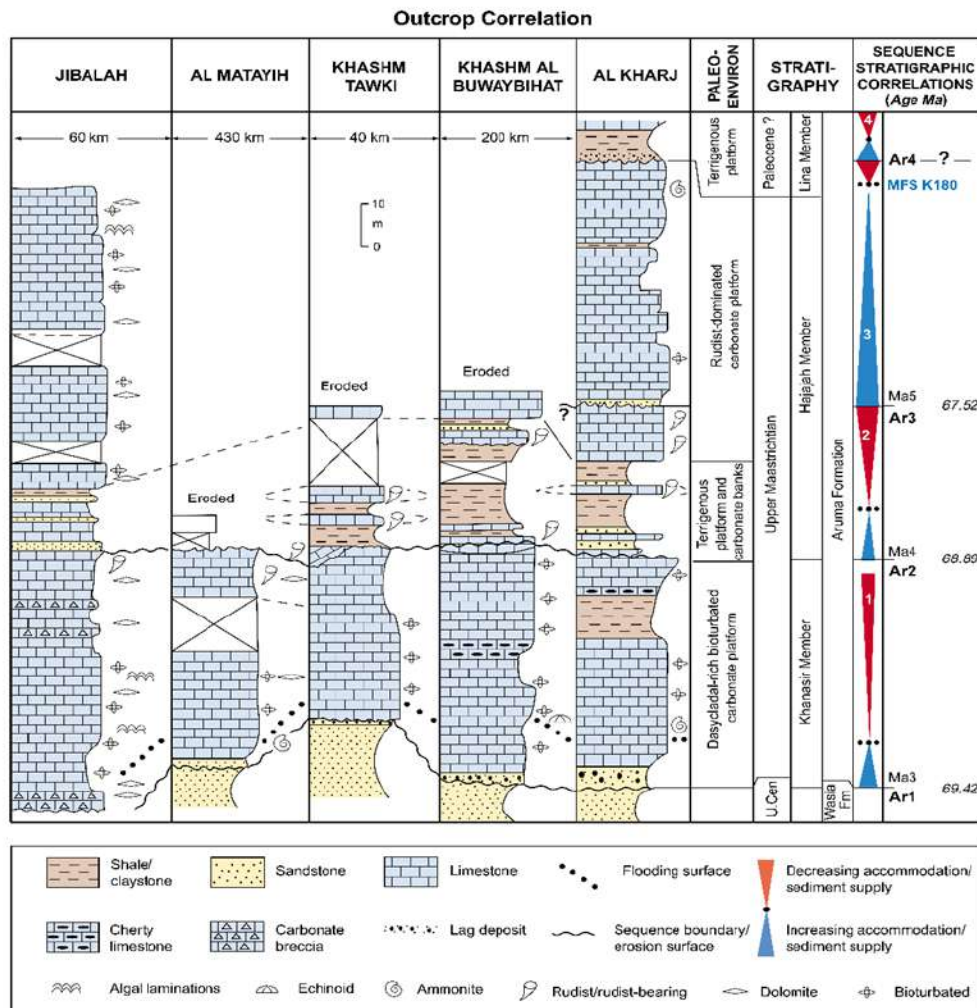


Figure 1.2: Correlation between the Aruma Formation outcrops (reference).

1.2.3. Paleogeography setting of the Aruma Formation

On the Arabian Plate, eustasy and tectonics influenced the development of sedimentary sequences (Haq & Al-Qahtani, 2005). For example, in many parts of the Arabian Platform, the late Cretaceous–Paleocene transgression was preceded by an extended hiatus spanning the majority of the Late Cretaceous. This hiatus, which corresponds to the pre-Aruma unconformity, is the result of the Arabian plate tilting eastward and tectonic along the Tethyan edge (Al-Husseini & Matthews, 2005; Haq & Al-Qahtani, 2005). The Aruma Formation is associated with the Arabian platform's late Cretaceous-Paleocene transgression, which occurred between 89 to 60.9 Ma (Ziegler, 2001; Al-Husseini & Matthews, 2000). During the Cenomanian, transgression allowed shallow-water carbonates to accumulate along basin margin coasts, while deeper-water shale and limestone accumulated further away from the basin margin (Gameil et al., 2020). Another transgression took place during the Campanian, which reached its maximum during the Maastrichtian period. A carbonate platform existed during the Aruma Formation's deposition, which began with the development of dasyclad algae and rudist, which thrived in relatively more restricted lagoonal to back reef marine conditions. Corals and stromatoporoids eventually replaced older fauna in areas with more open marine conditions (Al-Kahtany et al., 2016). In the upper Aruma Formation, continuous deepening increased shale deposition and decreased carbonates. For the purpose of this proposal, perhaps it is not necessary, but I would recommend finding or constructing a sea level (eustasy) plot.

1.2.4. Study Area

The Aruma Formation crops out in several locations throughout its approximately 1500 km length, ranging from SE of the Iraqi border and across northern Saudi Arabia's Al-Jawf

area, to the east of Riyadh, then south along the west of the Rub' Al-Khali (Philip et al., 2002). In Saudi Arabia, the lateral variation of the Aruma Formation in several locations such as Jibalah, Matayih, Khashm Tawki, Khashm Al Buwaybihat, and Al kharj has been explained by Philip et al. (2002) (Fig. 1. 2). Within Saudi Arabia's central region, the study area is ~55 km NE of Al Kharj. My research focuses on outcrops in the Aruma Formation's lower section (Khanasir Member). Several bioturbated layers are visible in this member, and the layers have large pores and good lateral exposure.

1.3. Methods

This research will accomplish its aims through a combination of field investigation and laboratory analysis. Each objective requires a particular method and analysis. The following section provides details of these methods.

1.3.1. Sedimentological, ichnologic, and stratigraphic description

This study describe several measured sections in the Aruma Formation. Descriptions include bed thickness, lithology, sedimentary structure and lateral changes within the beds. Burrows in the Aruma Formation will be described in detail. The description will include burrow morphology, filling, size and percentage. Samples will be collected from these measured sections at systematic intervals or bed-by-bed. Laboratory work will be carried out on these samples and will include, thin section preparation, microscopic scanning of the thin sections by Axio Scan, petrography, quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN), X-Ray Diffraction (XRD), and X-ray Fluorescence (XRF).

Results of the field investigation and laboratory analysis is expected to provide data that will help in interpretation of depositional environment of the interval of interest.

Such interpretation will help to understand controls on the distribution of burrows in a particular interval and how they influence petrophysical properties.

1.3.2. Burrow morphology

Pore systems associated with burrows in the Aruma Formation will be described using ground penetration radar (GPR) at the outcrop and from computed tomography scanning (CT) in the lab. Both methods will provide three-dimensional (3D) visualization of burrow morphology. Data collected by the GPR and CT scanning will be treated as a seismic cube (SEG-Y format) and viewed using Petrel software. GPR and CT scanning data is expected to offer 3D visualization of the pore system in the biogenically influenced flow media in the Aruma Formation. Such 3D visualization can help in the modeling and simulation of fluid flow in such media.

Chapter 2

Bioturbated strata in the Upper Cretaceous Aruma Formation, central Saudi Arabia: An analog for aquifers and hydrocarbon reservoirs with large burrows

Abstract

The upper Cretaceous Aruma Formation in Central Saudi Arabia exhibits *Thalassinoides*-bearing strata resembling a bioturbated carbonate reservoir with large burrows. These burrows possess distinct stratigraphic characteristics. Certain intervals within the formation feature open or partially filled *Thalassinoides*, creating three-dimensional permeability pathways, while others contain *Thalassinoides* filled with low-permeability sediments. This comprehensive study investigates the paleoenvironment, ichnological features, bulk permeability influence, and stratigraphic variations of these bioturbated intervals. Incorporating field observations, laboratory analyses (including petrography, geochemical assessments, petrophysical measurements, and computer tomography scanning [CT]), we present the division of the studied interval into three biogenically influenced fluid flow media (BIFM 1-3). BIFM 1 comprises solution-enlarged open *Thalassinoides* (average shaft diameter: 5 cm) hosted within a mud-dominated matrix. BIFM 2 consists of *Thalassinoides* with mud-dominated infills (average shaft diameter: 3 cm) embedded in a dolomite matrix. BIFM 3 exhibits compacted open *Thalassinoides*. These BIFM units demonstrate burrow percentages ranging from 10% to

50%, featuring interconnected networks. The identified units reflect diverse depositional settings, ranging from open marine to restricted lagoon, and distinct stratigraphic positions. By highlighting the sedimentological and stratigraphic controls on the petrophysical properties of carbonate strata containing *Thalassinoides* with large burrows, this research contributes to the prediction of super-permeability zones in analogous settings.

Keywords: Outcrop analog, Shallow marine strata, Carbonate reservoirs, Bioturbation, *Thalassinoides*, Super-permeability, Aruma Formation

2.1. Introduction

Carbonate strata have been known to contain vast reserves of oil and gas as well as significant aquifers for groundwater (Lucia et al., 2003; Moore and Wade, 2013). However, due to their inherent depositional properties and diagenesis, extracting these resources requires careful optimization. Bioturbation, the reworking and modification of sediments by organisms, is a significant contributor to the complexity of carbonate strata, and can either enhance or reduce their reservoir and aquifer quality (Cunningham et al., 2004; Pemberton and Gingras, 2005; Cunningham et al., 2006; Cunningham et al., 2009; Cunningham and Sukop, 2012; Baniak et al., 2013; Baniak et al., 2014; Baniak et al., 2015; Golab et al., 2017; La Croix et al., 2017; Eltom et al., 2018; Alqubalee et al., 2022; Niu et al., 2022; Yang et al., 2022). Despite its significance, the specific ways in which bioturbation controls reservoir properties are not yet fully understood (Baniak et al., 2022), because the subsurface data like seismic, conventional cores, and well logs are limited in characterizing the reservoir properties of these strata (Eltom, 2020; Eltom et al., 2021). Therefore, the documentation of bioturbated strata in outcrops, along with an understanding of how the characteristics of these strata vary stratigraphically, can

significantly improve the knowledge and prediction of the quality of hydrocarbon reservoirs and groundwater and CO₂ storage aquifers in carbonate strata, which in turn affects parameters such as recovery factor, estimated ultimate recovery, and sequestration potential (Eltom et al., 2019; La Croix et al., 2012).

Herein, we investigate outcrops of the Aruma Formation in central Saudi Arabia which contains strata that represent an analog to bioturbated carbonate reservoirs with large (cm-scale) burrows. These burrows have the potential to create super-permeability zones in the subsurface, characterized by extremely high flow capacity (referred to as super-k) (Meyer et al., 2000; Cosentino et al., 2001; Cunningham et al., 2009; Eltom et al., 2020). An illustrative case of such a super-k zone is observed in the stratigraphic interval of the Arab-D reservoir in Saudi Arabia, where it yields an impressive production rate of over 500 barrels per day per foot of thickness (Meyer et al., 2000). Furthermore, the outcrops of the Aruma Formation (Alsharhan and Nairn, 1990; Okla, 1995; Philip et al., 2002; Gameil and El-Sorogy, 2015; Al-Kahtany et al., 2016; Özer and El-Sorogy, 2017; Keller et al., 2019; Farouk et al., 2020; Hughes et al., 2020; Al-Hashim et al., 2022) provide data that are not limited to the boreholes' scale and allow recognition of sedimentary and stratigraphic patterns that are hard to observe from subsurface data alone. Using data from the Aruma Formation outcrops, the goal of the study was to describe burrow attributes, relate those attributes to depositional environment, and describe and interpret how burrows impact the storage and flow capacity of the Aruma Formation.

The findings of this study carry significant implications as they highlight a crucial stratigraphic interval that could serve as a valuable resource for both water and hydrocarbon extraction. The findings also shed light on how bioturbation varies

stratigraphically and the ways in which sedimentology plays a role in this variation, ultimately, how such variation controls storage and flow capacity of these strata. This knowledge is not limited to the specific location of the study but could have wider implications for other carbonate strata around the world.

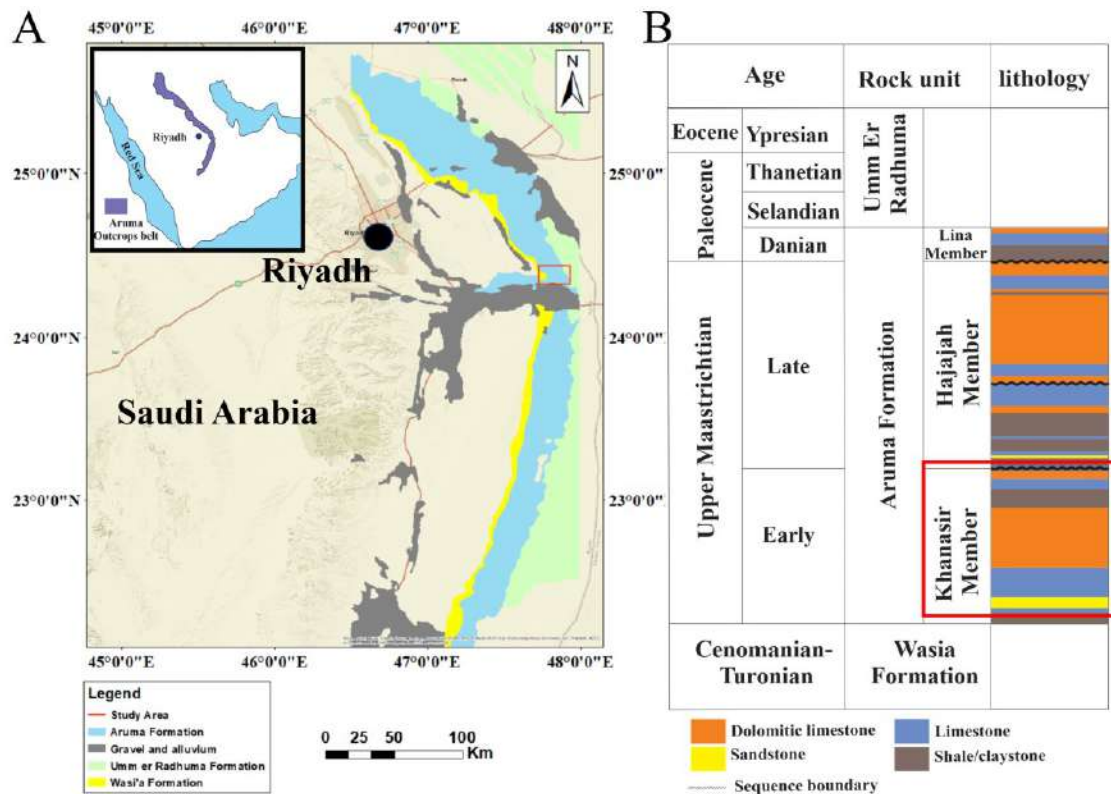


Figure 2.1: Location, stratigraphy, and sedimentology of the Aruma Formation. (A) Outcrop distribution of the Aruma Formation and study area (red square). (B) Stratigraphy and lithology of the Aruma formation (after Philip et al., 2002), red square shows focus of the this study.

2.2. Geological Background

The study area is situated approximately 55 km northeast of Al Kharj in central Saudi Arabia and is part of the Aruma Formation outcrop belt, which stretches for approximately 1500 km from the southeast of the Iraq-Saudi Arabia border to the west of the Rub' Al-Khali (Fig. 2. 1A)(Powers et al., 1966). The Aruma Formation, which is the focus of this

study, disconformably overlies the Wasia Formation and is disconformably overlain by the Umm er Radhuma Formation (Fig. 2. 1B). The lower contact of the Aruma Formation is characterized by the presence of varicolored clastic rocks of the Wasia Formation, and the upper contact (with the Umm er Radhuma Formation) is marked by the transition from dolomitic shale to crystalline dolomite rich in *Lockhartia* large benthic foraminifera (Powers et al., 1966).

The Aruma Formation consists of three members from bottom to top: the Khanasir, Hajajah, and Lina Shale Members (El-Asa'ad et al., 1983), with this study focusing on the Khanasir Member. This member contains burrowed strata that serve as an analog to bioturbated carbonate reservoirs with large-size burrows. The Aruma Formation was formed in a compressive foreland basin setting during the late Cretaceous to Paleocene transgression of the Arabian platform. This transgression followed the mid-Turonian ophiolite obduction along the plate's eastern boundary, which was caused by Arabian-Asian plate convergence (Martin, 2001; Haq and Al-Qahtani, 2005).

The Khanasir Member is dated as Campanian based on the rudist taxon (*Eodictyoptychus arumaensis*) (Skelton and El-Asa'ad, 1992) and to the Campanian-early Maastrichtian based on ammonites, large foraminifera, and nannoflora (Powers et al., 1966; Skelton and El-Asa'AD, 1992; Philip et al., 2002). According to Philip et al. (2002), the Khanasir Member is composed of claystone, bioturbated (*Skolithos*) sandstones, and bioturbated (*Thalassinoides*) limestones, which are rich in dasycladacean algae and other fossils. The Hajajah Member comprises two sequences, with the lower sequence consisting of shale interbedded with limestone that is rich in corals, large foraminifera, and rudists, and the upper sequence consisting of bioturbated mudstone to packstone with large

foraminifera, solitary corals, and brachiopods alternating with dolomitized mudstone to grainstone. Lastly, the Lina Shale Member comprises shale interbedded with subordinate dolomite and has very low fossil content except for a few mollusks and corals.

2.3. Methods

This study employed a combination of field observations and laboratory analyses to achieve its objectives. Field observations focused on the stratigraphic patterns of the Khanasir Member, including stratigraphic surfaces, bed thickness, and bedding style. Additionally, sedimentary and ichnological characteristics were examined, including carbonate constituents, diagenetic features, sedimentary structures, burrow types, burrow abundance (measured in burrow percentage, BP), burrow size, and burrow filling. Field images were processed and analyzed using ImageJ and JMicroVision software to determine burrow size and BP. For laboratory analysis, a total of 36 hand specimens were collected for thin section preparation and geochemical analysis. The sampling interval between the specimens was maintained at 1 meter where accessible and unobstructed. However, in certain cases where exact locations were difficult to access or covered with talus, the sampling interval was increased. Out of the 36 collected samples, 28 were used for porosity and permeability measurements. The remaining samples were excluded due to damage or the presence of open burrows cutting into the core. Despite excluding some samples due to damage or open burrows, we still had a sufficient number of samples (28) for porosity and permeability measurements in each unit. Two 10-inch core samples were obtained using a hand-operated drill and two hand specimens from the outcrop were used for Computed Tomography (CT) scanning to show the morphology and connectivity of burrows in the Khanasir Member. All the measurements and analyses of the thin sections, X-ray

Diffraction (XRD), X-ray Fluorescence (XRF), porosity, permeability, and CT scanning were conducted at King Fahd University of Petroleum and Minerals (KFUPM).

Thin sections were studied under an Olympus microscope to identify texture, fossils, and pore types of the host rock matrix of the Khanasir Member (Fig. 1B, 2). Blue dye epoxy was used to highlight the geometry of the pore spaces in the samples. The ZEISS Axio Scan instrument was used to scan thin sections, which were then visualized by ZEN software. Powders of each hand specimen were prepared and used to determine the mineral composition of lithofacies in their stratigraphic interval using a PanAnalytical X-Ray Diffraction (XRD) system. XRD patterns were measured with a diffractometer (CuK radiation, $U = 45$ kV, $I = 40$ mA), with a start position $[2\theta]$ of 4.0066 and an end position 2θ (degrees) of 70.0076 . XRF data (elemental and oxides composition) were also examined with a Bruker M4 TORNADO™. Porosity was measured for the 28 core plugs (diameter of 1.5 inches) using the Coretest System INC AP-608 Porosimeter, while permeability was measured using a multi-probe core scanner, NER Autoscan. The two 10-inch cores from unit 1 and the two samples from unit 2 were CT scanned using a medical CT scanner (Toshiba Alexion TSX-032A), and Petrel™ 2021 was used to visualize the CT scans after converting the CT scan data to SEG-Y seismic format.

2.4. Results

2.4.1. Sedimentology and stratigraphy

In the study area, the Khanasir Member can be subdivided into three distinctive stratigraphic units (Fig. 2.2), consistent with previous studies (Hughes et al., 2020; Philip et al., 2002). The subdivision of these units is based on their stratigraphic patterns, sedimentological features, and most significantly, their ichnological characteristics. The

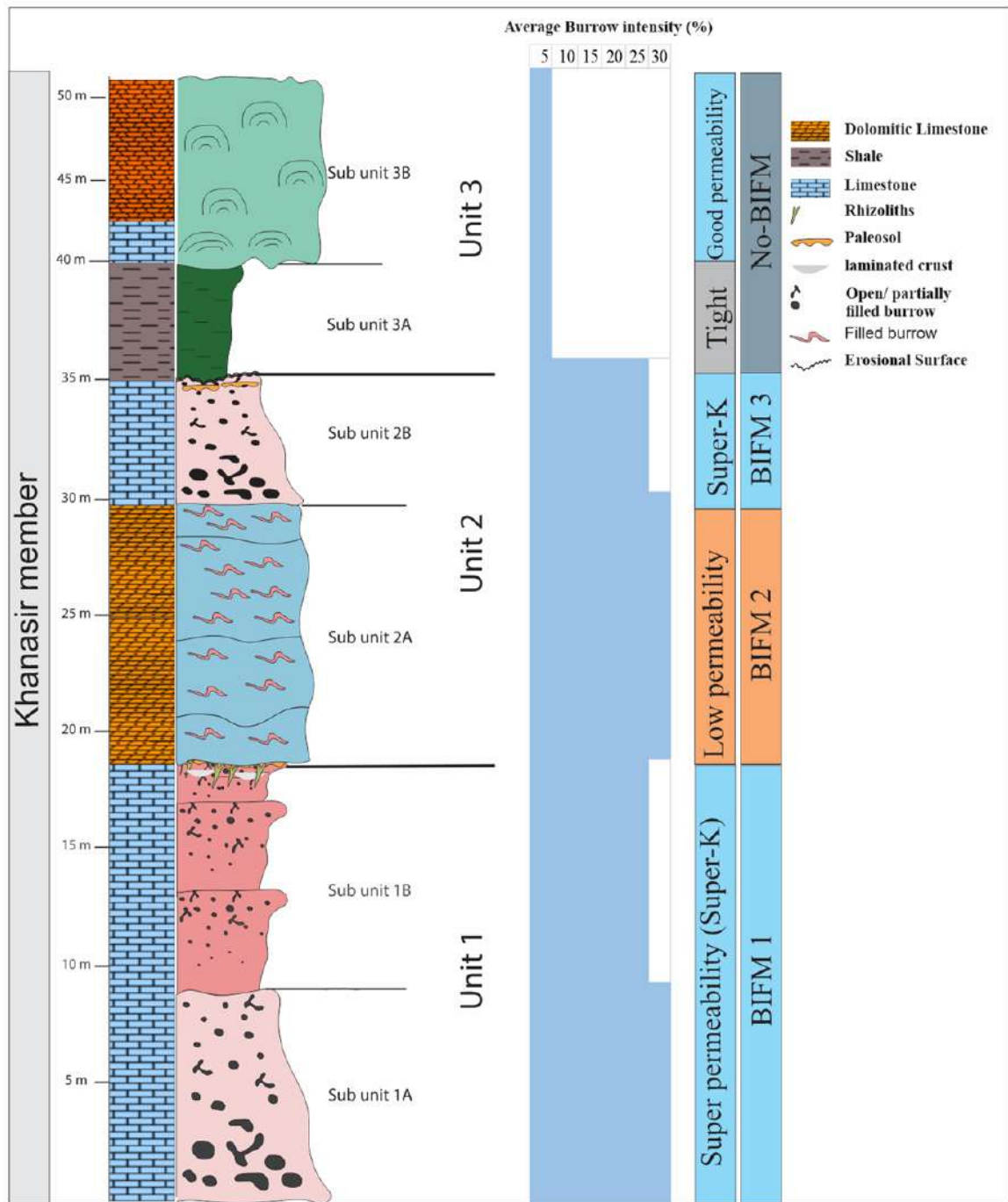


Figure 2.2: Measured section of the Aruma Formation in the study area showing three distinct stratigraphic units.

units are numbered from bottom to top as units 1 to 3 (Fig. 2.2).

A. Unit 1

The burrows in Unit 1, which has a thickness of approximately 18 meters (~ 18 m), are either open or partially filled with terra rossa soil, with BP ranging from 10% to 41% (Fig. 2.3A and B). Upon close examination of the burrows in this stratigraphic unit, they appear to be open or partially filled with soil composed of 51.8 % calcite, 33.4% quartz, and 14.7% palygorskite. This was confirmed by XRD and XRF data (Fig. 2.4 and Table 2.1). The host rock matrix of unit 1 consists of 100% calcite as confirmed by XRD and XRF. (Fig. 2.4 and Table 2.1).

From outcrop observations, the shaft cross sections of the burrows in unit 1 appear circular where they have not been solution-enlarged (Fig. 2.5A). However, in some cases, cross sections appear elliptical in form where there has been solution enlargement (Fig. 2.5B, C). The vertical shafts of these burrows are difficult to observe in outcrop, and they occur as solution-enlarged oblique shafts where they are exposed (Fig. 2.5D). Although the outcrop observations did not provide clear diagnostic criteria for the burrow type in unit 1, the CT scan data of two samples collected from this unit showed burrow morphology that pointed to *Thalassinoides* characteristics (Fig. 2.6) (Ekdale & Bromley, 1984; Pemberton & Gingras, 2005). Such criteria include the presence of vertical shafts and horizontal tunnels (Fig. 2.6A-D), connection angles between shafts and tunnels of 30°, 60°, 90°, and 120° (Fig. 2.6C-D, F), the presence of V and U shapes in 2D views (Fig. 2.6C-E), and the presence of *Thalassinoides* boxwork patterns in 3D views (Fig. 2.6A and F).

In unit 1, there is stratigraphic variation in burrow abundance and diameter (Fig. 2.7). Two sub-units are differentiated based on these variations, namely sub-units 1A and 1B.

The burrow diameter in sub-unit 1A decreases upward, but still remains in the range of large

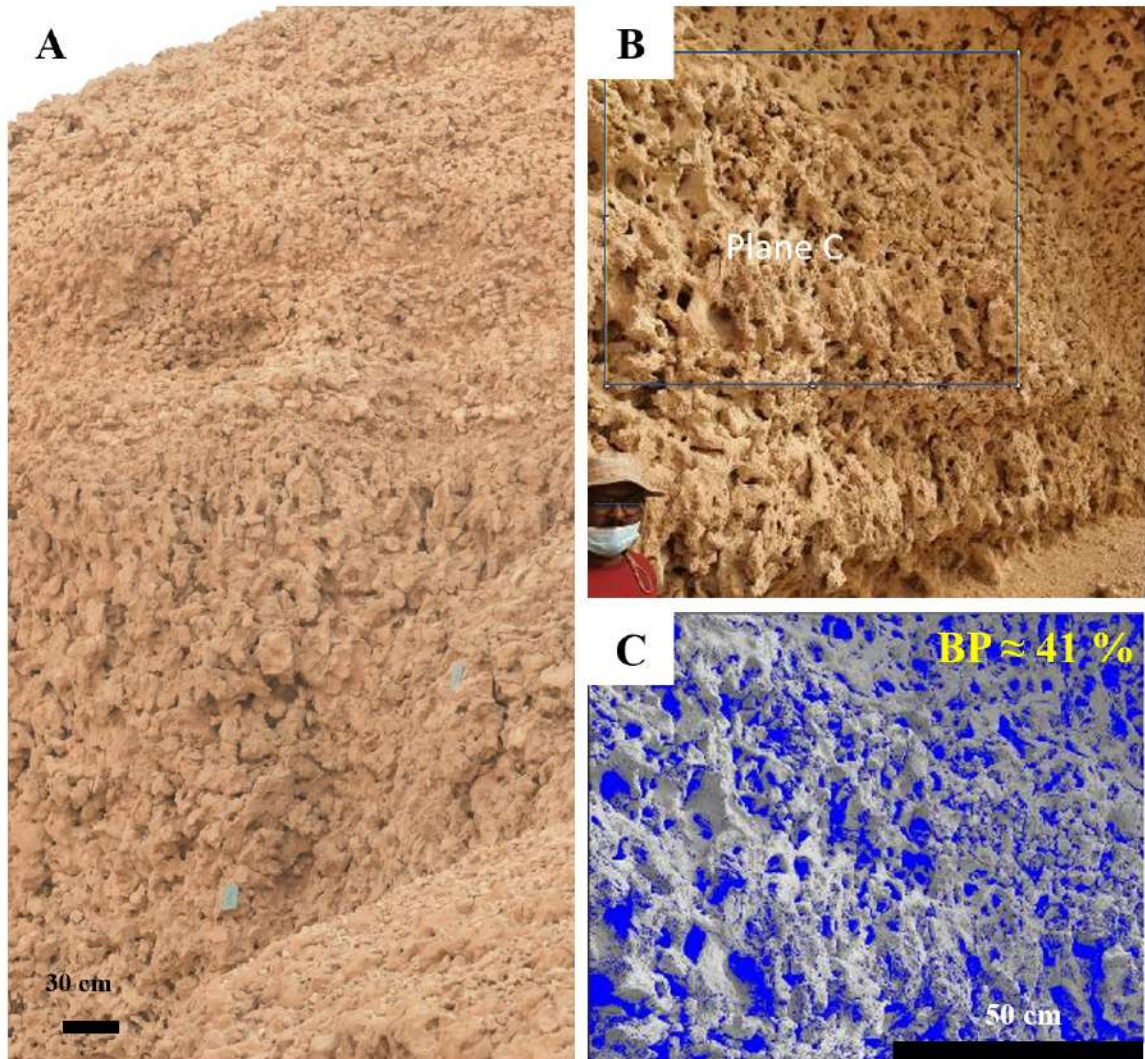


Figure 2.3: Outcrop photographs and image analysis showing open burrows in unit 1. (A) Ubiquitous open burrows in unit 1. Burrow size can reach up to 7.5 cm in diameter. (B) Close up view of the burrows showing open shafts and percentage. (C) Example of an image analysis to show the burrow percentage of 41%.

burrows, with shaft and tunnel diameters ranging from 3.0 to 6.5 cm (with a mean of 4.7 cm and a standard deviation of 1.43, Fig. 2.7). In contrast, sub-unit 1B, which has multiple subaerial exposure observations, marked by rhizoliths, laminated crust, and soil

development (Fig. 2.5E and F), shows an increase in burrow size upward. Burrow size in sub-unit 1B is smaller relative to sub-unit 1A, with shaft diameter ranging from 2.1 to 4.4

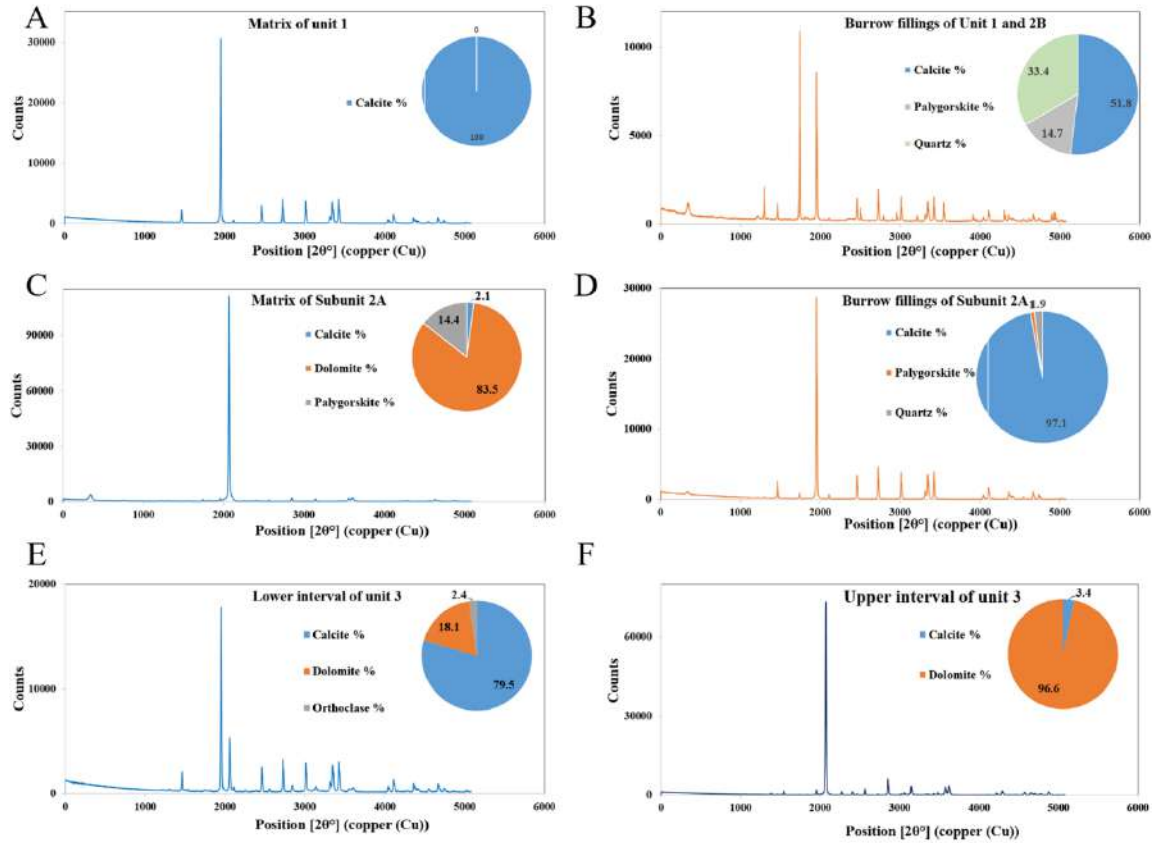


Figure 2.4: Results of representative XRD analyses of the matrix and burrow fillings of the Khanasir Member (unit 1 to unit 3). (A) Matrix of unit 1. (B) Burrow filling of unit 1 and subunit 2B. (C) Matrix of subunit 2A (D) Burrow filling of subunit 2A (E) Lower interval of unit 3. (F) Upper interval of unit 3.

cm (with a mean of 3.14 cm and a standard deviation of 0.74, Fig. 2.7).

There are many outcrop-scale karst features in unit 1, including sinkholes (Fig. 2.8A and B), caves (Fig. 2.8C), and sinking streams (Fig. 2.8D). The boulders in the collapsed roofs of the caves exhibit a network of *Thalassinoides* that were filled with terra rossa soil. The host rock matrix of unit 1 is composed of fossiliferous chalky limestone with a wackestone to packstone texture (Fig. 2.9 and 2.10). Foraminifera are less common in sub-unit 1A than

in sub-unit 1B, but there are more fragments of algae in sub-unit 1A than in sub-unit 1B. Sub-unit 1A is dominated by Dasycladacean green algae (Fig. 2.9A-D), planktonic foraminifera (Fig. 2.9E-F), a few large benthic foraminifera (Fig. 2.9G), Miliolids (Fig. 9H), Rotaliina (Fig. 2.9I-J), bryozoans (Fig. 2.9K), and gastropods (Fig. 2.9L). Sub-unit 1B, on the other hand, contains large benthic foraminifera (Fig. 2.10A), Miliolids (Fig. 2.10B), Rotaliina (Fig. 2.10C-D), planktonic foraminifera (Fig. 2.10E-H), Dasycladacean green algae (Fig. 2.10I-J), and a few echinoderms and bryozoans (Fig. 2.10K-L).

B. Unit 2

Unit 2, with a thickness of approximately 17 meters, consists of two sub-units (2A and 2B) (Fig. 2.2), which differ in burrow morphology, fillings, and host rock matrix texture (Fig. 2.12, 2.13). Both sub-units exhibit *Thalassinoides* burrows with a burrow percentage of ~25-45%. Sub-unit 2A is dominated by burrows with elliptical cross sections and horizontally dominated branching shafts and tunnels (Fig. 2.14). The average burrow diameter of the *Thalassinoides*, in sub-unit 2A, ranges from 1.2-7.5 cm with an average mean diameter of 3.2 cm and a standard deviation of 1.27 (Fig. 2.7). On the vertical face, the burrow diameter ranges from 1.1-5.9 cm with an average mean diameter of 2.8 cm and a standard deviation of 1.06, whereas on the horizontal face, it ranges from 1.13-7.5 cm with an average mean diameter of 3.7 cm and a standard deviation of 1.37. CT scan and field observation data confirm the *Thalassinoides* characteristics, including the presence of horizontal shafts, connection angles between shafts, and horizontal boxwork patterns (Fig. 2.14, 2.15). Outcrop-scale karst features, such as caves and sinkholes, and fractures are common in sub-unit 2A (Fig. 2.16).

The fillings of *Thalassinoides* in sub-unit 2A consist of mud-dominated limestone with a micritic matrix and scattered skeletal grains (Fig. 2.13D). The carbonate constituents and rock texture of the filling of *Thalassinoides* in sub-unit 2A are similar to those of the host

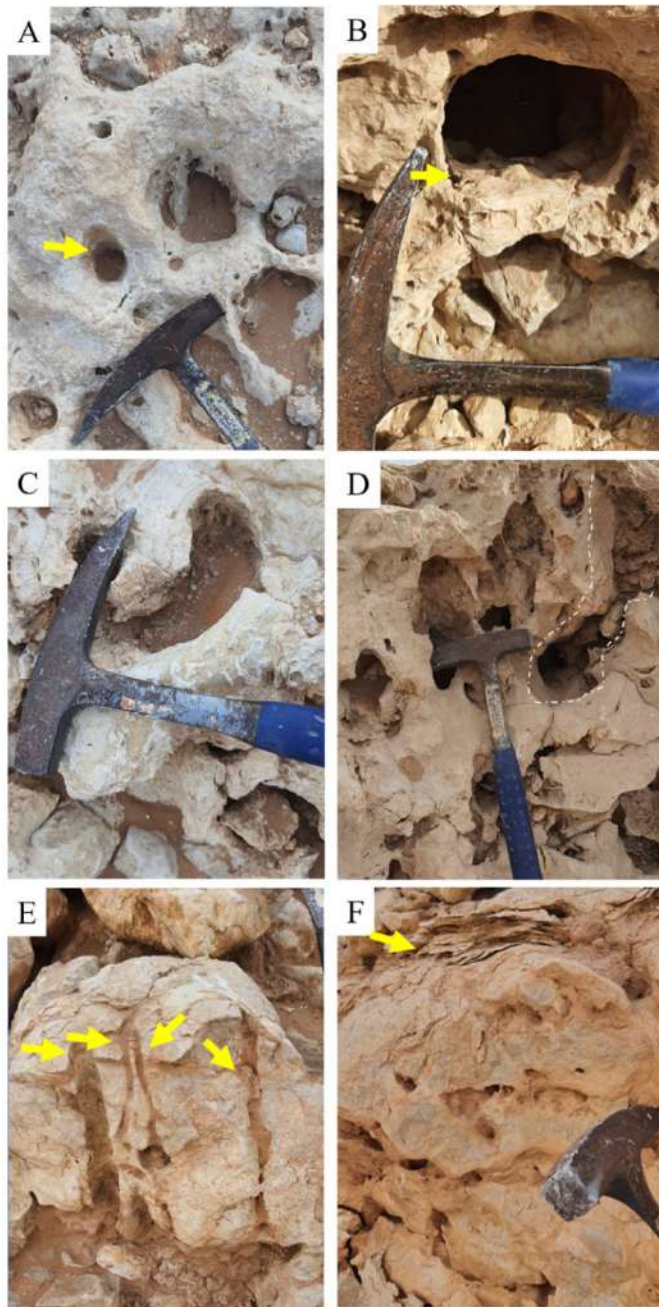


Figure 2. 5: Outcrop photographs showing (A) Circular burrow cross sections. (B) Elliptical burrow cross section. (C) Cross section of solution-enlarged elliptical burrow. (D) Oblique

shaft intersecting the lower tunnel. (E) Rhizolith. (F) Laminated crust. The yellow arrow points to the features in the figure captions.

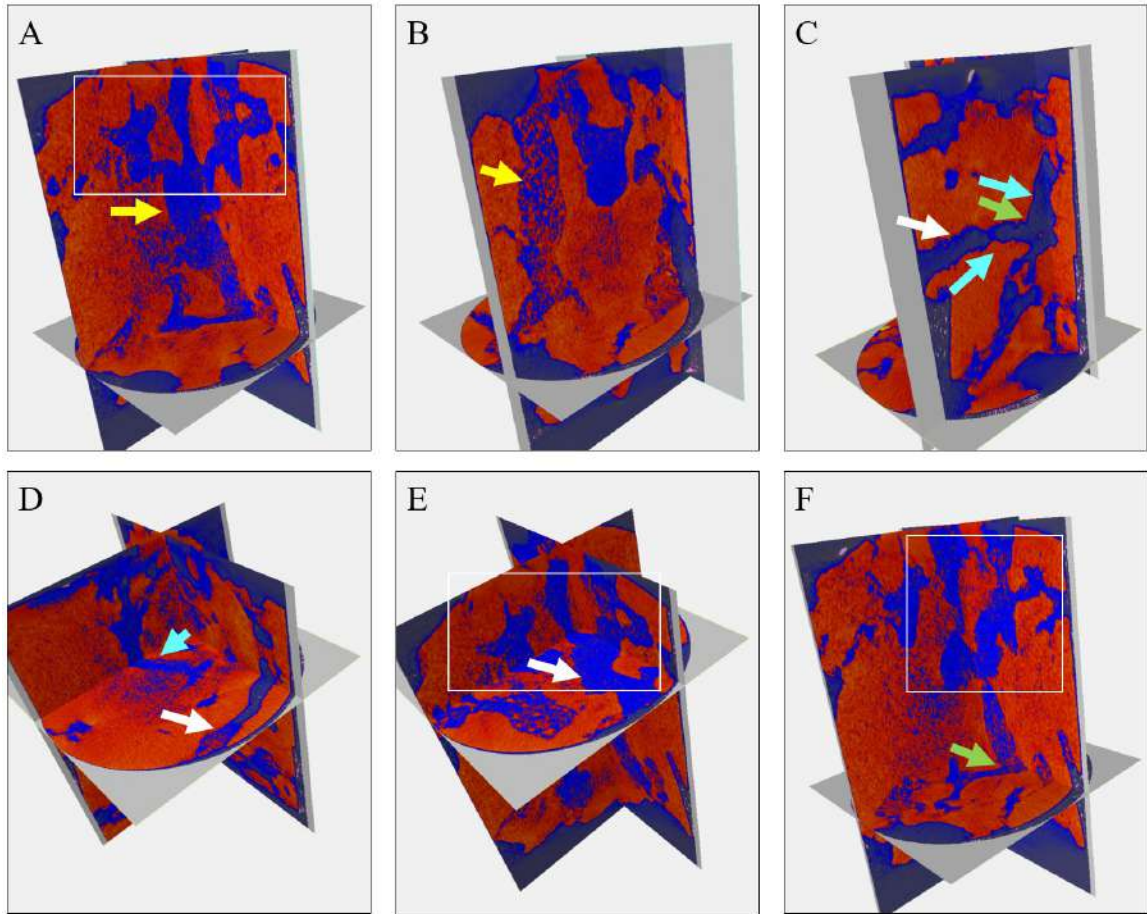


Figure 2.6. Rendering of the same core sample with varying views of a vertical and horizontal slice. (A-F) CT scan data show diagnostic criteria for *Thalassinoides* including: vertical (yellow arrow) and horizontal (white arrow) tunnel; angles of shaft connection (blue arrow); intersections between shafts and tunnels (green arrow); and boxwork of the *Thalassinoides* (white box). The burrows could be partially filled with sediment, as shown in fig. B, or the infill has been partially exhumed, as shown in fig. C. The core diameter is 10-inch.

rock matrix in unit 1, with less abundance of foraminifera and green algae than the lower unit (unit 1) (Fig. 2.13D). The host rock matrix in sub-unit 2A is predominantly composed of dolomite crystals with a non-fabric preserving texture, and a subordinate amount of clay minerals such as palygorskite (Fig. 2.4, 2.13). The dolomite crystals have an average cross section of ~125 μm and exhibit distinct zonation and intercrystalline porosity (Fig. 2.13F).

In contrast, sub-unit 2B exhibits *Thalassinoides* with comparable morphology and characteristics to those observed in unit 1B (Fig. 2.7F), with the exception that they are open compacted burrows, rather than solution-enlarged ones (Fig. 2.11). The host rock matrix in sub-unit 2B is primarily composed of limestone with a mudstone to wackestone texture and is largely dominated by Miliolids and large benthic foraminifera, with considerably lower abundance of dasycladacean algae compared to the other units (Fig. 2.12).

C. Unit 3

Unit 3, with a thickness of approximately 16 m, is characterized by a shale at the base that transitions upward into partially dolomitized limestone (Fig. 2.17A). The dolomite crystals in this unit have an average cross section of 40 μm and exhibit zonation (Fig. 2.17A). While the uppermost part of unit 3 is dominated by dolomite with a low faunal content (Fig. 2.17B), the underlying partially dolomitized limestone is characterized by a prevalence of ostracods (Fig. 2.17C), dasycladacean algae (Fig. 2.17D), and benthic foraminifera (Fig. 2.17E-F). Unit 3 does not display the same amount of bioturbation as the underlying units 1 and 2, and bioturbation is estimated to be less than 5%.

2.4.2. Biogenically influenced fluid flow media in the Khanasir Member of the Aruma Formation

An analysis of the ichnological characteristics of the Khanasir Member reveals that units 1 and 2 can be classified into three biogenically influenced fluid flow media (BIFM) due to their extensive burrows and the contrasting porosity within the burrows compared to the surrounding matrix. The rock matrix of unit 3 was not considered as BIFM because it possesses very low bioturbation percentage (< 5%).

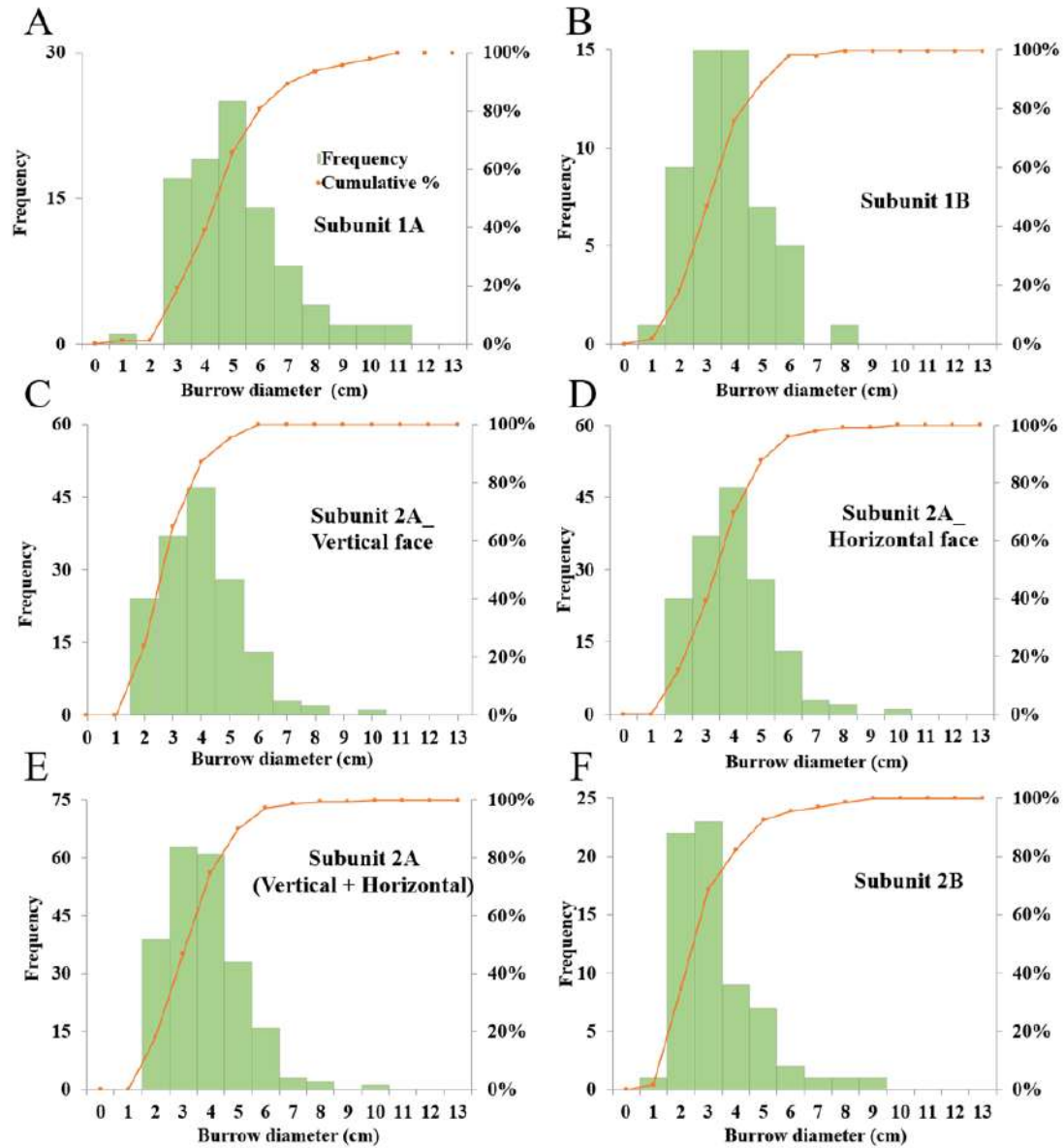


Figure 2.7: Burrow diameter measurements of Units 1 and 2. (A) Burrow diameter in subunit 1A. (B) Burrow diameter in subunit 1B. (C) Burrow diameter in subunit 2A, vertical face. (D) Burrow diameter in subunit 2A, horizontal face. (E) Average diameter in subunit 2A. (F) Burrow diameter in subunit 2B. Figure A, B, and F are super-K subunits. The burrow diameter in subunit 1A is slightly higher than the other subunits. Fig. 7A and 7B represent BIFM1; Fig. 7C-E represent BIFM2; and Fig. 7F represents BIFM1.

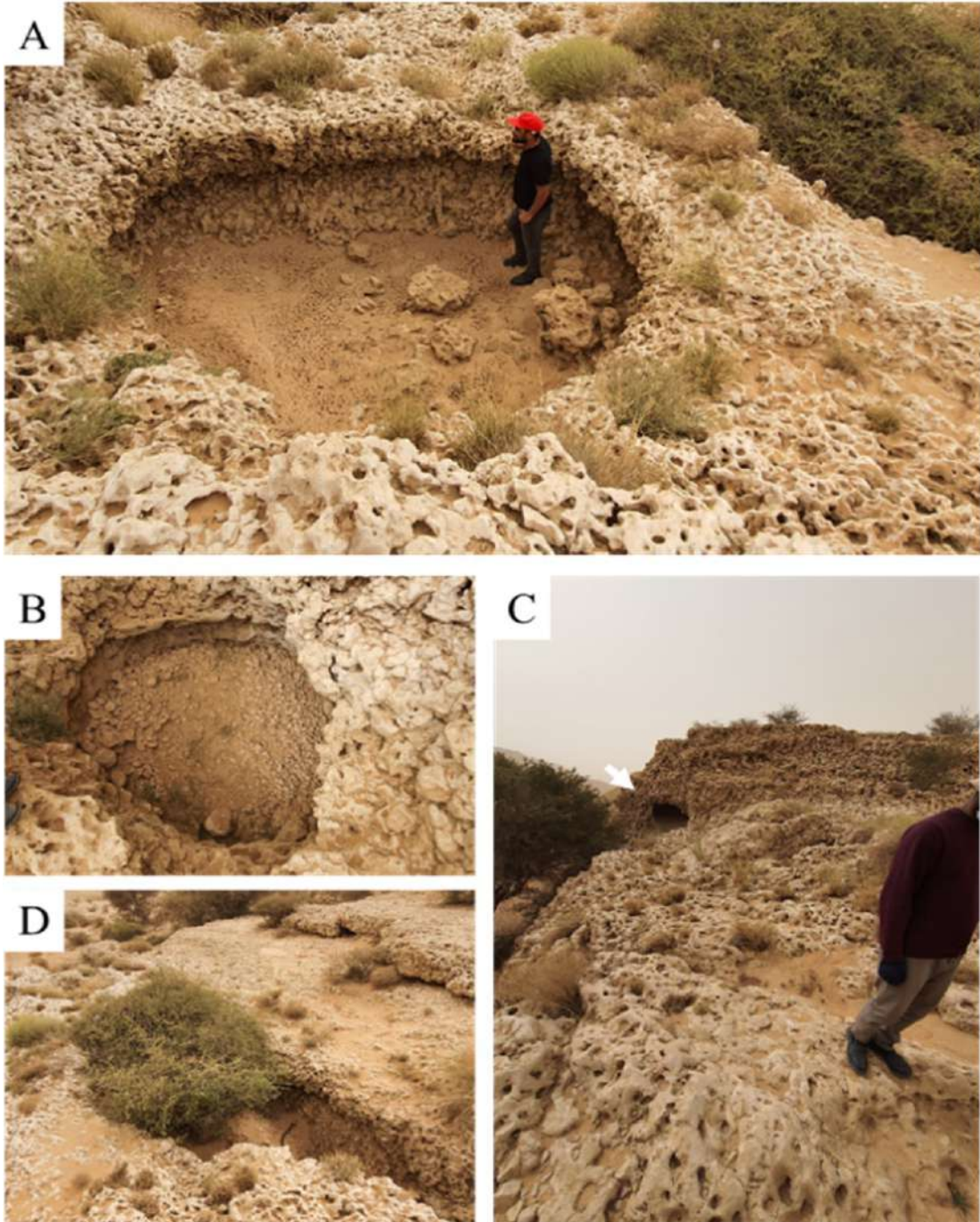


Figure 2.8: Outcrop photographs showing karst features in the Khanasir Member. Features include: (A) sinkholes with collapse boulders; (B) sinkholes with collapse breccia. (C) caves (white arrow). (D) sinking streams. In the Khanasir Member, these karst features offer flow pathways in addition to the burrows, and reflect modification of the burrows during subaerial exposure and karstification.

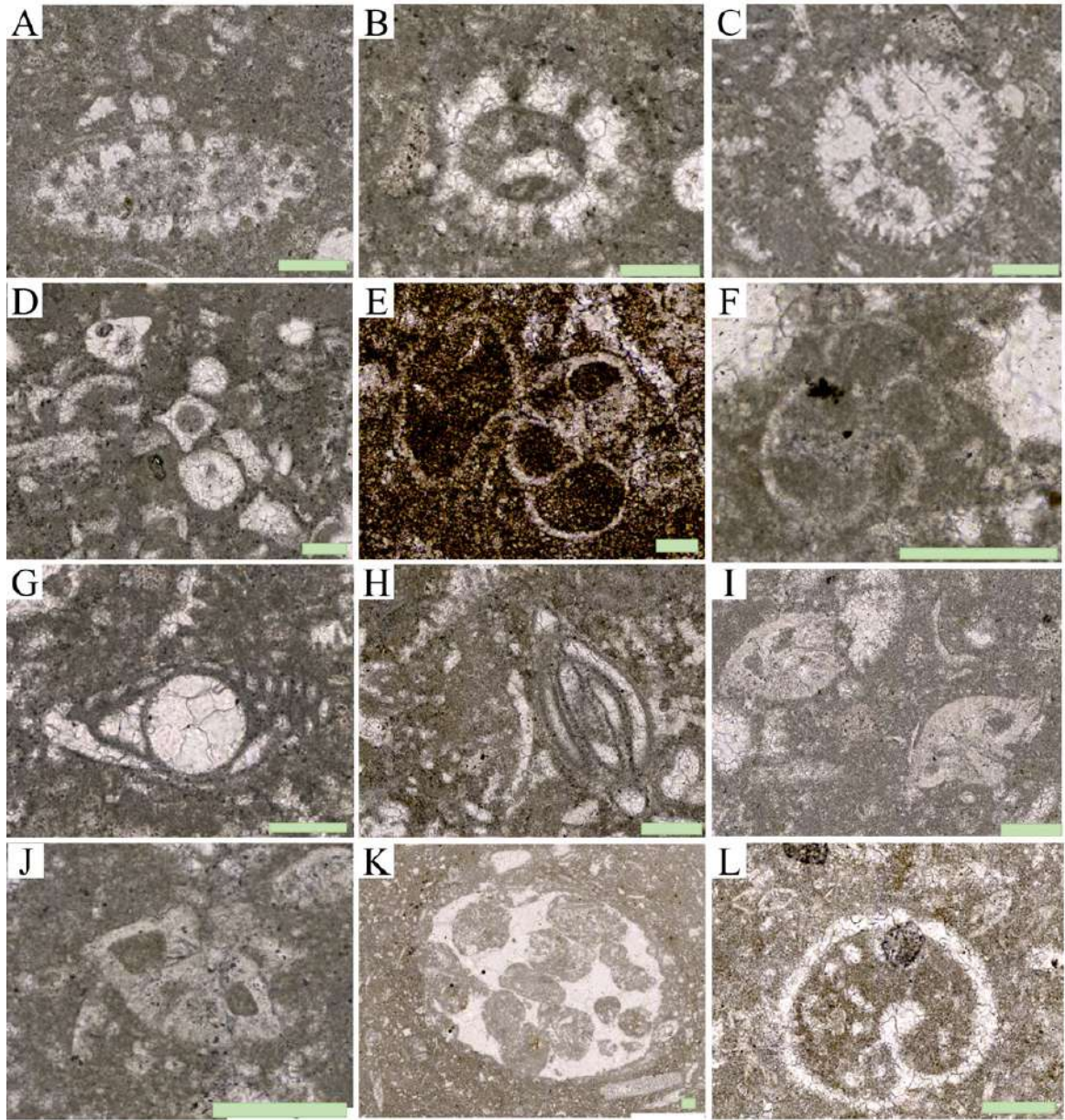


Figure 2.9: Thin section images of faunal content in unit 1A. (A-D) Dasycladacean green algae (E-F) Planktonic foraminifera (G) Large benthic foraminifera (H) Miliolids (I) Rotalina (I-J) Planktonic foraminifera (K) Bryozoans (L) Transverse section of gastropod. The scale bar (green rectangular) is 200 micrometers.

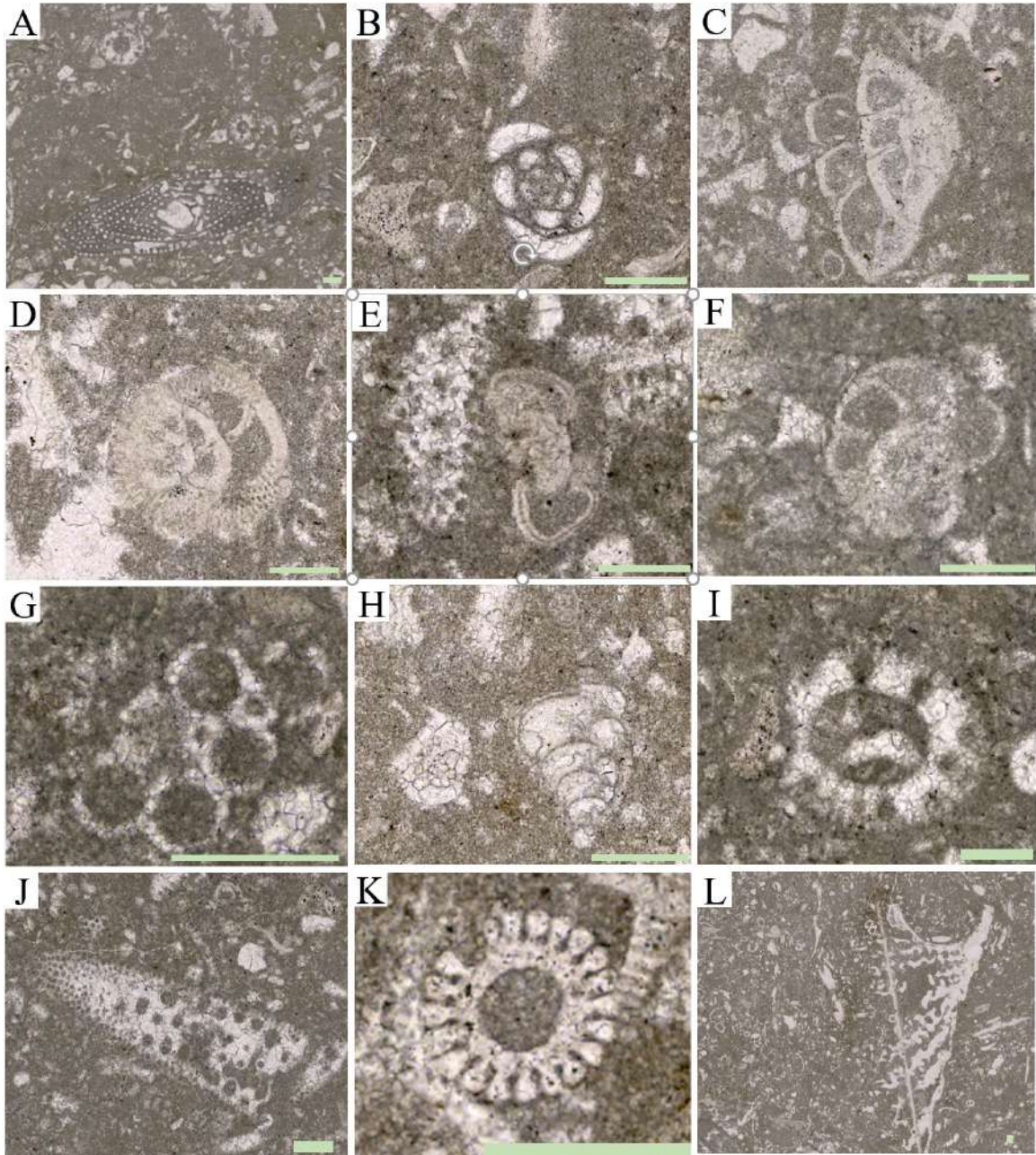


Figure 2.10: Thin section images of faunal content in unit 1B. (A) Large benthic foraminifera (B) Miliolids (C-D) Rotalina (E-H) Planktonic Foraminifera (I-J) Dasycladacean green algal (K) Echinoderms (L) Bryozoans. The scale bar (green rectangular) is 200 millimicron.

BIFM 1 comprises solution-enlarged open *Thalassinoides* in sub-unit 1A and part of sub-unit 1B, and solution-enlarged partially filled *Thalassinoides* in the upper part of sub-unit 1B (Fig. 2.3, 2.5). BIFM 2 is represented by filled *Thalassinoides* in sub-unit 2A (Fig. 2.14). The pore system, porosity, and permeability are all very different between these BIFMs (Table 2.2). Lastly, BIFM 3 comprises compacted open and partially filled *Thalassinoides* in sub-unit 2B (Fig. 2.11).

A. BIFM 1

Based on the analysis of CT scan data and image analysis, the burrow percentage of *Thalassinoides* is estimated to range from ~10% to 41% (Fig. 2.3), and these burrows are either open or partially filled. Thus, *Thalassinoides* contributes significantly to the total porosity of these strata. The solution-enlarged shafts and tunnels of the *Thalassinoides* make connected burrows with substantially large pores (reaching up to ~10 cm in diameter in cross-section). Therefore, they contribute substantially to the permeability of this BIFM. There is also a significant contribution to the total porosity of BIFM 1 from the porosity of the host rock matrix ranging from 3.4% to 14.4%, with a mean of 7.7%, and a standard deviation of 2.9 (Table 2.2). The matrix porosity comes from vug (Fig. 2.18B1, B2), moldic (Fig. 2.18C1-D2), and shelter (Fig. 2.18E1, E2) pores.

Spot permeability measurements indicate a tight host rock matrix with values that range from 0.08 to 0.88 mD, a mean of 0.25 mD, and a standard deviation of 0.42 (Table 2.2). Spot permeability could not be measured on the open *Thalassinoides* pores of BIFM 1. In such a case, permeability is expected to be extremely high, in the multiple Darcy range, similar to what has been reported elsewhere in the Upper Jubaila Formation, the Early Cretaceous Fort Terrett Formation in the eastern Edwards Plateau, Texas, and the Glen

Rose Limestone (GRL) in south-central Texas (Eltom et al., 2020; Golab et al., 2017; Cunningham et al., 2012).

B. BIFM 2

The burrow porosity indeed contributes to the total porosity, but its impact on reservoir quality is limited due to the tight permeability of the burrow fill material. Although the overall porosity is favorable, the restricted permeability diminishes its significance in enhancing reservoir quality. The porosity of the *Thalassinoides* filling ranges from 4.42% to 15.3% with an average of 9.16% and a standard deviation of 5.54%; the permeability ranges from 0.07 to 0.1 mD with an average of 0.08 mD. The host rock matrix of BIFM 2 contains fracture porosity (Fig. 2.18A1, A2) and intercrystalline porosity (Fig. 2.18F1, F2) that ranges from 15% to 24% with a mean of 18.4% and a standard deviation of 5.08%. The spot permeability of the host rock matrix ranges from 0.63 to 3.3 mD with an average of 1.98 mD and a standard deviation of 1.91 (Table 2.2). The combined average porosity and permeability of the *Thalassinoides* filling and host rock matrix are 12.62% and 0.74 mD, with standard deviations of 7.2 and 1.28, respectively.

C. BIFM 3

BIFM 3, on the other hand, has open *Thalassinoides* that contribute greatly to the total porosity of the strata. Based on image analysis, the burrow percentage of *Thalassinoides* ranges from 10% to 30% (Fig. 2.11). The compacted open shafts of the *Thalassinoides* form connected burrows with an average pore diameter of 3.3 cm. The porosity of the host rock matrix also contributes significantly to the total porosity of BIFM 3, ranging from 3.5% to 12.2% with a mean of 7.3% and a standard deviation of 4.4 (Table 2.2). The spot permeability

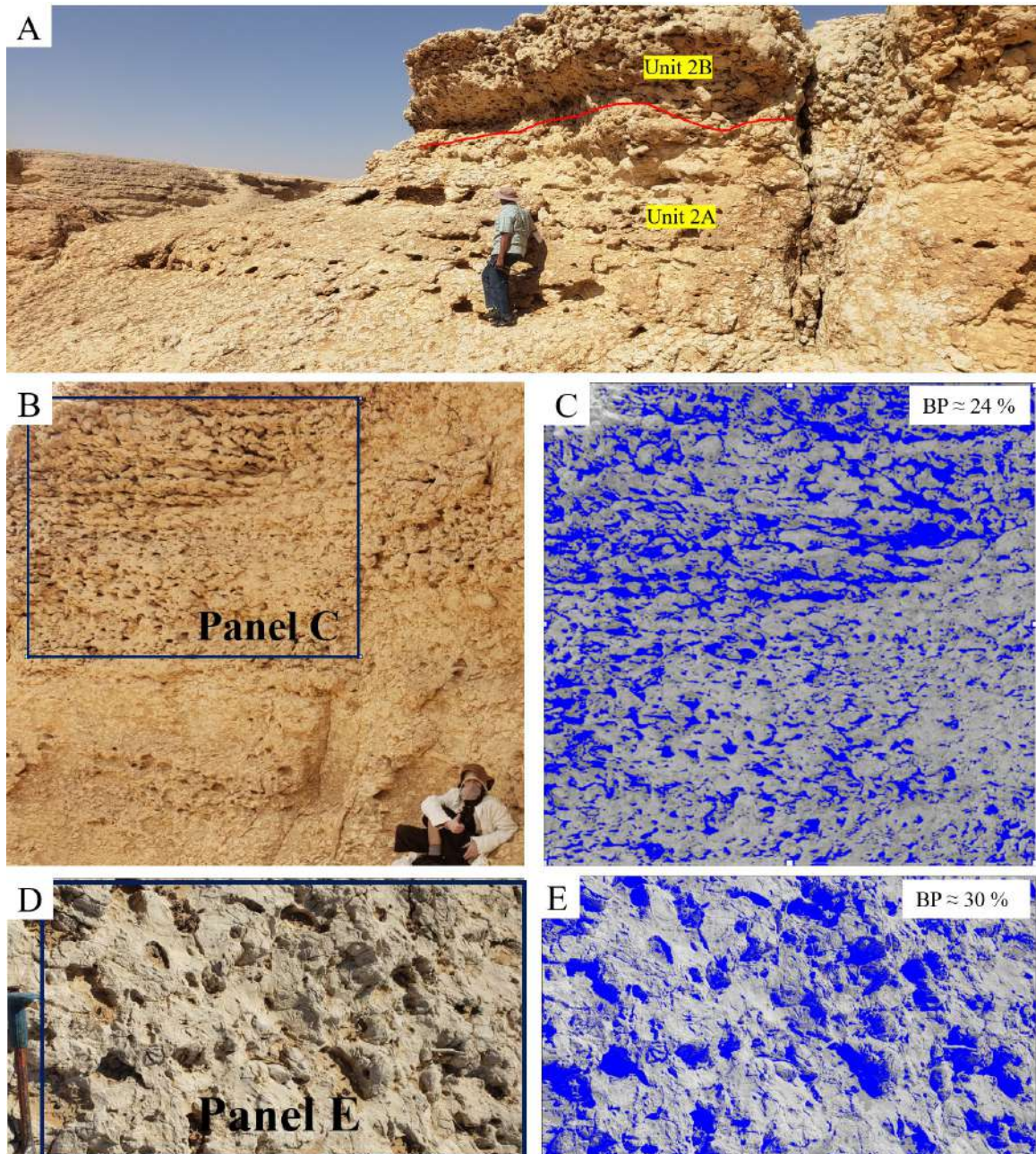


Figure 2.11: Outcrop photographs of unit 2B and image analysis. (A) Field photo showing relation between units 2A and 2B; (B) vertical face of unit 2B; (C) image analysis of Plane C showing the burrow percentage; (D) top of horizontal face in unit 2B showing large and open burrows; (E) image analysis of Plane D showing the burrow percentage.

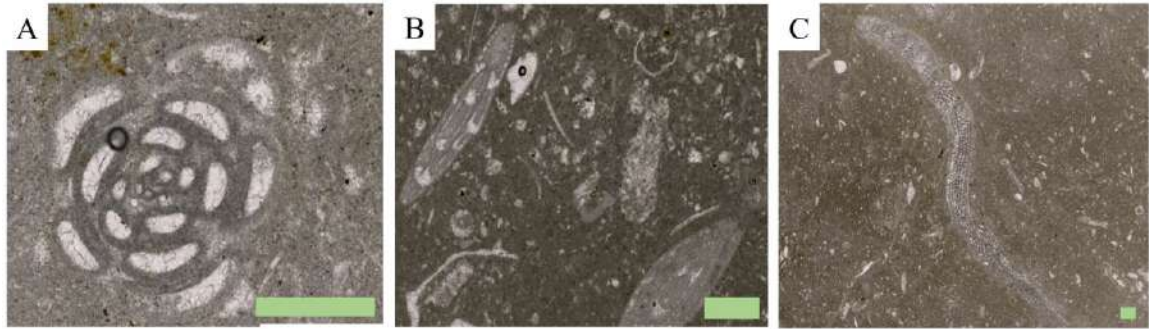


Figure 2.12: Thin section images of benthic and large benthic foraminifera in unit 2B. (A) Benthic foraminifera (B-C) Large benthic foraminifera. The scale bar (green rectangular) is 500 millimicron.

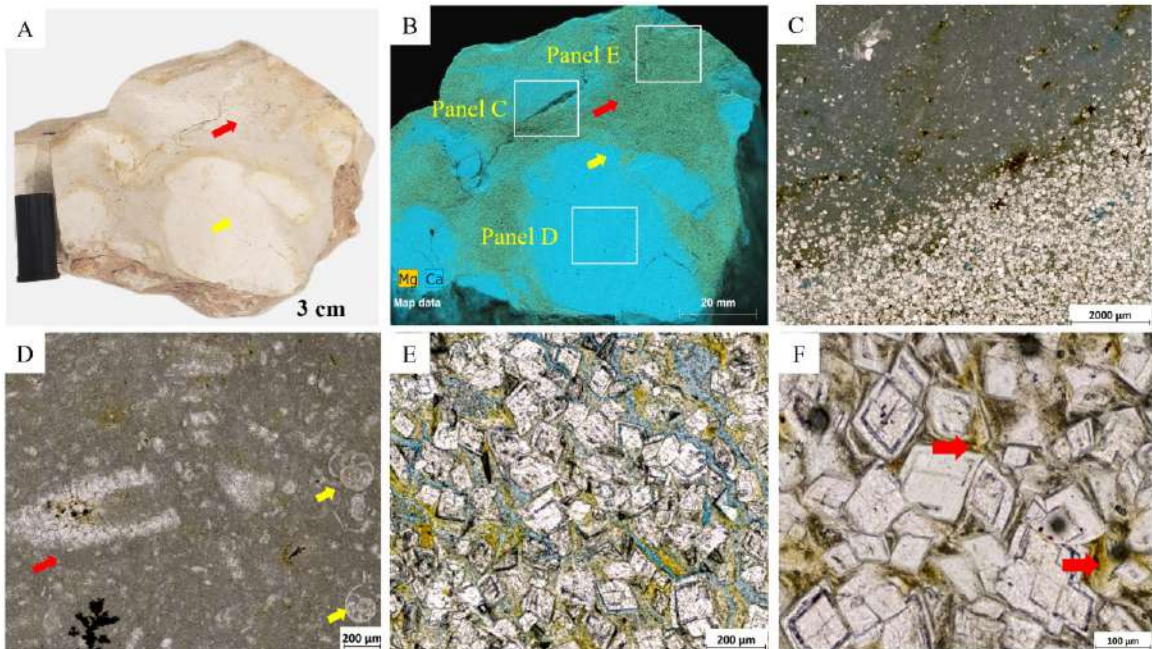


Figure 2.13: Photographs of a slabbed surface and thin section images of both burrow filling and host rock matrix from unit 2A. (A) Slabbed surface which exhibits both the burrow fills and the matrix; the white color is burrow filling and the gray color is host rock matrix. (B) Elemental maps for the same slabbed surface shows the variation in chemical composition, where the green color (red arrow) represents the matrix, and blue color (yellow arrow) indicates the burrow. (C) Thin section showing micritic burrow filling (upper section) and dolomite matrix (lower section). Note that most of the dolomitization occurred in the host rock matrix, whereas the dolomitization did not fully dolomitize the burrow fillings, except for a few isolated dolomite crystals. (D) Thin section of nodular limestone (burrow filling) containing dasycladacean algae (red arrow), planktonic foraminifera (yellow arrow). (E) Dolomitized matrix. (F) Close up view of the dolomite which shows zonation (red arrow points to clay minerals).

measurements show a tight host rock matrix with values ranging from 0.08 to 0.58 mD, an average of 0.34 mD, and a standard deviation of 0.25 (Table 2.2).

2.5. Discussion

2.5.1. Depositional Environment

The interpretation of the depositional environment in the Aruma Formation is based on a combination of field observations, laboratory analysis results, and previous works (Al-Kahtany et al., 2016; Farouk et al., 2020; Gameil et al., 2020; Hughes et al., 2020; Philip et al., 2002). The formation is believed to have been deposited in an open marine to restricted marine platform. The three BIFMs, which comprise distinct ichnological characteristics and host rock matrix, are interpreted separately below.

BIFM 1, characterized by solution-enlarged *Thalassinoides*, is interpreted to have been deposited in a platform interior (open marine setting). This is based on the presence of wackestone to packstone textures, benthic and planktonic foraminifera, algae, and other fossils such as bryozoans, bivalves, and gastropods in the host rock matrix (Fig. 2.9, 2.10). The microfacies correlate to the standard microfacies 18 of (Flügel, 2010), which is characterized by bioclastic grainstones and packstones that are rich in benthic foraminifera or calcareous algae. Furthermore, it aligns with facies zone (FZ) 7, as described by (Wilson, 1975), representing a "platform interior, open marine" environment. The upper part of Unit 1 (sub-unit 1B) shows a greater abundance of benthic and planktonic foraminifera and less dasycladacean algae compared to sub-unit 1A. The Unit 1 is believed to be deposited under moderate-energy conditions, as evidenced by wackestone to packstone texture, and fossils fragments (e.g., dasycladacean algae) (Čatalov, 1972; Plumley et al., 1962). The extensive bioturbation indicates a well-oxygenated water column (Allison et al., 1995; Gautreau et

al., 2020), and normal marine salinity is indicated by calcareous benthic foraminifera and Bryozoans (Flügel, 2010). The presence of Rotaliina and Miliolina foraminifera suggests warm to moderate temperatures (Flügel, 2010). Evidence of subaerial exposure is present in the top of sub-unit 1B, resulting in the enlargement of burrow shafts.

BIFM 2, representing sub-unit 2A, is characterized by filled *Thalassinoides*, and has a host rock matrix that consists of fabric-destructive dolomite and palygorskite. As a result, the host rock matrix does not provide abundant evidence for interpreting depositional environments. Nonetheless, the burrow filling and the remaining non-dolomitized matrix indicate that the depositional environment was a fairly restricted lagoon, based on the rock texture (mudstone to wackestone), the low diversity of fauna compared to BIFM1. This

ID	BIFM unit	Stratigraphic unit	Na	Mg	Al	Si	Ca	Calcite %	Dolomite %	Palygorskite %	Halite %	Orthoclase %	Quartz %
1	BIFM 1	1A	0	0.1	0.46	0.73	97.93	100					
2	BIFM 1	1A	0	0.24	0.37	0.26	98.73	100					
3	BIFM 1	1A	0	0.07	0.35	0.19	99	100					
4	BIFM 1	1A	0.11	0.09	0.36	0.27	98.79	100					
5	BIFM 1	1A	0.2	0.12	0.31	0.17	98.89	100					
6	BIFM 1	1A	0	0.11	0.29	0.16	99.15	100					
7	BIFM 1	1A	0	0.18	0.32	0.15	99.01	100					
8	BIFM 1	1A	0	0.12	0.34	0.14	98.89	100					
9	BIFM 1	1A	0	0.24	0.39	0.46	98.34	100					
10	BIFM 1	1B	0.04	0.28	0.3	0.34	98.49	100					
11	BIFM 1	1B	0	0.28	0.3	0.37	98.56	100					
12	BIFM 1	1B	0	0.23	0.39	0.63	98.06	100					
13	BIFM 1	1B	0.02	0.2	0.4	0.62	98.05	100					
14	BIFM 1	1B	0	0.32	0.36	0.45	98.29	100					
15	BIFM 1	1B	0	0.12	0.34	0.31	98.66	100					
16	BIFM 1	1B	0.02	0.15	0.34	0.43	98.34	100					
17	BIFM 1	1B	0	0.58	0.53	1.97	96.18	100					
18	BIFM 1	2B	0	0.5	0.62	3.03	94.96	100					
19	BIFM 1	2B	0.21	0.46	0.39	1.44	96.83	100					
20	BIFM 1	2B	0.1	0.29	0.36	1.04	97.69	100					
21	BIFM 1	2B	0	0.22	0.31	0.84	98.21	100					
22	BIFM 1	2B	0	0.25	0.31	0.73	98.2	100					
23	BIFM 1	2B	0	0.14	0.33	0.75	97.96	100					
24	BIFM 2	2A	0	16.32	2.72	14.06	62.35	2.1	83.5	14.4			
25	BIFM 2	2A	0	13.26	0.98	6.29	77.33	18	18.7	81.3			
26	BIFM 2	2A	0	13.12	1.11	7.27	75.88	19	17	83			
27	BIFM 2	2A	0.11	1.17	0.95	3.94	91.82	98.3		1.7			
28	BIFM 2	2A	0	0.67	0.74	3.57	94.07	97.1		1			1.9
29	BIFM 2	2A	0	1.02	0.52	2.38	95.11	94.8	4.3				0.9
30	No_BIFM	3	0	0.48	0.44	0.57	96.62	100					
31	No_BIFM	3	0	3.65	1.81	3.76	86.2	79.5	18.1			2.4	
32	No_BIFM	3	1.76	18.85	1.54	3.2	64.17		97.4		2.6		
33	No_BIFM	3	0	24.44	0.54	1	71.64		100				
34	No_BIFM	3	0	19.61	0.36	0.45	78.75	21.8	78.2				
35	No_BIFM	3	0	22.02	1.65	3.37	71.49		100				
36	No_BIFM	3	0	21.52	0.6	1.4	75.3	3.4	96.6				

Table 2.1.: The XRD and XRF results of the host rock matrix and burrow filling of the Khanasir Member. Note that samples from 1 to 23 represents the analysis of the host rock matrix of biologically influenced fluid flow media 1 (BIFM1) (unit 1 and subunit 2B), samples from 24-26 represent the composition of the host rock matrix of subunit 2A, samples from 27 to 29 represent the composition of the burrow filling of subunit 2A, and samples from 30 to 36 represent the composition of the host rock matrix of unit 3.

microfacies aligns with facies zone (FZ) 8, as described by (Wilson, 1975), representing "platform interior - restricted". The ratio of the burrow filling (nodular limestone) to the matrix (replacement dolomite) [B/M] noticeably varies within this sub-unit, with an overall upward decrease in B/M (Fig. 2.14A, D). These variations are interpreted as variations in bioturbation percentage and compaction along this sub-unit. The greater the percentage of burrowing at a given interval, the greater the volume of nodular limestone (e.g. Fürsich, 1972). Sediment compaction also reduced the distance between burrow horizons, causing the burrow fillings approach on another more closely (Fig. 2.14C, F).

BIFM 3, sub-unit 2B, characterized by compacted *Thalassinoides*, is interpreted to have been deposited on a restricted marine platform due to the presence of mudstone to wackestone texture, reduced fauna diversity, and abundance of individual fauna such as miliolids and large benthic foraminifera (Fig. 2.12). The BIFM 3 facies aligns with facies zone (FZ) 8, as described by (Wilson, 1975; Flügel, 2010), representing "platform interior – restricted".

2.5.2. Impact of the *Thalassinoides* on fluid flow and storage capacity

The classification of the bioturbated strata (units 1 and 2) into three BIFMs has important implications for understanding the aquifer and reservoir properties of these units. BIFM 1 and BIFM 3, which comprise solution-enlarged open and partially filled *Thalassinoides* in unit 1 and compacted open and partially filled *Thalassinoides* in sub-unit 2B, respectively,

Sample ID	BIFM unit	Stratigraphic unit	Porosity %	Permeability (mD)			Note
				Min	Mean	Max	
1	BIFM 1	1A	13.51	1.10	1.66	1.89	
2	BIFM 1	1A	14.42	0.74	0.89	1.06	
3	BIFM 1	1A	8.88	0.11	0.13	0.21	
4	BIFM 1	1A	9.75	0.17	0.20	0.28	
5	BIFM 1	1A	8.99	0.22	0.41	0.54	
6	BIFM 1	1A	9.12	0.39	0.49	0.55	
7	BIFM 1	1A	8.50	0.11	0.12	0.13	
8	BIFM 1	1A	4.82	0.09	0.09	0.09	
9	BIFM 1	1A	7.61	0.09	0.09	0.09	
10	BIFM 1	1B	6.44	0.08	0.08	0.08	
11	BIFM 1	1B	3.46	0.08	0.08	0.08	
12	BIFM 1	1B	5.15	0.07	0.08	0.08	
13	BIFM 3	2B	4.90	0.08	0.08	0.08	
14	BIFM 3	2B	3.52	0.07	0.59	3.62	
15	BIFM 3	2B	6.29	0.08	0.08	0.09	
16	BIFM 3	2B	12.27	0.09	0.35	0.86	
17	BIFM 2	2A	8.00	0.12	0.24	0.44	represent both burrow filling and matrix
21	BIFM 2	2A	16.00	1.78	3.34	4.42	represent both burrow filling and matrix
22	BIFM 2	2A	24.26	0.08	0.63	3.71	represent the matrix
18	BIFM 2	2A	15.30	0.10	0.10	0.11	represent the burrow filling
19	BIFM 2	2A	4.42	0.07	0.08	0.08	represent the burrow filling
20	BIFM 2	2A	7.77	0.08	0.09	0.09	represent the burrow filling
23	NO-BIFM	3	13.93				
24	NO-BIFM	3	26.41	5.29	7.26	9.52	
25	NO-BIFM	3	35.62	37.50	73.00	134.00	
26	NO-BIFM	3	19.96	0.94	1.09	1.34	
27	NO-BIFM	3	35.63	68.67	82.59	93.62	
28	NO-BIFM	3	36.13	86.72	98.07	109.71	

Table 2.1: Porosity and permeability measurements of 28 cores of the biologically influenced fluid flow media 1 and 3 (BIFM1 and 3) matrix, as well as the burrow fills and matrix of BIFM2, and unit 3 which is referred to as NO-BIFM since it does not exhibit the same bioturbation as the underlining units 1 and 2.

are expected to have high reservoir quality due to the enhanced porosity of the mud-dominated host rock matrix (average porosity values of the host rock matrix are 8%) and open *Thalassinoides*. These two BIFMs (1, 3) are separated by BIFM 2, which has filled *Thalassinoides* in sub-unit 2A. The tight burrow fillings and fair petrophysical properties of its host rock matrix (average porosity and permeability are 18% and 2 mD, respectively) make BIFM 2 act as a baffle to fluid flow in the porous media. Consequently, the reservoir

quality in this unit is poor to fair due to the unfavorable petrophysical characteristics of the host rock matrix and burrow filling, which have an average bulk porosity and permeability of 12.62% and 0.74 mD, respectively.

The differences in porosity and permeability between the three BIFMs have significant consequences for water and hydrocarbon exploration and production. BIFM 1 and 3 have a larger potential for economically hosting water and hydrocarbon than BIFM 2. Therefore, understanding the geographical distribution and variability of these BIFMs within the Khanasir Member is crucial for effective natural resource exploration and development. This knowledge can be used to identify areas of high potential for water and hydrocarbon accumulation, and to optimize the location and design of wells to maximize production. Additionally, the results of this study can contribute to the understanding of the hydrogeological processes occurring within the Aruma Formation, which can inform resource management and conservation efforts.

2.5.3. Implications

The findings of this study have significant implications for the understanding and exploration of bioturbated carbonate reservoirs, both locally and globally. The identification of three distinct BIFMs within the Aruma Formation, with varying porosity and permeability characteristics, emphasizes the importance of a detailed understanding of the depositional environment and bioturbation influence on reservoir quality.

Locally, in Saudi Arabia, the Aruma Formation is a widespread formation that has not been extensively studied in terms of its hydrocarbon and water potential. The identification of BIFM 1 and 3 as potentially super-permeable zones with high reservoir quality suggests that these units should not be disregarded during exploration for hydrocarbons or aquifers.

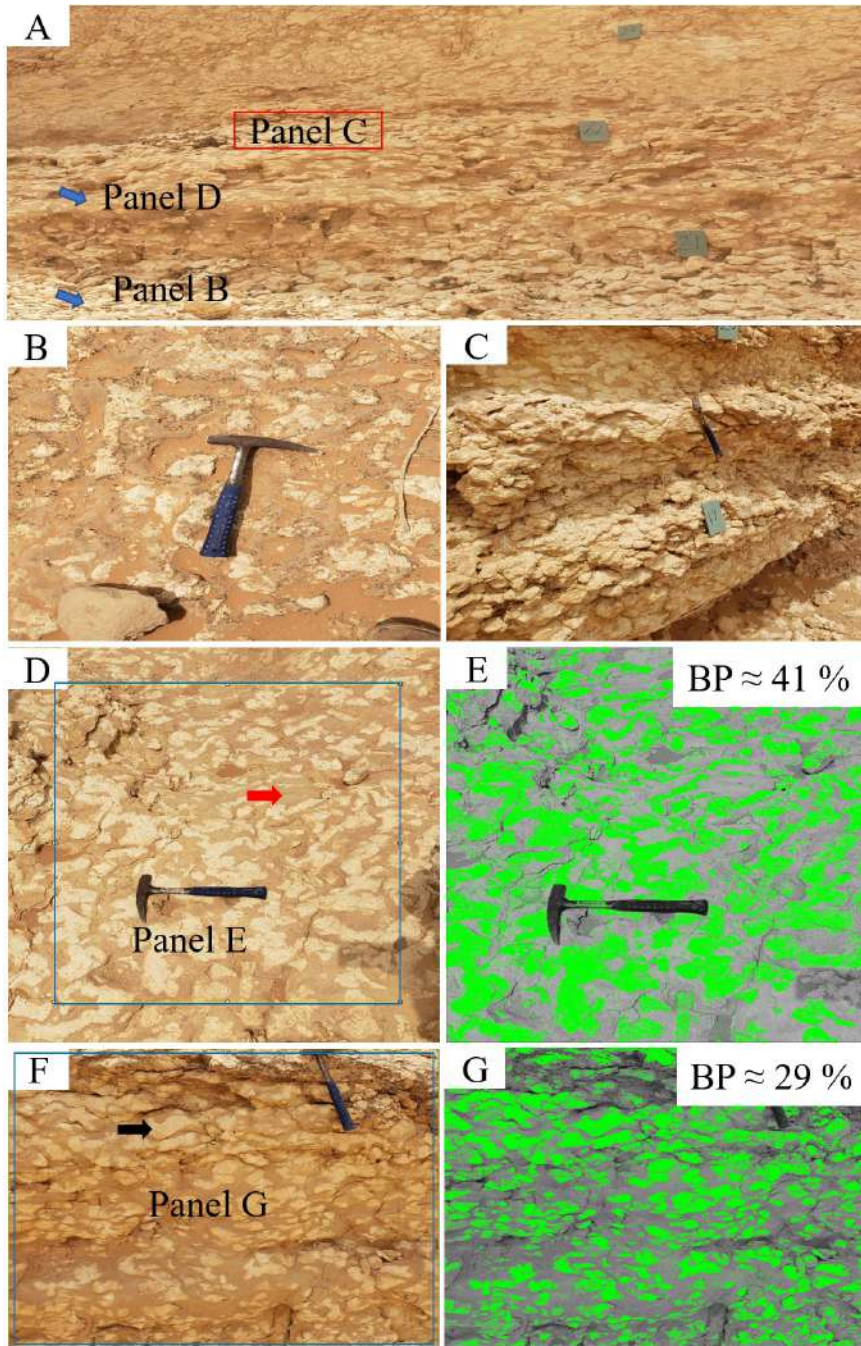


Figure 2.14: Outcrop photographs of unit 2A and image analysis. (A) Cross section view of the nodular limestone (burrow filling) and dolomite (matrix). (B) Bedding plane view of the nodular limestone (burrow filling) and dolomite (matrix) with noticeable decrease of burrow-matrix ratio (B/M) compared to Fig. 2.14D. (C) Vertical cross section view of the nodular limestone (burrow filling) and dolomite (matrix) with a noticeable increase of B/M compared with Fig. 2.14F. (D) Bedding plane view of the nodular limestone (burrow filling) and dolomite (matrix) with noticeable increase of B/M compared to Fig. 2.14B (red arrow points to the matrix). (E) Image analysis of plane E shows an example of the burrow percentage of

subunit 2A. (F) Vertical cross section view of the nodular limestone (burrow filling) and dolomite (matrix) with a noticeable decrease of B/M compared to Fig. 14C (black arrow points to the burrow filling). (G) Image analysis of plane G shows an example of the burrow percentage of subunit 2A. Variation in B/M is related to the bioturbation percentage and compaction.

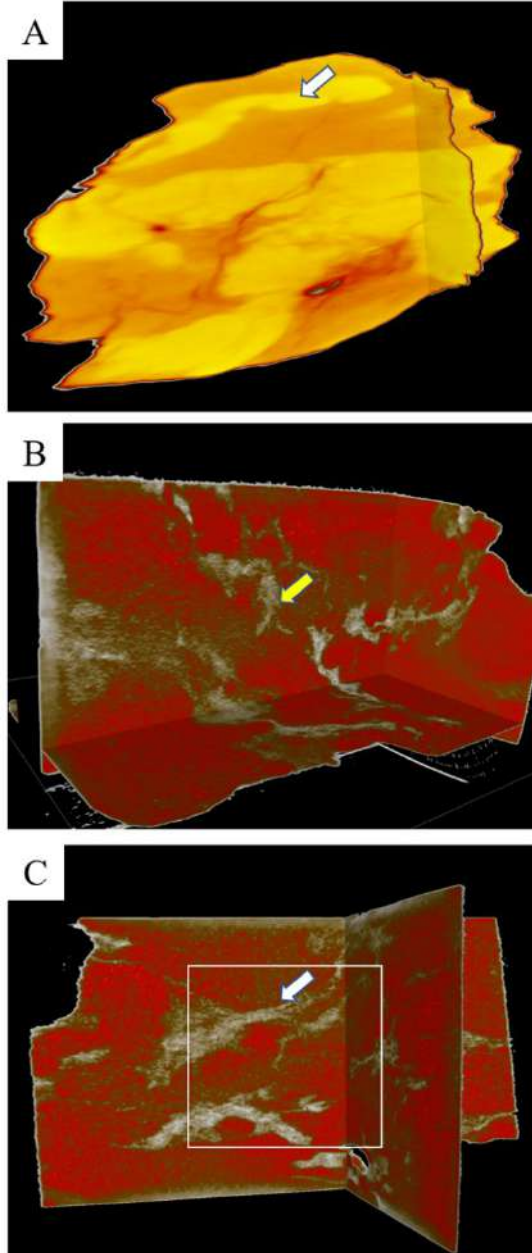


Figure 2.15: Screen captures of the CT scan data of: (A) Irregular-shaped sample, where the orange color represents the matrix, and blue color indicates the burrow; and (B-C) rectangular-shaped sample. The CT scan results show diagnostic criteria for the *Thalassinoides* including: vertical shafts (yellow arrow) and horizontal tunnels (white arrow); and boxwork of the *Thalassinoides* (white box).

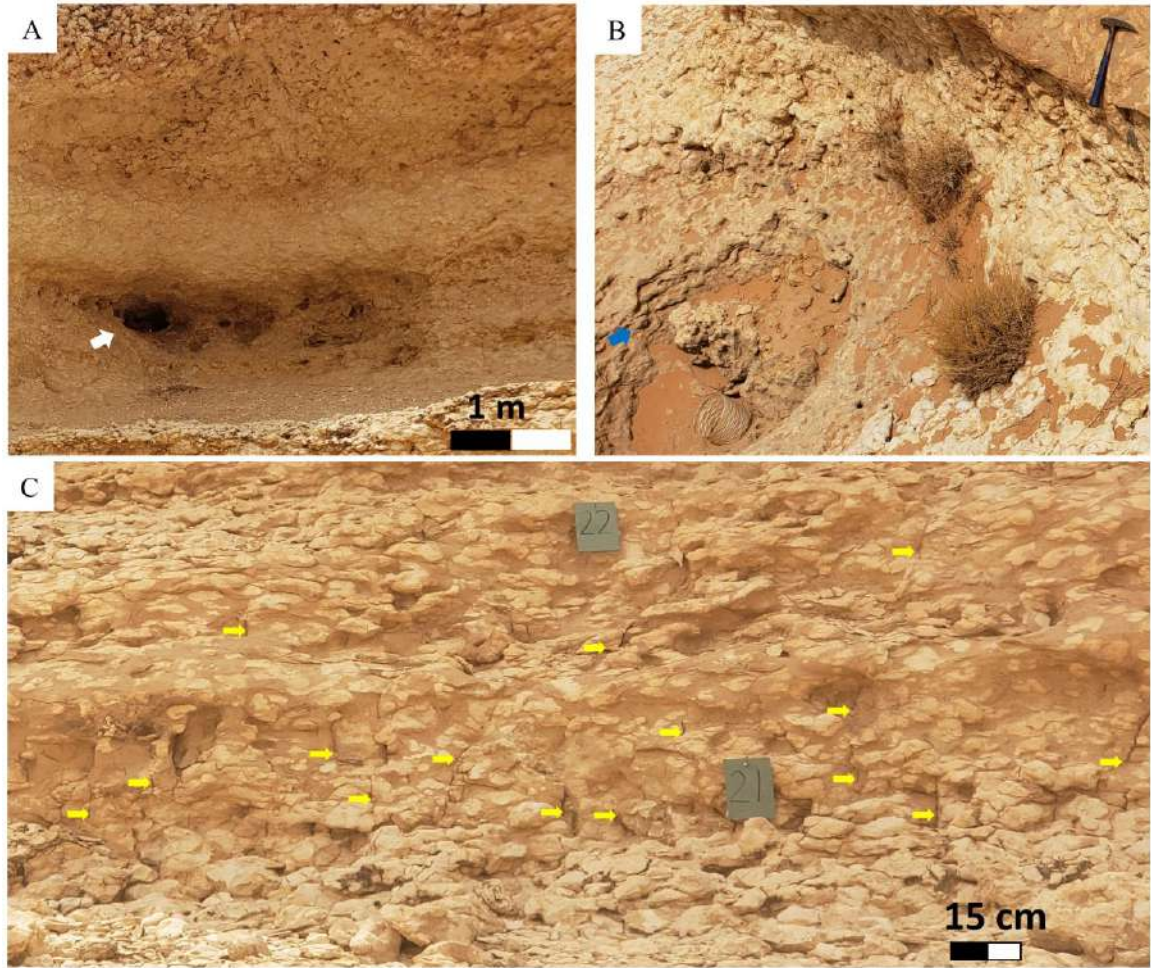


Figure 2.16: Outcrop photographs showing karst features in the Khanasir Member in subunit 2A. Features include (A) Caves; (B) Sinkhole; and (C) Discontinuous semi-vertical solution-enlarged fractures (yellow arrows). In subunit 2A, these karst features and fractures are features of fluid flow pathways.

Additionally, the significant findings of our study open up new perspectives on the CO₂ storage potential within BIFM 1 and 3 due to their favorable rock quality and flow characteristics. However, it's important to note that the feasibility of CO₂ storage is contingent upon the proper depth and pressure conditions of the Aruma formation in the subsurface. While earlier studies (Alsharhan & Nairn, 1990; Kalbus et al., 2011; Keller et al., 2019) suggested the Aruma Formation was an aquitard with limited water supply potential, our findings suggest a more promising scenario. Additionally, our study

emphasizes the significance of integrating an understanding of depositional environment, stratigraphic history, and bioturbation to comprehend reservoir properties. This integration is exemplified by our identification of BIFM 2 acting as a baffle to fluid flow, both within the subunit itself and between BIFM 1 and 3. By considering these factors holistically, we can gain valuable insights into the complex behavior of subsurface formations and their potential impact on fluid flow and resource distribution.

Globally, the findings of this study have practical implications for hydrocarbon and water resources (Cunningham et al., 2009, 2012 ; Golab et al., 2017), as they can be used to optimize exploration and production of bioturbated reservoirs and aquifers in the subsurface. The identification of super-permeable zones and baffles to fluid flow in bioturbated carbonates may help in the prediction of similar reservoirs elsewhere and contribute to the development of new exploration strategies.

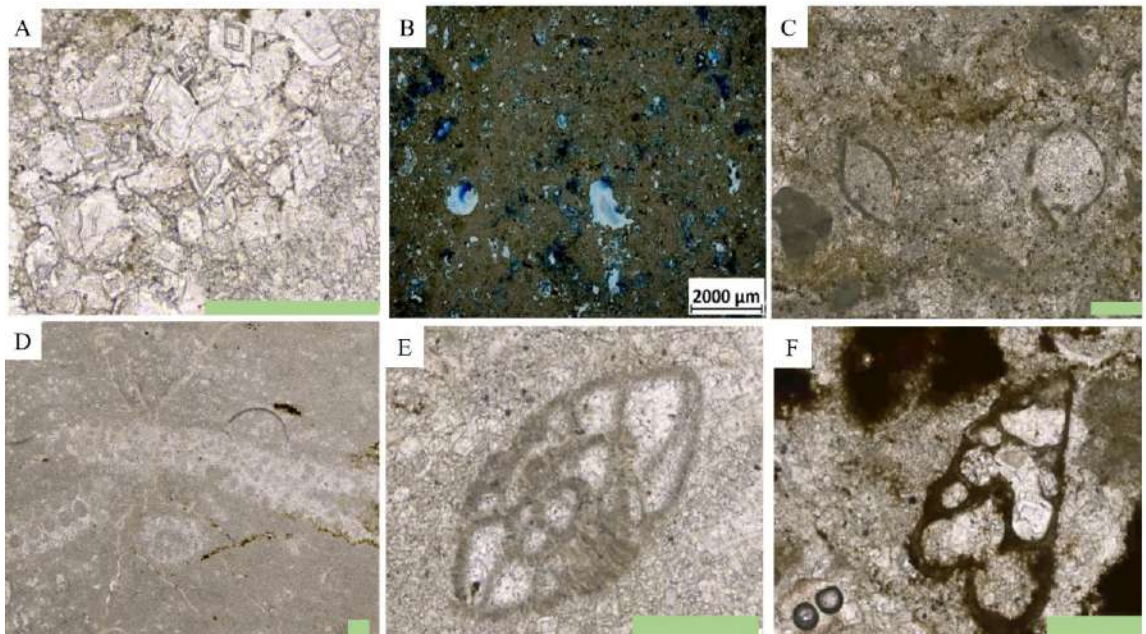


Figure 2.17: Thin section images from the upper unit of the Khanasir Member (unit 3). (A) Dolomite crystals showing zonation. (B) Thin section photomicrograph showing dolomite with high porosity (blue epoxy). (C) Ostracods. (D) Dasycladacean algae. (E-F) Benthic Foraminifera. The scale bar (green rectangular) is 200 millimicron.

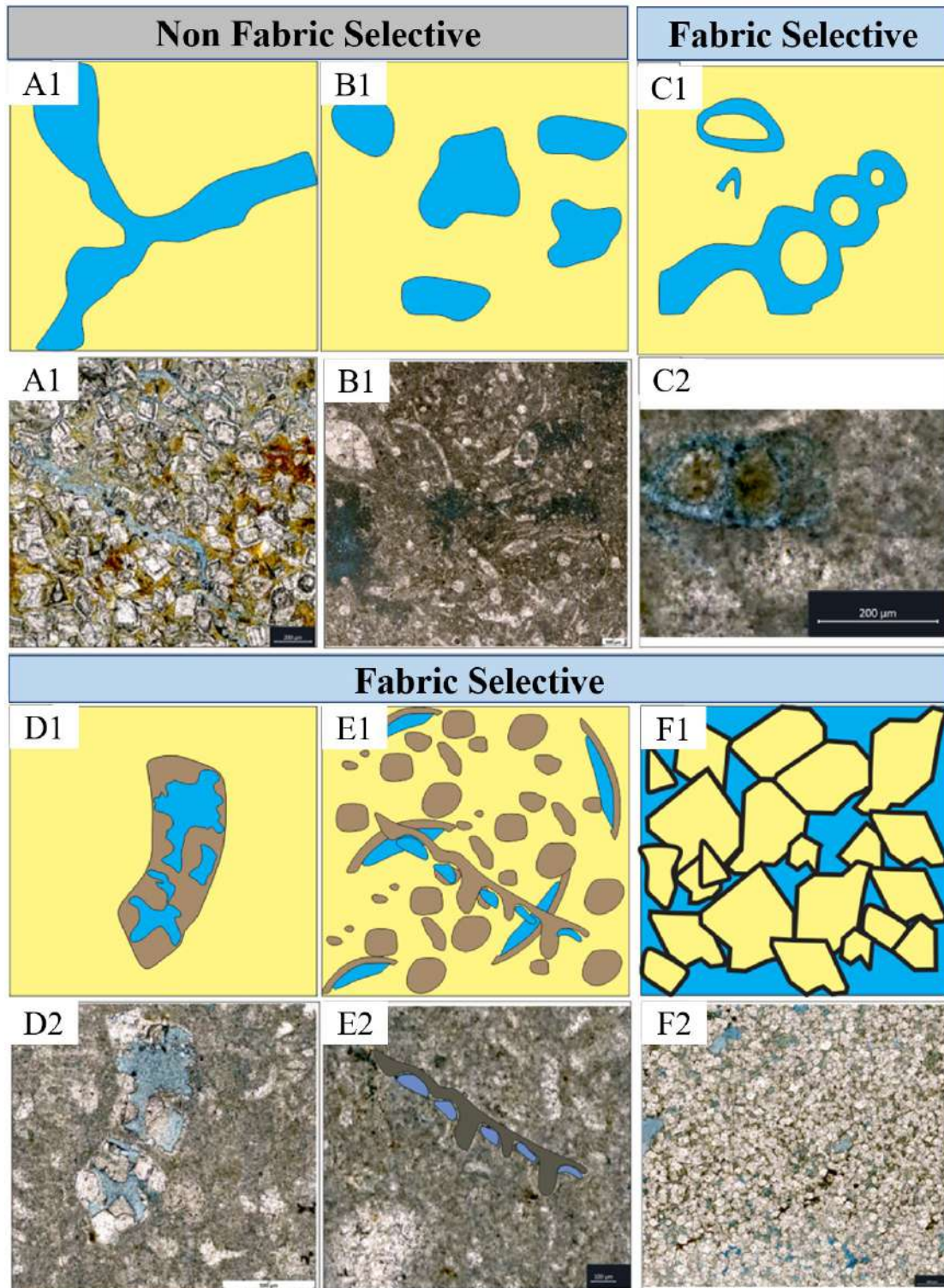


Figure 2.18: Nonfabric and fabric selective porosity of the rock matrix of unit 1 and unit 2. (A1-A2) Channel porosity. (B1-B) Vug porosity. (C1-D2) Moldic porosity. (E1-E2) Shelter porosity. (F1-F2) Intercrystal porosity.

Overall, the detailed analysis of the Aruma Formation in this study provides valuable insights into the complex relationship between bioturbation and reservoir properties, highlighting the importance of a comprehensive understanding of depositional environments for successful exploration and production of hydrocarbons and water resources.

2.5.4. Future Considerations

The findings of this study provide a foundation for future research aimed at understanding the characteristics and behavior of bioturbated carbonate reservoirs. Some possible areas for future work include investigating 1) the reasons why burrows with open shafts remain open, and 2) the origin of the dolomite in the host rock matrix of unit 2. To achieve these objectives, a larger sample size for CT-scan analysis and a high-resolution ground-penetrating radar (GPR) survey on the tops of these sub-units are recommended. This will help to provide a better understanding of the connectivity of the burrows and the bulk permeability.

Additionally, further research could focus on characterizing the acoustic properties of the bioturbated strata, using various representative elementary volumes starting from the core to seismic scale, and measuring their acoustic responses. These steps will enhance understanding of the factors that control the permeability and porosity of bioturbated carbonate reservoirs, and could potentially lead to improved exploration and production of hydrocarbons and water resources in such reservoirs. A limitation of this study is that it focuses on outcrops; the extent of burrow porosity in the subsurface remains uncertain. To address this limitation, the researchers propose the need for future investigation involving the drilling of a wide diameter corehole. Such research would provide valuable insights

into the distribution of porosity beyond the outcrop and enhance our understanding of the subsurface conditions.

2.6. Conclusions

In summary, this study contributes to understanding the factors that control the permeability and porosity of bioturbated carbonate reservoirs. By identifying and characterizing three distinct biogenically influenced fluid flow media facies (BIFMs) within the Aruma Formation, we have demonstrated how the same trace fossils can occur in different depositional settings, resulting in contrasting petrophysical properties that have significant implications for reservoir quality and potential. Our findings reveal that the lower and upper units (BIFM 1 and BIFM 3) are likely to create super-permeable zones due to their interconnected open burrows that enhance the storage and fluid capacity of these strata. These zones may have high potential for serving as aquifers and hydrocarbon reservoirs. Conversely, BIFM 2, which represents filled *Thalassinoides* with poor petrophysical properties, acts as a baffle between two permeable strata, thereby reducing the overall reservoir quality.

The local implications of this study are significant for Saudi Arabia, where the Aruma Formation is a widespread formation and an important target for hydrocarbon exploration and development. Our findings highlight an important stratigraphic interval that could serve as a valuable hydrocarbon reservoir or aquifer, and provide new insights into the sedimentological and stratigraphic controls on the petrophysical properties of *Thalassinoides*. Moreover, our research has global implications for the petroleum industry, as it provides a framework for optimizing the exploration and production of bioturbated

reservoirs in the subsurface and predicting analogous super-permeable and impermeable zones elsewhere.

To further advance our understanding of the bioturbated strata in the Aruma Formation, future research should focus on investigating the factors that control the permeability and porosity of burrows with open shafts and tunnels, as well as the origin of dolomite in the host rock matrix of BIFM 2. The study identifies a limitation in the knowledge of intra-burrow porosity extent beyond exposed surfaces of *Thalassinoides*-bearing outcrops, suggesting the need for further research through the drilling of a wide diameter corehole. Moreover, high-resolution imaging techniques such as CT-scans and ground-penetrating radar (GPR) surveys can be utilized to acquire more data and provide a better understanding of the connectivity of the burrows and the bulk permeability of the strata. Finally, an investigation of the acoustic properties of the bioturbated strata could also contribute to a better understanding of the reservoir properties and potential of these units.

Chapter 3

Controls on fracture propagation in bioturbated carbonate rocks: Insights from the Aruma Formation, central Saudi Arabia

Abstract

Previous research has explored the linkage between bioturbation, porosity, and permeability in carbonate reservoir rocks. The impact of bioturbation on natural fractures in such rocks remains relatively unexplored, however, but is crucial for effective subsurface resource management. This study focuses on the relationship between bioturbation and fracture characteristics in a well-exposed outcrop, the upper Cretaceous Khanasir Member of the Aruma Formation, central Saudi Arabia. The approach includes field investigation, petrography, imaging analysis, and CT scanning to quantify the relationship between burrows and fracture characteristics at scales from thin section to outcrop scale. At the outcrop scale, the Khanasir Member comprises three distinct units based on their fracture and burrow characteristics. These units reveal two primary categories of fractures: (1) burrow-related fractures, influenced and controlled by bioturbation; and (2) non-burrow-related fractures, unaffected by bioturbation. The characteristics of fractures within these units are influenced by multiple factors including: if burrows are filled; composition of the burrow fillings; mineralogy of host rock matrix; texture of the host rock matrix; and burrow percentage. The interplay of these factors

affects fracture attributes such as density, length, and spacing, all of which have a direct impact on fluid flow behavior within subsurface reservoirs.

Keywords : *Thalassinoides*; Geomechanics; CT-scan, Triple-porosity, Carbonate reservoirs

3.1. Introduction

In recent decades, the scientific literature has been replete with studies showcasing the capacity of bioturbated sedimentary strata to serve as high-quality hydrocarbon reservoirs and prolific groundwater aquifers. Here, the term *bioturbated sedimentary strata* refers to sedimentary rocks that have been extensively modified by the burrowing activities of organisms (e.g. Buatois et al., 1999; Gingras et al., 1999; Pemberton and Gingras, 2005; Cunningham and Sukop, 2012; Gingras et al., 2012; Knaust et al., 2012; Knaust, 2013; Knaust, 2014; La Croix et al., 2017; Knaust et al., 2020; Rodríguez Tovar et al., 2021; Baniak et al., 2022). Numerous prior investigations have explored the interplay of bioturbation and its influence on porosity and permeability (Gingras et al., 1999; Cunningham et al., 2009; Cunningham and Sukop, 2012; Baniak et al., 2013; La Croix et al., 2013; Baniak et al., 2014a; Baniak et al., 2014b; Baniak et al., 2015; Golab et al., 2017; Eltom et al., 2019; Deshnenkov and Polo, 2020; Eltom et al., 2020; Niu et al., 2020; Chandra et al., 2021; de Araújo et al., 2021; Eltom et al., 2021; Baniak et al., 2022; El-Husseiny et al., 2022; Niu et al., 2022; Yang et al., 2022). These studies have provided valuable insights and offered practical applications for the exploration and exploitation of hydrocarbon reservoirs and water aquifers.

Whereas the positive and negative correlations between bioturbation and porosity/permeability have been examined (Cunningham et al., 2009, Dey and Sen 2017;

Golab et al., 2017; Alqubalee et al., 2021; Baniak et al., 2022; Saraih et al., 2023) the relationship between bioturbation and natural fractures within sedimentary strata has received only limited research attention, despite the acknowledged significance of fractures in subsurface reservoirs (Ferrill and Morris, 2008; Wennberg et al., 2018). This poses a significant challenge when investigating natural resources, as it hampers the ability to accurately predict the quality of reservoirs and aquifers in the subsurface. Studies by Knaust et al. (2020) and Valencia et al. (2023) have suggested possible connections between bioturbation and fractures. Eltom et al. (2019) and Knaust et al. (2020) proposed that the *Thalassinoides* ichnofabric with its open or passively filled burrows may contribute to high permeability through connectivity with fractures. Late-stage bioturbation in stiffgrounds and firmgrounds was also found to be commonly cross-cut by fractures. Similarly, Valencia et al. (2023) mentioned water expulsion from clay-filled burrows due to overburden pressure and the cementation of substrata as factors influencing fracture development. By elucidating the mechanisms through which bioturbation impacts fracture creation, propagation, or sealing, geologists can enhance their understanding of reservoir connectivity, fluid migration pathways, and the overall dynamics of subsurface fluids. Addressing this knowledge gap will provide valuable insights for investigating and managing natural resources in subsurface environments.

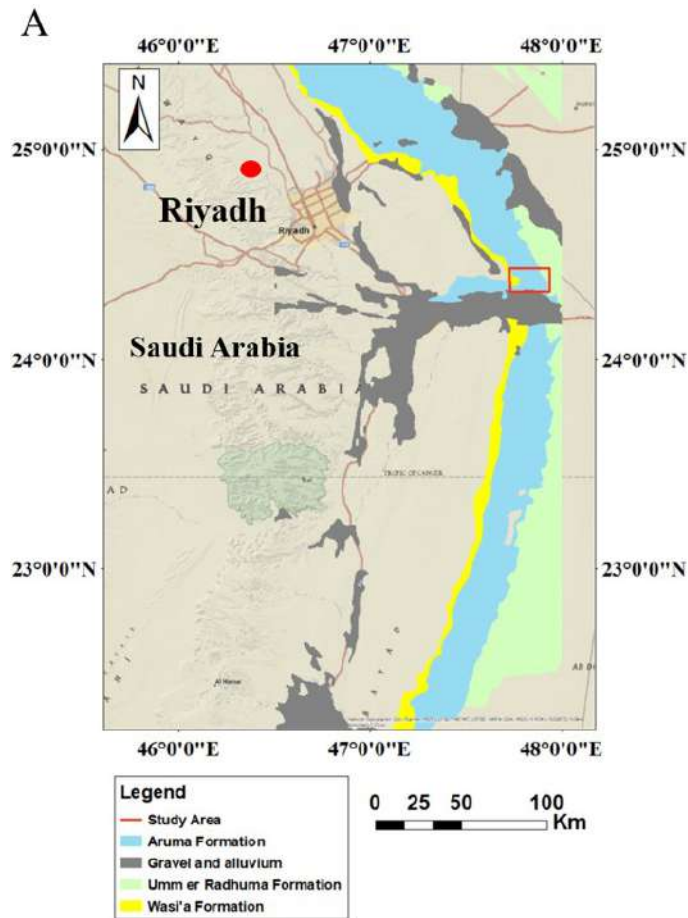
Within this framework, this study aims to test the hypothesis that the distribution of fractures within bioturbated strata is influenced by burrow attributes such as if burrows are filled or not, and their size, the composition and the diagenesis of the host rock matrix and burrow fillings which have an impact on the mechanical properties. To test these hypotheses, this study investigates a well-exposed outcrop of carbonate strata exposing the

Cretaceous Khanasir Member of the Aruma Formation (Fig. 3.1). We employ an integrated methodology including field investigation, petrography, and computed tomography (CT) scanning. The study seeks to unravel the mechanisms through which bioturbation and other factors influence the propagation and distribution of fractures within carbonate strata. The outcomes of this investigation yield insights into the intricate relationship between burrow attributes, other lithologic properties, and fractures, shedding light on the complex geological processes at play. Such insights are paramount in advancing our understanding of fracture behavior in carbonate reservoirs, and potentially increasing our ability to predict and optimize hydrocarbon production from carbonate reservoirs.

3.2. Geological Background

3.2.1. Stratigraphy

The Aruma Formation (Fig. 3.1) was first named by [Steineke and Bramkamp \(1952\)](#), and it extends over a vast distance, stretching more than 1,600 km from Wadi ad Dawasir to the Iraq-Saudi Arabia border ([Powers et al. 1966](#)). Along this expansive range, the outcrop belt of the Formation undergoes a gradual change in strike, transitioning from northeast to north and eventually northwest, wrapping around the central Arabian arch (Fig. 3.1A). The width of the outcrops widen toward the north associated with a reduction in dip. The Aruma Formation in the structurally active Jawf-Sakakah basin is affected by a series of small faults. These faults typically have a strike of about N 20° W (340°) and are either vertical or dip at high angles. They exhibit minimal vertical displacement, likely less than 15 meters, and do not show significant horizontal movement such as drag folds, shear fractures, or offsets. These faults are believed to be associated with adjustments in underlying rock layers ([Power et al., 1966](#)).



B

Periods	Epochs	Stages	Formation	Member
Paleogene	Eocene	Ypresian	Umm Er Radhuma	
	Paleocene	Thanetian		
		Selandian		
Cretaceous	Late	Danian	Aruma	Lina
				Hajajah
		Maastrichtian		Khanasir
	Early	Cenomanian - Turonian	Wasia	

Figure 3.1: Outcrop distribution and stratigraphy of the Aruma Formation (A) The exposed outcrops map of the Aruma Formation and the location of the study area (red square) (B) Stratigraphy of the Aruma formation; the red square points to the studied interval.

The Aruma Formation disconformably overlies the Cenomanian to Turonian Wasia Formation (Sharief et al., 1989), and is disconformably overlain by the Paleocene to Early Eocene Umm er Radhuma Formation (Powers et al., 1966) (Fig. 3.1B). The Aruma Formation comprises three members from bottom to top: the Khanasir, Hajajah, and Lina Shale Members (Fig. 3.1B) (El-Asa'ad, 1983). The Khanasir Member (Fig. 3.1B), which is the focus of this study, is the lower member of the Aruma Formation and is dated as Campanian based on the rudist taxon (*Eodictyoptychus arumaensis*) (Skelton and El-Asa'ad, 1992) and as Campanian-early Maastrichtian based on ammonites, large foraminifera, and nanoflora (Vaslet et al., 1988, 1991; Powers et al., 1966; Philip et al., 2002). The overlying member (the Hajajah Member) was assigned as late Maastrichtian by Vaslet et al. (1988, 1991), whereas the upper member (the Lina Shale Member) was assigned as Paleocene, based on evidence from marine vertebrates such as *Selachian* and *Actinopterygian* fish (Thomas et al. 1999).

The Khanasir Member, according to Philip et al. (2002), consists of claystone, bioturbated (*Skolithos*) sandstones, and bioturbated (*Thalassinoides*) wackestones. It is characterized by abundant dasycladacean algae and various invertebrate fossils such as gastropods, sponges, echinoderms, and ammonites. The upper part of the Khanasir Member is composed of shales, which are overlain by wackestones containing diverse benthic biota including foraminifera, solitary corals, gastropods, and echinoids.

3.2.2. Lithological Units

At the outcrop scale, Saraih et al., (2023) divided the Khanasir Member of the Aruma Formation into three lithostratigraphic units (Fig. 3.2). Each unit exhibits a distinct association of burrow fillings and host rock matrices. The lowest unit, labeled as unit 1,

has a thickness of 18 meters. Directly above it lies unit 2, with a thickness of 17 meters; this unit is subdivided into two distinct subunits: subunit 2A, which measures 11 meters in thickness, and subunit 2B, with a thickness of 6 meters (Fig. 3.2). Both units 1 and 2 exhibit extensive bioturbation. Unit 3, the uppermost unit, has a thickness of 15 meters and consists of two subunits, 3A and 3B. Unit 3 exhibits less bioturbation compared to the underlying units 1 and 2, with an estimated bioturbation amount of less than 5%.

A. Unit 1

Saraih et al., (2023) divided unit 1 into subunit 1A and 1B. These subunits are similar in their burrow attributes and host rock matrices but differ slightly in their burrow percentage (BP). They are considered as one unit in this paper. The signature feature of unit 1 is its mostly open burrows, with some partially filled with a pedogenic material consisting of 52% calcite, 33% quartz, and 15% palygorskite. These burrows account for 10 to 40 % of the rock volume and have an average diameter around 4 cm. While many retain a circular shape, some have been altered to elliptical or irregular forms due to solution enlargement. Distinct characteristics, like boxwork patterns and certain connection angles, correspond to the *Thalassinoides* burrow type as described by Ekdale & Bromley (1984). This complicated burrow system occurs within a wackestone to packstone host rock matrix made up of 100% calcite. Moreover, evidence of subaerial exposure events, including paleosol and laminated crust, has been identified at the top of unit 1.

B. Unit 2

Unit 2 consists of subunit 2A and 2B (Saraih et al., 2023). Subunit 2A prominently features burrows filled with mud-dominated carbonate rock textures, which consist of 97% calcite, 2% palygorskite, and 1% quartz. These burrows, predominantly horizontal in alignment, constitute 10 to 35% of the rock volume with a mean diameter of 3.2 cm. As in

unit 1, specific burrow features, including connection angles and boxwork patterns, suggest *Thalassinoides* type (Ekdale & Bromley, 1984). The host rock matrix here is made of 83% dolomite, 14% palygorskite, and 3% calcite, with the dolomite distinctly exhibiting unimodal, planar-e, and non-mimetically replaced allochem textures (after Sibley and Gregg, 1987). Moving to subunit 2B, burrows here either remain open or are partially filled with pedogenic material. They account for 10 to 30% of the rock's volume, measure around 3.2 cm in diameter, and they may exhibit a more compacted appearance in comparison to those observed in unit 1. These burrows are hosted within a wackestone matrix that is 100% calcite.

C. Unit 3

Unit 3 diverges significantly in burrow percentage compared to units 1 and 2, with less than 5%. Its lower part, subunit 3A, consists of a shale interval covered by talus, with no observed bioturbation. In contrast, subunit 3B begins with a partially dolomitized limestone base, evolving upward into a more dolomitized upper layer. The dolomitized limestone at the base is approximately 79% calcite, 18% dolomite, and 3% orthoclase, whereas the upper part of subunit 3B consists of 95% dolomite and 5% calcite, with the dolomite exhibiting mimetically replaced allochem textures.

3.2.3. Study area

The studied outcrops of the Khanasir Member are located 130 km southeast of Riyadh City (Fig. 3.1A). They were selected because of the good exposure of strata with extensive but variable bioturbation and a variety of natural fractures at different scales. From our documentation of the lithologies in this area (Saraih et al., 2023), it is important to note that there were differences from those reported by Philip et al. (2002), including a complete

absence in our area of bioturbated sandstone with *Skolithos* trace fossils. The base of the studied section (unit 1) is at latitude 24°28'28.64"N, longitude 47°43'43.40"E, the middle of the section (unit 2) is at latitude 24°28'41.32"N, longitude 47°43'50.50"E, and the top (unit 3) is at latitude 24°28'40.13"N, longitude 47°44'1.53"E.

3.3. Methodology

This study integrated multiple scales of analysis (from outcrops to core to thin section scale), including field sampling, field observation, petrographic analysis, and CT-scan imaging, for analyzing and characterizing the attributes of burrows and fractures across multiple scales. Detailed fracture characterization involved assessment of fracture spacing, density, orientation, fillings, and length. The characterization process involves capturing multiple photographs in the field, wherein their scale and orientation are defined. These photographs were taken from each unit, with a specific focus on capturing varying burrow percentages, shapes, and orientations to enhance the diversity of the data set. Subsequently, these photos are analyzed using image J software for determining burrow percentage and JmicroVison software for fracture density, spacing, and length. These analyses included measurement and assessment of fracture length, orientation, density, burrow percentage, and diameter, providing quantification of burrow and fracture character. Similarly, burrow characterization includes identification of burrow type, geometry, burrow percentage, and filling were conducted. Thirty-six samples were collected from the Khanasir Member for petrographic analysis in thin section, using Zeiss software after imaging the thin section using the ZEISS Axio

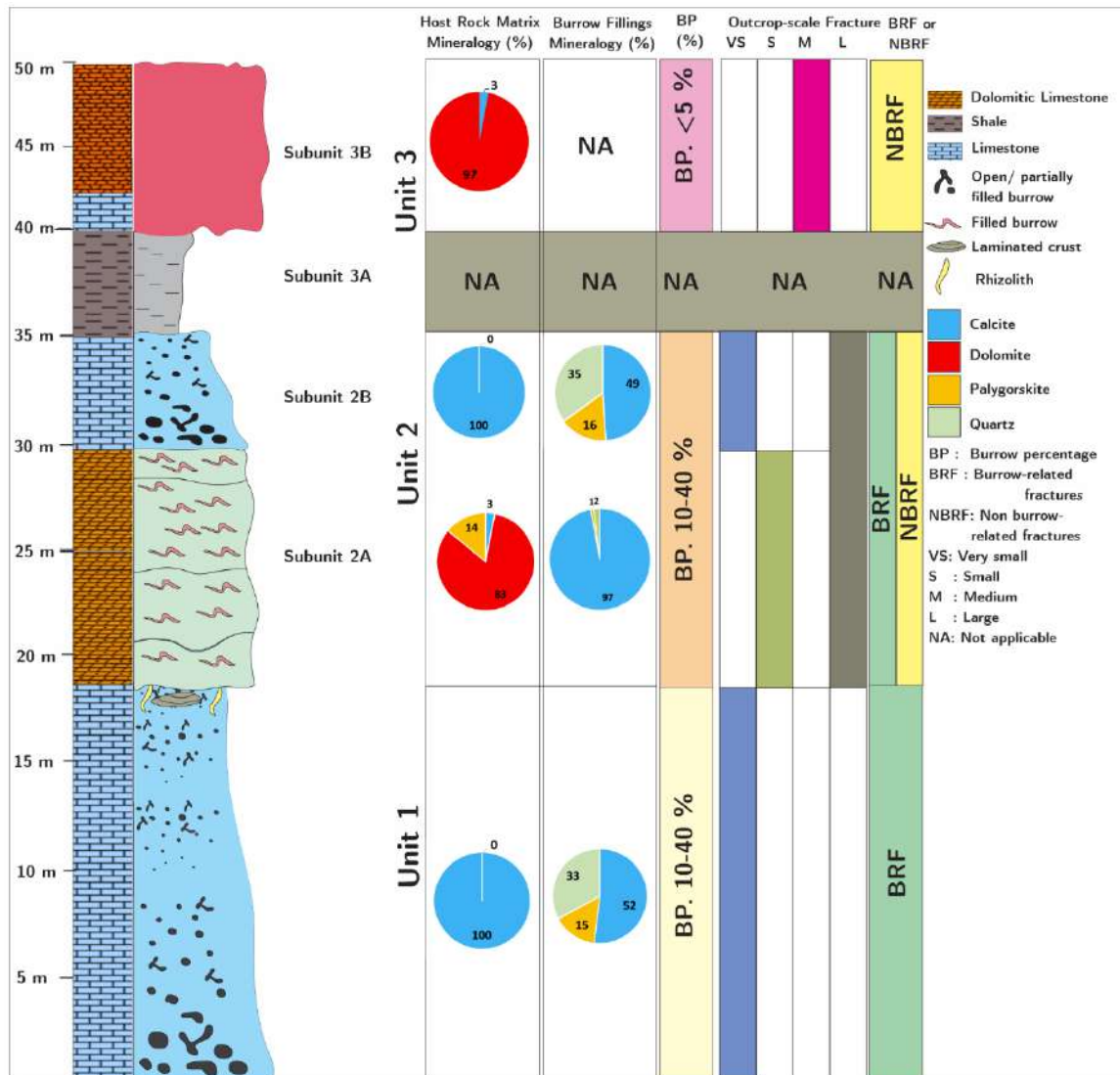


Figure 3.2: Measured section of the Khanasir Member in the study area showing sedimentological characteristics, mineralogical composition, burrow percentage, and fracture classification.

Scan Z1 slide scanner. The stratigraphic spacing between the specimens was consistently kept at 1 meter in accessible and unobstructed areas. However, in instances where precise locations were challenging to reach or covered with talus, the sampling interval was extended. The thin sections were used to identify mineralogical compositions, textures, and

micro-fractures. Special attention was given to microfractures, including their distribution, type, and fillings.

CT-scan imaging was employed to obtain detailed three-dimensional data on burrow and fracture networks, and their spatial arrangements. Six samples, including both regular-shaped (cubic with lengths ranging from 20-50 cm) and irregular-shaped samples, were scanned using a Toshiba Alexion TSX-032A CT-scanner. The CT-scan data obtained were converted to SEG-Y format and subsequently visualized and analyzed using Petrel 2021™ software.

3.4. Results

Fractures within the Khanasir Member have been observed at two distinct scales, macroscopically on outcrop and microscopically in thin section. Each scale will be elaborated upon in the sections that follow.

3.4.1. Fracture System at Outcrop Scale and CT-scan Scale

Fractures at outcrop scale were categorized into four distinct classes based on their lengths (Fig. 3.2): (1) Very small-scale fractures (VS) with lengths less than 5 cm; (2) Small-scale fractures (S) ranging from 5 to 40 cm in length; (3) medium-scale fractures (M) with lengths ranging from 40 to 500 cm, and (4) Large-scale fractures (L) exceeding 500 cm in length. While these fracture classes can be found throughout various units, specific units within the Khanasir Member tend to showcase a predominant fracture class.

A. Fracture System in Bioturbated Strata with Open Solution-Enlarged Burrows: Example from Unit 1.

Unit 1 is characterized by extensive bioturbation (BP 10 to 40 %) featuring open or partially filled solution-enlarged *Thalassinoides* burrows hosted within a wackestone to

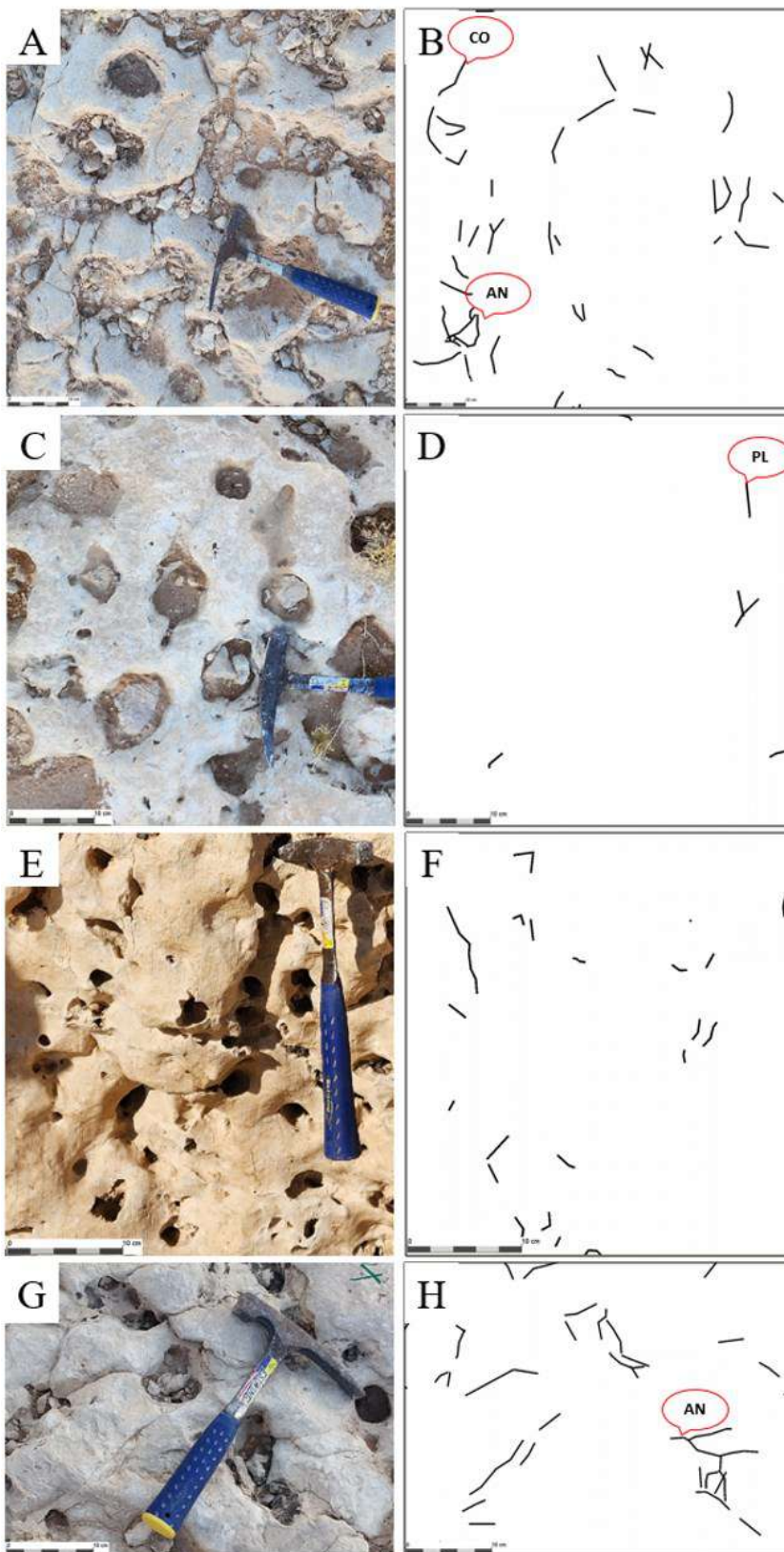


Figure 3. 3: Unit 1 outcrop images depict bedding and vertical faces along with corresponding fracture analyses. (A, C, E, G) showcase various views of the outcrop. (B, D, F, H) provide fracture analyses for images A, C, E, and G, respectively. Notably, Figures 3A and 3G exhibit a higher density of fractures associated with elongated, irregularly shaped burrows affected by dissolution, in contrast to the more circular burrows seen in Figure 3C. Additionally, Figure 3E emphasizes the variability of fractures on the vertical plane, influenced by the orientation and morphology of the burrows. PL stands for Planar fractures, CO for Contorted fractures, and AN for Anastomosing fractures.

packstone matrix. The fractures within the open *Thalassinoides*-bearing strata exhibit diverse patterns (Fig. 3.3): intersecting the burrow pores, forming in isolation, or connecting two burrow pores.

Fracture concentration demonstrates variability in relation to the BP, burrow shape, and burrow radius (Fig. 3.3A-D). In regions characterized by a high percentage of burrows with shapes deviating from perfect circles (Fig. 3.3A), there is a noticeable increase in fracture concentration compared to areas with fewer burrows and more circular burrow shapes (Fig. 3.3B). Additionally, the spatial distribution of fractures can also vary depending on the orientation of the burrow pores (Fig 3.3E).

In this unit, the fracture density varies from 20 to 150 fractures/square meters (m^2), with an average of 77 fractures/ m^2 (Figs. 3.3, 3.4A). These fractures typically exhibit a mean spacing of 3 fractures/meter (m) (Fig. 3.4B). Their lengths predominantly range from 0.3-15 cm, with an average of 3 cm (Fig. 3.4C). However, in specific regions, fractures uncommonly demonstrate greater extent, in some cases surpassing a meter in length. Whereas, the fractures can be categorized into very small, small, and medium classifications, class 1 - representing very small-scale fractures - is the most prevalent type. The fractures exhibit a varied orientation. Predominantly, these fractures are oriented in two dominant directions: N-NW to S-SE and N-NE to S-SW (Fig. 3.5A). The apparent dip

angle of these fractures ranges between 1 and 86°, with an average apparent dip of approximately 46° (Fig. 3.5B). These fractures occur in two principal conditions: they can be either open (Fig. 3.6A, B) or occluded with secondary infill materials such as calcite cement (Fig. 3.6A) or pedogenic material that formed during exposure events (Fig. 3.6C, D).

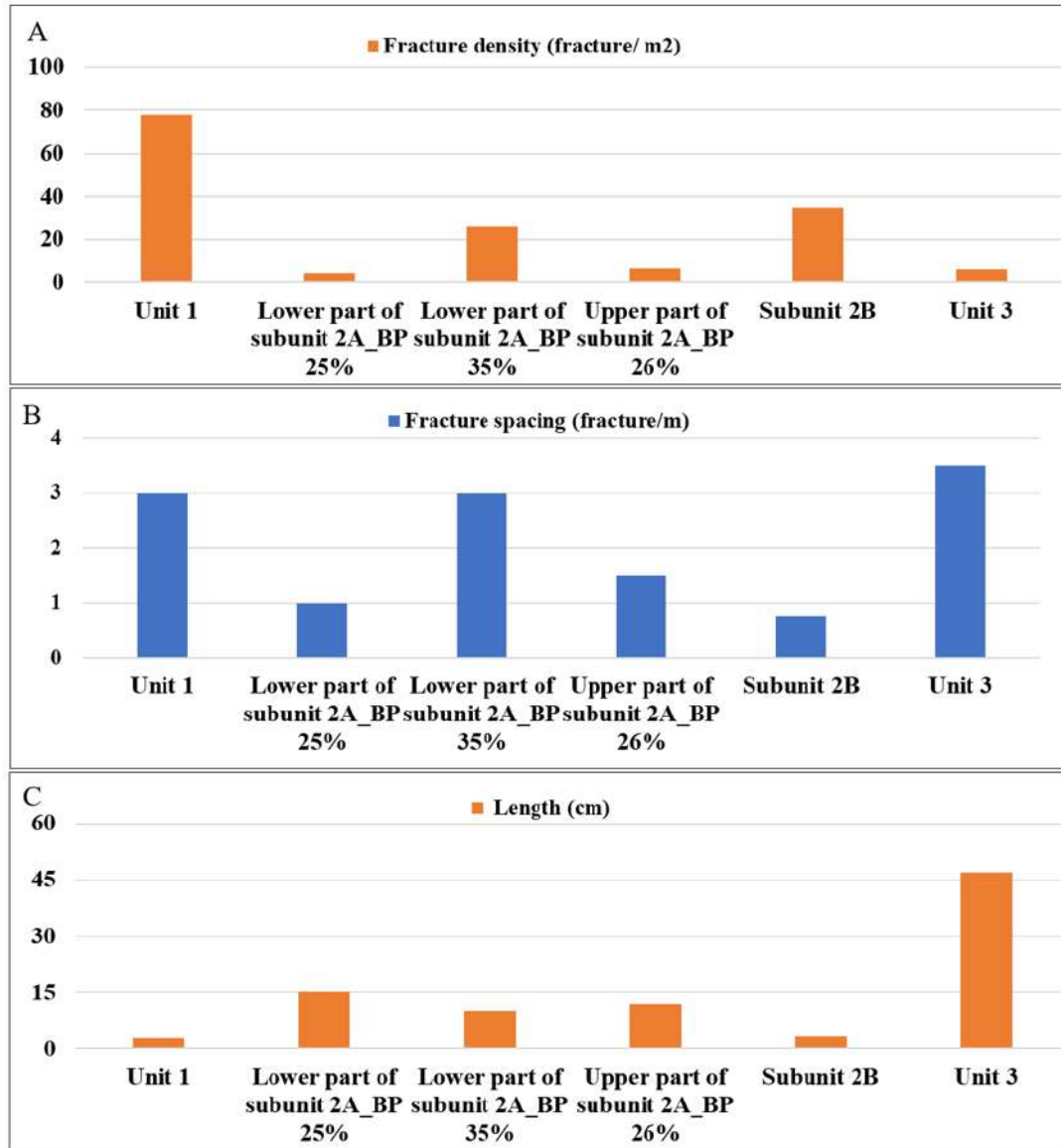


Figure 3.4: Statistical analysis of fracture density, spacing, and length (A) Fracture density. (B) Fracture spacing. (C) Fracture length.

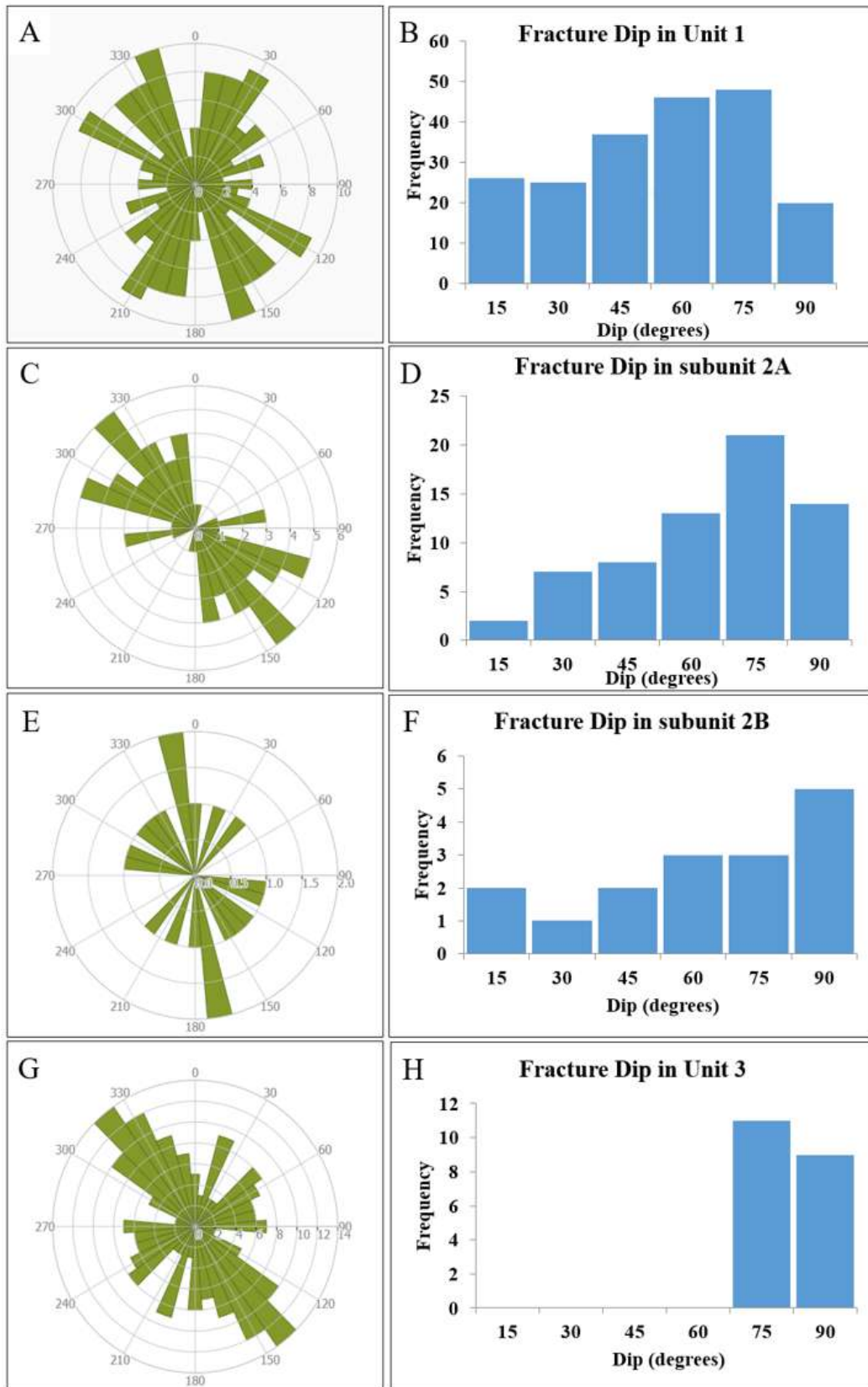


Figure 3.5: Fracture orientation and apparent dip for all the units. (A-B) Fracture orientation and apparent dip of unit 1. (C-D) Fracture orientation and dip of the lower part of subunit 2A. (E-F) Fracture orientation and apparent dip of the upper part of subunit 2A. (G-H) Fracture orientation and apparent dip of subunit 2B. (I-J) Fracture orientation and apparent dip of unit 3.

B. Fracture System in Bioturbated Strata with Filled Burrows: Example from Subunit 2A.

Subunit 2A is characterized by extensive bioturbation (BP 25-40%) featuring *Thalassinoides* burrows filled with mud-dominated material. These burrows are hosted within a dolostone matrix consisting of dolomite and palygorskite. Fractures in the filled burrow unit present in various ways: they may cut through both the filled burrow and its surrounding matrix (Fig. 3.7A, B); occur along the interface between the host rock matrix and the filled burrow (Fig. 3.7C-F); or appear as isolated fractures within either the burrow fillings or the matrix itself (Fig. 3.7D, E).

To investigate the relationship among burrow percentage, fracture characteristics, and the composition of both the host rock matrix and burrow fillings, we analyzed these variables in various instances along subunit 2A. In the lower section of subunit 2A (Fig. 3.8). At BP 25%, the average fracture density is 4.5 fractures/m² (Figs. 3.4A, 3.8A, B). The average fracture spacing is approximately 1 fracture/m (Fig. 3.4B), and their length ranges from 13-16 cm, with an average length of 15 cm (Fig. 3.4C). However, as BP increases to 35%, we observe a considerable shift, with the average fracture density increasing to 25 fractures/m² (Figs. 3.4A, 3.8A, B), and the average spacing expanding to 3 fractures/m (Fig. 3.4B). At BP 35%, the fracture lengths range from 4 cm to 25 cm, with an average length of 10 cm (Fig. 3.4C). Moving to the upper section of subunit 2A where the matrix

displays a less dominant presence of palygorskite compared to the lower part of Subunit 2A (Fig. 3.9), particularly at

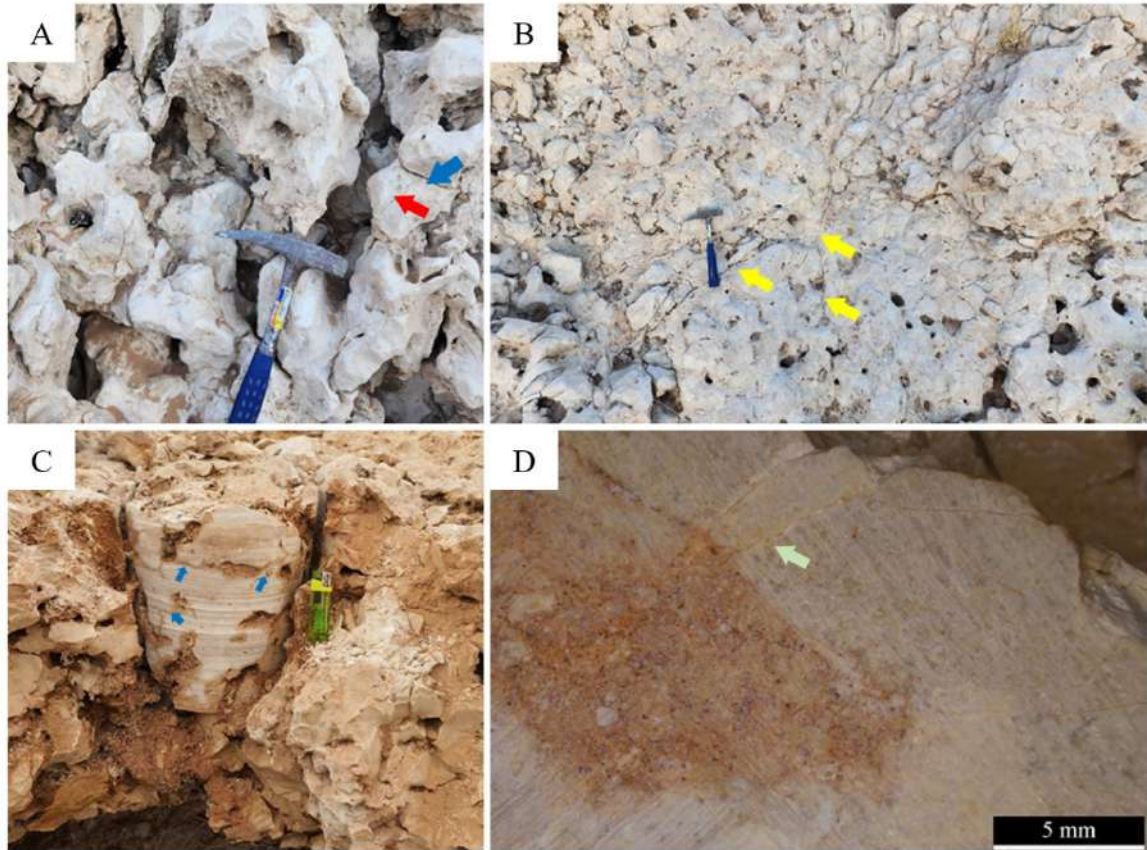


Figure 3.6: Outcrop and slabbed sample photographs displaying variations in fracture length and filling. (A) Outcrop photograph showcasing intense bioturbation and open fractures (blue arrow) and filled fractures (red arrow). (B) Outcrop photograph displaying a fracture (yellow arrow) exceeding a meter in length, in contrast to the typical fractures in this unit, which typically have an average of less than 5 cm. (C) Photograph of a core, which exhibits small fracture propagation between the burrow pores (blue arrow). (D) Slabbed surface of a filled fracture (green arrow), filled with pedogenic material.

BP 26%, we record a fracture density of approximately 6.6 fractures/m² (Figs. 3.3A, 3.9A, C). The average spacing of these fractures is 2 fractures/m, while their lengths vary from 2.8 cm to 36 cm, with an average length of 12 cm (Fig. 3.4B-D). However, despite high burrow percentage, there are certain areas where fractures are not common (Fig. 3.8).

Despite the variety in fracture classes observed in this subunit, which include fractures of very small scale (Fig. 3.7C-F), small scale (Fig. 3.7B), and large scale (Fig. 3.7A) that span across both subunits 2A and 2B. The fractures are predominantly of class 2, characterized as small-scale fractures. Their orientation is mainly to the NE-SW (Fig. 3.5C). These fractures display an apparent dip that ranges between 5 and 85°, with an average of 56° (Fig. 3.5D). Fractures within subunit 2A exhibit two distinct filling characteristics; they can be open (Fig. 3.7C, E) or filled (Fig. 3.7C, D).

Focusing on the very-small scale fractures—those with lengths less than 5 cm—their density is more pronounced within the burrow fillings compared to the host rock matrix (Fig. 3.9D-F). The CT-scan data further support these observations, confirming that the fractures predominantly occur within the burrow fillings (Fig. 3.10).

C. Fracture System in Bioturbated Strata with Compacted burrows: Example from Subunit 2B

Subunit 2B displays extensive bioturbation (BP 10-30%), characterized by open or partially filled compacted *Thalassinoides* burrows hosted within a wackestone to packstone matrix. The fractures exhibit diverse patterns, including those that intersect the burrow pores (Fig. 3.11A) and those that form in isolation (Fig. 3.11B).

In terms of fracture concentration, this unit shows less variability and density compared to the open solution-enlarged *Thalassinoides*-bearing strata (unit 1). The fracture density varies from 10 fractures/m² to 52 fractures/m², with an average of 34 fractures/m² (Figs. 3.4A and 3.11). These fractures exhibit an average fracture spacing of 1 fracture/m (Fig. 3.4B). In terms of length, they typically vary from 0.5-19 cm, with an average length of 3.5 cm (Fig. 3.4C). The fractures in this subunit are both small and very small-scale, yet it is the very small-scale fractures that dominate. Though the orientations of these fractures

can vary, the majority take N-S directions (Fig. 3.5C). Their apparent dip angles range from 1 to 82°, with an average dip of 42° (Fig. 3.5D). The fractures in this subunit are filled with either pedogenic material or calcite cement.

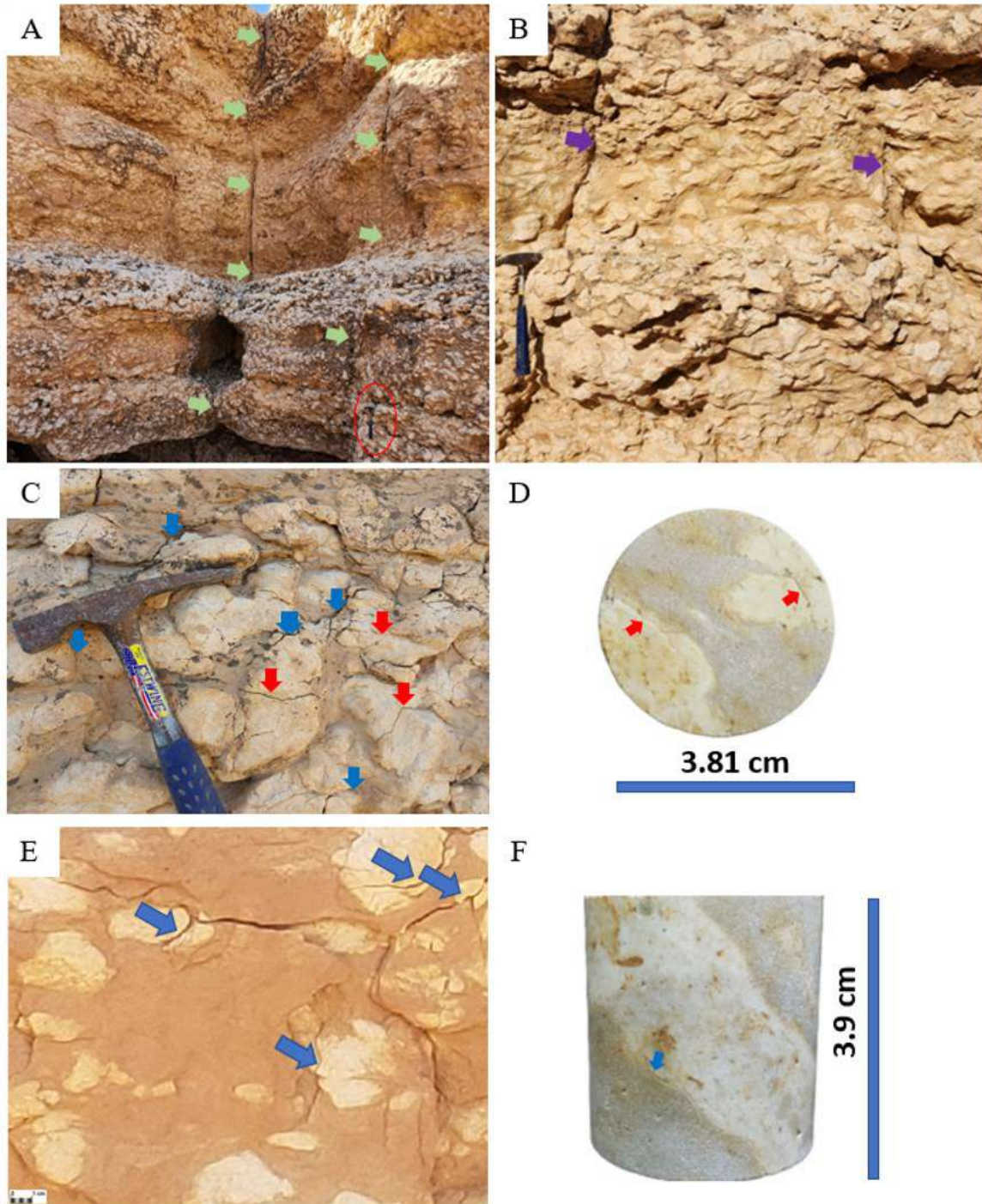


Figure 3.7: Outcrop and core samples from Subunit 2A provide insight into the scale of fractures. (A) Reveals a large-scale fracture intersecting Subunits 2A and 2B. (B) Shows a small-scale fracture affecting both the burrow fillings and the host matrix in Subunit 2A. (C) Offers a detailed view of very small-scale fractures; note the fractures within the burrow fillings (indicated by red arrows) and at the contacts between burrow fillings and the host rock matrix (indicated by a blue arrow). (D-E) Core samples illustrate fractures predominantly within the burrow fillings, noting that the gray color represents the matrix and the white color represents the burrow fillings. (H) A core sample exhibits fractures at the interface between burrow fillings and the host rock matrix.

D. Fracture System in Non-bioturbated Strata: Example from Unit 3

This unit lacks the bioturbation observed in the underlying units. While the bottom of unit 3 comprises a shale interval covered by talus, making it challenging to observe fractures in this section, the upper subunit, 3B, characterized by partially dolomitized limestone transitioning into dolostone at its uppermost part, displays observable fractures. Within the upper interval of the unit, the fracture density varies from 8 fractures/m² to 4 fractures/m², with an average of 6.5 fractures/m² (Figs. 3.4A, 3.12). The average fracture spacing is 3 fractures/m (Fig. 3.4B). In terms of length, these fractures span 5 cm up to 300 cm, with an average length of 50 cm (Figs. 3.4C, 3.12B, D).

According to these measurements, medium-scale fractures are the dominant ones. These medium scale fractures have orientations that predominantly align in a NW-SE direction (Fig. 3.5G), though there is a notable, but less abundant, alignment in a NE-SW direction (Fig. 3.5G). The apparent dip angle of these fractures exhibits a range between 20 and 86°, with an average of 73° (Fig. 3.5H). Due to the low presence or complete absence of burrows, no obvious relationship between burrows and fractures is observed.

3.4.2. Fracture System at Microscopic Scale

At the thin section scale, fractures are open, partially filled, or entirely filled. These microscopic fractures have been differentiated into two categories:

- 1- Systematic Fractures: Often referred to as planar fractures; these have a regular and predictable pattern (Ameen, 2016).
- 2- Non-systematic Fractures: this category encompasses two distinct types:
 - Composite or Contorted Fractures: These fractures consist of multiple segments and lack a uniform dip angle or orientation (e.g., Abouelresh and Babalola in 2020; Ameen, 2014, 2016).
 - Anastomosing Fractures: These fractures are characterized by their intricate network of interconnected fractures (e.g., Ameen, 2014, 2016).

A. Microfracture System in Bioturbated Strata with open burrow: Example from Unit 1 and subunit 2B

In unit 1 and subunit 2B which have similar open burrow pores and tight host rock matrices, microfractures are observed within the host rock matrix, because burrows within these units are open or partially filled with pedogenic materials. These microfractures display a wide array of types, including planar, contorted, and anastomosing fractures. Planar fractures demonstrate varied levels of calcite cement fills (Fig. 3.13A, B, C). However, these planar fractures are less common compared to contorted fractures in unit 1, where contorted fractures are the dominant fracture type. In contrast, in subunit 2B, planar to sub-planar fractures prevail as the dominant type. The contorted fractures can be seen in various stages of mineralization: fully filled with calcite cement (Fig. 3.13E), partially filled (Fig. 3.11F), or open (Fig. 3.13D). They commonly interlink, making complex networks of anastomosing fractures (Fig. 11G, H). There are clear indications of multiple fracture sets (set 1 and set 2) (Fig. 3.13I, J), as evidenced by filled fractures cutting across one another (Fig. 3.13J).

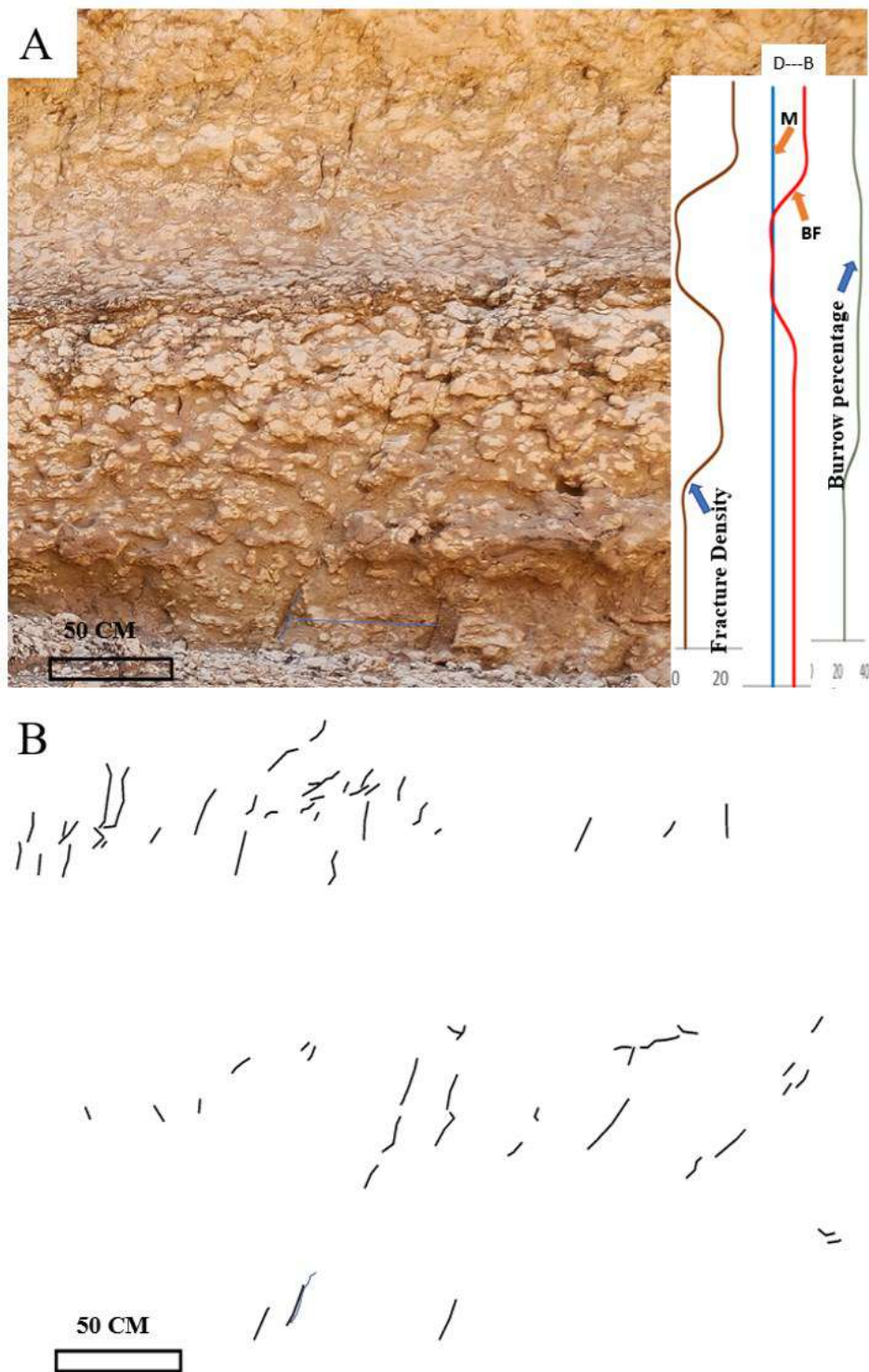


Figure 3.8: (A) An outcrop photograph of Subunit 2A displaying the variability of fracture density in relation to the brittleness (B) and ductility (D) of both the burrow fillings (BF) and the host rock matrix (M), as well as the burrow percentage. Notably, areas with a higher percentage of burrows tend to have increased fracture densities, where the burrows show greater brittleness. **(B)** This is a fracture analysis of the photograph shown in Fig. 3.8A.

B. Microfracture System in Bioturbated Strata with Filled burrow: Example from Subunit 2A

Subunit 2A revealed a diverse range of fracture types and fillings, observable both within burrow fillings and the host rock matrix. Fractures within burrow fillings have a more complicated geometry than those seen in the host rock matrix. Predominantly, these fractures appear as fully mineralized contorted types (Fig. 3.14A, B), with some evolving into anastomosing fractures (Fig. 3.14B). In contrast, the host rock matrix—whether it is entirely or partially dolomitized—exhibits open fractures that range from planar to sub-planar (Fig. 3.14. C-D).

C. Microfracture System in Non-Bioturbated Strata: Example from Unit 3

As mentioned previously, the lower interval of unit 3, of predominantly claystone covered by talus, did not yield any collected samples. The middle interval, characterized by dolomitic limestone, shows prominent open anastomosing fractures (Fig. 3.15A, B). Interestingly, the uppermost interval of this unit is dominated by dolostone and lacks any observable microfractures. Instead, it shows large, irregularly shaped intercrystalline pores (Fig. 3.15C).

3.5. Discussion

Structural elements such as fractures play a crucial role in determining the quality of carbonate reservoirs ([Wennberg et al. 2016](#); [Miranda et al. 2018](#); [Rashid et al. 2020](#);) . Thus, understanding the controls of such elements is crucial for reservoir characterization

and management (Agosta et al. 2010; Kosari et al. 2017; Liu et al. 2020). Fractures within the Khanasir Member, based on their length, are separated into categories ranging from very small to large-scale fractures, offering a valuable framework for understanding their

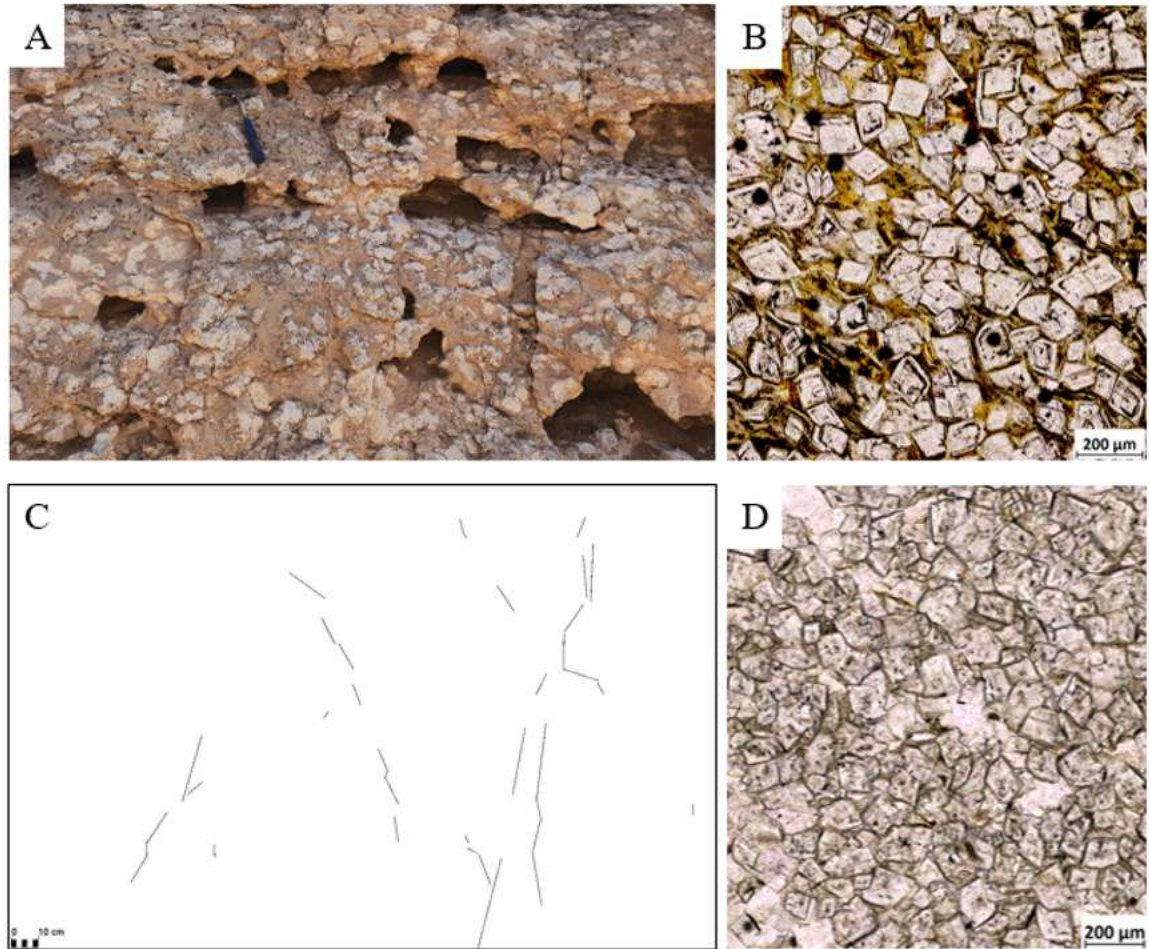


Figure 3.9: Fractures in the upper part of Subunit 2A. (A) Displays a photograph of the upper part of Subunit 2A. (B) A thin section from the lower part of Subunit 2A reveals a significantly higher concentration of palygorskite compared to the upper matrix of Subunit 2A, as shown in (D). (C) Offers a fracture analysis of the photograph in (A). (D) Presents a thin section from the upper part of Subunit 2A, highlighting a lower presence of palygorskite relative to the lower part, as depicted in (B).

distribution. This classification not only aids in characterizing the fractures but also offers insights into their potential origins, controlling factors, and geological significance. These fractures can be further classified on the basis of their relation to bioturbation yielding the

classes: non-burrow-related fractures (NBRF) and burrow-related fractures (BRF) (e.g. Valencia et al. 2023). A closer examination of their distribution across the geological units within the Khanasir Member reveals an interesting pattern. Unit 1 predominantly hosts BRF, indicating a strong influence by bioturbation processes. Unit 2 has both NBRF and BRF. In contrast, unit 3 is dominated by NBRF. Categorizing the fractures in this manner provides a clearer understanding of the impact of the bioturbation on fracture characterization.

3.5.1. Impact of Bioturbation on the Fracture Characteristics

A. Case 1- Strata with Open Burrows

Unit 1 and subunit 2B are the primary geological units within the Khanasir Member containing strata where open burrows of *Thalassinoides* are hosted within a tight host rock matrix. However, these two units exhibit variation in fracture characteristics. Within unit 1, the fractures are thought to be BRF and demonstrate variations in fracture density (Fig. 3.3). These variations are linked to the inherent heterogeneity of the burrow system, encompassing differences in both burrow percentage and shape, as well as the texture of the surrounding host rock matrix. The presence of burrows plays an important role in the formation of fractures. Unit 1 features strata with intensive bioturbation, which significantly influences the occurrence and propagation of fractures. Therefore, networks of pores created by burrows, in turn, establish distinct fracture-prone zones and conduits for fluid flow (Bednarz and McIlroy, 2012). While there is limited direct research on bioturbation's impact on fracture propagation, parallels can be drawn from studies on vugs (Carter 1992, Liu et al. 2019, Zeng, Liu, Yao 2021, Cai et al. 2023). Cai et al. (2023) noted

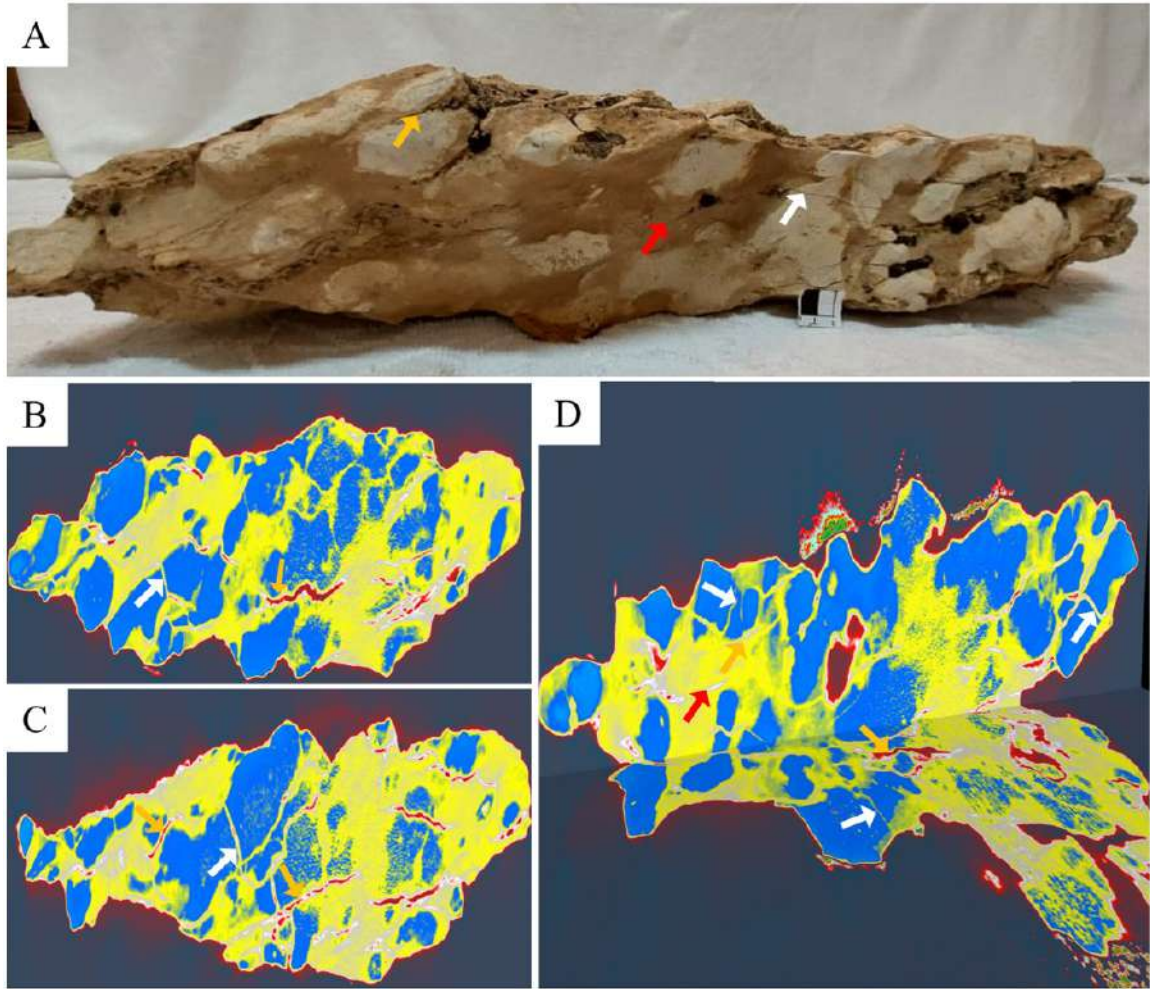


Figure 3.10: Field sample and its CT scan result: (A) Irregular-shaped. sample showing fracture within the burrow fillings (white arrow), fracture on the interface between the host rock and the burrow filling (orange arrow), and the host rock matrix (red arrow). (B-D) Screen captures of the CT scan data showing the fractures from a sample of subunit 2A. In the CT scan data, the yellow color indicates the matrix, while the blue represents the burrow fillings.

that the presence of a hole in a rock sample compromises its mechanical properties, including brittleness, load capacity, and stiffness. Carter (1992) further explains that as the size of holes in materials increases, the stress required to initiate fractures decreases, eventually stabilizing at a horizontal asymptote for larger cavities. In unit 1, regions with a high burrow percentage, especially those that have been solution enlarged, altering the

burrows' original shape and size, there is a notable increased likelihood of fractures (Fig. 3.3A). This contrast is particularly pronounced when compared to areas where burrows remain circular, and unaffected by solution enlargement (Fig. 3.3E). Li et al. (2017) noted that the presence of larger holes in materials typically leads to reduced strength due to stress concentration effects. They found that, under uniaxial compression, materials with circular holes exhibit lower stress concentration compared to those with elliptical holes. The fracture patterns observed in elliptical or irregular burrows may exhibit varied stress concentrations, potentially related to the alignment of the burrows relative to the direction of stress. This aligns with findings from Li et al. (2017), who noted that the stress distribution around elliptical holes is significantly influenced by their inclination angle. Thus, the orientation of such burrows in relation to prevailing stress fields could be a key factor in determining fracture behavior and distribution. Despite the absence of a direct impact of the burrow on fracture formation, burrows can still contribute to the cementation of the host rock matrix. Wright and Cherns (2016) stated that combined effects of intense burrowing, bio-irrigation, and burrow penetration might contribute substantially to an increase in the degree of cementation within the host rock matrix. As a result, cementation within the host rock matrix (Figs. 3.13, 3. 6A) makes the rocks more brittle, further increasing the probability of fracturing. So, the burrow characteristics and the cementation of the host rock matrix are the main factors influencing fracture development and density within Unit 1.

In subunit 2B, which is characterized by very small-scale fractures and classified as BRF, a notable decrease in the abundance of fractures is observed in contrast to unit 1. Interestingly, despite having a high burrow percentage exceeding 15 (Fig. 3.4C), it does not display the same degree of fracturing as unit 1 (Fig. 3.3). The variation in fracturing between subunit 2B and unit 1 can be attributed to the higher ductility of subunit 2B, evidenced by the presence of compactionally deformed burrows (Fig. 3.11A), compared to the non-compactional solution-enlarged burrows in unit 1 (Fig. 3.3). The compactional deformation of burrows in subunit 2B suggests less early cementation, indicating higher



Figure 3.11: Outcrop photographs in subunit 2B, alongside corresponding fractures. (A, C) Photographs of subunit 2B. (B, D) Fracture analysis of the photographs in A, and C respectively.

ductility and reduced fracturing during compactional collapse into open spaces. The complexity of these factors contributes to the varied fracture patterns observed in subunit 2B compared to unit 1, despite the similar burrow percentage.

The presence of burrows within unit 1 and subunit 2B impacts not only the density of fractures but also their length. The burrows contribute to the formation of very-small scale fractures. These burrow holes act as barriers, hindering the propagation of fractures, with the length of fractures being limited by the matrix's bridging length. Liu et al. (2019) and Zeng, Liu, Yao (2021) found that vug size and horizontal stress differences significantly impact hydraulic fracture behavior, causing either crossing, arrest, or bypassing of fractures. Luo et al. (2020) showed that fractures tend to deviate from maximum horizontal stress directions due to caverns, influenced by stress fields and fluid pressure. In essence, both vug size and cavern characteristics crucially dictate fracture propagation paths.

The fractures within Unit 1 and subunit 2B are interpreted to result from compactional forces, and possible desiccation during early subaerial exposure. In both unit 1 and subunit 2B, despite the fractures resulting from compaction and desiccation displaying diverse orientations, a notable, yet not fully understood, preferred orientation emerges. This observation suggests the possibility of a localized stress field exerting partial control over these fractures or different time and formation mechanism. Furthermore, it's important to note that the exposure event documented by Saraih et al. in 2023 within this unit 1 is proposed to have introduced additional fractures and early cementation in unit 1 compared to subunit 2B. Lastly, certain fractures within unit 1 and subunit 2B may occur on the outcrops as a result of weathering. Additionally, during uplift, limestone usually undergoes

mechanical changes, making it more prone to developing tensile fractures or joints (Fossen 2016).

In Unit 1 the fractures, as seen in their cross-cutting relationships (Fig. 3.13I, 3.13J), intersect one another. Notably, these intersecting fractures share similar filling materials,

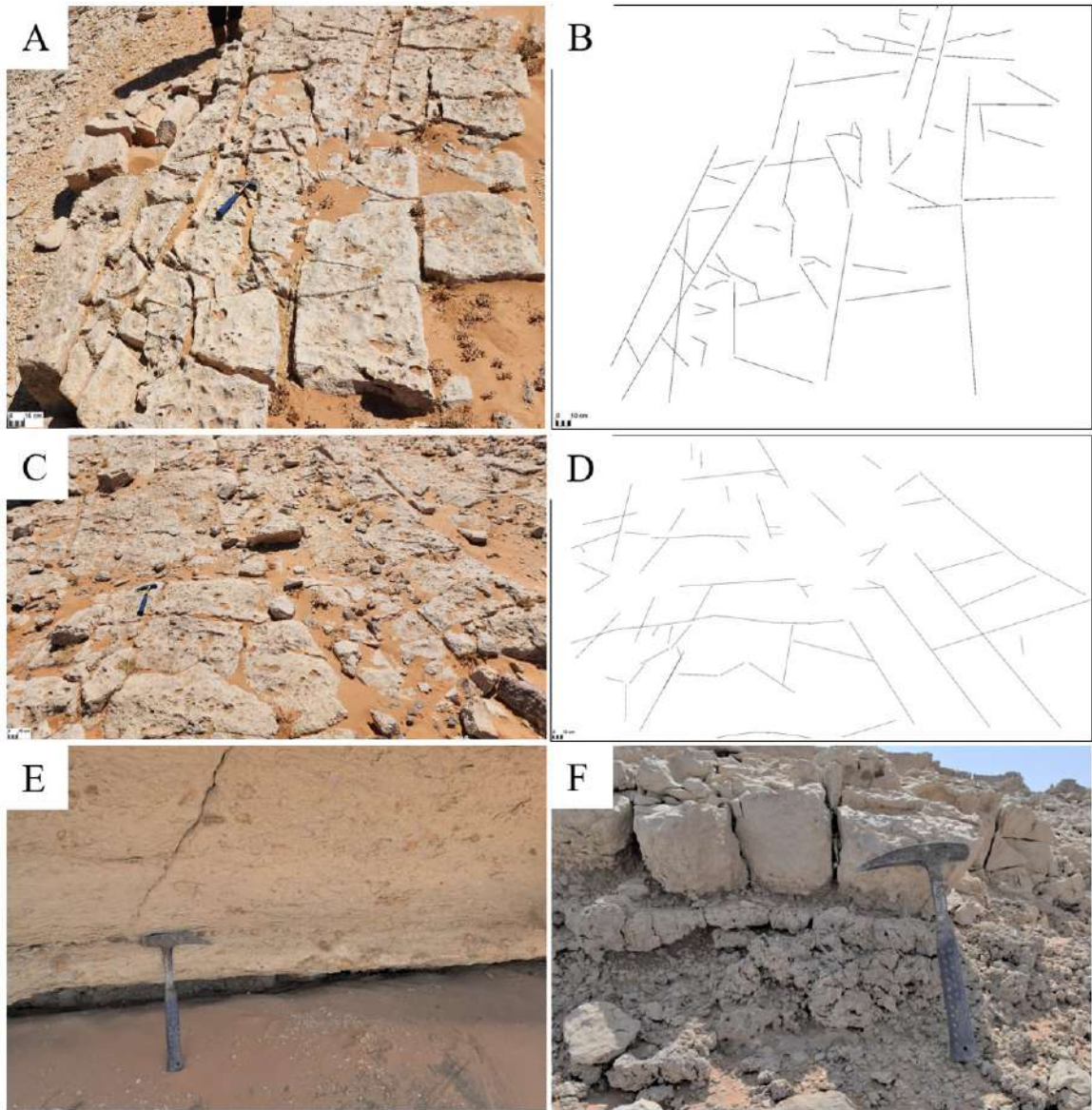


Figure 3.12: Outcrop photographs in unit 3 from bedding and vertical faces, alongside corresponding fracture traces. (A, C) Photographs from a horizontal face. (B, D) Fracture analysis of the photographs in A, respectively. (E_F) Photographs from a vertical face.

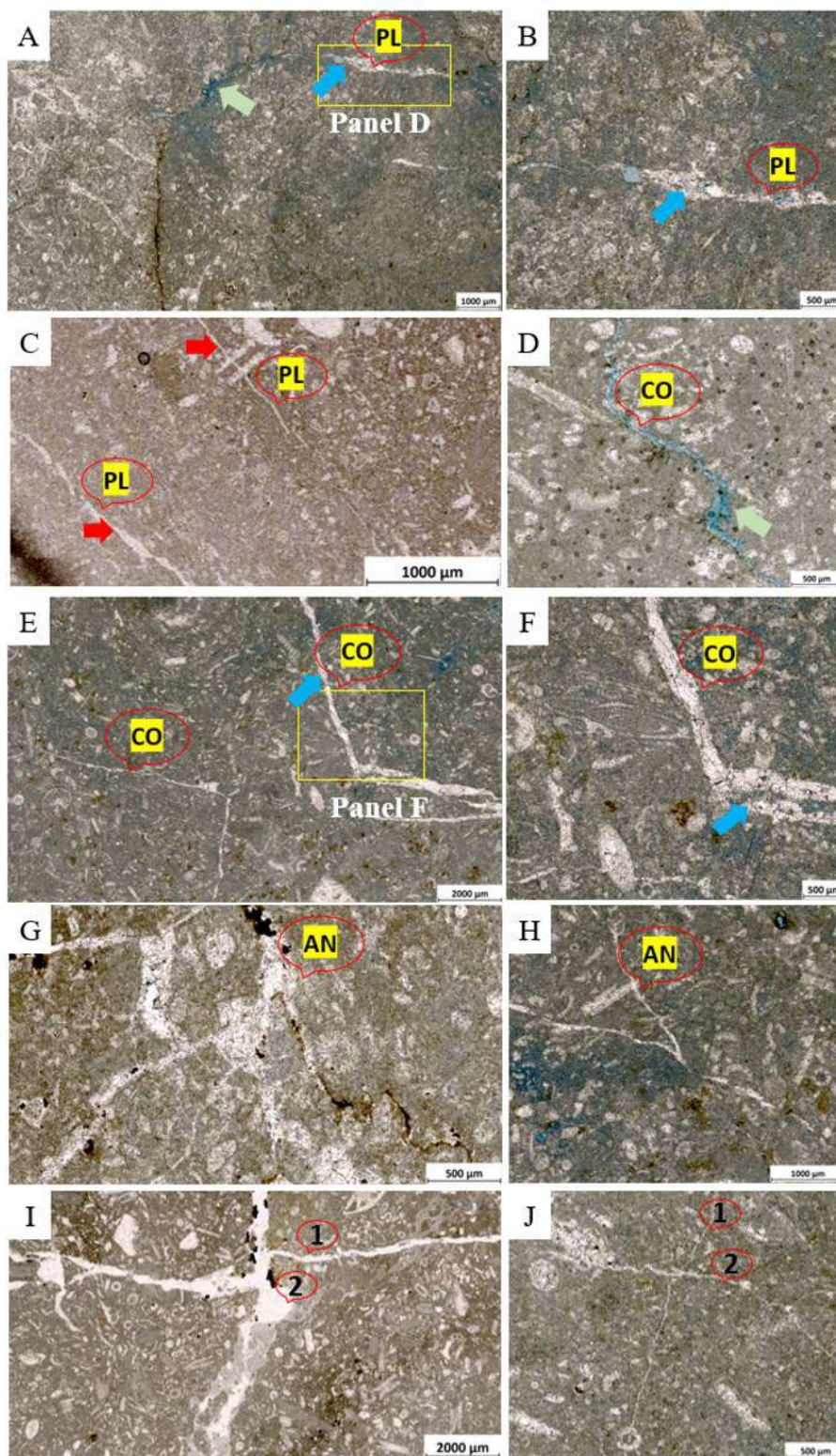


Figure 3.13: Thin section photomicrographs of the host rock matrix of unit 1 and subunit 2B reveal the rock textures and associated micro-fractures. (A) Wackestone with a planar [P] to sub-planar fracture. In all photomicrographs, the blue arrow indicates a partially filled

fracture, and the green arrow highlights an open fracture. (B) A close-up view of the panel in Figure 12A, showing the partially filled fracture. (C) Fully filled planar fractures. In all photomicrographs, the red arrow points to fully mineralized fracture (D) Open contorted [C] fracture. (E) Fully and partially filled contorted fractures. (F) A close-up view of the panel in Figure 7E, demonstrating the partially filled contorted fracture in its vertical segment and partially filled in its horizontal segment. (G-H) Fully mineralized anastomosing fractures [A]. Note the branches of the fractures. (I-J) Fully mineralized planar fractures intersecting. It is important to note that fracture 1 is older than fracture 2. PL: Planar fractures, CO: Contorted fractures, AN: Anastomosing fractures.

which could imply one of two scenarios: either they formed around the same time, with a possibility that Set 1 fractures preceded Set 2, as observed in Figure 3.13I and 3.13J, or they formed at different times but were subsequently filled with comparable material. Furthermore, clear crosscutting relationships may emerge when filled fractures are intersected and cut by an open fracture (Fig. 3.6A). As result of these crosscutting relationships, it has been suggested that the fractures filled with calcite cement might have formed first then followed by an open fractures (Fig. 3.6A) and incompletely mineralized fractures (Fig. 3.13D, F). These cross-cutting features are not common in subunit 2B and are difficult to constrain with confidence. The fractures exhibit diversity, ranging from planar to contorted and even anastomosing in unit 1 and subunit 2B. This variability serves as an indication of the host rock matrix's varying ductility during compaction and provides evidence that these fractures may indeed be a result of compaction.

B. Case 2- Strata with Filled Burrows

Subunit 2A within unit 2 features strata characterized by burrow fills hosted within dolostone matrix. Subunit 2A has a higher degree of macro-fracture scale diversity, encompassing fractures ranging from very small to large scale, and exhibiting a wider range of fracture types. This suggests the presence of a more complex geological system in this unit, influenced by several factors that govern fracture type, scale, density, and

origin. Subunit 2A exhibits notable characteristics, including BRF represented by very small and small-scale fractures (Fig. 3.7B-F), and NBRF represented by large-scale fractures (Fig. 3.7A). Within subunit 2A, it is noteworthy that BRF display vertical variations in fracture density and spacing (Figs. 3.2, 3.4, 3.8A, B) which are attributed to several factors. These factors include the burrow percentage, and the relative brittleness and ductility of the burrow fillings and host rock matrix

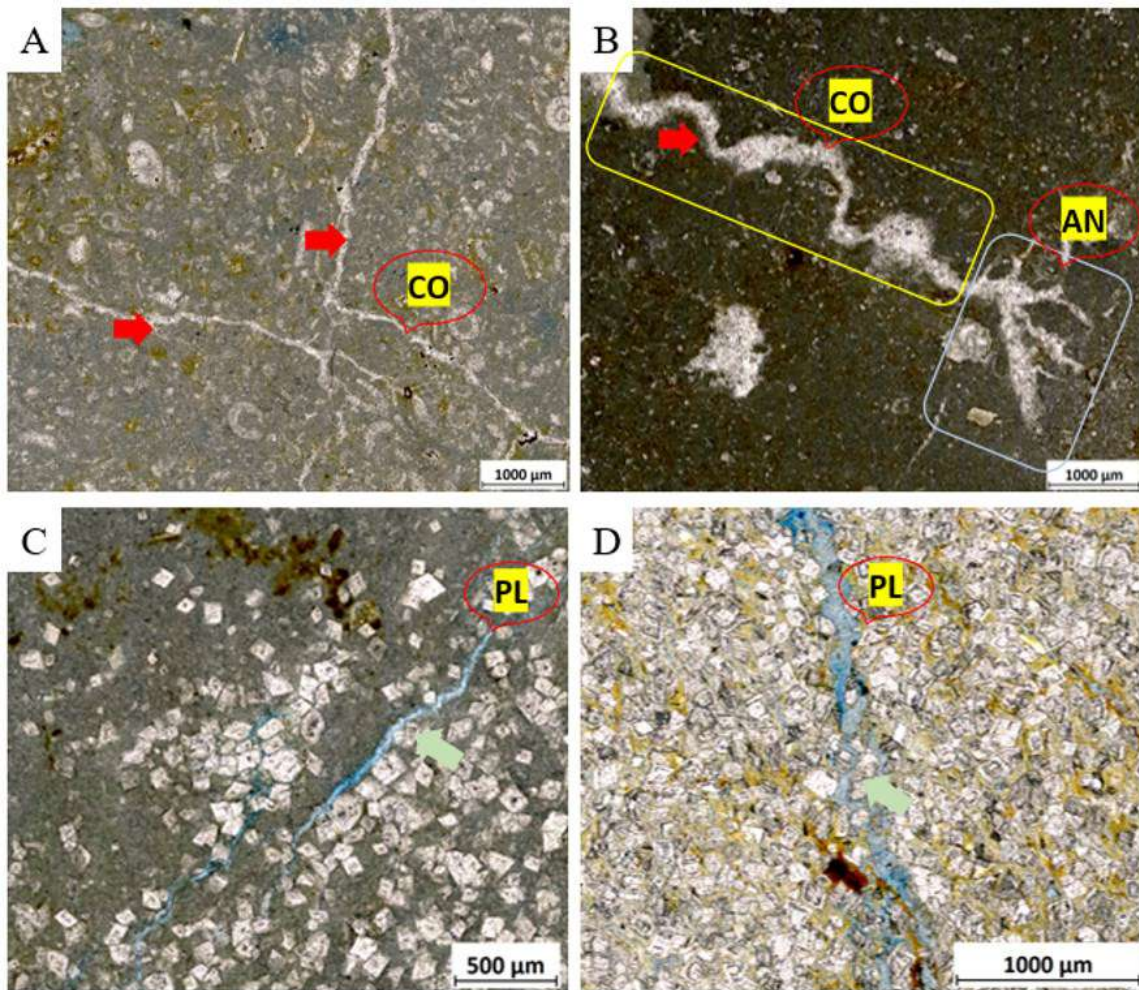


Figure 3.14: Thin-section photomicrographs of the burrow fillings and the host rock matrix revealing the rock texture and associated micro-fractures of subunit 2A. (A) Burrow filling exhibiting a wackestone texture and fully mineralized contorted fractures. The red arrow points to fully mineralized fracture (B) Fully mineralized contorted-anastomosing fracture. Notably, this fracture appears as a contorted fracture [C] the yellow square and as an anastomosing fracture [A] in blue square, highlighting the complexity of this fracture. The red arrow points to fully mineralized fracture. (C) Open planar to sub-planar fractures in

the partially dolomitized limestone burrow fillings. The green arrow points to an open fracture. (D) Open planar fractures in the dolomitized host rock matrix, resulting in the formation of fracture porosity. The green arrow points to an open fracture. PL: Planar fractures, CO: Contorted fractures, AN: Anastomosing fractures. PL: Planar fractures, CO: Contorted fractures, AN: Anastomosing fractures.

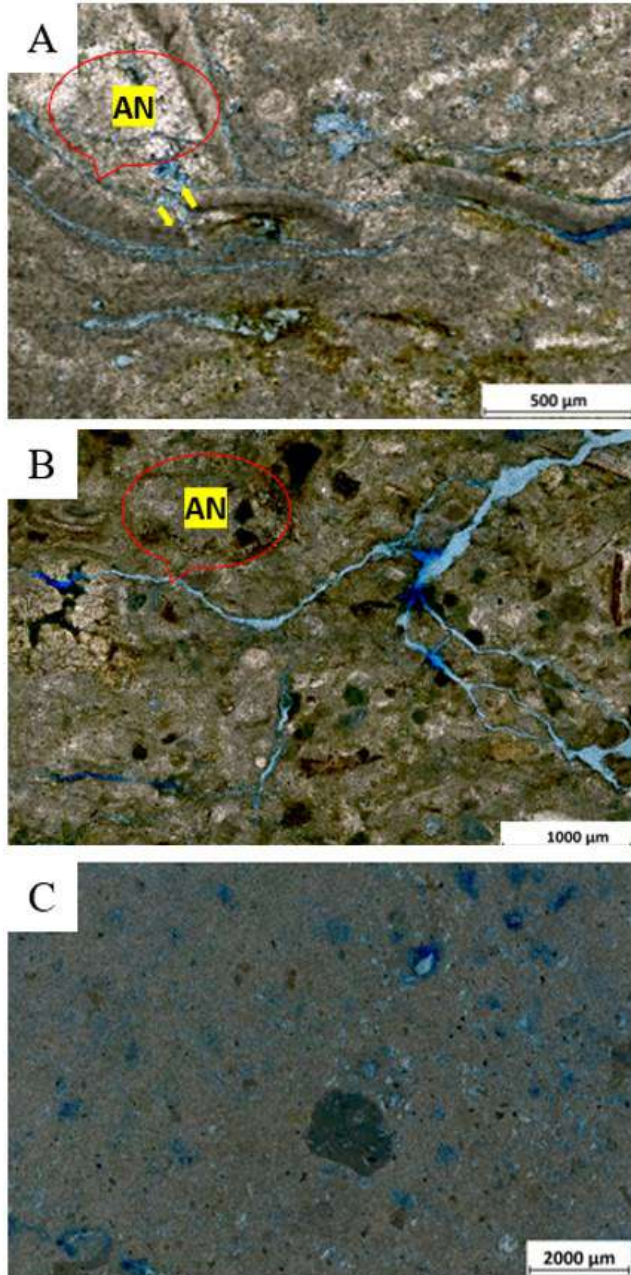


Figure 3.15: Thin section photomicrographs of unit 3. (A-B) Partially dolomitized limestone featuring open anastomosing fractures [A]. Yellow arrows point to the anastomosing

fractures [A]. (C) Dolomite with mimetically replaced allochem. Observe the notable high porosity. AN: Anastomosing fractures.

The brittleness and ductility of burrow fillings, primarily composed of wackestone, and the host rock matrix, mainly consisting of dolomite and palygorskite, significantly influence fracture characterization within Subunit 2A (Fig. 3.8). In the lower part of Subunit 2A, early cementation of the burrow fillings (Fig. 3.14A, B) makes them substantially more brittle, leading to an increased likelihood of fractures, even when the matrix exhibits ductile behavior (Figs. 3.7E, 3.8, 3.9B). These fractures commonly take the form of parallel and diverging structures within the burrow fillings, typically extending into the host rock matrix (Fig. 3.7C, E). On the other hand, the presence of palygorskite in the host rock matrix, along with dolomite (Fig. 3.9B, 3.14D), increases ductility, thereby enhancing their resistance to fracturing, as observed in field data (Fig. 3.8) and CT-scan images (Fig. 3.10). However, when the burrows are soft and become compacted in a ductile state, and the matrix is also ductile, fractures are less common, as seen in Figure 3.8A. At the top of Subunit 2A, the host rock matrix may exhibit less ductile behavior than in the lower part of subunit 2A due to a reduced amount of palygorskite mineral, as observed in thin sections (Fig. 3.9D), resulting in an increased fracture density. Therefore, the combination of the brittleness and ductility of burrow fillings and the host rock matrix plays a crucial role in fracture characterization.

The very small-scale fractures that are in the burrow fillings are hypothesized to be linked to local differential compaction. In the burrow fillings, the hypothesis gains support from the common presence of contorted and anastomosing fractures. Generally, when dealing with variably ductile materials prone to differential compaction, early fractures

may emerge. Subsequently, as these materials remain susceptible to compaction, open fractures can deform, transitioning into contorted fractures that deviate slightly from a purely planar configuration (Fig. 3.14A, B). However, small-scale fractures that cut across multiple burrow fillings may have a different origin. This could be attributed to the compaction of underlying beds and the resultant deformational response above, or it might be influenced by a regional stress field, or potentially be the result of other factors. At the interfaces between burrow fillings and the host rock matrix, fractures commonly occur. This phenomenon arises from the juxtaposition of distinct lithologies, such as dolomitic and nodular limestone, resulting from bioturbation. Differences in lithology lead to variations in mechanical properties at lithological interfaces, which in turn facilitate fracture initiation (Douma et al. 2019).

On the other hand, the host rock matrix typically exhibits open planar to sub-planar fractures (Fig. 3.14C, D). This characteristic could be attributed to the relatively lower compactibility of the host rock matrix when compared to the burrow fillings. The fractures within the burrow fillings that are primarily caused by compactional forces is proposed to form relatively early. In contrast, the planar fractures that cut through the matrix and potentially the burrow fillings appear to develop later.

C. Case 3- Strata without the Influence of Burrows.

Unit 3 does not exhibit the same burrow percentage as the underlying unit and instead shows a prevalence of non-burrow-related fractures (NBRF). This unit showcases a distinctive fracture pattern in contrast to the underlying units. Notably, unit 3 predominantly features medium-scale fractures, while micro fractures within the matrix are

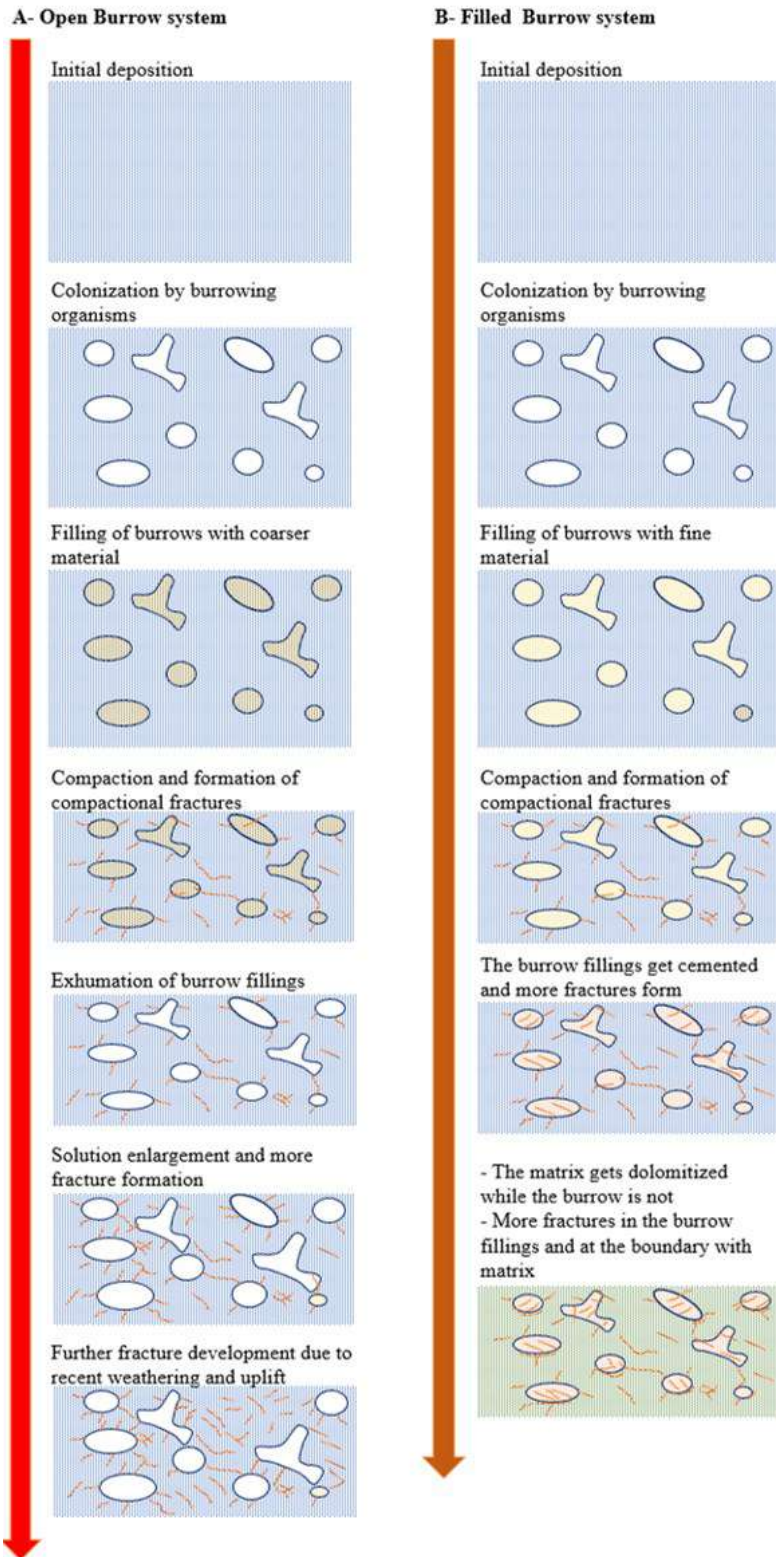


Figure 3.16: Conceptual model of fracture formation. (A) Fractures that occur with an open burrow. (B) Fractures that occur in association with a filled burrow

notably absent, and substantial bioturbation is lacking. In contrast, unit 1 and unit 2 exhibit a profusion of micro fractures and very small to small-scale fractures, along with extensive bioturbation. The absence of bioturbation in unit 3 is thought to be a key factor in the formation of medium-scale fractures. The presence of burrows would typically serve as barriers, impeding the propagation of fractures. This is due to the fact that Unit 3 fractures seem to be continuous, without interruption by burrow pores that serve as barriers, impeding the propagation of fractures. The characteristics of the fractures may have been influenced by the mineral composition of the strata, along with the high observed porosity within this unit (Fig. 3.15C). Increased porosity within the matrix of unit 3 could potentially lower the overall strength of the rock (Geltmacher, and Koss 1990), making it less resistant to fracturing.

3.5.2. Conceptual model

A. Open Burrow Settings: Example from Unit 1

The fracture formation in this setting area is a result of a sequential and integrated process (Fig. 3.16A). Initially, it commences with the deposition of sedimentary matrix layers. This undergoes significant modification due to burrowing organisms, and burrows are subsequently filled. As the sediment layers become compacted, compactional fractures emerge. Over time, these filled burrows are exhumed, and solution enlargement occurs and contributes to the formation of additional fractures, some of which get cemented. This setting is further influenced by recent weathering and geological uplift, leading to the development of additional fractures.

B. Filled Burrow Settings: Example from Subunit 2A

The fracture formation in this context initiates with the deposition of sedimentary layers (Fig. 3.16B), which are profoundly modified by the burrowing activities of organisms. These activities lead to the subsequent filling of the burrows. As the sediment undergoes compaction, the burrows become more densely compacted, leading to the emergence of compactional fractures. Over time, the process of differential dolomitization further differentiates the burrows from the surrounding matrix; the matrix becomes dolomitized while the burrows remain less affected due to their lower susceptibility to dolomitization. This leads to differential brittleness behavior between the two, with the burrows exhibiting a higher concentration of fractures compared to the surrounding matrix. The matrix, notably enriched with palygorskite, shows an enhanced resistance to fracturing, thereby presenting fewer fractures. Additionally, the boundary between the burrow fillings and the matrix becomes a critical zone where fractures develop due to mechanical weakness, a consequence of the stark lithological contrast.

3.5.3. Implications

The relationship between the bioturbation and fractures has not been thoroughly evaluated. Few studies have mentioned such a relationship (Bednarz and McIlroy 2012; Knaust et al., 2020; Valencia et al. 2023). Some studies stated that the combination of fractures and bioturbation significantly enhance reservoir quality (Eltom et al. 2020; Golab et al. 2017). Knaust et al., (2020) observed a connection between micro-burrows, such as *Thalassinoides* and *Virgaichnus*, and fractures, noting that these burrows are generally linked to fractures but without further implications or explanations. Bednarz and McIlroy (2012) emphasized that the presence of burrow holes alters the fracture planes direction, suggesting that subsurface burrows can enhance reservoir connectivity by localizing

induced fractures near porous burrow halos. Additionally, they mentioned that these burrows, possibly filled with quartz-rich materials, could increase brittleness, thereby inducing fractures in otherwise non-brittle rocks like mudstone, potentially contributing to the fracture porosity within the reservoir. However, Valencia et al. (2023) mentioned that the fracturing process might be due to differential compaction between clay-filled burrows and the firmer, carbonate-rich host sediment. Increased pressure could force water out of the saturated clay within the burrows, leading to natural hydraulic fracturing in the surrounding host rock matrix. This study confirmed a relationship between fractures and bioturbation and provides some new insight. The identification of fractures within the lithological units of the Khanasir Member in the study area reveals diverse responses to stress influenced by the lithological compositions and diagenesis, and burrow characteristics of these units. In Unit 1 and subunit 2B, characterized by open burrows, the fracture characteristics are primarily controlled by the burrow features (burrow percentage, morphology) and the diagenesis of the host rock matrix (e.g. cementation). These parameters hold significance in predicting fracture characteristics in similar settings worldwide. On the other hand, in settings where the burrows are filled, such as subunit 2A, a combination of diagenetic processes that the burrow fillings have undergone, like cementation, along with the composition of the host rock matrix, becomes the primary determinant of the ductility and brittleness of both the burrow fillings and the host rock matrix. This, in turn, governs the overall fracture characteristics in these settings. The significance of bioturbation in this context is particularly important when it takes place in a ductile matrix, as observed in Subunit 2A. Consequently, the preceding discussion on the influence of bioturbation on fracture initiation and propagation within the Khanasir

Member not only contributes valuable insights into the geological dynamics of this particular region but also provides crucial implications for understanding the reservoir quality of carbonate formations.

Furthermore, regardless of the mechanism responsible for the formation of BRF and NBRF, our study shows that, in addition to the *Thalassinoides* burrows and the possible but limited input of micropores from the rock matrix, open macro and micro-fractures might contribute to increasing the production of hydrocarbons (or groundwater) in this member. In the study area, the *Thalassinoides* ichnofabric plays a significant role in determining reservoir quality, particularly in unit 1 and subunit 2B, where it creates a potential reservoir zone. Moreover, the presence of *Thalassinoides* burrows influences fracture generation and the diagenesis of both fractures and the host rock matrix which results in enhancing permeability by establishing connections among isolated burrows. Additionally, the presence of *Thalassinoides* burrows, combined with local or regional stress fields, leads to a preferred orientation of compactional fractures. This orientation induces anisotropy in the permeability distribution. Within subunit 2A, the significance of fractures in terms of fluid flow differs notably between the burrow fillings and the host rock matrix. Cemented fractures serve as barriers within the burrow fillings, whereas open fractures enhance the petrophysical properties of the host rock matrix by providing pathways for fluid flow. From a petrophysical point of view, burrows, open fractures, and the matrix form a triple-porosity system (e.g. [Abadassah and Ershaghi 1986](#); [Aguilera and Aguilera 2004](#)). If this kind of burrow-controlled fracturing occurred in a carbonate reservoir in the subsurface, it would help improve reservoir connectivity by localizing fractures around porous burrow halos. Understanding the relationship between bioturbation

and fractures is crucial for reservoir compartmentalization. It impacts reservoir quality, fracture distribution, and fluid behavior. This knowledge enhances resource management and hydrocarbon production optimization.

This study significantly enhances our understanding of the intricate interplay between bioturbation and its substantial influence on the formation and distribution of fractures within geological formations. These valuable insights play a pivotal role in accurately predicting the quality and behavior of subsurface reservoirs and aquifers, essential for effective resource management and the potential optimization of hydrocarbon production.

3.6. Conclusions

This study examines the impact of bioturbation on natural fractures. Our findings show that the fractures in the Khanasir Member of the Aruma Formation could be: burrow-related fractures and non-burrow-related fractures. Burrow-related fractures predominate in units 1 and 2, while non-burrow-related fractures are more common in unit 3. This study identifies three distinct scenarios based on the presence or absence of burrows: strata containing open burrows, those with filled burrows, and strata without any burrows. The study reveals that the fracture characteristics vary significantly across these scenarios.

In strata with open burrows (e.g., Unit 1 and Subunit 2B), fracture characteristics are influenced by burrow density, shape, and host rock cementation. Higher burrow density promotes pore network formation, leading to fracture-prone zones and fluid flow pathways. Elongated, irregularly shaped burrows increase fracture likelihood more than circular ones. Additionally, the cementation of the host rock enhances its brittleness, thus elevating the potential for fracturing.

In strata containing filled burrows, fracture scales range widely, influenced by burrow fillings and percentage, and host rock matrix composition, affecting brittleness and ductility, as well as tectonic influences. A ductile matrix with brittle burrow fillings, especially those with early cementation, tends to show more fractures. Conversely, uniformly ductile conditions in both burrows and matrix result in fewer fractures. Open burrows enhance fracture density, yet filled burrows result in longer fractures, as open burrow can impede fracture spread.

In a setting that exhibits strata lacking bioturbation (e.g., unit 3), fracture characterization is influenced by their texture and mineralogy. Unit 3 primarily comprises dolomitized limestone and dolostone, and is characterized by non-burrow-related fractures. Unlike burrow-related fractures, which are influenced by bioturbation, the characteristics of these fractures are primarily controlled by other geological forces unrelated to bioturbation. Finally, this study significantly enhances our understanding of the intricate relationship between bioturbation and fracture formation within geological formations. These insights are not only crucial for predicting the behavior of subsurface reservoirs and aquifers but also hold the potential to optimize hydrocarbon production and resource management in carbonate reservoirs.

Chapter 4

Characterizing the attributes of large burrows in the Upper Cretaceous Aruma Formation: Insights from ground penetrating radar

Abstract

Previous research highlights the importance of thoroughly characterizing burrow attributes (morphology, diameter, percentage, and fillings) to understand effects on petrophysical properties such as porosity and permeability. However, while traditional samples such as hand-specimens, core plugs, standard reservoir cores, and outcrops aid in detailed characterization, their limitations are evident when analyzing exceptionally large three-dimensional burrows (cm-scale). This study introduces a new approach using ground penetrating radar (GPR) to capture these attributes, a technique not previously utilized in such research. We focus on the Upper Cretaceous Aruma Formation in central Saudi Arabia, that is characterized by extensive burrow networks with burrow percentages reaching up to 40%. Utilizing a 2.7 GHz antenna, covering an area of 1 meter by 1 meter, our goal was to analyze the burrow percentage, diameter, and morphology using GPR and compare these findings with field observations and CT scans of two samples. This approach was intended for a more comprehensive comparative analysis and to assess the effectiveness and capabilities of GPR compared to field observation and CT-scan analysis. This comparison highlighted GPR's ability to detect complex burrow networks, revealing significant variations in burrow percentage (BP), diameter, and morphology that are not

fully captured by other methods. Specifically, GPR data revealed deviations in BP from CT scans by 5% and from field observations by 9%, attributed to its more extensive volume of coverage and deeper penetration. Further analysis across multiple 2D slices also confirm GPR's precision in measuring burrow diameters ranging from 0.45 to 8.5 cm and its effectiveness in detailed morphology analysis, identifying diverse patterns that are indicative of *Thalassinoides* burrows.

GPR provides valuable data that would be challenging to acquire through other means, and offers non-destructive, in-situ analysis. The insights obtained from GPR data are invaluable for understanding the attributes of large burrow systems, thereby facilitating a more thorough assessment of their attributes.

4.1. Introduction

The enhancement of storage and flow capacities in sedimentary strata due to burrowing activity is a well-established concept in the field of sedimentary geology (Baniak, Gingras, and Pemberton 2013; Cunningham et al. 2009a, 2009b; Gingras and Pemberton 2015; Knaust, Dorador, and Rodríguez-Tovar 2020; Valencia et al. 2023; Saraih., et al 2023). Numerous studies have demonstrated that permeable burrow fillings or the presence of open shafts and tunnels within burrows can significantly increase the porosity and permeability of these strata (Cunningham et al. 2009b; Eltom et al. 2020; Golab et al. 2017; Valencia et al. 2023). These investigations have underscored the necessity of conducting comprehensive characterizations of burrow attributes to gain an in-depth understanding of their impact on these critical properties. Key burrow attributes identified by these studies for detailed analysis include the morphology, diameter, percentage or abundance, and the nature of the fillings of the burrows.

While conventional samples like hand-specimens, core plugs, standard reservoir cores, and outcrops are useful for detailed characterization of burrow attributes, their limitations become apparent, especially when dealing with exceptionally large three-dimensional burrows, which have been documented in various stratigraphic sections worldwide. For instance, Rodríguez-Tovar (2008) reported *Thalassinoides* burrows in the Miocene outcrops of southeast Spain, exhibiting shafts up to 22 cm in diameter and 200 cm in length. Similarly, in the Cretaceous Aruma Formation of central Saudi Arabia, *Thalassinoides* burrows have been found with shaft diameters exceeding 8 cm (Saraih et al., 2023). In these large burrow systems, conventional (small) samples may provide insights into the fillings and diameter of the burrows but fall short in fully capturing their overall connectivity, morphology, and abundance. This limitation highlights the need for more comprehensive methods to accurately assess the complex nature of large burrow systems.

The use of Ground Penetrating Radar (GPR) emerges as a promising approach to surpass the limitation of rock samples in thoroughly capturing the complexity of large burrow systems. Evolving as an easy-use geophysical technique, GPR has demonstrated its effectiveness across a diverse range of applications, encompassing engineering (Benson, 1995; Grasmueck, 1996; Knight, 2001; Aranha et al., 2002; Hanafy, 2010; Chlaib et al., 2014), archaeological (Masini et al., 2010; Ristić et al., 2020), geophysical, and geological fields (Hanafy & Schuster, 2007; Hanafy et al., 2023; Tsoflias, 2008; Lane et al., 2000; McMechan et al., 1997; Grégoire & Hollender, 2004; Grasmueck, 1996; Cunningham, 2004; Chlaib et al., 2014; Knight, 2001; Benson, 1995; Aranha et al., 2002; Hanafy & Hagrey, 2006; Hanafy et al., 2021; Ramdani et al., 2022). Its utility in these domains is well-documented, from infrastructure analysis to archaeological site exploration and

geological assessments. However, despite its widespread use and proven capabilities, the application of GPR in investigating the complex nature of burrow systems has not been extensively investigated. This gap presents an opportunity for pioneering research, suggesting that GPR could open new avenues for understanding and characterizing these geological features more comprehensively.

Within this framework, the primary aim of this study is to explore the large burrow systems present in the outcrops of the Aruma Formation, located in central Saudi Arabia, using GPR. The study outlines a comprehensive set of field protocols customized for acquiring GPR data in such geological contexts. It includes a detailed methodology addressing the processing of GPR raw data, with a specific focus on overcoming challenges related to noise and signal attenuation. Additionally, the study delineates strategies for rigorous quality control of the acquired data. The outcome of this study is the successful generation of three-dimensional images of large burrow system using GPR, which effectively maps the extensive burrow systems within the Aruma Formation. These results surpass the limitations inherent in traditional rock sample analysis, offering improved understanding of the subsurface features. This approach not only enhances the visualization of the burrow systems but also contributes significantly to our knowledge of their spatial distribution and structural complexity.

4.2. Geological Setting and Study Area

The study area is situated 55 km northeast of Al Kharj in central Saudi Arabia (Fig. 4.1A). It specifically investigates the Aruma Formation, with a primary focus on its lower

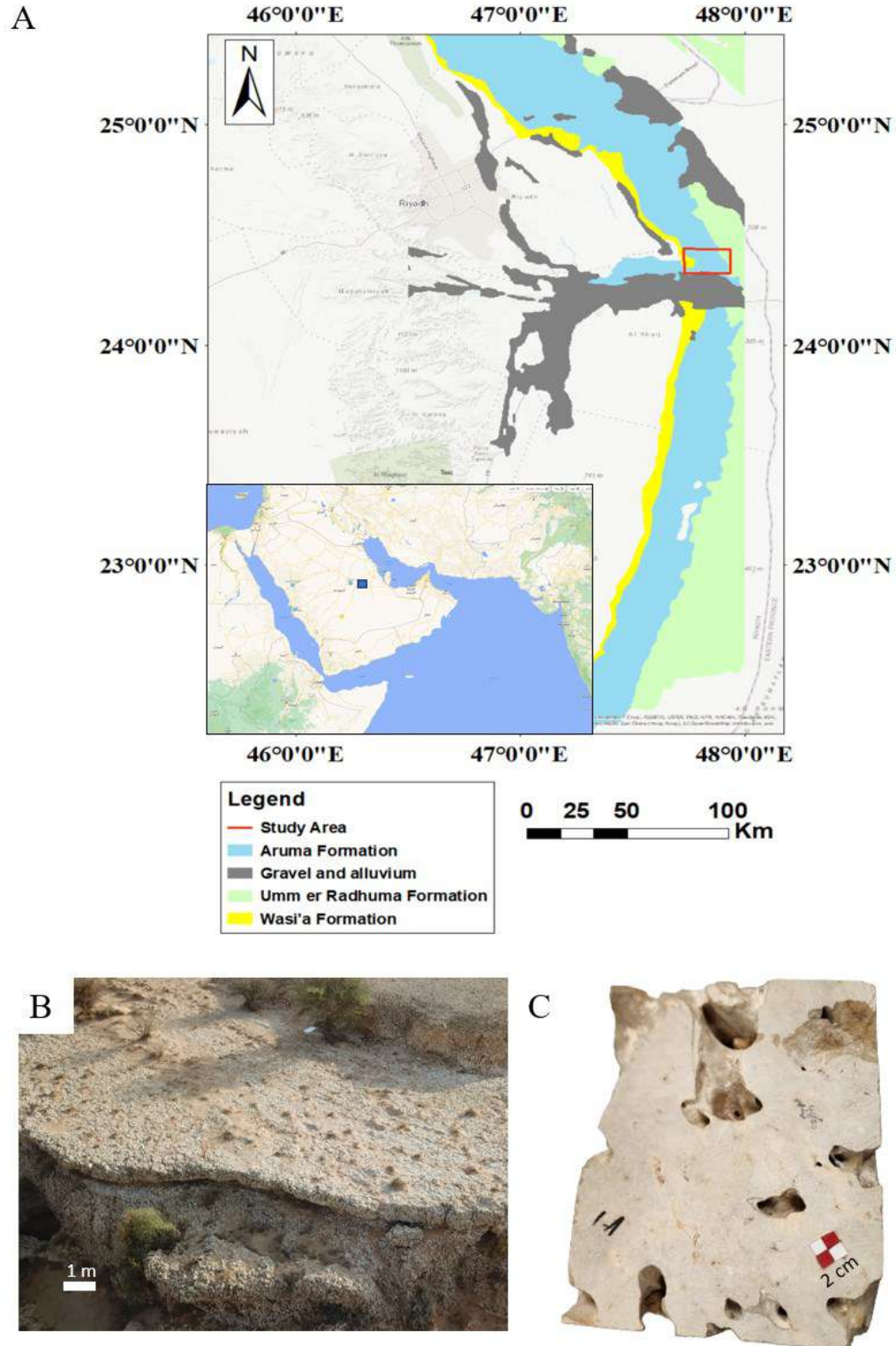


Figure 4.1: Overview and detailed views of the Aruma Formation outcrops. (A) Map depicting the exposed outcrops of the Aruma Formation with the study area marked by a red square. Inset shows location (red square) of the detailed map. (B) Close-up photograph of

Subunit 1A, where the GPR survey was carried out. Note that the burrows are mostly open. (C) Hand specimen from subunit 1A. This sample then analyzed using a medical CT.

member, the Khanasir Member. This member exhibits remarkable burrowed strata characterized by extensive large burrow systems (Fig. 4.1B-C). The Aruma Formation was deposited during the Late Cretaceous to Paleocene transgression of the Arabian platform in a foreland basin setting. The Aruma Formation overlies the Wasia Formation, which is overlain by the Umm er Radhuma Formation. The age of the Khanasir member has been determined to be Campanian-early Maastrichtian based on its large foraminifera and ammonite assemblages (Powers et al., 1966; Skelton and El-Asa'AD, 1992; Philip et al., 2002).

Saraih et al. (2023) divided the Khanasir Member into three units. The main focus of this research will be on unit 1, particularly subunit 1A, which is used as a representative analogue for bioturbated carbonate strata. Unit 1, which is characterized by wackestone to packstone hosting solution-enlarged open and partially filled burrows. Unit 1 is further subdivided into subunit 1A and subunit 1B (Saraih et al., 2023), where subunit 1A shows a slight increase in the burrow size compared to subunit 1B.



Figure 4.2: Field sampling and challenges. (A) Hand specimen used for CT-scan, collected from Subunit 1A, shows open and partially filled burrows. (B) Field photograph depicting the attempt to obtain a core sample from Subunit 2A, this attempt failed due to the large burrow size and fracturing.

4.3. Methodology

4.3.1. Characterization of burrow attributes

The initial investigation of burrow attributes in this study was conducted in the field. This involved observing and recording various aspects of the burrows, including the percentage of burrowed area, as well as the diameter of the shafts and tunnels. To augment this data, photographs of these features were taken, providing a rich source of information for robust statistical analysis. These images were then processed using ImageJ and JMicrovision software, tools that facilitated the extraction of precise numerical data for these burrow attributes.

To investigate deeper into the characteristics of the burrows, particularly the interconnections between shafts and tunnels, two rock samples were collected from subunit 1A: one of irregular shape (Fig. 4.2A) and another that was carefully prepared in the lab to possess well-defined dimensions, measuring 22 cm by 27 cm along the x and y axes. These samples were then analyzed using a medical CT scanner at the laboratory of the College of Petroleum Engineering and Geosciences (CPG) at King Fahd University of Petroleum and Minerals (utilizing a Toshiba Alexion TSX-032A medical CT scanner). The CT scans provided two-dimensional (2D) slices, which served as another valuable image source for measuring the shaft diameter and length. Additionally, the three-dimensional (3D) views obtained from these CT scans were crucial in examining the angular connections between the shafts and tunnels, as well as in assessing the overall morphology of the burrows. These

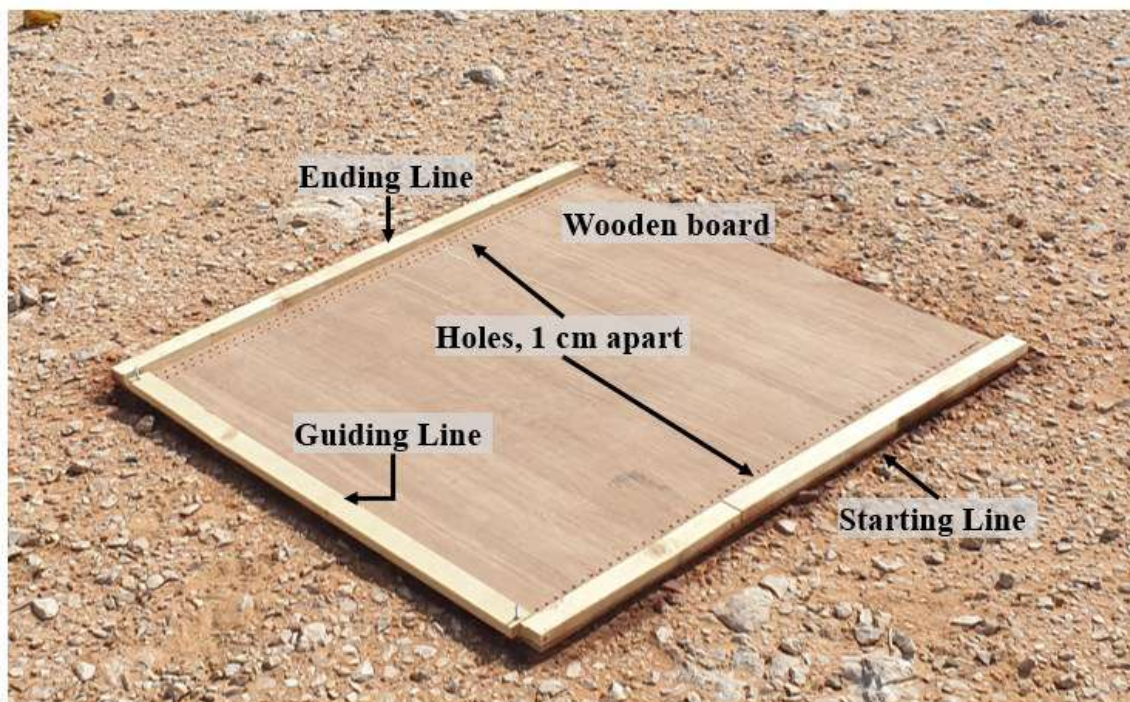


Figure 4.3: The wooden board utilized as a stable platform during the GPR survey to ensure consistent data recording.

3D views were rendered using Petrel™ 2022 software after the data were imported in SEG-Y format. This comprehensive approach, combining field observations, photographic analysis, and advanced CT scanning, offered a multifaceted understanding of the burrow systems in the Aruma Formation. Such data form the bases for the quality controls on the outcome of the GPR data. It should be noted that coring within the studied interval did not succeed (Fig. 4.2B), potentially due to the presence of large open burrows or fractures that prevented the retrieval of complete core samples

4.3.2. GPR data acquisition

GPR works by transmitting electromagnetic (EM) pulses into the subsurface. These pulses interact with different subsurface layers with different electromagnetic properties, such as permittivity and electrical conductivity. As the EM pulses encounter boundaries between these distinct layers, such as the interface between the host rock matrix and the

burrow structure and its fillings, they are reflected back to the surface and received by the receiver antenna.

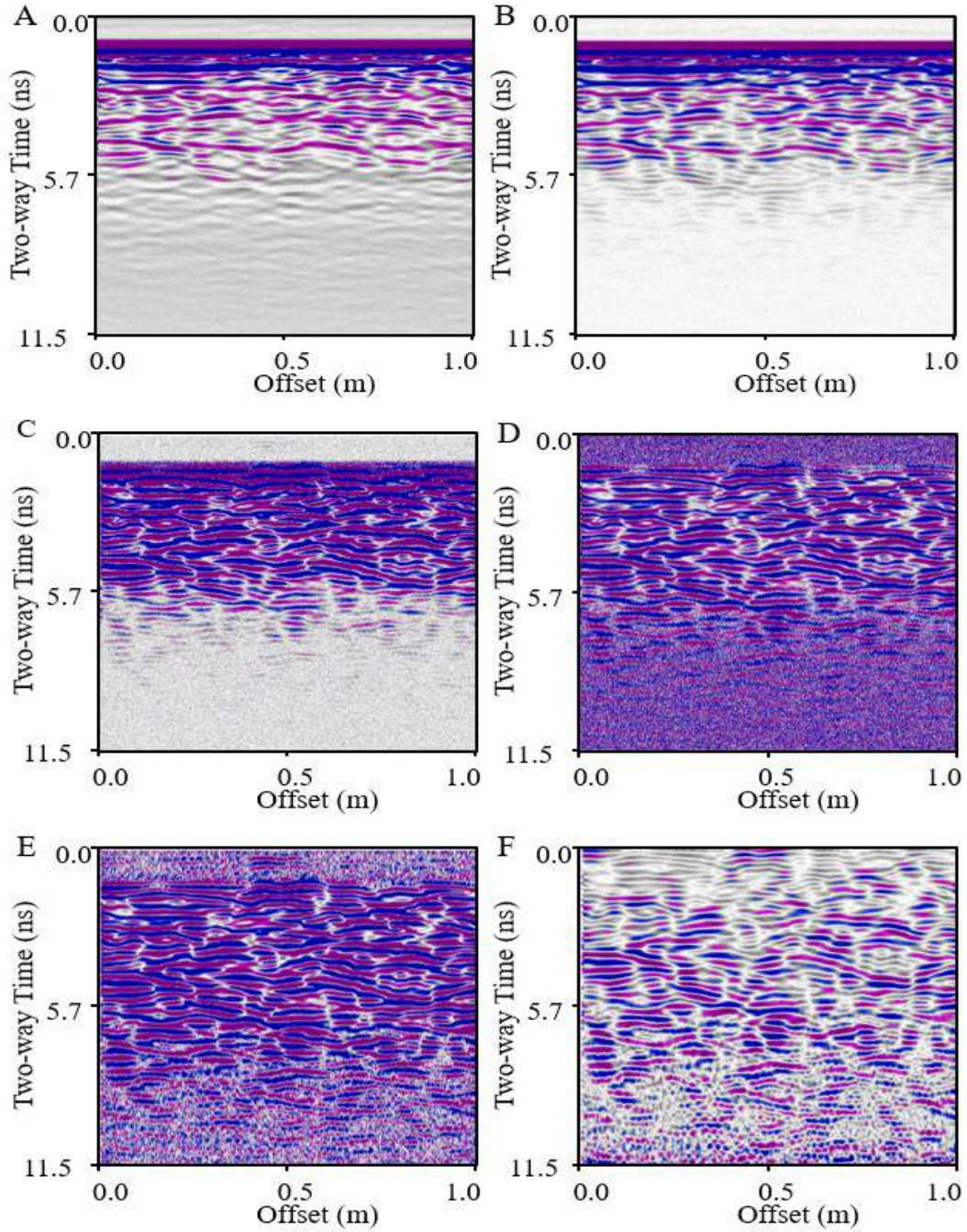


Figure 4.4: Data processing filters plied to GPR survey (A) Raw data. (B) Subtracting average (dewow). (C) Background removal. (D) Energy decay (E) Bandpass butterworth. (F) Manual gain

In this study, the GPR surveys were conducted with a 2.7 GHz antenna, which was selected specifically for its capability to provide high-resolution data that aligned with our research objectives to detect the burrow attributes such as BP, diameter, and morphology. The 2.7 GHz antenna offers high spatial resolution (millimeter scale) but yields shallow penetration depth (less than 70 cm).

The GPR surveys were executed utilizing the 2.7 GHz antenna at the top of subunit 1A of the Aruma outcrop, which contains strata with open or partially filled solution-enlarged burrow shafts. Partial fillings consist of paleosol material composed of 52% calcite, 33% quartz, and 15% palygorskite. All outcrops can be considered to be totally dry. To avoid inconsistent data recording due to higher chance of irregular movement of the antenna, we used a special wooden board during the surveys to ensure precision, consistency, and accuracy in data recording (Fig. 4.3). The wooden board was designed with a series of holes spaced 1 cm apart at two opposite sides to help guide the measurements. Wooden pegs marked the start and end points for each survey line, and another peg helped keep the antenna moving straight during the survey (Fig. 4.3). In total, 101 profiles with the 2.7 GHz antenna were acquired, each spaced 1 cm apart. Typically, the profiles extended from north to south.

After successfully acquiring the data using the 2.7 GHz antenna, our next phase involved subjecting the acquired datasets to a series of essential processing steps (Fig. 4.4A-F) conducted using ReflexW software. These steps encompassed the application of 1D and 2D filters, and gain filter to enhance the quality of the GPR data (Fig. 4.4). In our data processing, two 1D filters were used, including subtract-mean (dewow) and bandpass Butterworth filter. The dewow filter was applied with a 26 ms time window (Fig. 4.4A).

This filter was crucial because it removed any low-frequency noise or trends that may obscure any higher-frequency reflections from subsurface features (Annan, 2003). The Lowpass Butterworth filter, with a lower cutoff at 0 and an upper cutoff at 3.9 GHz (Fig. 4B), further refined the data by eliminating low- or high-frequency noise, i.e., we kept the signals and attenuated unwanted noise (Oppenheim & Schaffer, 1999). Furthermore, two 2D filters were used, including running average and background removal filters (Fig. 4.4C). The running average is employed as a filter to smooth the radar signal by sequentially averaging 3 traces of data, within a moving window across the dataset (Daniels, 2004). The background removal was also applied to enhance visibility of subtle, weaker signals (Annan, 2003). The zero-time of the processed data was adjusted to exclude any readings above the direct arrivals. The gain filters, including energy decay (Fig. 4.4D) and manual gain filters (Fig. 4.4F), were essential for improving GPR data clarity. These filters enhanced signal quality, and ensured a clear representation of subsurface features. Upon finalizing the processing of the 2D GPR data, the information was exported to generate a three-dimensional block that represent the subsurface features.

4.3.3. 3D block construction

The creation of the 3D block was conducted in MATLAB where several steps were involved. Initially, we began by importing the processed GPR data. These files served as the foundational dataset for our analysis. In this study, GPR data analysis was conducted, utilizing a velocity value (vel) of 12.45 cm/ns. Data preparation involved constructing a spatial grid (x and y) spanning from 0 m to 1 m for the data acquired by the 2.7 GHz antenna, with an initial cell size of 0.01 cm. Each trace is recorded using 0.025 ns and 456 samples per trace, which give a total recording time of 11.4 ns and average of 720 traces

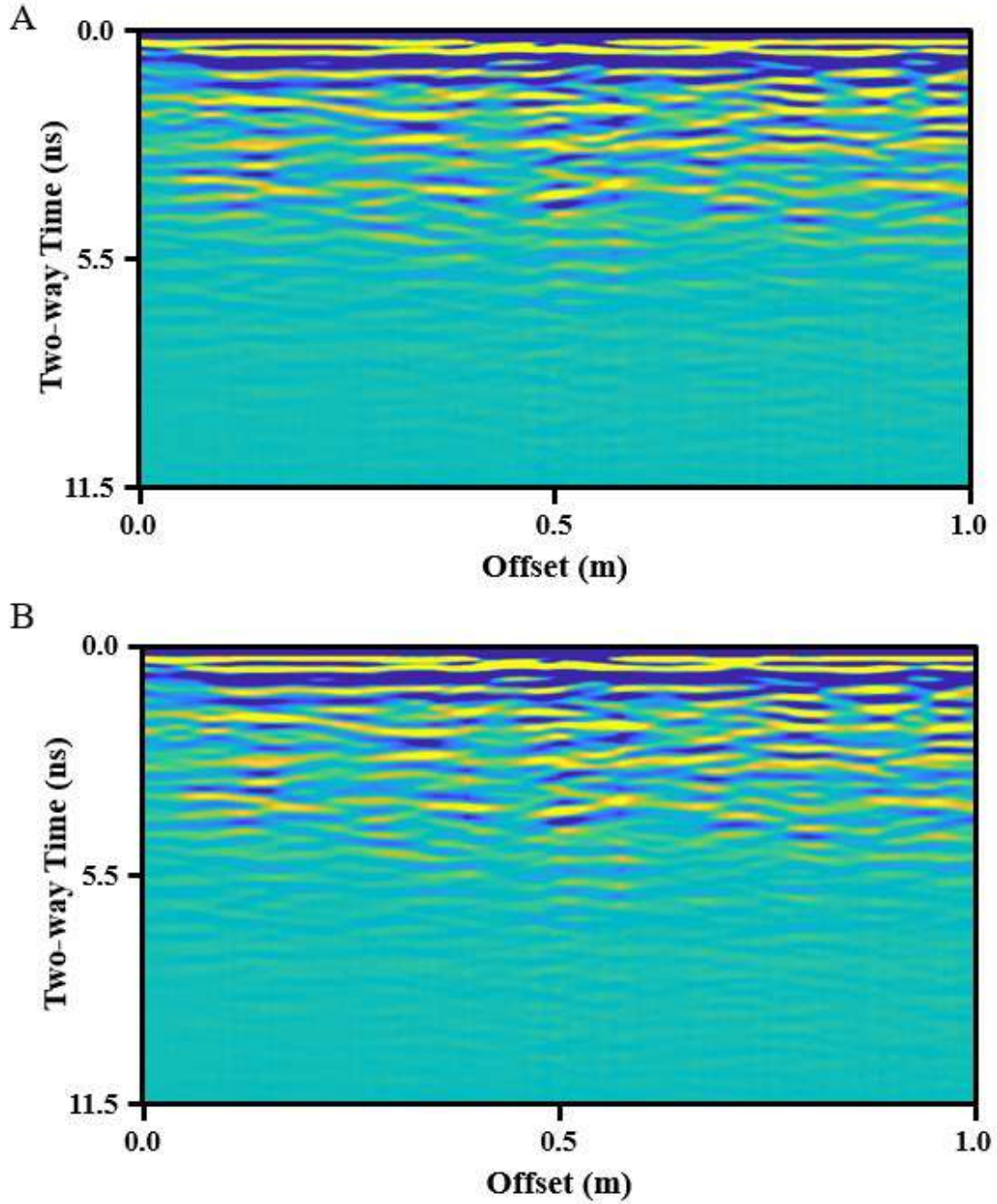


Figure 4.5: Comparison of raw and resampled GPR Data. (A) Raw GPR data, profile # 1, composed of 722 traces. (B) The same profile after resampling, updated number of traces is 101.

in each profile. To ensure the data were suitable for analysis and all 101 recorded profiles has the same number of traces, the recorded data are resampled to ensure uniformity in size. The dataset was resampled to 101 traces/profile without compromising the accuracy

of the data (Fig. 4.5). This preprocessing step proved essential in preparing the GPR data for subsequent analysis. Furthermore, to reduce background noise, local averaging was applied within a window of three traces ($ws = 3$). The original and noise-reduced data are then normalized, where each trace is divided by its maximum amplitude value. The final 3D file consists of 4 columns; the first three are the pixel's x, y, and z location, and the fourth is the amplitude. Ultimately, we transformed the processed data into the desired 3D block format, allowing for comprehensive analysis and visualization of the subsurface information. The initial 3D grid, sized at 101 x 101x 456 pixel³ along the x,y, and z axes, was enhanced to a finer resolution of 400 by 400 for improved visualization and analysis. The constructed 3D grid was visualized and analyzed using Voxler™ and Petrel™ software. This visualization allowed us to gain insights into the burrow morphology, percentage, and connectivity.

4.4. Results and Discussion

4.4.1. Burrow morphology

The processed and enhanced GPR data provided 3D views of the large burrow system within the Aruma Formation, capturing the full morphology of these burrows in remarkable detail (Fig. 4.6). Upon visual examination of both 2D slices (Fig. 4. 6A) and the 3D rendered volumes (Fig. 4.6B) derived from the GPR data, we observed burrow morphologies that closely resembled those identified in the field, photographs, and CT scans (Figs. 4.7, 4.8). This consistency was essential in validating the effectiveness of GPR in this context.

Comparative analysis of the GPR data and CT scans from identical survey locations revealed both similarities and differences. The GPR survey detected vertical shafts and

horizontal tunnels that closely matched observations from the CT scans. However, it also revealed a more complex and extensive network of burrows than what was evident in the CT scan data.

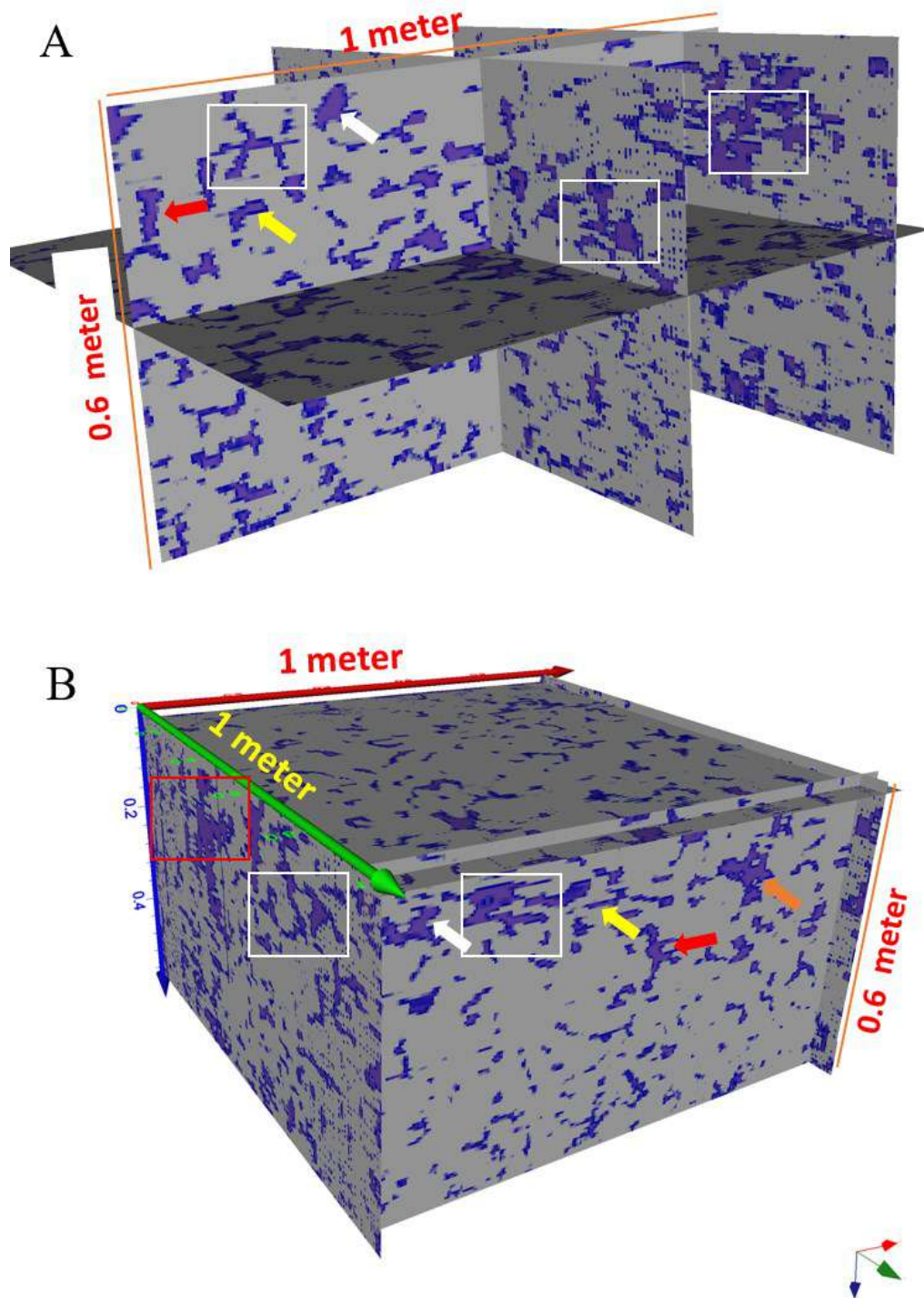


Figure 4.6: GPR data visualization for Subunit 1A. (A) A 2D slices from horizontal and vertical direction, highlighting vertical shafts (red arrows), horizontal tunnels (yellow arrows), oblique shafts (white arrow) and a range of burrow shapes such as U, V, and boxwork pattern (white square). (B) 3D cube of the GPR data showing the same features in the Fig. 4.6A. note that some areas were subjected to solution enlargement (red square). Some of these burrows form “circular” complete burrow systems (orange arrow). The grey color indicates the matrix while the blue/purple indicates the burrow.

The morphology of the burrow network as visualized in the GPR data revealed U and V shapes (Fig. 4.6), with some connections forming circular patterns suggestive of complete burrow systems (Fig. 4.6). The burrows exhibited boxwork patterns, and the angles of these structures varied significantly, ranging from horizontal to vertical orientations (Fig. 4.6A). The cross sections of these burrows displayed various forms, including circular, elliptical, and branching patterns, commonly with noticeable bulbous enlargements at their intersections (Fig. 4.6). These observations, particularly the complexity of the burrow shapes and patterns, strongly suggest characteristics typical of *Thalassinoides* burrows, aligning with the descriptions provided by Ekdale and Bromley (1984) and Pemberton and Gingras (2005); and with our interpretation based on field photographs and CT scan data.

4.4.2. Burrow diameter

Burrow diameters were assessed from the GPR data, with measurements extracted from 15 2D slices. Over 850 points were measured in total to ensure a comprehensive assessment. Burrow diameters ranged from 0.45 cm to 8.5 cm, with an average diameter of 2.22 cm and a standard deviation (SD) of 0.92 cm. The findings from the GPR were further compared to the measurements taken from CT-scan data (Fig. 4.7) and field photographs (Fig. 4.8). In the field photographs, the burrows ranged from 0.34 to 7.62 cm, with an average diameter of 2.28 cm and a SD of approximately 1.12 cm. On the other

hand, CT-scan data revealed burrow diameters within the range of 0.44 to 8.65 cm, with an average diameter of 2.34 cm and a SD of 1.36 cm. It is essential to note that these measurements were specific to the GPR survey location, and diameters across the entire units may exhibit variations, potentially being larger or smaller than the recorded measurements. The means of burrow diameters obtained from field photographs, CT scans, and GPR data are relatively similar.

Box and whisker plots of burrow diameter from 100 measurements reveal similar distributions across GPR, CT scans, and field photography, with respective interquartile ranges (IQR) of 1.8-3.18, 1.5-2.97, and 1.5-2.9. While GPR and CT scans each presented three outliers, field photography demonstrated only one, indicating minimal variance among the methods. An ANOVA was conducted to statistically evaluate the similarities in burrow diameter measurements across these techniques, yielding a P-value of 0.12. This result suggests no statistically significant difference among the groups, reinforcing the conclusion that despite minor variations in outliers, the measurement techniques for burrow diameter are comparably.

4.4.3. Burrow percentage

The GPR survey provided a 3D visualization of the burrows, enabling the extraction of numerous 2D slices across three distinct orientations: X, Y, and Z. To assess variations in the BP, the burrows and surrounding matrix were segmented and analyzed in 48 2D slices for each orientation. This analysis was aimed at identifying two levels of variability: firstly, the variation in BP representation within the GPR data across the different orientations; and secondly, the variation in BP representation when comparing the GPR data (across all

three 2D orientations) to the CT scan data, which was also sectioned into the three orthogonal 2D slices. This comprehensive approach seeks to understand the consistency

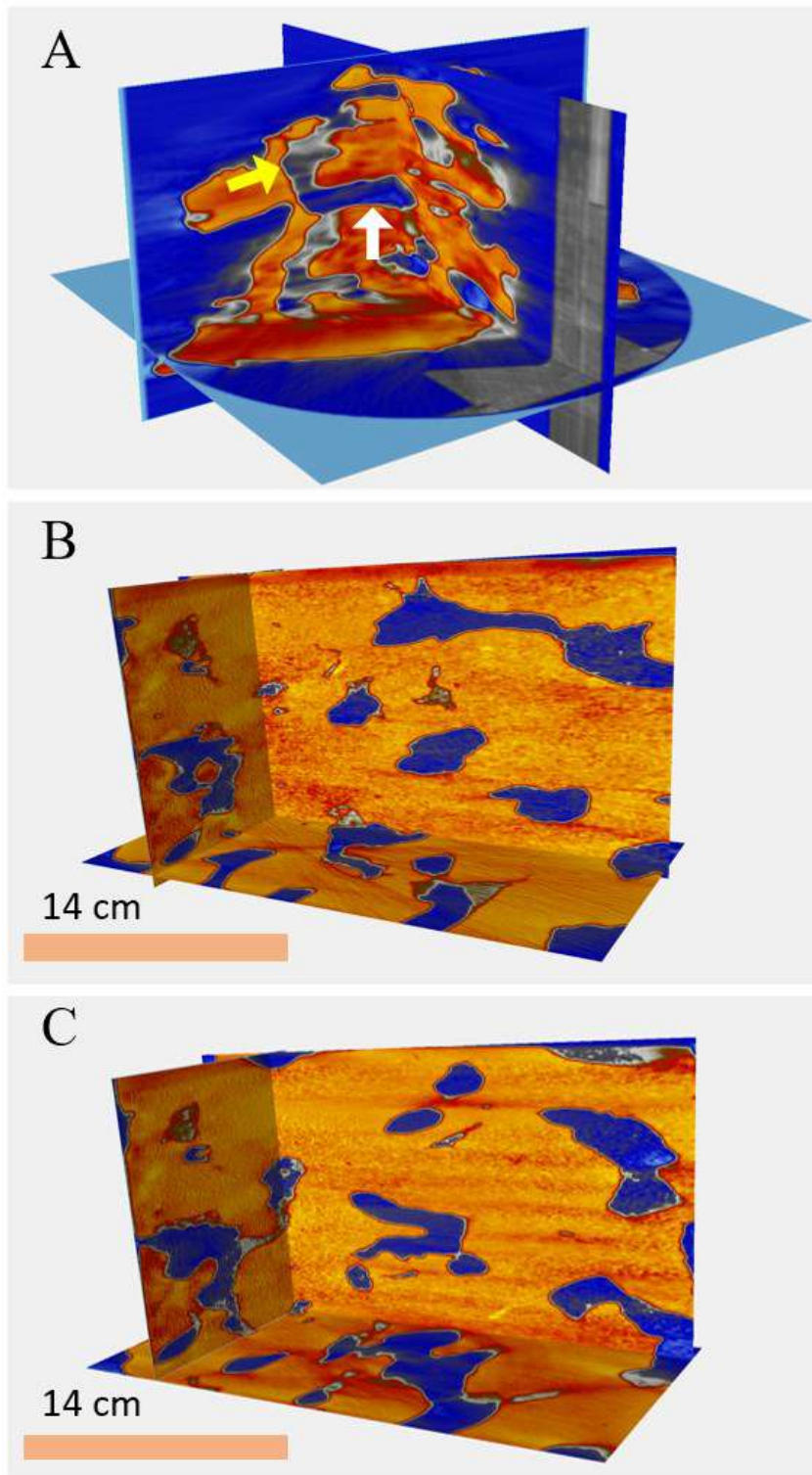


Figure 4.7: CT Scan captures of bioturbated samples from Subunit 1A .(A) CT scan snapshots of the hand specimen illustrating vertical burrow shafts (yellow arrows) and horizontal tunnels (white arrows). (B-C) CT images of the rectangular sample displaying burrows with circular to elliptical shapes. Blue color indicates the burrows, whereas orange color indicates the surrounding matrix.

and accuracy of BP quantification using GPR data in reference to the CT scan, which was used here as approximate ground truth for BP. Because the CT scan sample could not exactly duplicate the GPR sampled area, the CT scan can only be considered as an approximate representation. It is not expected to be exactly the same as the GPR-sampled volume.

Number	Pair 1	Pair 2	p-value (T-test)	Different
1	CT-X-axis	CT-Y-axis	0.53	No
2	CT-X-axis	CT-Z-axis	0.52	No
3	CT-X-axis	GPR-X-axis	0.00	Yes
4	CT-X-axis	GPR-Y-axis	0.00	Yes
5	CT-X-axis	GPR-Z-axis	0.00	Yes
6	CT-Y-axis	CT-Z-axis	0.98	No
7	CT-Y-axis	GPR-X-axis	0.00	Yes
8	CT-Y-axis	GPR-Y-axis	0.00	Yes
9	CT-Y-axis	GPR-Z-axis	0.00	Yes
10	CT-Z-axis	GPR-X-axis	0.00	Yes
11	CT-Z-axis	GPR-Y-axis	0.00	Yes
12	CT-Z-axis	GPR-Z-axis	0.00	Yes
13	GPR-X-axis	GPR-Y-axis	0.00	Yes
14	GPR-X-axis	GPR-Z-axis	0.85	No

15	GPR-Y-axis	GPR-Z-axis	0.00	Yes
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Table 4. 1: The results of ANOVA with post hoc and Bonferroni correction to evaluate the burrow percentage difference across X, Y, and Z-axis of the Ct-scan and GPR data.

In the GPR survey X-orientation, BP ranged from 12.57 to 31.3, with a mean of 18.49 and an SD of 5.17. The Y-orientation showed a range from 16.7 to 31, with a mean of 22.94 and an SD of 3.95. The Z-orientation ranged from 13.22 to 26.9, with a mean of 18.32 and an SD of 3.47 (Fig. 4.10A). Conversely, CT scan data across 48 2D slices in each orientation revealed: X-axis BP ranging from 5.16 to 25.93 with a mean of 12.69 and an SD of 5.45, Y-axis from 6.73 to 24.24 with a mean of 12.06 and an SD of 4.32, and Z-axis from 7.39 to 24.36 with a mean of 12.03 and an SD of 4.50 (Fig. 4.10B). A mean-to-mean comparison highlights a difference in BP between the GPR and CT scan data. This difference is further emphasized in box plots, which illustrate distinct IQRs and whisker lengths across all axes. The x-axis for the GPR data reveals an IQR of 14.67 to 22.4 and whiskers of 12.6 to 31.3; the y-axis IQR ranges from 20.17 to 26.3 with whiskers of 16.8 to 31; and the z-axis IQR ranges from 15.98 to 19.51 with whiskers of 13.5 to 24.08 (Fig. 4.11). For the CT scan, the x-axis IQR ranges from 8.59 to 15.4 with whisker lengths of 5 to 25.3; the y-axis IQR ranges from 8.83 to 15 with whiskers of 6.8 to 24.4; and the z-axis IQR ranges from 8.19 to 16 with whiskers of 7.4 to 24.4 (Fig. 4.11). This pattern of broader IQRs and longer whiskers in GPR data suggests a variability in BP measurements when compared to CT scan data (Fig. 4.11). It is acknowledged that BP might differ beyond the survey points; however, the focus of this study remains on this specific location (GPR location).

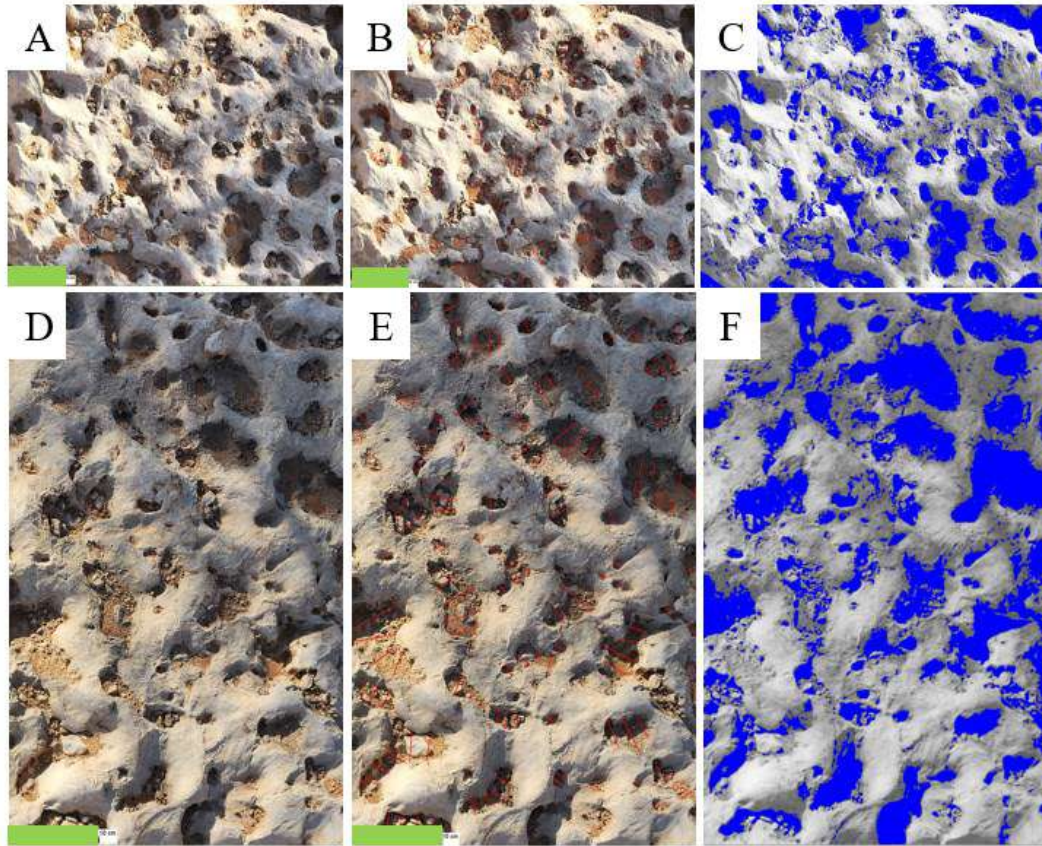


Figure 4.8: Field photographs and analysis of Subunit 1A. (A, D) Showcasing varying field photographs from the vicinity of the GPR survey site. (B, E) Illustrate the analysis of burrow diameters corresponding to the photographs in A, D. (C, F) Displaying the percentage of burrows as observed in the field photographs A, D.

4.4.4. Comparative analysis of burrow attributes

The ANOVA results indicate a statistically significant difference among the BP groups—three each from CT scans and GPR—with a p-value < 0.05 , aligning with expectations based on the descriptive statistics and visual data representations. To pinpoint where these differences specifically lie, post hoc analyses and Bonferroni correction comparisons were conducted across the six groups of BP data (X, Y, and Z orientations for both GPR and CT scans), encompassing 15 unique pairings. The analysis revealed that four pairings exhibited

no significant differences, notably three within the CT scan data and one between the GPR X-axis and Z-axis values. However, the remaining pairings showed significant differences, all with p-values < 0.05 , as detailed in Table 1. This comprehensive analysis helps clarify the specific areas of divergence within the BP measurements across the two imaging techniques. Three key characteristics of burrows—morphology, percentage, and burrow diameter—were thoroughly analyzed and assessed. While the morphology and burrow diameter exhibited similarities across data obtained from GPR surveys, CT scans, and field photographs, the BP presented notable differences among these methods. In this section, we discuss these similarities and differences, exploring the underlying reasons behind them.

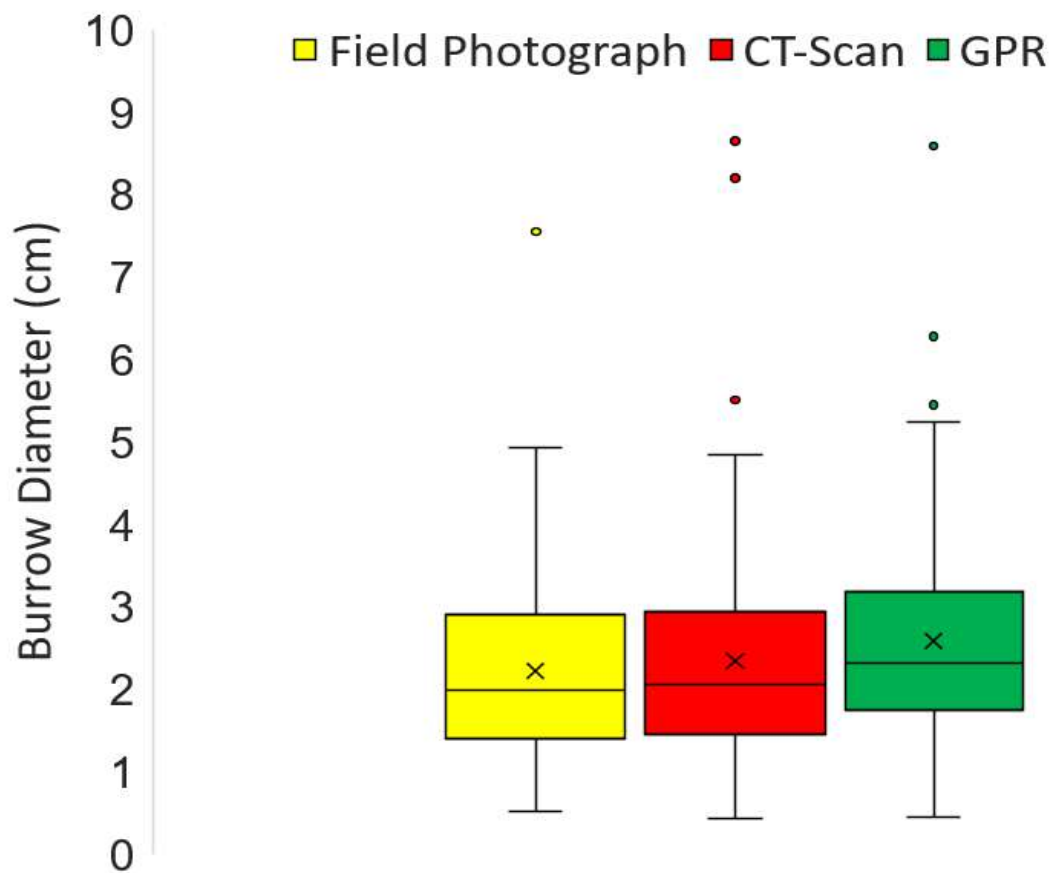


Figure 4.9: Box and whiskers plot of the burrow diameter measurements obtained from field photographs, CT scans, and GPR data.

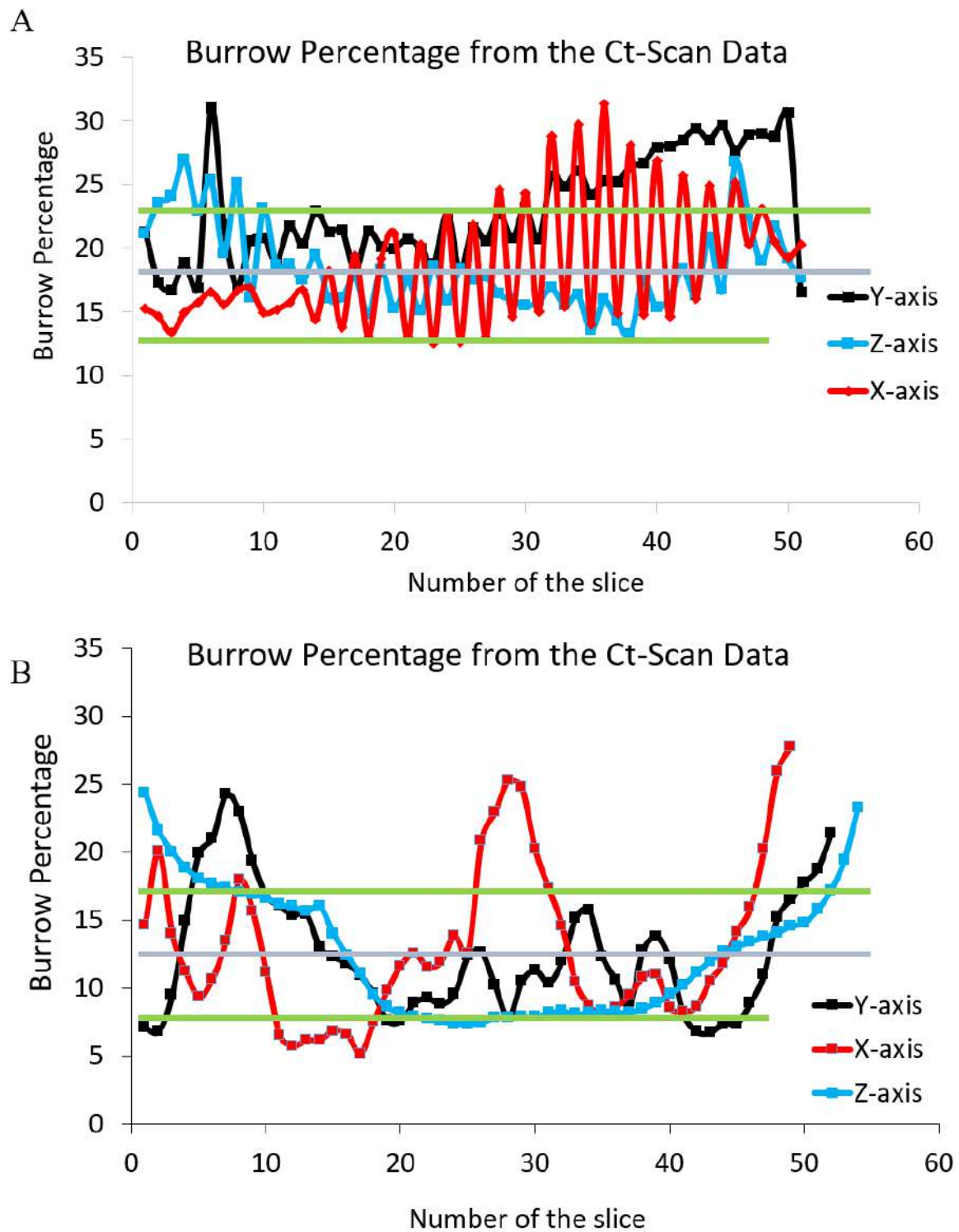


Figure 4.10: Cross-plots showing variations in burrow percentage, as derived from 2D slices (in different orientations: X, Y, and Z) of the CT –scan hand specimen sample and 2D slices from the GPR data. (A) The burrow percentage derived from GPR data, and it exhibits fluctuations around a mean value of approximately 18% (grey line), most values fall within the standard deviation, approximately 6.0% (green lines). The 2D slices on the X and Y-axis are arranged at 10 cm intervals, but the 2D slices on the Z-axis are arranged at 5 cm intervals, sequenced in descending order from the top to the bottom slice. (B) The burrow percentage is calculated from CT scan, and it exhibits fluctuations around a mean value of approximately 13% (grey line), most values fall within the standard deviation, approximately 5.0% (green lines).

For the burrow morphology, when synthesizing the data from field observations, CT scans, and GPR, it becomes evident that each method provides a perspective on burrow morphology. Field observations offer initial insight into the burrow shafts and surface-level structures. CT scans provide 2D and 3D views of burrow interiors but in a limited volume of rock. GPR data excel in revealing the extent and complexity of the burrow networks in a larger volume of rock, providing insights into burrow morphology that are not entirely apparent through field observations and CT-scan data such as boxwork pattern, different shapes and orientation of the burrow shafts and tunnels.

The diameter of burrows, as measured by various techniques (GPR, CT scans, and field photographs), shows no significant difference, indicating that GPR performs effectively in capturing the accurate size of burrows. On the other hand, to accurately estimate BP, it is essential to have a detailed representation of the entire burrow network throughout the volume of the rock. The observed differences in BP measurements between GPR and CT scan data, as highlighted by statistical analyses, box plots, and ANOVA results, can be

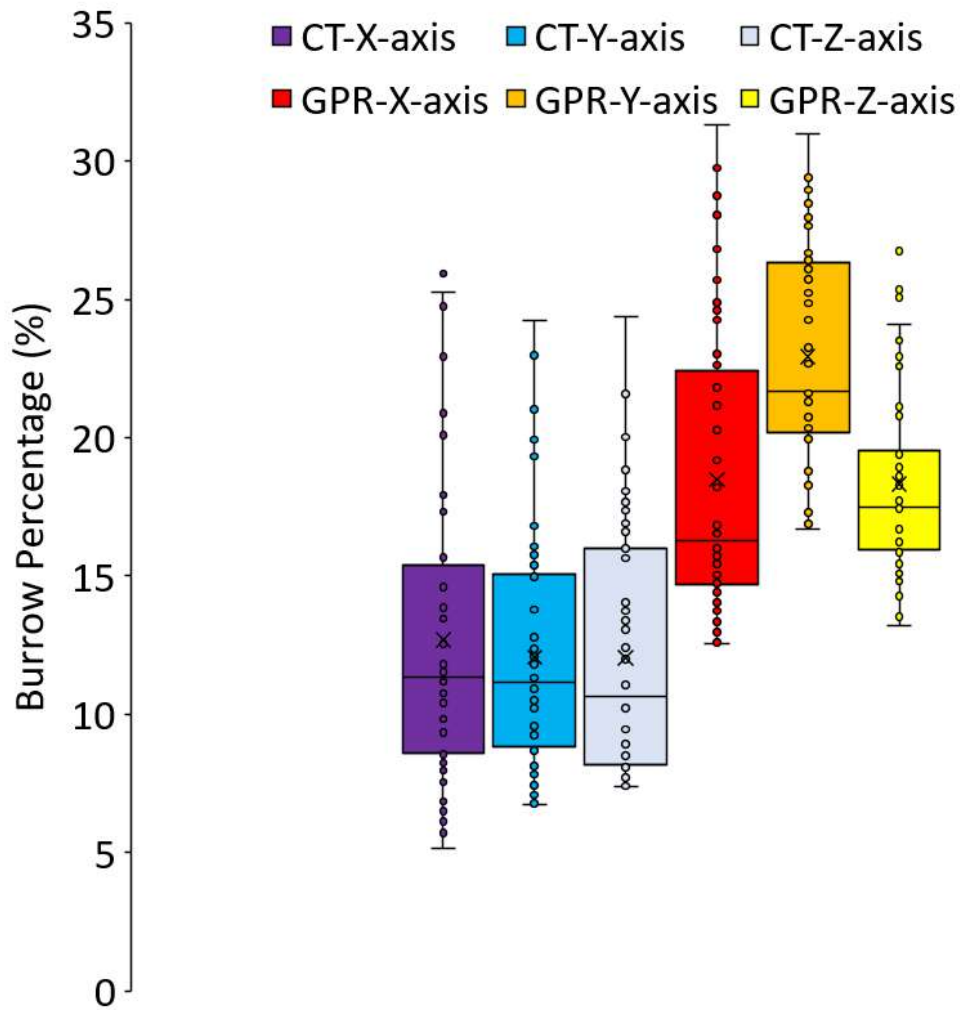


Figure 4.11: Box and whiskers plot of the burrow percentage measurements obtained from the three orientations of the CT scans and GPR data.

attributed to differences in the volume captured or the representative elementary volume (REV) covered by each method. This interpretation is bolstered by GPR survey visualizations, which illustrate the extent and complexity of the burrow networks over larger areas and depths. Comparison between the volumes analyzed by CT scans and those covered by GPR surveys further elucidates this point. The volume represented by the CT scans constitutes only 0.69% of the total volume covered by the GPR in our study area,

meaning the GPR's coverage exceeds that of CT scans by more than 144 times. This significant difference in surveyed volumes ensures that the REV for BP measurements is more likely to be accurately captured by GPR, highlighting the importance of scale in obtaining reliable geological data. Within the GPR BP data, a statistically significant difference exists between the BP measurements in the X and Y orientations, despite both being calculated in the horizontal dimension. This discrepancy could be attributed to lateral variability in BP, where trace fossils may not be randomly and equally distributed within the host rock matrix. This kind of variability can be challenging to detect using a relatively smaller volume of rock.

4.4.5. Advantages of GPR in studying trace fossils

GPR offers a notable advantage compared to methods like coring for studying burrow attributes of bioturbated strata with large burrow system (cm- scale). It overcomes the limitations associated with the sample size of coring and CT scans by enabling the examination of wide areas without the need for physical rock samples. This capability is particularly valuable as evidenced by the challenges we encountered in our study from core breakage (Fig. 4.2), making it difficult to retrieve unbroken cores from the studied interval. Therefore, GPR facilitates uninterrupted data recording across large areas, offering detailed subsurface profiles for a comprehensive analysis of the large burrow systems. Significantly, the usefulness of GPR is not limited to large burrow systems (cm-scale); it is also effective in detecting smaller burrows with diameters less than 0.5 cm. This demonstrates its capability to accurately measure burrow diameters of various sizes, suggesting its applicability across a range of burrow dimensions and systems. Moreover, as a non-invasive technique, GPR also enables the survey of large areas without the

disruption or potential damage associated with coring or excavation, an attribute particularly advantageous for sites where preservation is crucial.

4.4.6. Implications

Understanding burrow attributes such as percentage, diameter, and morphology obtained from GPR will improve our insight into the depositional environments and conditions that lead to the formation of these biogenic structures. Seilacher (1967) suggested that water depth was a primary influence of the burrow type, percentage, and diameter. In contrast, Ekdale and Lewis (1991) and Ekdale and Mason (1988) emphasized the role of oxygen levels in the water column as a factor controlling these parameters. Frey et al. (1990) expanded this to include a range of parameters like hydraulic energy, oxygen concentration, salinity, turbidity, and food availability that affect the distribution of trace fossils. Therefore, GPR provides critical data that will improve scientists' ability to characterize ichnofossils and constrain the ancient depositional environment. Moreover, this depth of understanding is essential for the accurate characterization and modeling of bioturbated strata. Utilizing such precise data facilitates the creation of realistic geological models, crucial for the effective evaluation of bioturbated reservoirs or aquifers. Therefore, this rich dataset from GPR, not only would improve the comprehension of the burrow attributes and their association with depositional environments, but also could improve the accuracy of the geological modeling and resource assessments.

4.5. Conclusions

The limitations of studying large burrow systems through coring or CT scans have been effectively addressed by the GPR method, which has not been traditionally employed in this type of research. The effectiveness of GPR in studying bioturbated carbonate strata

with large burrow systems is confirmed by its high accuracy and consistency with CT scans and field observations, highlighting its precision in capturing key burrow attributes such as percentage, diameter, and morphology. GPR not only mirrors the findings from CT scans and field observations but also extends beyond them due to its large horizontal and vertical coverage. It provides additional insights into BP variation with depth and a more comprehensive view of the complex morphology of the burrow system in 2D and 3D, surpassing the information gathered from CT scans and field observations.

The capability of GPR to accurately characterize burrow diameters smaller than 0.5 cm extends its utility beyond large burrow systems to include smaller systems as well. Therefore, the results obtained from GPR suggest its potential as a powerful tool in paleoecological and sedimentological research, enabling scientists to examine biogenic structures in detail without the need for destructive field excavation. Furthermore, GPR findings, including variations in burrow percentage, diameter, and morphology, are crucial for assessing outcrop analogs to the quality of subsurface reservoirs with bioturbated strata. These detailed observations can be incorporated into subsurface reservoir or aquifer modeling, and are expected to significantly enhance the accuracy of the geologic model and, therefore, reservoir quality evaluation.

Chapter 5

Conclusions

Conclusions

This comprehensive study on the Aruma Formation enhances understanding of the sedimentological, stratigraphic, and ichnological controls on petrophysical properties in bioturbated carbonate reservoirs. By identifying three biogenically influenced fluid flow media facies (BIFMs) within the formation, it illustrates how different depositional settings (e.g. open marine setting, fairly or restricted lagoon environments) influence burrow attributes and, as result, petrophysical properties of *Thalassinoides*-bearing strata, impacting reservoir quality and potential. The interconnected burrows in BIFM 1 and BIFM 3 suggest potential super-permeable zones, valuable for aquifers and hydrocarbon reservoirs. Conversely, BIFM 2, with its filled *Thalassinoides*, acts as a barrier, reducing overall reservoir quality. The findings have significant implications for reservoir quality and exploration in Saudi Arabia and offer a framework for optimizing bioturbated reservoir exploration globally.

Additionally, the study examines the impact of bioturbation on natural fractures, classifying fractures into burrow-related and non-burrow-related categories. Factors influencing fracture characteristics include burrow percentage, morphology, cementation, burrow fillings, and host rock matrix composition. Fracture density is higher in strata with open burrows, but fractures are longer in strata with filled burrows. In non-bioturbated

strata, fractures are influenced by texture and mineralogy. These findings are vital for predicting subsurface reservoir behavior and optimizing hydrocarbon production.

Finally, the use of Ground Penetrating Radar is validated as an effective tool in bioturbation studies, showing reliability in mapping burrow networks and attributes. This non-invasive technique aligns well with CT scans and field observations, proving valuable information in sedimentological and ichnological research, assessing in reservoir quality evaluation of bioturbated strata.

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- 141) Zeng, Qingdong, Wenzheng Liu, and Jun Yao. 2021. “Effect of Vugs on Hydraulic Fracture Propagation with Phase Field Method.” *Lithosphere* 2021(SpecialIssue 4).

- 142) Ziegler, M. A. (2001). Late Permian to Holocene paleofacies evolution of the Arabian countries and their hydrocarbon occurrences. *Petroleum Play Assessment*, 6(3), 445–504.

Vitae



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26, 00967



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Now- Khobar-Saudi Arabia,
Yemen

SKILLS

Good presentation
skills

Teamwork and
collaboration

Familiarity with
software including:
Petrel GeoFrame, GIS
Techlog Omega
Eclipse, voxler, surfer,
MATLAB, Petromod,
and others

Subsurface and
Outcrop Modeling

LANGUAGES

Arabic
Native or Bilingual Proficiency

English
Full Professional Proficiency

France
Elementary Proficiency

INTERESTS

Photography

Play the bowling,
Chess, Foot ball

Nabil Saraih

Integrated Geoscientist Engineer

With more than 10 years of experience in the petroleum and mining sectors, as well as in academia, I stand as a knowledgeable Geologist and Geophysicist Support Engineer. My unique advantage is the integration of academic insights with practical industry expertise. Proficient in addressing intricate subsurface and outcrop modeling challenges, I'm also familiar with industry-leading software tools such as Petrel, GIS, Techlog, Omega, petromod, Reflex, Voxeler, and Eclipse. Trusting in my skills and experience, I am confident in my ability to bring valuable contributions to your organization.

WORK EXPERIENCE

Trainee

Geological Survey & Mineral Resources Board

01/2008 - 02/2008

Yemen

Field Geo-scientist Engineer

Schlumberger , WesterGeco Segment

06/2009 - 06/2013

Design the Seismic Survey. Conduct Seismic Data Acquisition and Processing. Ensure Quality Control of Acquired Data. Coordinate with all segments and delegate the necessary tasks. Represent the Company in Technical Meetings with the Client.

SPE Student Chapter Vice President

Lorraine University ,Nancy-France.

09/2012 - 09/2013

Geo-Scientist Engineer

Schlumberger , Schlumberger Information Solution Segment ,
Yemen and Pakistan

12/2013 - 06/2016

Yemen and Pakistan

Resolving all reported geological and geophysical issues from client companies such as SAFER, TOTAL, OMV, Petromasilah, DNO, and others related to subsurface modeling and the calculation of Oil Initially In Place.

Trainer and Instructor

Institutes and Universities

07/2016 - 12/2018

Yemen

I have had the opportunity to instruct various courses at international institutions like Emirates University and Thamar University. My teaching portfolio includes subjects such as Reservoir Engineering, Reservoir Simulation Modeling, Geological Modeling, Seismic Data Interpretation, and Principles of Geology. In addition to my academic roles, I have also led training courses in geological and simulation modeling for professional and senior engineers.

Teaching Assistance

King Fahd University of Petroleum and Minerals

01/2019 - 11/2023

Dhahran, Saudi Arabia

I have taught a range of courses including Subsurface Geology, Integrated Petroleum Geology, and Seismic Interpretation, and Integrated Design I. My role involves educating students and providing training in seismic and geological interpretation and modeling, utilizing widely recognized software and authentic data.

SELECTED PUBLICATIONS AND CONFERENCE

Three-dimensional modeling and fluid flow simulation for the quantitative description of permeability anisotropy in tidal flat carbonate-Energies Journal (09/2020 - 09/2020)

Hassan A Eltom, Nabil A Saraih, Oliver G Esteve, Lundi Kusuma, Saleh Ahmed, Mohamed A Yassin

Bioturbated strata in the Upper Cretaceous Aruma Formation, central Saudi Arabia: An analog for aquifers and hydrocarbon reservoirs with large burrows-Marine and petroleum geology Journal (09/2023 - 09/2023)

Nabil A Saraih, Hassan A Eltom, Robert H Goldstein, Scott A Whattam, Ammar El-Husseiny, Sherif Hanafy, John Humphrey

Controls on Reservoir Sand-Body Architecture: Modelling and Fluid Flow Simulation of Modern Analog, East Sudan- International Petroleum Technology Conference (02/2022 - 02/2022)

Abid Khogali, Rika Syahputra, Nabil Saraih, Hassan Eltom

Controls on fracture propagation in bioturbated carbonate rocks: Insights from the Aruma Formation, central Saudi Arabia- Submitted to Marine and petroleum geology Journal (10/2023 - 10/2023)

Nabil A Saraih, Hassan A Eltom, Robert H Goldstein, Scott A Whattam, Ammar El-Husseiny, Sherif Hanafy, John Humphrey, Moaz Salih

Advanced imaging techniques for bioturbated carbonate reservoir: insights from the upper cretaceous Aruma Formation, Saudi Arabia: Will be Submitted soon to Sedimentary geology Journal

Nabil A Saraih, Hassan A Eltom, Robert H Goldstein, Scott A Whattam, Ammar El-Husseiny, Sherif Hanafy, John Humphrey, Moaz Salih

Understanding reservoir zones with biogenically influenced flow media, Aruma Formation, central Saudi Arabia -- AAPG 2023 ICE, Madrid, Spain. (11/2023 - 11/2023)

Nabil A Saraih, Hassan A Eltom, Robert H Goldstein, Scott A Whattam, Ammar El-Husseiny, Sherif Hanafy, John Humphrey

CURRENT RESEARCH

Foraminifera of the upper cretaceous Aruma Formation, Saudi Arabia: implication for paleoenvironment and sequence stratigraphy (09/2022 - 11/2023)

- I have studied the foraminifera in the upper cretaceous and provide the ages of them and these data will be published soon

Dasyclad green algae of the upper cretaceous Aruma Formation, Saudi Arabia: implication for paleoenvironment (09/2022 - 10/2023)

- These data will be published soon

Velocity signature of the bioturbated carbonate reservoir: Insights from the Upper cretaceous Aruma Formation, central Saudi Arabia (09/2021 - Present)

- I have conducted comprehensive velocity measurements on bioturbated carbonate reservoir analogues, spanning from core scale to large cube samples, outcrop scale, and up to the regional scale. The findings from this research are in the process of being submitted.

Dual porosity system of bioturbated carbonate reservoir with large burrows: Insights from the Upper cretaceous Aruma Formation, central Saudi Arabia (09/2022 - Present)

EDUCATION

English Language Diploma
Academic British Institute

Sana'a-Yemen, grade: 97%

EDUCATION

Bachelor in Geophysics and hydrogeology

Earth Science and Environment Department.

08/2004 - 08/2008

*Sana'a University, Yemen.
Ranked the first among my
collages*

Graduation project

- Geophysical, Hydrological and Hydrogeological studying of Wadi Dhahar,

Master in Subterranean Reservoirs of Energy: Hydrodynamics - Geology – Modelling

ENSG, Lorraine university.

09/2011 - 10/2013

Nancy, France. Grade 15/20

Master's thesis

- Dynamic Reservoir Simulation of Kharir Biyad Field (in TOTAL Dubai) for six months as industrial internship which required as a partial fulfillment of the Master degree

Ph.D. in Geology

King Fahd University of Petroleum and Minerals

01/2019 - 12/2023

*Dhahran, Saudi Arabia, GPA:
3.9/4*

PhD thesis

- An Integrated Study to Characterize and Model Strata with Biogenically Influenced Flow Media in the Upper Cretaceous Aruma Formation, Central Saudi Arabia