

**Foraminifera assemblages and sequence stratigraphy
within the Dhurma Formation D7, Saudi Arabia's Central
Region Middle Jurassic: Implications for
paleoenvironmental reconstruction**

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MASTER OF SCIENCE

**In
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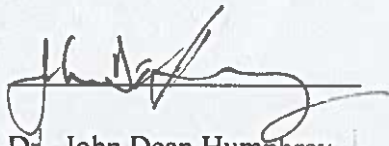
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Dedication

This work is dedicated to my mother, Fatmata Bah; late father, Chernoh Madieu Jalloh; beloved wife, Adamah Mohamed Jalloh; and my supportive supervisor, Distinguished Prof. Michael A. Kaminski. With the help of Allah, their love, care, advice, and patience have guided me throughout my academic journey.

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LIST OF ABBREVIATIONS

T-R: Transgressive-Regressive

MFS: Maximum Flooding Surface

TST: Transgressive Systems Tract

LST: Lowstand Systems Tract

HST: Highstand Systems Tract

n. sp: new species

sp: species

sp.cf: species confer

Pl:Plate

P:Page

Figs: Figures

EPF: Epifauna foraminifera

SIF:Shallow infauna foraminifera

DIF: Deep infauna foraminifera

ABSTRACT

Full Name : [Chernoh Mohamed Jalloh]

Thesis Title : [Foraminifera assemblages and sequence stratigraphy within the Dhurma Formation D7, Saudi Arabia's Central region Middle Jurassic: Implications for paleoenvironmental reconstruction.]

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The Middle Jurassic Dhurma Formation in Central Saudi Arabia represents a significant depositional sequence within the Arabian epicontinental shelf, providing extensive paleontological and stratigraphic data essential for regional biostratigraphic correlation and hydrocarbon exploration. This study analyzed the foraminiferal assemblages of the formation's D7 unit (Atash and Hisyan Members) to enhance the taxonomic framework and refine sequence stratigraphic models. A total of 62 lithified limestone and marl samples are processed from surface outcrops using the acetic acid disaggregation method. Thirty-three foraminiferal species representing 19 genera are documented, including the previously unreported benthic taxa *Bulbobaculites* n.sp. and *Gerochammina* n.sp.

Detailed foraminiferal composition, morphogroup classifications, biodiversity indices, and cluster analyses reveal intricate transgressive-regressive (T-R) cycles characterized by deepening and shallowing upward sequences within these members. Calcareous epifauna (e.g., *Nautiloculina*, *Quinqueloculina*, *Trocholina*, *Spirillina*, *Krunubia*, and *Miliolinella*) dominate the lower part of the Atash member, indicating a shallow lagoonal to inner shelf environment during the initial transgressive phase. The upper Atash and overlying Hisyan member basal section show increased species diversity and abundance of calcareous and

agglutinated shallow and deep infauna (e.g., *Frondicularia*, *Lenticulina*, *Nodosaria*, *Bulbobaculites*, and *Gerochammina*). These indicate a shift to deeper intra-shelf basin environments, representing peak transgression where the maximum flooding surface (MFS) is indicated. The top of the Hisyan is dominated by calcareous epifauna and shallow agglutinated infauna, indicating restricted marine conditions during the regressive phase.

The planktic taxon (*Globuligerina* sp.) and deep-water indicators (*Gerochammina* n.sp. and *Bulbobaculites* n.sp.) serve as critical markers for recognizing the J40 Maximum Flooding Surface (Sharland et al., 2001), enhancing high-resolution sequence stratigraphic correlations within the Arabian epicontinental shelf. The study's paleobathymetric model highlights the influence of eustatic sea-level variations on depositional systems, illustrating transitions from shallow lagoonal to deeper intra-shelf basin settings during peak transgression, and a return to shallow-water conditions during the regressive phase.

This study provides critical advancements in high-resolution sequence stratigraphy and new data that significantly enhance the paleontological record of Saudi Arabia's Jurassic Central Basin. It offers novel insights into paleoenvironmental and climatic shifts in epicontinental shelf systems, thereby enhancing the understanding of these dynamic depositional environments.

Keywords: Dhurma Formation, Foraminiferal assemblages, Maximum flooding surface, Paleobathymetry, Sequence stratigraphy.

ملخص الرسالة

الاسم الكامل: شرنوه محمد جالوه

عنوان الرسالة: تجمعات الفورامينيفيرا والتسلسل الطبقي ضمن وحدة D7 من تكوين الدروما، منطقة وسط المملكة العربية السعودية خلال العصر الجوراسي الأوسط: دلالات على إعادة بناء البيئات القديمة.

التخصص: علم الجيولوجيا

تاريخ الدرجة العلمية: ديسمبر، 2024

تشكّل تكوين الدروما في وسط المملكة العربية السعودية، الذي يعود إلى العصر الجوراسي الأوسط، تسلسلاً ترسيبياً هاماً ضمن الجرف العربي القاري، حيث يوفر بيانات بالغة الأهمية في مجالي علم الأحافير وعلم الطبقات لتحديد العلاقات البيوستراتيغرافية الإقليمية واستكشاف الهيدروكربونات. تناولت هذه الدراسة تجمعات الفورامينيفيرا لوحدة D7 من التكوين (عضويتي عطاش وحصيان) بهدف تعزيز الإطار التصنيفي وتحسين نماذج التسلسل الطبقي. تم معالجة إجمالي 62 عينة من الحجر الجيري والمارل الصلب من مكاشف سطحية باستخدام طريقة تفكيك الحمض الخليكي. وتم توثيق 33 نوعاً من الفورامينيفيرا تمثل 19 جنساً، بما في ذلك أصناف قاعية جديدة لم يتم الإبلاغ عنها من قبل مثل *Bulbobaculites n.sp.* و *Gerochammina n.sp.*

كشفت دراسة تركيب الفورامينيفيرا بالتفصيل، وتصنيفات مجموعات الأشكال، ومؤشرات التنوع الحيوي، وتحليلات التجمعات عن دورات دقيقة للغمر والتراجع (T-R) تتسم بتسلسلات تعمق وضحالة صاعدة ضمن هذه العضوين. تتسم أسفل عضو عطاش بسيطرة الكائنات الكلسية القاعية (مثل *Nautiloculina*، *Quinqueloculina*، *Trocholina*، *Spirillina*، *Krunubia*، و *Miliolinella*)، مما يشير إلى بيئة بحيرة ضحلة إلى الجرف الداخلي خلال المرحلة الغمرية الأولى. ويظهر الجزء العلوي من عطاش وقاعدة عضو حصيان تنوعاً أكبر في الأنواع وزيادة في وفرة الكائنات الكلسية والقاعية العميقة (*Fronicularia*)، *Lenticulina*، *Nodosaria*، *Bulbobaculites*، و *Gerochammina*، مما يدل على انتقال إلى بيئات أعمق في حوض الجرف الداخلي، تمثل ذروة الغمر حيث يتم تحديد السطح الأعلى للغمر (MFS). وتهيمن الكائنات الكلسية القاعية والكائنات القاعية الضحلة القاعية في قمة الحصيان، مما يشير إلى ظروف بحرية محدودة خلال المرحلة التراجعية.

تُعد الكائنات العوالقية (*Globuligerina sp.*) والمؤشرات البحرية العميقة (*Gerochammina n.sp.*) و (*Bulbobaculites n.sp.*) علامات حاسمة للتعرف على السطح الأعلى للغمر (Sharland et al., 2001) J40 ، مما يعزز الارتباطات الطباقية عالية الدقة ضمن الجرف القاري العربي. يبرز النموذج الباليوباثيمتري للدراسة تأثير التغيرات العالمية في مستوى سطح البحر على الأنظمة الترسيبية، موضحة التحولات من بيئات البحيرات الضحلة إلى أحواض الجرف الداخلي الأعماق خلال ذروة الغمر، والعودة إلى ظروف المياه الضحلة خلال المرحلة التراجعية.

توفر هذه الدراسة تقدماً حاسماً في مجال التسلسل الطبقي عالي الدقة وبيانات جديدة تعزز بشكل كبير السجل الأحفوري لحوض الجوراسي الأوسط في المملكة العربية السعودية. كما تقدم رؤية جديدة حول التحولات البيئية القديمة والمناخية في أنظمة الجرف القاري، مما يعزز فهم هذه البيئات الترسيبية الديناميكية.

الكلمات المفتاحية: تكوين الدروما، تجمعات الفورامينيفيرا، السطح الأعلى للغمر، الباليوباثيمتري، التسلسل الطبقي.

CHAPTER 1

INTRODUCTION

1.1 Study Background

The Middle Jurassic Dhurma Formation in Central Saudi Arabia offers unique access to both surface outcrop exposures (Al-Saad, 2008), which is critical for understanding the region's complex depositional environments. This accessibility has significantly advanced hydrocarbon exploration and biostratigraphic research in the region. The formation consists mainly of transitional sediments from continental to shallow marine (mixed marine) deposits (Hughes, 2004, 2006; Al-Mojel and Razin, 2022). The foraminiferal assemblages of the Dhurma Formation have been defined from subsurface sections using thin-section analysis to establish biozones and sequence stratigraphy (Hughes, 2018; Al-Dhubaib, 2010; Lindsay et al., 2008; Hughes et al., 2010, Hughes, 2004a). Disaggregation techniques have been applied to the basal shaley and intermediate marly units of the formation to improve understanding of the depositional setting and to enable biostratigraphic correlation (Kaminski et al., 2018a, 2018b, 2020; Malik et al., 2020). This study builds on these investigations by analyzing the foraminiferal contents in the surface outcrops of the upper Dhurma Formation (Atash and Hisyan Members).

The modified acetic-acid (CH_3COOH) disaggregation method is applied to extract foraminiferal species from indurated limestone and marl samples of the studied outcrops. It is considered effective for recovering high species diversity and abundance from lithified

samples, thereby enhancing taxonomic resolution (Malik et al., 2020; Kaminski et al., 2018a). It enables detailed statistical analysis of foraminiferal composition and morphogroups, providing new data for interpreting the unit's paleobathymetry. The objectives of this study are to expand the taxonomic record by documenting previously unreported benthic foraminifera, interpret sea-level variations to identify sequences of deepening and shallowing trends, and identify the maximum flooding surface (MFS). This study contributes to advancing scientific and hydrocarbon research by providing new data critical for improving high-resolution sequence stratigraphy and understanding depositional settings of the Middle Jurassic in the Arabian region.

The Dhurma Formation has attracted significant interest in scientific research and hydrocarbon exploration due to its diverse foraminiferal assemblages, which extend beyond previously documented endemic species (Hughes, 2004, 2006, 2009, 2018; Al-Saad, 2008; Kaminski et al., 2018a, 2018b, 2020; Malik et al., 2020), and its economic importance, particularly the Lower Fadhili reservoir, which correlates with the D7 unit Lower Atash Member (Al-Mojel, 2010). It is the second oldest formation within the Jurassic Shaqra Group . This group extends from the basal Marrat Formation to the Hith Formation, transitioning from carbonate-rich deposits to evaporites (Powers et al., 1966; Vaslet, 1987; Al-Husseini, 1997; Al-Dhubaib, 2010), and includes some of the world's most productive reservoirs, such as the Arab Formation within the Ghawar onshore oil Field (Al-Husseini, 1997; Hughes, 2000, 2009; Cantrell et al., 2014).

Age			Group	Formation	Member	Reservoir	Lithology	
Jurassic	Upper	Tithonian	Shaqra Group	Hith		Manifa		
				Arab	A	A		
					B	B		
					C	C		
		D			D			
	Kimmerodgian	Jubaila		J1				
				J2				
	Oxfordian	Hanifa		Ulayyah	Hanifa			
				Hawtah				
	Middle	Callovian		Tuwaiq Mountain	T3	Hadriya		
					T2			
					T1	Upper Fadhilli		
		Dhruma		D7	Hisyan			
					Atash			
				D6	Lower Fadhilli			
				D5	Sharar			
				D4	Faridah			
				D3				
				D2				
	D1							
	Lower	Toarcian		Marrat	Upper	Marrat		
					Middle			
					Lower			
				Anhydrite	Limestone			

Figure 1: The Jurassic Shaqra Group, and its seven geological formations (Dubai, 2010).

The Dhruma Formation lies unconformably over the Lower Jurassic Marrat Formation and is conformably overlain by the Middle Jurassic Tuwaiq Mountain Limestone (Hughes, 2006; Al-Mojel and Razin, 2020, 2022). It is subdivided into seven informal rock units, D1 to D7 (Powers et al., 1966; Manivit et al., 1985), with measured thicknesses of approximately 143 meters for the basal section (D1 and D2), 193 meters for the intermediate section (D3 to D6), and 111 meters for the upper section (D7, comprising the Atash and Hisyan Members) (Manivit et al., 1990). Previous studies (Hughes, 2004, 2006,

2018) have assigned the D7 Unit to the overlying Tuwaiq Mountain Limestone based on genetic lithological relationships.

The ages of the Dhurma Formation units, from the lower (D1 and D2) to the intermediate sections (D3 – D6, are assigned as lower Bajocian to upper Bathonian. Unit D1 corresponds to the lower Bajocian, with the D2 basal portion dated to the early Bajocian (Humphriesianum Zone) and the upper D2 (Dhibi Limestone Member) to the late Bajocian (Niortense Zone). Units D3 and D4 represent the late Bajocian to early Bathonian, with D5 dated to the Aurigerus Zone and D6 characterized by an endemic ammonoid fauna suggesting an early to possibly late Bathonian age (Tinant, 1987; Cooper, 1989). The overlying Hisyan Member of the D7 unit (Figure 2) has been dated to the middle Callovian (Coronatum Zone) based on its distinct ammonite faunas, including rare *Grossouvria*, *Erymnoceras*, and *Pachyerymoceras*. The unit lower Atash member has not yielded ammonites (Hughes, 2006; Enay et al., 2009; Powers et al., 1966, 1968), which rendered its age determination difficult. Its middle Callovian age is supported by nannoflora such as *Watznaueria manivatae* and *Stephanolithion bigoti*, indicating the *Stephanolithion bigoti* Zone (Haq et al., 1988; Le Nindre et al., 1990).

LITHOSTRATIGRAPHIC UNITS			LITHOLOGY	ARABIAN AMONITE ZONES	ARABIAN FORAMINIFERA ZONES	AGES		PALEO-ENVIRONMENTS
SHAQRA GROUP	HITH ANHYDRITE				Him 1-3	TITHONIAN		
	ARAB FORMATION	Arab-A Member						
		Arab-B Member						
		Arab-C Member						
		Arab-D Member						
	JUBAILA LIMESTONES							
	HANIFA FORMATION	unit J2			Jm-2			
		unit J1		Cavelieri	Jm-1	Early	KIMMERIDGIAN	Sabkha
		unit H2						
		Ulayyah Member		?	Hm-2	Late		Lagoon
	HANIFA FORMATION	unit H1		Catena H.	Hm-1	Middle	OXFORDIAN	Clastic channels
		Hawtah Member						Reef
	TUWAIQ MOUNTAIN LIMESTONE							Backreef
	DHRUMA FORMATION	unit T3		Solidum	Tm-5	Late		Outer lagoon
		unit T2						
		unit T1		Ogivalis	Tm-3	Middle	CALLOVIAN	Subtidal
		unit D7		Kuntzi H.	Tm-1-2			Backreef
		Atash Member		?		Early		Barrier
		unit D6		Cardioceratoides	Dm-6	Late	BATHONIAN	W. Dawisir (delta)
		unit D5		Clydocromphalus	Dm-5	Middle and Early		Subtidal
		unit D4		Tuwaigensis	Dm-4	Early		Back-barrier
		unit D3		Planus Mogharensis	Dm-3			Upper infralittoral
		unit D2		Runcinatum	Dm-2	Late	BAJOCIAN	Clastic fans
	MARRAT FORMATION	unit D1		Glabrum				Lower infralittoral (no barrier)
		unit D1		Stephani	Dm-1	Early		
		upper Marrat		Arabica				
		middle Marrat		Bramkampfi				
		lower Marrat		Nitescens	Mm-X	Late to Middle	TOARCICAN	Subtidal
		lower Marrat		? unconformity		?	TOARCICAN	Tidal flat Coastal plain

Figure 2 : Lithostratigraphy, biostratigraphy, chronostratigraphy, and paleoenvironment of the Shaqra Group. Modified from Enay and Mangold (2021) and Hughes (2018). The studied D7 unit (Atash and Hisyan members) of the Dhruma Formation is highlighted in green.

1.2 Problem Statement

Significant progress has been made in characterizing the Middle Jurassic Dhurma Formation through foraminiferal studies; previous studies mainly focused on the basal shaley (D1–D2) and intermediate marly (D5–D6) units, with the aim of enhancing understanding of depositional environments and regional biostratigraphy (Kaminski et al., 2018a, 2018b, 2020; Malik et al., 2020; Bu Khamsin, unpublished thesis, 2021). Interpretations of Jurassic biofacies cycles across the Arabian Platform, based on thin-section analysis of subsurface core samples, generally depict shallowing-upward sequences associated with relative sea-level changes (Hughes, 2004, 2006). Al-Mojel and Razin (2022) recently integrated subsurface biostratigraphic data (after Hughes, 2013a, 2014; unpublished internal report) to interpret the sequence stratigraphy and depositional settings of the Middle Jurassic. These studies highlight a significant gap in data on foraminiferal assemblages from surface outcrops in the upper Dhurma Formation (Atash and Hisyan Members). Foraminifera are valuable tools for identifying the maximum flooding surfaces defined by Sharland et al. (2001) in the region (Kaminski et al., 2018b).

Studies by Saudi Aramco micropaleontologists (Hughes, 2004, 2006, 2009, 2018; Al-Dhubaib, 2010) primarily relied on thin-section analysis of subsurface reservoir cored samples. A detailed examination of foraminifera from lithified surface outcrops could reveal greater species diversity and abundance (Kaminski et al., 2018; Malik et al., 2020), critical to redefine existing biozones and enhance high-resolution sequence stratigraphy.

This study applies detailed micropaleontological techniques to analyze benthic and planktic foraminifera from surface outcrops in the D7 Unit, with the aim of evaluating sea-level variations and establishing a high-resolution sequence stratigraphic and paleobathymetric model to infer water depths, interpret depositional sequences, and identify maximum flooding surfaces (MFS). It also documents previously unreported agglutinated species, which hold potential as correlation tools for identifying the J35–J40 maximum flooding surfaces (Sharland et al., 2001) within the Early–Middle Callovian (Atash and Hisyan Members) of the upper Dhurma Formation in Central Saudi Arabia, thereby advancing scientific research, environmental studies, and hydrocarbon exploration in the region.

1.3 Aims and Objectives

1.3.1 Aims

The study aims to conduct a detailed micropaleontological and sequence stratigraphic analysis of the Middle Callovian Dhurma Formation (D7 Unit) to improve understanding of sea-level variations, paleoenvironmental reconstruction, and depositional settings in the Middle Jurassic of Central Saudi Arabia. It focuses on documenting foraminiferal assemblages, thereby refining biozones and establishing new correlation tools that have the potential to identify the J35–J40 maximum flooding surfaces (Atash and Hisyan Members) as defined by Sharland et al. (2001) in the region.

1.3.2 Research Objectives

The primary objectives of this study are:

- i. To document foraminiferal assemblages (benthic and planktic) in the D7 Unit, focusing on identifying previously unreported agglutinated species that could serve as a new tool to enhance the region's biostratigraphic framework.
- ii. To construct a high-resolution sequence stratigraphic framework for the D7 Unit by correlating vertical foraminiferal distribution patterns with sea-level variations, identifying shallowing and deepening sequences, and pinpointing the maximum flooding surface (MFS).
- iii. Develop a conceptual paleobathymetric model for the D7 Unit to define paleoenvironmental conditions and assess the relationship between foraminiferal morphogroups and inferred water depths, providing insights into depositional trends and facilitating correlations within the Arabian epicontinental shelf.

1.4 Research Questions

The study addresses the following research questions:

- i. What new insights into foraminiferal assemblages can be obtained from the D7 Unit of the Dhurma Formation, and do these include previously unreported species that could serve as potential tools for refining existing biozones within the Middle Jurassic?
- ii. How does the vertical distribution and diversity of foraminiferal assemblages relate to sea-level variations, and what implications does this have for identifying depositional sequences and the maximum flooding surface (MFS)?

- iii. What does the paleobathymetric model of the D7 Unit reveal about the depositional environments and paleoenvironmental shifts within the Dhruma Formation, and how do these findings compare with similar Jurassic formations in the Arabian region?

1.5 Study Scope

While the Middle Jurassic succession of Central Saudi Arabia includes both the Dhurma and Tuwaiq Mountain Limestone Formations, this study is mainly focused on the upper Dhurma Formation (Atash and Hisyan Members). Previous investigations have examined foraminiferal assemblages in the intermediate (D5–D6) and basal (D1–D2) sections, contributing to biostratigraphic correlations and depositional environment interpretations (Bu Khamsin, unpublished thesis, 2022; Malik et al., 2020; Kaminski et al., 2018a). Although the D3 and D4 units remain relatively understudied, they are part of the middle section that has been studied.

Subsurface samples are not included in this study. The biofacies of the lower Atash Member, correlated to the Fadhili Reservoir (Al-Mojel, 2010), and the overlying Hisyan Member have been examined through thin-section analysis from subsurface cored samples, establishing biozones (Hughes, 2004, 2006, 2018; Al-Dhubaib, 2010). This has left a gap in understanding foraminiferal assemblage trends within surface outcrops, which are essential for refining stratigraphic depositional sequences and potentially identifying previously unreported species to improve Middle Jurassic biozones.

This study employs advanced micropaleontological techniques beyond traditional thin-section analysis to analyze foraminiferal assemblages, excluding isotopic methods due to poor microfossil preservation in this formation (Malik et al., 2020). Through detailed interpretation of benthic and planktic species along the stratigraphic levels of the Atash and Hisyan outcrops, the study aims to enhance our understanding of the depositional

environment and sequence stratigraphy of the Dhurma Formation, offering new insights into sea-level variations within the Middle Jurassic of Central Saudi Arabia.

1.6 Thesis Structure

This study is organized into six chapters, each addressing a specific aspect of the research and aligning with the study's core objectives. The findings lay the groundwork for four proposed article topics intended for publication: (1) Descriptions of previously unreported agglutinated species (i. *Bulbobaculites* n.sp., ii. *Gerochammina* n.sp.); (2) Paleoecology and paleobathymetry of the upper Dhurma Formation, Central Saudi Arabia; and (3) Taxonomy and systematics of Middle Jurassic shallow- and deep-water benthic and Planktic foraminifera, Central Saudi Arabia.

The introductory chapter provides an overview of the research background, problem statement, geological framework, and study scope. It defines the study's objectives, emphasizing the aim to expand the taxonomic framework and deepen understanding of Middle Jurassic depositional sequences through detailed analysis of the foraminiferal assemblages within the D7 Unit of the Dhurma Formation. The literature review section presents a synthesis of prior studies on the geological setting of the Dhurma Formation, as well as relevant research on foraminifera and their ecological and paleoenvironmental implications, establishing the context for this research.

The methodology presented here as the third chapter outlines the fieldwork procedures, laboratory analyses, and statistical methods applied in the research. It also describes the data visualization techniques employed, such as stacked bar charts and vertical distribution

charts, to effectively represent findings. This approach ensures a systematic analysis of the foraminiferal data and supports clear interpretation of paleoenvironmental trends and the depositional sequences.

The findings are presented across two core chapters (four and five), which include identified paleoecological and paleoenvironmental conditions, paleobathymetric reconstructions, and depositional sequences of the Upper Dhurma Formation. The results also document the taxonomy and systematics of the identified shallow- and deep-water benthic and planktic foraminiferal species. The concluding chapter synthesizes the study's findings, offering recommendations for future research to build on the foundational insights established in this thesis.

1.7 Study Location

The lower Bajocian to middle Callovian Dhurma Formation is prominently exposed in the Darma quadrangle of the Riyadh region, central Saudi Arabia. The upper unit of this formation (Atash and Hisyan Members) is located mainly along Highway 5395 near Haniya Village (24°10.779'N, 46°26.853'E), approximately 82 km northwest of Riyadh and 4 km from the Riyadh Cement Factory (Figure 3).

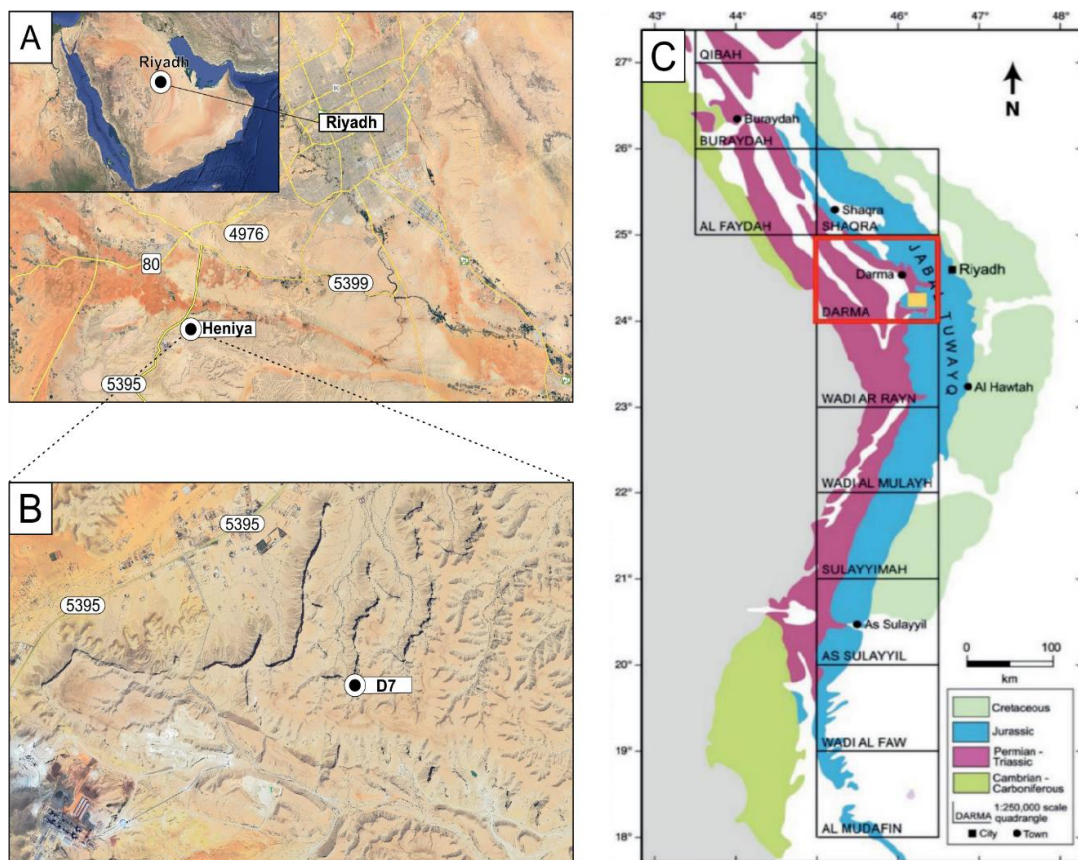


Figure 3 : A. Satellite image showing the study locality (from Google Earth). B. Enlarged satellite image showing Road 5395 leading to the studied outcrop location (D7 unit) (from Google Earth). C. Indicates the studied Darma quadrangle in red square of the Jurassic in Central Saudi Arabia (Fisher et al., 2001).

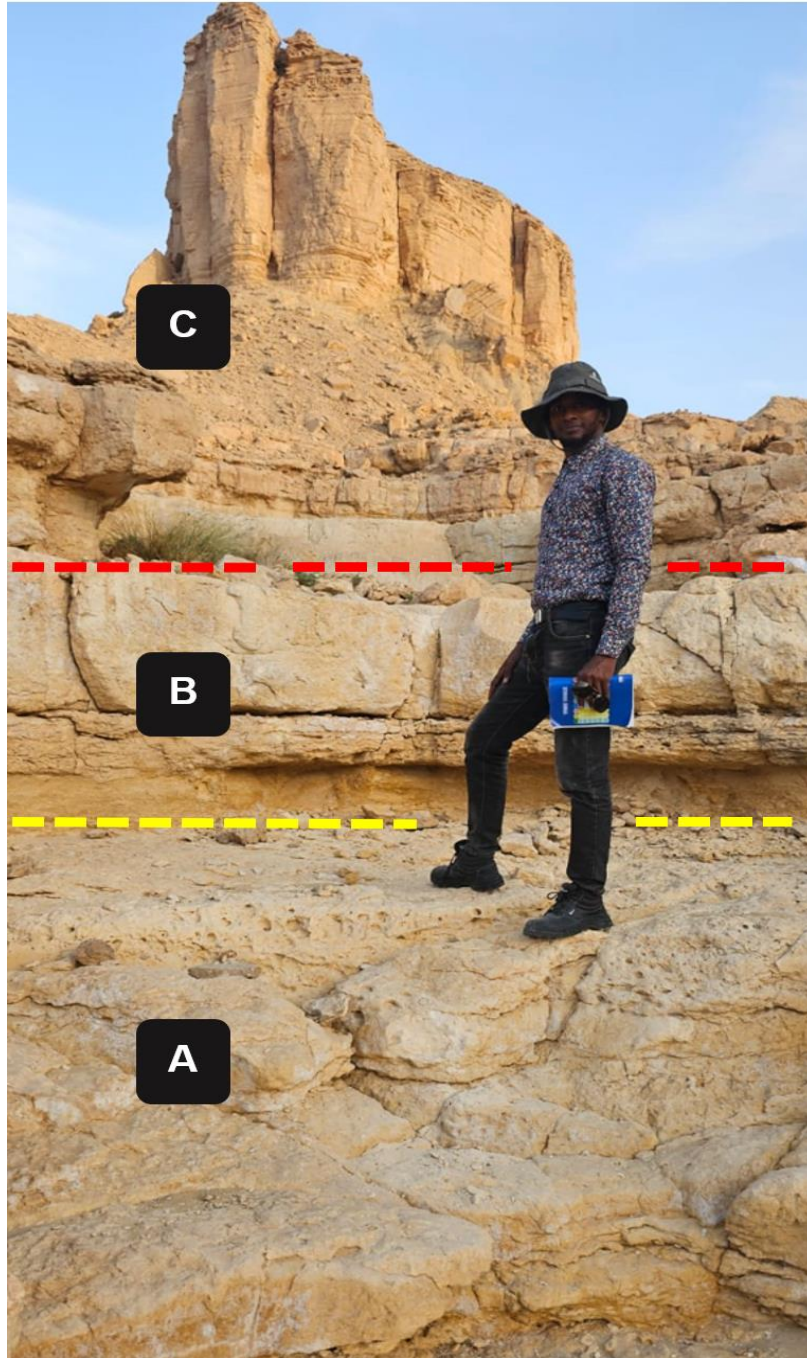


Figure 4: Field photograph showing the irregular base of the studied Atash outcrop, featuring limestone and marly sediments. A distinct contact is observed between the upper Hisyan (B) and underlying Atash member (A) of the Dhurma Formation, as well as the overlying Tuwaiq Mountain Formation (C).

1.8 Geological Framework

1.8.1 Tectonic Setting

This tectonic setting of the Jurassic was influenced by eustatic sea-level changes and slight extensional faulting in the eastern Arabian Plate (Sharland et al., 2001). During this period, the Arabian Plate's tectonic evolution transitioned through five phases: accretion, intra-cratonic, back-arc, passive margin, and active margin settings (Sharland et al., 2001). The Mesozoic extensional phase on the Arabian Plate is represented by three Tectonostratigraphic Megasequences (AP6–AP8) within the larger sequence framework (AP1–AP11) of Arabian stratigraphy. The Dhurma Formation, including the Lower Fadhili reservoir, falls within the AP7 Megasequence, spanning the Early to Late Jurassic (Sharland et al., 2001) (Figure 5). The formation and stratigraphy of this megasequence are bounded by regional unconformities shaped by rifting and sea-level changes. The basal unconformity of AP7 resulted from northern rifting associated with Neo-Tethys margin development, while the top unconformity was driven by the Indian Plate's divergence from Oman, which created additional accommodation space along the Neo-Tethys passive margin (Sharland et al., 2001).

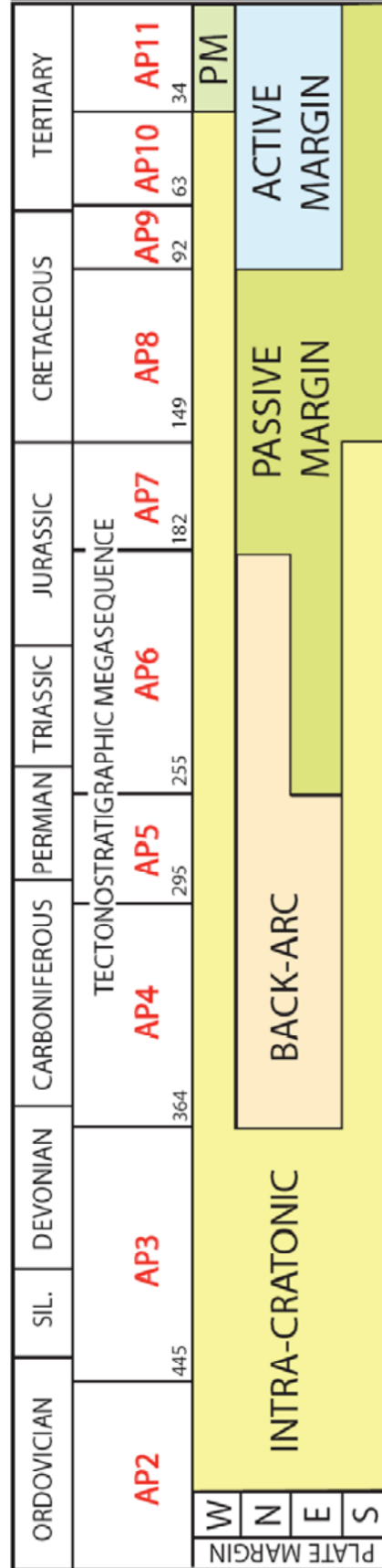


Figure 5: Geological time scale showing time intervals for the tectonic evolutionary phases of the Arabian Plate and the Tectonostratigraphic Megasequence of Sharland et al. (2001). (After Sharland et al., 2001)

The Arabian Plate tectonic setting comprises three structural orientations aligned with present-day trends. These include the dominant N–S to NNE–SSW Arabian trend, responsible for the structural arches and troughs within the Intrashelf Arabian Basin; the NE–SW trend, associated with the collision of the Arabian and Eurasian plates and the opening of the Red Sea; and a left-lateral NW–SE strike-slip fault created in response to Indian Plate movement (Edgell, 1992; Ziegler, 2001; Konert et al., 2001; Stewart et al., 2016). In eastern Saudi Arabia, the slight extension along these fault trends led to the development of intra-shelf basins, including the Summan Platform, Dibdibah Trough, Khurais-Burgan Anticline, Ghawar-Safaniya Anticline, and Qatar Arch (Figure 6) (Ziegler, 2001; Breton et al., 2004). These intra-shelf basins evolved in the late Middle Jurassic (Late Callovian) to early Late Jurassic (Middle Oxfordian) as the N-S fault system created structural highs and lows, leading to basinal subsidence (Sharland et al., 2001).

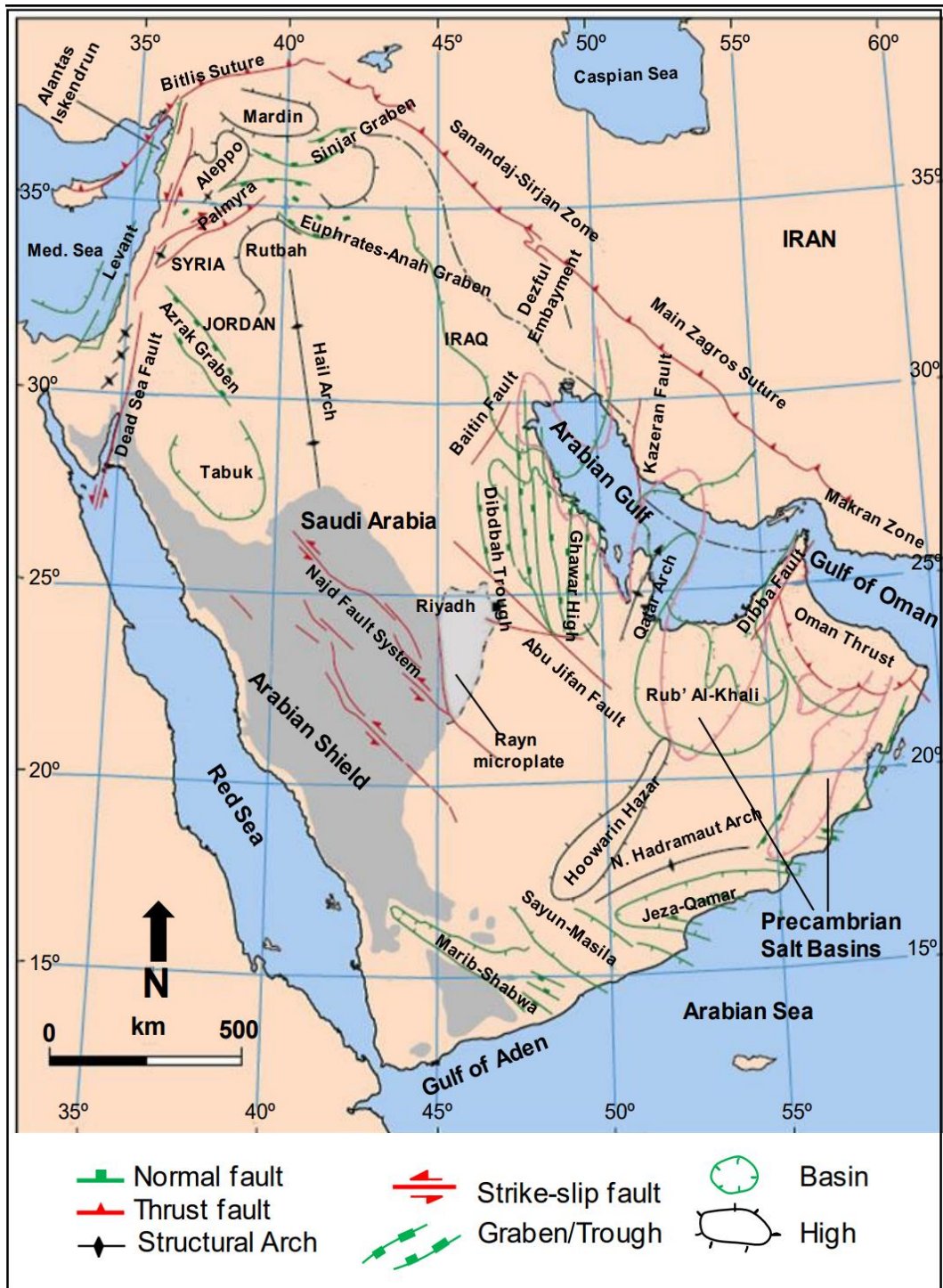


Figure 6 : Key tectonic features within the Arabian Plate (Breton et al., 2004).

The Dhurma Formation, occupying the lower part of the Shaqra Group as its second oldest formation (Figure 1), was first identified by Max Steineke in 1937 and named after the town of Dhurma, northwest of Riyadh (Powers et al., 1966). Based on ammonite findings, it has been assigned a Middle Jurassic (Bajocian–Bathonian) age (Arkell, 1952; Énay et al., 1987). The Dhurma Formation is predominantly carbonate in the subsurface; in exposed areas and at the type section, its lithology varies from carbonate to claystone. The type section was defined by Bramkamp and Steineke (1952) between Kashim Ad- Dhibi (24°12'24''N, 46°07'30''E) ,and Kashim Al Mazrui (24°19'00'' N, 46°19'36''E). The formation's thickness varies across the region, reaching up to 300 meters in basinal areas of Iraq and Kuwait and thinning to about 20 meters over the southeastern paleo-high at Qatar Arch (Alsharhan and Magara, 1995; Stewart et al., 2016). Near Khashm Adh Dhibi, about 70 km southwest of Riyadh, the type section was initially measured at 375 meters by Powers et al. (1966) and later revised to 447 meters by Vaslet et al. (1985).

1.8.2 Paleogeography

During the Jurassic, the Arabian Plate occupied an equatorial position along the southern margin of the Neo-Tethys Ocean, forming part of a stable, intracratonic passive margin in northeastern Gondwana (Al-Husseini, 1997; Ziegler, 2001; Golonka et al., 2006). The Middle Jurassic succession is centrally located on the Arabian Plate within this passive margin setting (Figure 7). This tectonically stable, tropical shallow marine platform stretched across more than 1,000 km and included extensive carbonate deposition environments, with adjacent organic-rich intrashelf basins that developed in response to slight subsidence and eustatic sea-level changes (Thierry, 2000; Ziegler, 2001). The Arabian shelf, with a gentle dip towards the north-northeast, is interpreted as a ramp or

platform with a low gradient that facilitated the deposition of carbonate sediments in shallow to open marine settings (Sharland et al., 2001; Hughes, 2004, 2006).

The paleogeographic configuration of the Arabian Plate led to the formation of four intrashelf basins in the Middle to Late Jurassic on the eastern Arabian shelf: the Arabian Basin, Gotnia Basin, Rub' Al-Khali Basin, and Ras al Khaimah Basin (Ziegler, 2001). These basins were separated by paleotopographic highs, such as the Qatar Arch and Rimtham Arch, which restricted basin connectivity with open marine waters (Énay et al., 2009). The Jurassic transgression, which started in the Early Jurassic, continued into the Middle Jurassic and resulted in widespread shallow carbonate platform development, characterized by open marine limestones and minor siliciclastic deposits (Murriss, 1980; Le Nindre et al., 1990; Al-Husseini, 1997; Sharland et al., 2001; Hughes, 2004).

By the Middle Jurassic, expanding seas fostered a carbonate platform with open marine conditions on the Arabian Shelf, where eustasy primarily controlled deposition over subsidence (Ziegler, 2001; Sharland et al., 2001). This early Jurassic transgression deposited the Dhurma Formation and continued until the Middle Callovian, when exposed sections shifted in lithology from carbonates to claystones (Bramkamp and Steineke, 1952; Powers et al., 1966). The type section of the Dhurma Formation, located between Khashm Ad Dhibi and Khashm Al Mazrui, illustrates this transition with a varying lithology of carbonates and claystones (Arkell, 1952; Énay et al., 1987).

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The accessible surface and subsurface outcrops in the Middle Jurassic succession of Central Saudi Arabia provide a focal point for studying foraminiferal assemblages (Al-Saad, 2008), which are essential tools for reconstructing paleoenvironmental environmental. These microfossils are critical to understanding sea-level variations, thereby facilitating interpretations of depositional sequences and enhancing stratigraphic resolution. Past studies on the foraminifera of the Dhurma Formation (Hughes, 2004, 2006, 2009, 2018; Kaminski et al., 2018a, 2018b, 2020; Malik et al., 2020) highlight their importance in understanding the region's paleoenvironmental history, biostratigraphy, sequence stratigraphy, and depositional settings, all contributing to scientific research and hydrocarbon exploration. This literature review synthesizes past research on Middle Jurassic foraminiferal assemblages to identify gaps that could enhance our understanding of taxonomy, paleoenvironmental conditions, and paleobathymetric significance in inferring water depth, thereby improving interpretations of depositional settings and refining the sequence stratigraphy of the upper Dhurma Formation.

2.2 Arabian Peninsula Jurassic Foraminiferal Assemblages

Researchers such as Beydoun (1988), Al-Husseini (1997), and Sharland et al. (2001) have studied the Middle Jurassic sediments and foraminiferal assemblages within the Arabian Peninsula, focusing on the regional geology. The Middle Jurassic fauna of Qatar have gained limited attention (Smout and Sugden, 1968; Sugden and Standring, 1975; Hewaidy and Al-Saad, 1993; Ibrahim et al., 2002). Ghalandari et al. (2019) used thin sections to report Middle Jurassic foraminiferal biostratigraphy from an offshore region in the Iranian Gulf. Kuwait Oil Co. Micropaleontologists investigated foraminifera from the lateral equivalent of the Dhruma Formation in Kuwait's subsurface using thin sections (Crespo de Cabrera et al., 2019, 2020). Basha (1983) provided significant insights into Jordan's Middle Jurassic foraminifera.

In Egypt, the foraminiferal assemblages of the same period have been investigated for their taxonomic details and environmental implications (Abd Elshafy et al., 1990; Kerdany and Cherif, 1990; Geological Survey of Egypt, 1992; Abdel-Gawad and Gameil, 1999). Gordon (1970 and 1974) conducted the sole paleogeographic research on Middle Jurassic foraminifera in the southern Tethys. The Tethyan zone was distinguished by its distinctive foraminiferal assemblages, which included planktonic and complex internal structural arenaceous foraminifera. Al-Saad (2008) compared the foraminiferal assemblages of the Arabian Gulf, particularly Qatar and Saudi Arabia, with those in Jordan and Egypt, categorizing them into three unique groups that reflect a range of paleoenvironments from carbonate platforms and clastic shelves to shorelines, thereby underscoring the Middle East's ecological diversity during the

Middle Jurassic period.

2.2.1 Jurassic Shaqra Group Foraminifera

The endemic species of Saudi Arabia's Jurassic Shaqra Group have been central to paleontological investigations, including ammonites (Arkell, 1952), echinoids (Kier, 1972), gastropods (Fisher et al., 2001), nannofossils (Manvit et al., 1987), ostracods (Depeche et al., 1987), and brachiopods (Cooper, 1989). These studies have laid the foundation for the region's biostratigraphy, aiding in age assignments for various formations and their members. The first micropaleontological study on foraminiferal aspects within the Jurassic of Saudi Arabia started with Redmond (1964a, 1964b, 1965), who identified and described two previously unknown subfamilies of foraminifera, namely Pfenderininae and Kurnubiinae. Redmond (1965) discovered three new genera: *Pseudomarssonella*, *Riyadhella*, and *Dhrumella* in the Jurassic of Saudi Arabia. Eight new species of litiolids from the Upper Jurassic and Lower Cretaceous of Saudi Arabia were also described by Redmond (1964a). These studies laid the foundation for advanced studies in foraminiferal assemblages, especially benthic species to define the region paleoenvironments, biostratigraphy, and improve sequence stratigraphy.

Microfossil analysis of the Jurassic succession has been conducted on subsurface core samples through thin-section analysis to interpret paleoenvironmental conditions and sequence stratigraphy, offering insights into subsurface reservoirs for hydrocarbon exploration. Identified biofacies and depositional cycles on the Arabian Platform were linked to relative sea-level changes, forming shallowing-upward sequences (Hughes, 2004b, 2006). These interpretations are limited due to their reliance on traditional thin-

section analysis and lack of detailed micropaleontological examination of foraminifera from indurated surface outcrops, which is essential for refining interpretations of regional depositional sequences (Malike et al., 2020).

2.2.2 Middle Jurassic Foraminiferal Studies

The scope of research in the Jurassic of Saudi Arabia was expanded Powers et al. (1966), who described eight new foraminiferal biostratigraphic zones within the Middle Jurassic Dhurma Formation. Two identified late Bajocian species, *Haurania amiji* and *Haurania deserta*, led to the assignment of the lower section of the formation to the Haurania Zone (Powers et al., 1966). Hughes (2004, 2006, 2009, 2013), documented a diverse group of thirteen foraminiferal species within the Dhurma Formation. These include *Ophthalmidium* spp., “*Pfenderina*” *trochoidea*, *Satorina apuliensis*, *Trocholina elongata*, *Ammobaculites* spp., *Nautiloculina oolithica*, “*Pfenderina*” *salernitana*, *Redmondoides lugeoni*, *Redmondoides* sp. cf. *rotundata*, *Valvulina* sp., *Trochamijiella gollehanehi*, *Parurgonia caelinensis*, and *Pseudocyclammina* sp. cf. *lituus*. This work has unveiled a rich tapestry of foraminiferal life in the Middle Jurassic of Saudi Arabia, marking a crucial advancement in our general understanding of the formation’s paleobiological landscape.

In the formation’s upper section, a range of species, such as *Riyadhella elongata*, *Pseudomarssonella bipartita*, *Trocholina aptiensis*, *Meyendorffina bathonica*, as well as different species of *Neotrocholina* and *Andersenolina* were identified through thin section analysis (Al Dhubaib, 2010). Hughes (2018) subdivided the lower and middle Dhurma Formation into six biozones (Dm1–Dm6) using the initial and final appearances of microfauna in drilling cuttings and assigned the Atash and Hisyan members, upper Dhurma (D7 unit), to two biozones (Tm1– Tm2) in the

lower Tuwaiq Mountain Formation (T1) (Figure 8). Studies on foraminifera in the Middle Jurassic Dhurma Formation by Saudi Aramco micropaleontologists have primarily focused on reservoir horizons in the subsurface, using thin-section methods to improve subsurface correlation and refine sequence stratigraphy (Lindsay et al., 2008; Hughes et al., 2010).

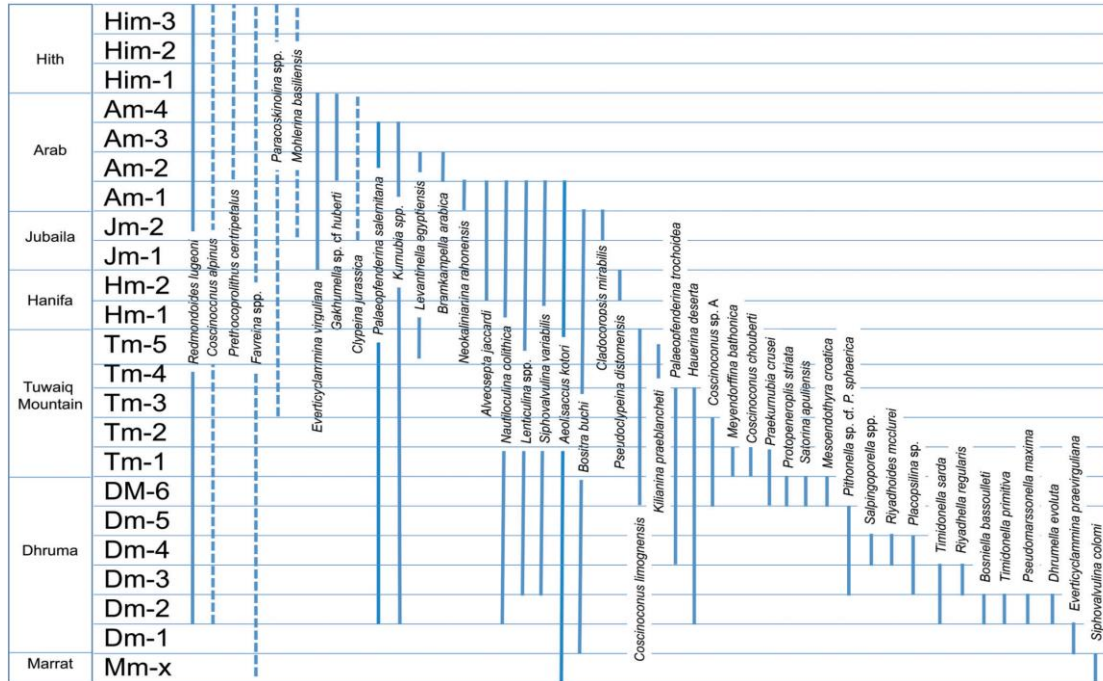


Figure 8 : Stratigraphic ranges of key species identified in thin sections of Saudi Arabia Jurassic succession (from Hughes, 2018).

Recent advancements in micropaleontological study, mainly through disaggregation methods, have facilitated in-depth studies of microfauna within the Middle Jurassic Dhurma Formation's lower shaley (D1-D2) and intermediate marly (D5-6) units. Bu Khamsin (2021, unpublished MSc thesis) identified ten new species out of 63 foraminiferal species documented, from the formation's lower sections. Kaminski et al. (2018a, 2021b; 2020) reported the occurrence of

planktonic and agglutinated benthic species: *Globuligerina* sp., *Conoglobigerina* sp., and the benthic *Ammobaculoides dhrumaensis*, from the marly unit (D5) and lower shaley unit, respectively. This marks the first report of planktonic and shallow water benthic foraminifera in the region, significantly providing a new correlation tool for the detailed recognition of the J30 maximum flooding surface as identified by Sharland et al. (2001) in the Kingdom of Saudi Arabia. In a similar study, Malik (2016, unpublished MSc thesis; Malik et al., 2020) extended this knowledge by documenting thirty-five foraminiferal species belonging to nineteen genera from the middle sections (D5-D6 units) of the formation. Their work highlights the critical need for detailed micropaleontological studies to enhance our understanding of biodiversity in the Middle Jurassic formations. An important point made in Malik's study is the fact that disaggregation techniques reveal a much higher species diversity in the Dhruma Formation than the traditional thin-section studies. This approach extends beyond the limited insights gained from thin section analysis of core samples, which has previously restricted detailed foraminiferal identification in the region.

Although various authors have studied the Middle Jurassic foraminifera of Central Saudi Arabia, focusing on subsurface reservoirs and the basal shaley and intermediate marly units of the Dhruma Formation, the foraminiferal assemblages of the D7 unit, marked by the Atash and Hisyan members (Powers et al., 1968), remain unexplored through detailed field mapping and disaggregation techniques from surface outcrops. This gap highlights the need for a comprehensive micropaleontological study of the Dhruma Formation's upper section. Such

research would be critical for scientific understanding, environmental assessment, and hydrocarbon exploration by documenting previously unreported foraminiferal species, enhancing regional biostratigraphic correlation, and identifying sea-level fluctuation patterns to refine depositional sequences and sequence stratigraphy in the region.

2.3 Jurassic Paleobathymetry and Taxonomy

2.3.1 Taxonomy

The taxonomic record of shallow Jurassic carbonate deposits in the Middle East remains incomplete, although most commonly observed species are well-documented (Hughes, 2004). Previous taxonomic studies on Saudi Arabian agglutinated species are limited to works by Redmond (1964, 1965), Banner (1970), and Maync (1965). Recent studies by Kaminski et al. (2018a, 2018b) have expanded the regional taxonomic framework by documenting the first occurrence of planktonic foraminifera (*Globuligerina* sp. and *Conoglobigerina* sp.) in the basal marly beds (D5 unit) and shallow-water *Ammobaculoides*-dominated assemblages in the lowermost green shale member (D1) of the Middle Jurassic Dhurma Formation.

Previous taxonomic studies in the Middle East (e.g., Banner and Highton, 1990; Banner and Whittaker, 1991; Banner et al., 1991; Whittaker et al., 1998; Clark and Boudagher-Fadel, 2001) have primarily focused on shallow-marine species outside of Saudi Arabia. This highlights the need for detailed research on the Middle Jurassic foraminiferal assemblages in Central Saudi Arabia, especially within the upper unit of the Dhurma Formation. Establishing taxonomic records that extend beyond the existing shallow-water

benthic species would provide deeper insights into paleoenvironmental gradients and enhance biostratigraphic correlation across the region.

2.3.2 Paleobathymetry

The Upper Dhurma Formation (D7 Unit) in Central Saudi Arabia, dating to the Middle Jurassic, offers accessible surface outcrops critical for detailed analysis of foraminiferal assemblages (Al-Saad, 2008). These assemblages provide an ideal framework for constructing a conceptual paleobathymetric model to infer water depth and interpret depositional sequences. Previous studies in the Middle Jurassic of Saudi Arabia have primarily focused on high-resolution sequence stratigraphy and sedimentology from subsurface core samples, relying on foraminiferal biofacies to interpret depositional sequences (Al-Mojel, 2022; Hughes, 2006). However, these studies did not fully consider shell composition or morphogroups from surface outcrops, leaving limited information on the abundances of calcareous, agglutinated, and planktic foraminifera across the Upper Dhurma Formation's stratigraphy, which are critical for assessing water depth and refining depositional sequences linked to sea-level changes (Hughes, 2004b).

Benthic foraminifera are essential in estimating paleobathymetry, especially in Mesozoic formations like the Jurassic (Lagoe, 1988). The vertical distribution of benthic foraminifera, interpreted through paleobathymetric changes, is instrumental in identifying depositional sequences, including shallowing and deepening trends and systems tracts such as TST, HST, LST, and MFS (Natland, 1933; Bandy, 1960). Planktonic foraminiferal abundance further serves as a proxy for water depth; higher abundances generally indicate deeper waters, although this index can be affected by factors such as productivity and

dissolution (Grimsdale and van Morkhoven, 1955). These criteria support the interpretation of water depth fluctuations in the Dhurma Formation, enhancing the understanding of depositional sequences and paleoenvironmental gradients.

Quantitative paleobathymetric studies, pioneered by Bandy and Arnal (1957), use metrics such as species diversity, planktonic-to-benthic ratios, and agglutinated-to-calcareous benthic ratios to infer paleodepths. In epeiric carbonate settings like the Dhurma Formation, these criteria must be adapted to account for shallow marine conditions. Species diversity reflects environmental stability, with higher diversity indicating open marine, well-oxygenated settings and lower diversity suggesting restricted or slightly deeper areas (Zorina, 2018; Bandy and Arnal, 1957). Planktonic foraminifera, though rare in shallow epeiric settings, indicate depth variations when present, often in slightly deeper zones on the ramp (Grimsdale and van Morkhoven, 1955). The ratio of agglutinated to calcareous foraminifera indicates water chemistry, with higher agglutinated proportions suggesting more restricted environments (Bandy and Arnal, 1957; Reolid, et al., 2008, 2012, 2019).

Foraminiferal size and morphology provide insight into paleodepth and energy conditions, as smaller, robust forms dominate higher-energy shallow settings, while larger forms suggest deeper, lower-energy zones (Murray, 1991). These adapted criteria are essential for developing a conceptual paleobathymetric model of the Middle Jurassic Upper Dhurma Formation, enabling a detailed understanding of sea-level variation patterns and enhancing high-resolution sequence stratigraphy to interpret depositional sequences. This approach not only advances stratigraphic insights but also supports hydrocarbon exploration and scientific research in Saudi Arabia.

2.3.3 Paleoenvironment

Although specific benthic foraminiferal species have been studied in detail in the Mediterranean (Derin and Reiss, 1966; Pelisse and Peybernes, 1983), their broader paleoenvironmental significance in the Middle East remains less well-defined (Hughes, 2004). Paleoenvironmental assessments of complex-walled agglutinated species were presented by Banner and Highton (1990), while *Alveosepta* and *Trocholina* species were explored by Banner and Whittaker (1991) and Manicelli and Coccia (1999), respectively. Jurassic calcareous algae and their paleoenvironmental associations with coexisting foraminifera were investigated by Hughes (2003).

Paleoenvironmental analysis of Middle to Upper Jurassic carbonates in Saudi Arabia has primarily relied on semi-quantitative assessments of thousands of thin sections, mostly from subsurface samples collected in the Ghawar, Khurais, and Berri oilfields in eastern Saudi Arabia (Hughes, 2004). This Jurassic sequence is thought to have been deposited on a broad shelf platform with intra-shelf basins, similar to the Great Bahama Bank, functioning as a shelf lagoon in the sense of Bates and Jackson (1980). The open marine areas likely exceeded depths of 10 meters, possibly reaching 50 meters, as sediments in these regions show evidence of storm activity rather than continuous wave reworking (Sharland et al., 2001). The Dhurma Formation depositional environment has been interpreted from foraminiferal assemblages in its basal (D1–D2) and middle (D5–D6) units (Kaminski et al., 2018a, 2018b, 2020; Malik et al., 2020), leaving a gap in understanding the paleoenvironmental conditions of the formation's upper section (Atash and Hisyan Members).

2.4 Sequence stratigraphy

The global framework for sequence stratigraphy was first established by Vail et al. (1977), followed by Haq et al. (1988), who provided a detailed chronostratigraphy and sea-level cycle chart for the Mesozoic and Cenozoic eras. In Central Saudi Arabia, Le Nindre et al. (1990) were the first to examine Mesozoic transgressive-regressive sequences, later expanded by Vaslet et al. (1991). Al-Husseini (1997) further advanced this work, correlating Jurassic strata across the Arabian Gulf using biostratigraphic and stratigraphic tools. His research focused on key Jurassic events, such as the early Jurassic hiatus, the Toarcian transgression, and the Callovian–Kimmeridgian sequence, leading to the distinction of the Lower Dhurma Shale as a separate sequence and the Upper Dhurma and Tuwaiq Mountain Limestone as a single sequence.

Sharland et al. (2001, 2004) formalized 63 maximum flooding surfaces across the Arabian Plate, providing a foundation for regional sequence stratigraphy. Haq and Al-Qahtani (2005) later produced a chart detailing regional sea-level cycles impacting the Arabian platform. Enay et al. (2009) analyzed the Middle Dhurma Formation, using biostratigraphy to separate the previously grouped D4 to D6 members. Their work identified the lower Bathonian shales (D5) as a maximum flooding surface, with the upper D5 representing a regressive system. The D6 and lower D7 members (Atash Member) were interpreted as a transgressive systems tract, while the Hisyan Member shales were designated as a maximum flooding surface tract (Figure 9).

Al-Mojel and Razin (2022) integrated high-resolution sequence stratigraphy with semi-quantitative micropaleontological analysis to reassess the biofacies of the Dhurma

Formation and Tuwaiq Mountain Limestone. Their research largely relied on biofacies data from Hughes (2013a, 2014, unpublished internal report), revealing a need for more comprehensive micropaleontological studies. Kaminski et al. (2018b) marked a pivotal discovery with the identification of planktonic foraminifera in the basal marly beds of the D5 Unit, presenting a new correlation tool for recognizing the J30 maximum flooding surface (Sharland et al., 2001) in Saudi Arabia. Targeting foraminiferal assemblages within the Upper Dhurma Formation could thus provide more nuanced interpretations of regional sea-level changes and foster a deeper understanding of paleoenvironmental conditions in the region.

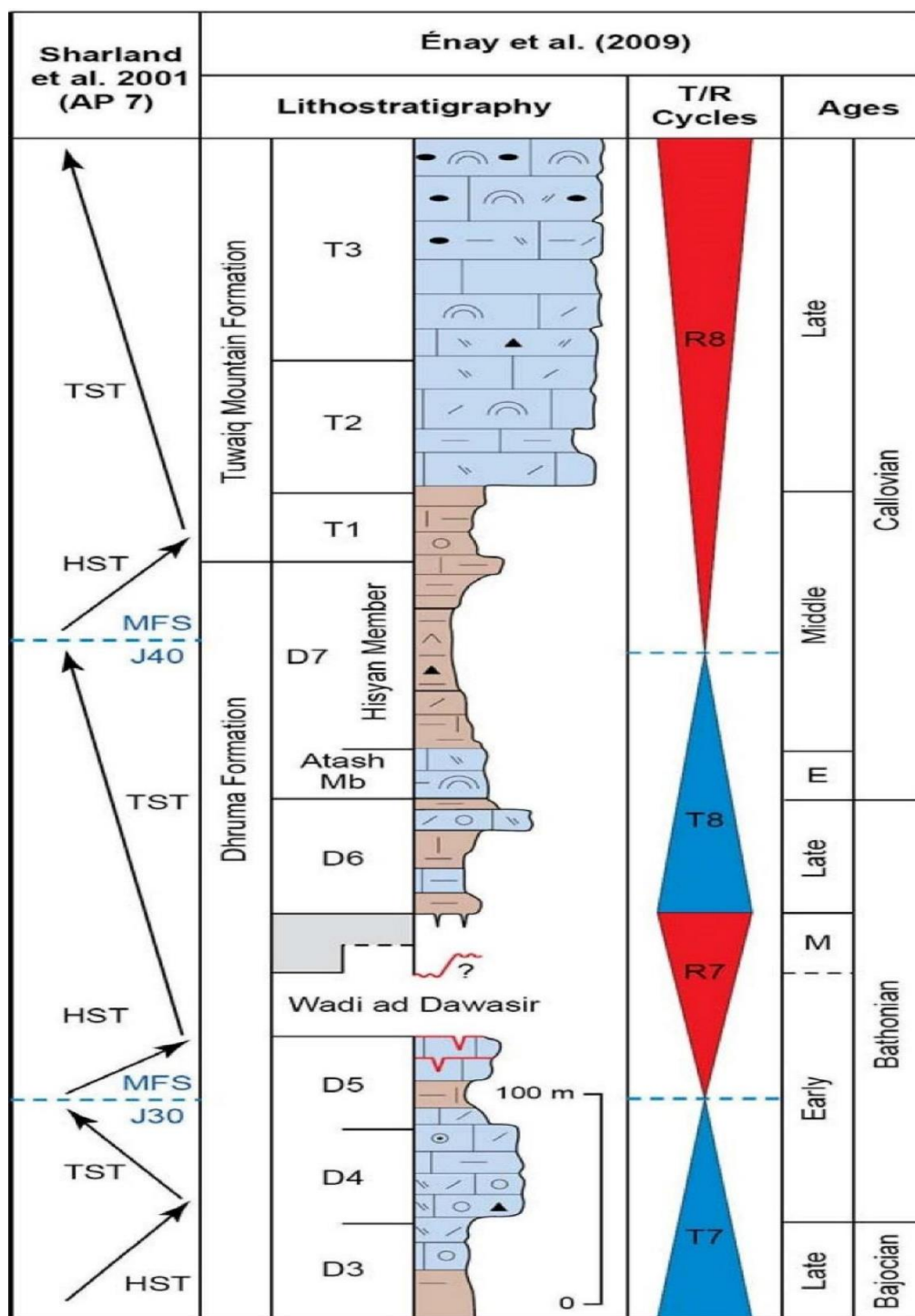


Figure 9 : Sequence stratigraphic interpretation of Jurassic formations in Saudi Arabia (Énay et al., 2009).

CHAPTER 3

METHODOLOGY

3.1 Introduction

This study is based on two field trips sponsored by the Geoscience Department of CPG-KFUPM. The first trip, conducted in February 2023, resulted in the collection of 33 surface outcrop samples from the Atash Member of the upper Dhruma Formation. A second trip in April 2024 provided additional data, with 7 samples collected from the basal Atash and 22 from various sections of the overlying Hisyan Member, summing the total to 62 samples, representing the entire D7 unit of the Middle Jurassic Dhruma Formation in Central Saudi Arabia. Three additional samples are collected from the Riyadh Limestone (upper D6) to serve as reference points for analyzing the maximum flooding horizon within the D7 section; these samples yielded no foraminifera and are therefore excluded from this study.

3.2 Field work and sample collection

This study analyzed 62 samples of indurated limestone and marl, with 40 samples from the lower Atash Member and 22 from the overlying Hisyan Member of the D7 Unit, Middle Jurassic Dhruma Formation, represented as AH1–AH62 in the stratigraphic log (Figure 3). The outcrops exhibit irregular exposure, with some sections being well-exposed and others difficult to access. This variability rendered systematic sampling at regular intervals infeasible, resulting in varying sampling intervals across the outcrop sections.

3.3 Laboratory analysis and sample processing

To facilitate sample disintegration and microfossil recovery, two standard micropaleontological techniques are applied: the soap disaggregation method and the acetic acid leaching technique (Figure 8). These methods are chosen due to the lithified nature of certain samples, as described below.

3.3.1 Soap Disaggregation Method

Disaggregation of muddy samples using industrial soaps is a standard method for extracting microfossils from light to moderately indurated muddy or unconsolidated samples (Malik et al., 2020). This technique involves soaking the samples, gently boiling them, and then washing and wet-sieving them through a 63-micron mesh. In this study, foraminifera are recovered from samples SH9, SH12, SH16, SH33, and SH53 using this technique, as these samples were less lithified and highly muddy.

The samples are repeatedly boiled with industrial soap to enhance the recovery process. The soap acts as a surfactant, quickly dispersing the clay matrix that adheres to the grains and microfauna. This procedure is continued until all the mud is removed. The remaining sample residue is then dried, sieved, and examined under a microscope to pick out the microfossils.

3.3.2 Acetic Acid Leaching Method

The acetic acid (CH_3COOH) leaching method is applied to extract foraminifera from the remaining 57 samples, which are well-lithified limestone and marl. Initially used by Bourdon (1962) to extract ostracods from limestone, this technique has since been adapted with varying acid concentrations and reaction times for foraminiferal recovery from

indurated limestone (Notzold, 1965; Stouge et al., 1983; Reolid and Herrero, 2004; Malik et al., 2022). Recent studies on the lower and middle sections of the Middle Jurassic Dhurma Formation in Central Saudi Arabia have demonstrated that this method yields a higher abundance and diversity of foraminiferal assemblages compared to the traditional thin-section technique (Kaminski et al., 2018a, 2018b; Malik et al., 2020; Bu Khamsin, 2021, unpublished masters thesis).

Each sample is broken to a size of about 2–5 mm to increase surface area, and weighed into 100 g portions to facilitate efficient dissolution and microfossil recovery. A diluted solution of 60% acetic acid is used to dissolve the samples for 8–10 hours. The dissolved samples are thoroughly washed through a 63 μm sieve to extract the foraminifera. Cleaned samples are dehydrated in an electric oven at 100°C for 8 hours. Residue from the >125 μm sieve is selected and mounted on cardboard microslides. The foraminiferal content is carefully sorted under a binocular microscope based on shell morphology. The identified foraminifera are classified into agglutinated, calcareous, and planktic assemblages based on their wall composition, mode of life, and ecological preferences.

The identified species are prepared on faunal slides and photographed using a Nikon-1500 photomicroscope (Lab 3050). Representative specimens are selected and examined with a JSM-5900LV scanning electron microscope (Lab 3051, Geosciences Department, KFUPM) to support taxonomic (species-level) analysis. These techniques are essential for the detailed statistical analysis conducted in this study.

3.4 Statistical Analysis

3.4.1 Benthic morphogroup analysis

The Benthic Morphogroup Analysis in this study classifies foraminiferal assemblages to assess environmental conditions and depositional settings based on morphological characteristics. Morphogroup analysis relies on the principle that variations in test shapes correlate with specific habitat preferences, influenced by feeding strategies and environmental factors (Corliss, 1985; Jones & Charnock, 1985; Kaminski et al., 1995; Kaminski & Gradstein, 2005; Murray et al., 2011; Cetean et al., 2011; Setoyama et al., 2012). Temporal changes in the abundance of these morphogroups reflect shifts in paleoenvironmental conditions.

For this analysis, the ecological niches and depositional environments of foraminiferal assemblages are interpreted through the redefined agglutinated and calcareous morphogroup frameworks of Setoyama et al. (2012), Ansari et al. (2021), and Reolid et al. (2019a). The assemblages are grouped into three morphogroups based on test shape, coiling patterns, and chamber arrangement: epifauna, shallow infauna, and deep infauna. The assemblages are also categorized by shell composition such as agglutinated, calcareous, and planktic, following the relative abundance frameworks of Setoyama et al. (2012). This dual classification provides a comprehensive understanding of ecological niches and paleoenvironmental settings, linking foraminiferal assemblages to specific depositional environments within the Upper Dhruma Formation of the Middle Jurassic.

3.4.2 Biodiversity Indices

Biodiversity indices are used to assess species richness, diversity, and community structure. The Fisher alpha-index (Fisher, 1943) is calculated to evaluate species diversity and richness. This index is known for being less sensitive to variations in sample size, making it particularly useful for paleoecological studies (Setoyama et al., 2012; Magurran, 2004). The percentage dominance is also determined, representing the highest percentage abundance of a single foraminiferal species within a sample (Samir et al., 2003). This metric provides insights into community structure and species dominance patterns (Walton, 1964). The calculations are performed using Python with libraries such as **SciPy** and **NumPy**.

3.4.3 Cluster Analysis

The cluster analysis for this study integrates Q-mode clustering (sample-based) and hierarchical clustering (species-based) to analyze how species distribution aligns with environmental changes across the stratigraphy of Upper Dhurma Formation (Atash and Hisyan Members). Python's **scipy** for clustering and **matplotlib** for visualization reveal paleoenvironmental trends, indicator species, and depositional sequences (e.g., MFS, deepening, and shallowing phases) in the studied unit. Q-mode clustering employs the Bray-Curtis similarity coefficient (Bray and Curtis, 1957) and the unweighted pair-group method, while dendrograms are generated following Rohlf (1989), as adopted by Reinhardt et al. (1996).

The vertical distribution of foraminiferal assemblages is visualized using MATLAB and CorelDRAW. MATLAB processes raw data and generates bubble plots, showing species

distribution across the vertical section represented in the stratigraphic log. These charts illustrate species abundance trends, depositional shifts, and sea-level fluctuations throughout the D7 Unit of the Middle Jurassic Dhruma Formation.

To construct depositional sequence stratigraphy and paleobathymetric models, we apply analyses of morphogroups and shell compositions. These analyses provide insights into Middle Jurassic water depths and sea-level variation patterns, enhancing the high-resolution sequence stratigraphic framework for the region.

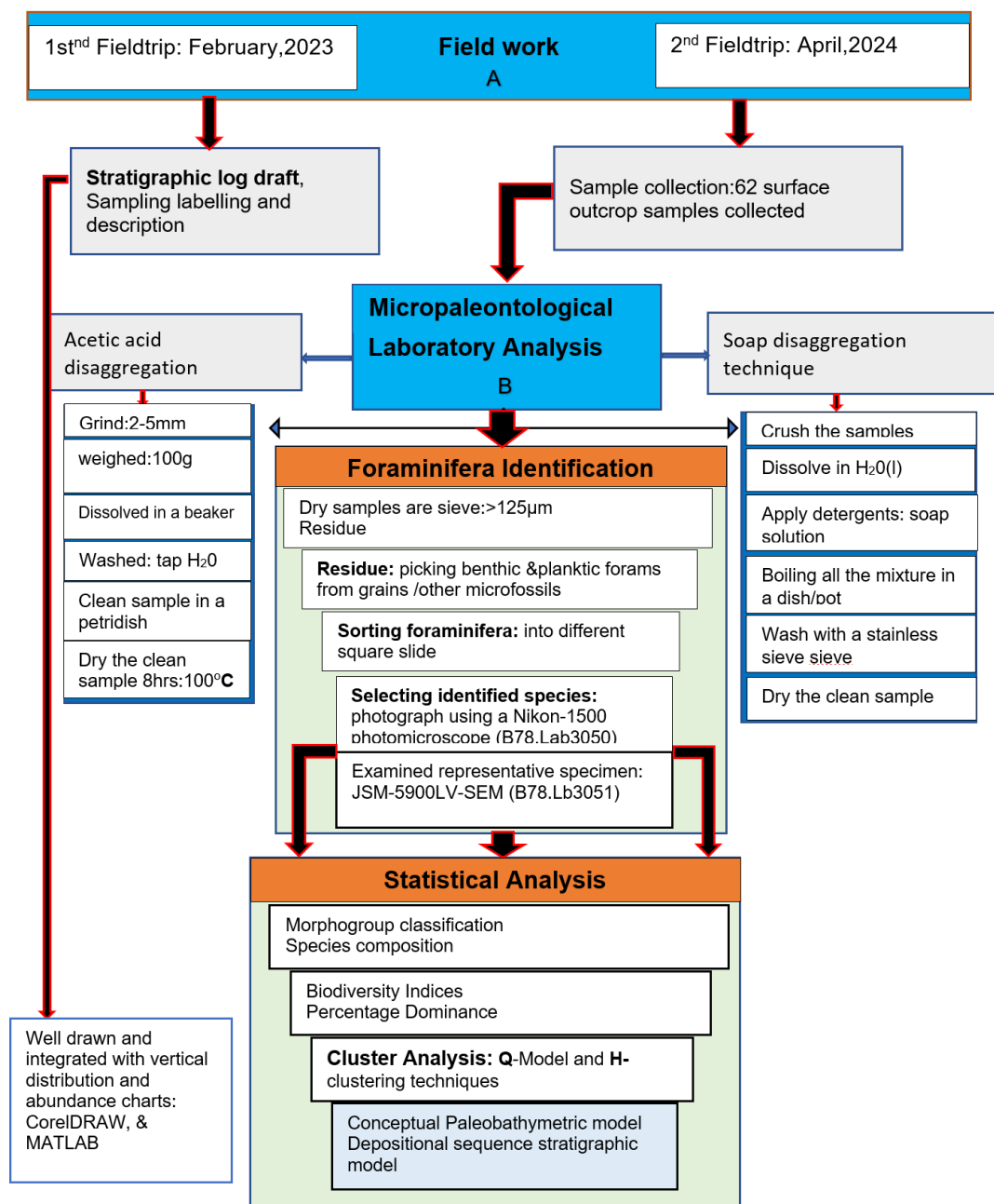


Figure 10: A flow chart summarizing the study methods and materials (methodology)

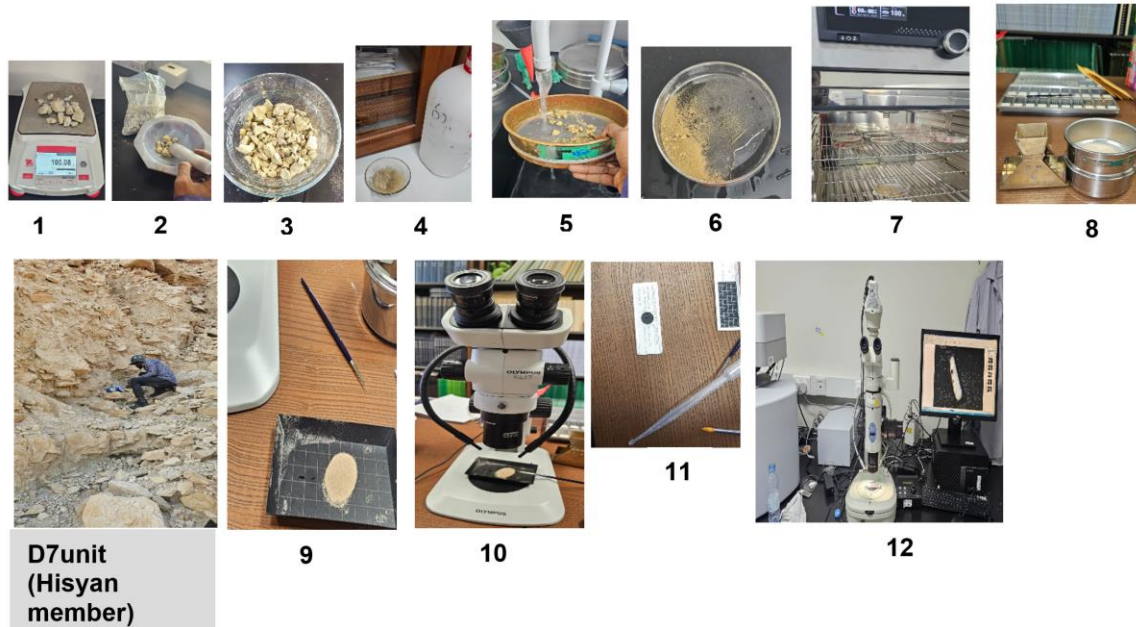


Figure 11: Summarized flow chart of acetic acid disaggregation techniques for foraminifera extraction from lithified limestone and marl samples.

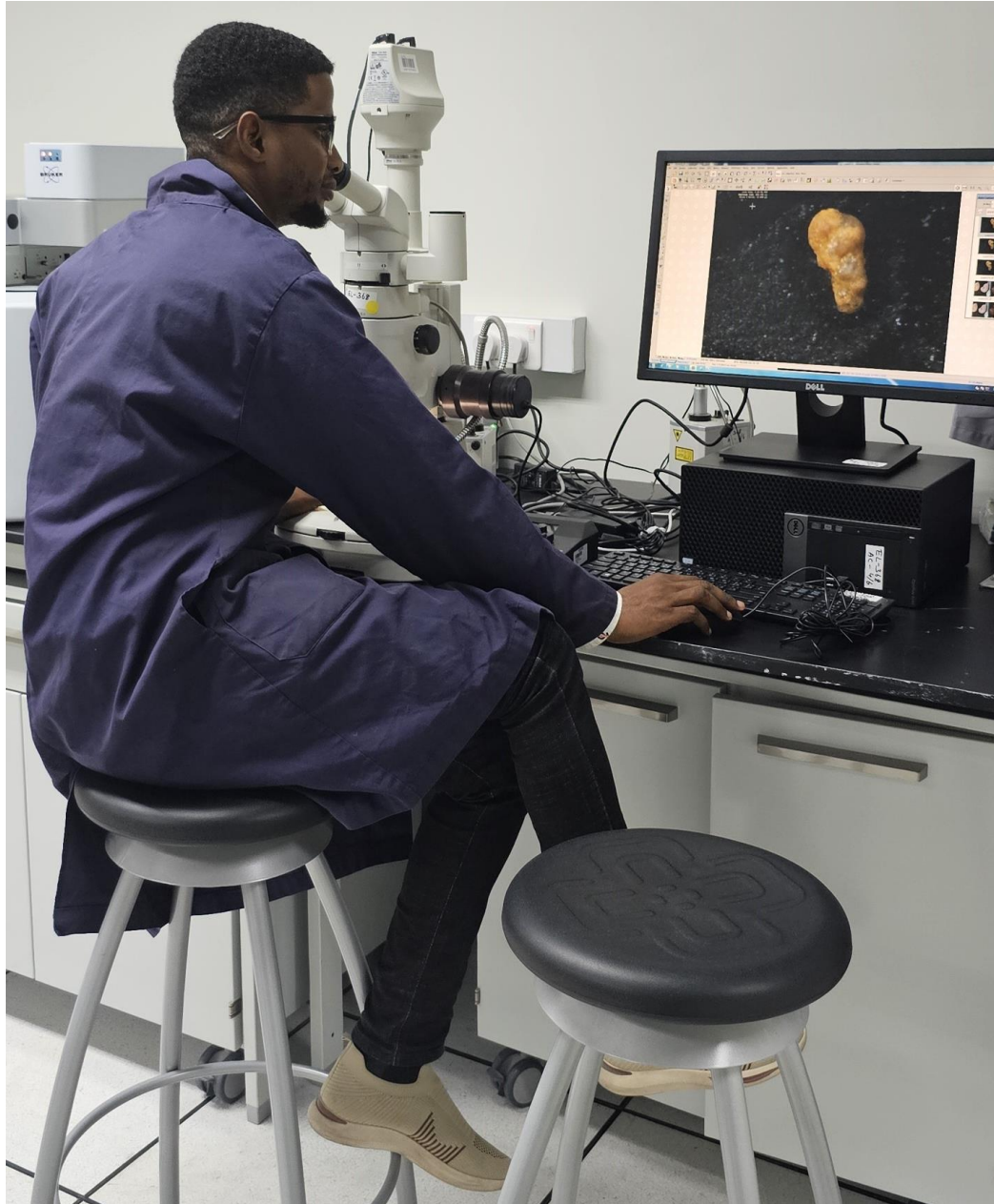


Figure 12: Analyzed samples from the residue being photographed by Nikon 1500 microscope (*Bulbobaculites* n.sp.)

CHAPTER 4

D7- PALEOECOLOGY AND PALEOBATHYMETRY

4.1 Introduction to results and discussion

This chapter analyzes the foraminiferal content from surface outcrops within the D7 Unit of the Middle Jurassic Dhurma Formation in central Saudi Arabia. Although the formation is known for its accessible outcrops and diverse fossil assemblages (Alsaad, 2008), previous studies have primarily focused on biofacies analysis from subsurface reservoirs using thin-section techniques (Hughes, 2004, 2018; Hughes et al., 2009; Al-Dhubaib, 2010) to establish biozones and improve subsurface sequence stratigraphic correlations.

Building on these studies and recent discoveries of shallow-water foraminiferal species in the basal shaley (D1–D2) and planktonic species in the intermediate marly units (D5–D6) of the formation from surface outcrops (Kaminski et al., 2018a, 2018b), this chapter aims to answer the question: How does the vertical distribution and diversity of foraminiferal assemblages relate to sea-level variations, and what implications does this have for identifying depositional sequences and the maximum flooding surface (MFS)? These insights are critical for improving the high-resolution sequence stratigraphic framework and recognizing the J40 Maximum Flooding Surface (MFS) of Sharland et al. (2001) in the region.

Detailed statistical analyses of foraminiferal species are conducted on species composition, including calcareous, agglutinated, and planktic types, as well as morphogroup classifications (epifauna, shallow and deep infauna). These data supported the construction of a conceptual paleobathymetric model and a depositional sequence stratigraphic model, critical for inferring Middle Jurassic water depths and refining the region's sequence stratigraphic framework.

Morphogroup analysis is essential for paleoenvironmental interpretations, revealing gradients in oxygen levels and other ecological factors (Reolid et al., 2012; Davies et al., 2020). Benthic and planktic species serve as key marine indicators for robust paleobathymetric reconstructions of depositional sequences (Katz et al., 2013). By examining the relationship between species composition, morphogroup distributions and sea-level fluctuations across the unit stratigraphy, this chapter identifies depositional sequences, including deepening and shallowing upward trends; and the MFS, thereby providing a high-resolution stratigraphic framework (Figure 19) crucial for refining Middle Jurassic depositional processes on the Arabian Shelf.

4.2 Foraminiferal paleoecological and paleoenvironmental trends

4.2.1 Foraminiferal composition across the D7 unit

The lower section of the D7 Unit is dominated by calcareous benthic foraminifera (63.34%), accompanied by agglutinated species (36.66%) with no planktic forms (Figure 16). Dominant agglutinated genera include *Valvulina*, and *Siphovalvulina*, while the calcareous assemblage primarily consists of *Nautiloculina*, *Trocholina*, *Spirillina*,

Quinqueloculina, and *Milolinella*. Its intermediate section exhibits a distinct ecological shift with the appearance of the planktic species *Globuligerina terquemi* (~4.54%), most abundant in marl sample AH33 (Figure 20). An increase in agglutinated species (38.93%) is observed, including the previously unreported *Bulbobaculites* n.sp., and *Gerochammina* sp., typically found in deeper marine environments (Setoyama et al., 2012). Calcareous forms (56.52%) remain prevalent, dominated by the genera *Nautiloculina*, *Lenticulina*, *Nodosaria*, *Andersonella*, *Paleomarsonella*, and *Fronicularia*.

While the overlying portion shows a sharp return to calcareous dominance (62.36%), with recurring genera from the basal part, including *Spirillina*, *Nautiloculina*, *Trocholina*, *Milolinella*, *Kurnubia*, *Riyadhella*, and *Paleomarsonella*. Planktic species are nearly absent, with only *Globuligerina* sp., identified in a marl sample AH53 (~0.05%). Agglutinated species (37.59%) are represented by *Ammobaculites*, and *Bulbobaculites*, with *Siphovalvulina* remaining dominant. The foraminiferal vertical distribution and abundance patterns across the D7 Unit highlight the impact of sea-level fluctuations on shaping assemblages and depositional environments throughout the stratigraphy of the Middle Jurassic upper Dhurma Formation.

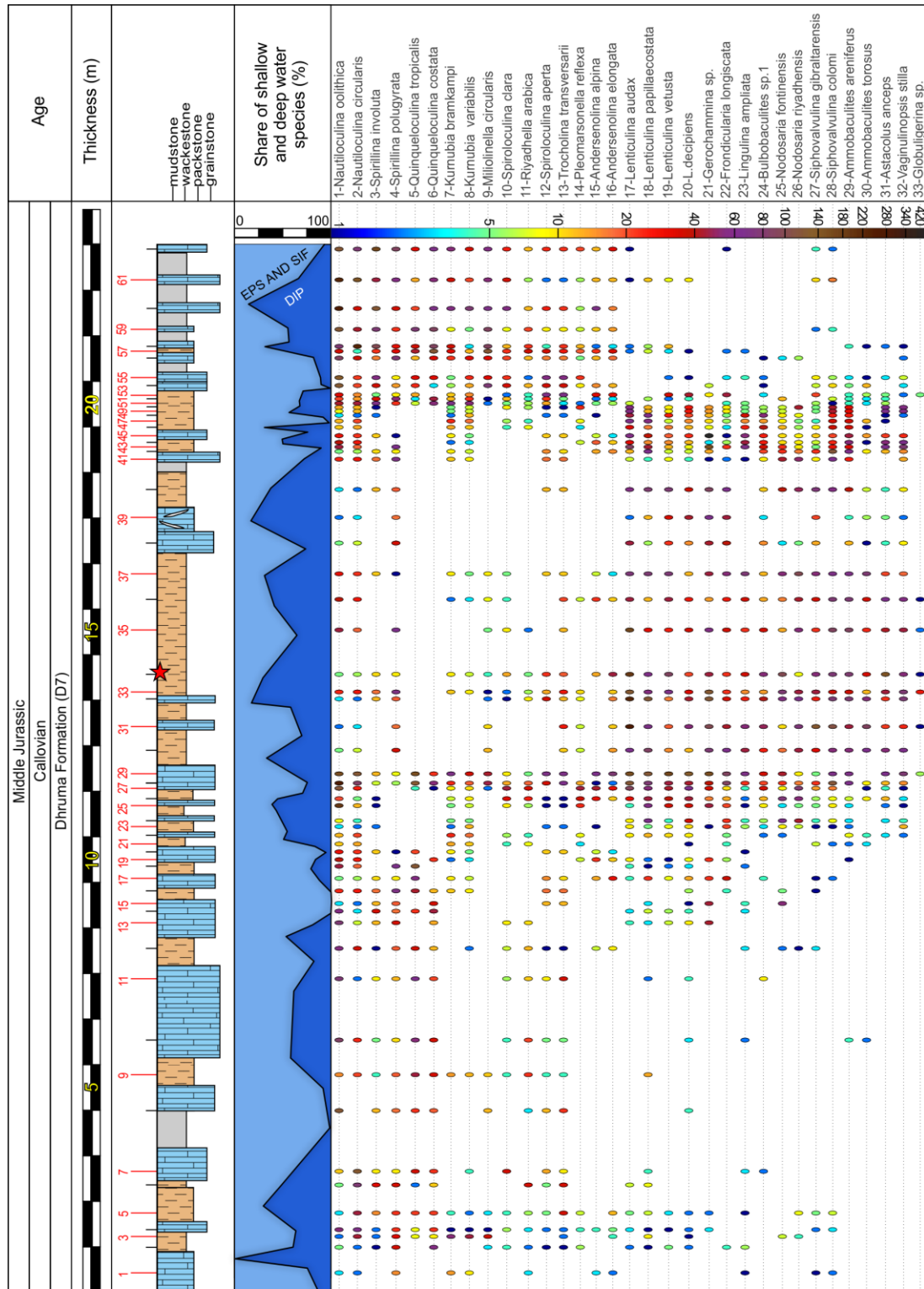


Figure 13: Stratigraphic log, vertical distribution and abundance charts of Atash and Hisyan Members (D7 unit)

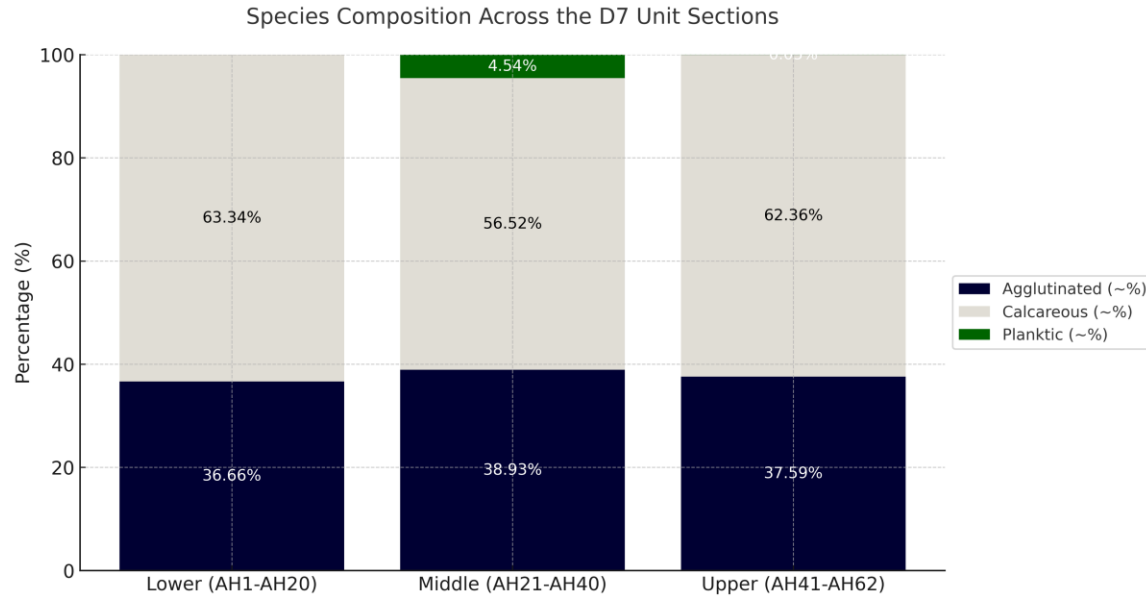


Figure 14: Foraminiferal distribution across the Atash and Hisyan Member-D7 unit.

4.2.2 Foraminiferal morphogroup distribution

The D7 Unit's morphogroup distribution shows a dynamic pattern across stratigraphy (**Error! Reference source not found.**). In the lower section (AH1–AH23), the dominant epifaunal species include *Nautiloculina oolithica*, *Trocholina* sp., *Spirillina vivipara*, and *Quinqueloculina* sp. Shallow infauna such as *Ammobaculites agglutinans*, *Lingulina* sp., *Valvulina* sp., and *Andersonolina alpina* are also present, indicating moderate substrate variability, while deep infauna like *Gerochammina* n.sp., *Siphovalvulina* sp., *Fronicularia* sp., and *Bulbobaculites* n.sp., appears sporadically, likely reflecting minor environmental fluctuations. The middle section (AH24–AH53), shows an increase in both shallow and deep infaunal species like *Gerochammin* n.sp., *Lenticulina* sp., *Nodosaria* sp., indicating greater substrate heterogeneity and variable oxygen levels. This section aligns with the peak transgression phase. While the upper part of the unit (AH54–AH62) is characterized by a return to epifaunal dominance including *Spirillina vivipara*,

Nautiloculina oolithica, *Riyadhella arabica*, *Kurnubia* sp., suggesting a shallowing trend and a transition to restricted marine conditions associated with a regressive phase. These distributions are summarized in (Table 1a and b).

4.2.3 Biodiversity Indices and Percentage Dominance

The biodiversity indices reveal the highest species richness in the middle section, and Fisher's alpha index reaching 5.47 with the least dominance (18.58%). The lowest species richness, with a Fisher's alpha of approximately 2.0 and moderate dominance (27.79%), is recorded in the lower section of the D7 Unit, corresponding to its lower Atash Member. In contrast, the upper section, comprising the overlying Hisyan Member, shows the highest species dominance (30.46%) with moderate species richness (Fisher's alpha: 3.55).

4.2.4 Cluster Analysis

The combined analysis of sample-and species-based (Q-Mode and Hierarchical Clusters) identifies six distinct clusters, reflecting variations in species composition, ecological preferences, and environmental conditions (Table 2). These groups range from very shallow lagoonal environments to deep marine/intra-shelf basin settings, encompassing calcareous, agglutinated, and planktic/transitional species. This classification highlights the influence of transgressive-regressive cycles on depositional environments, offering a comprehensive understanding of the paleoenvironmental gradients within the D7 Unit.

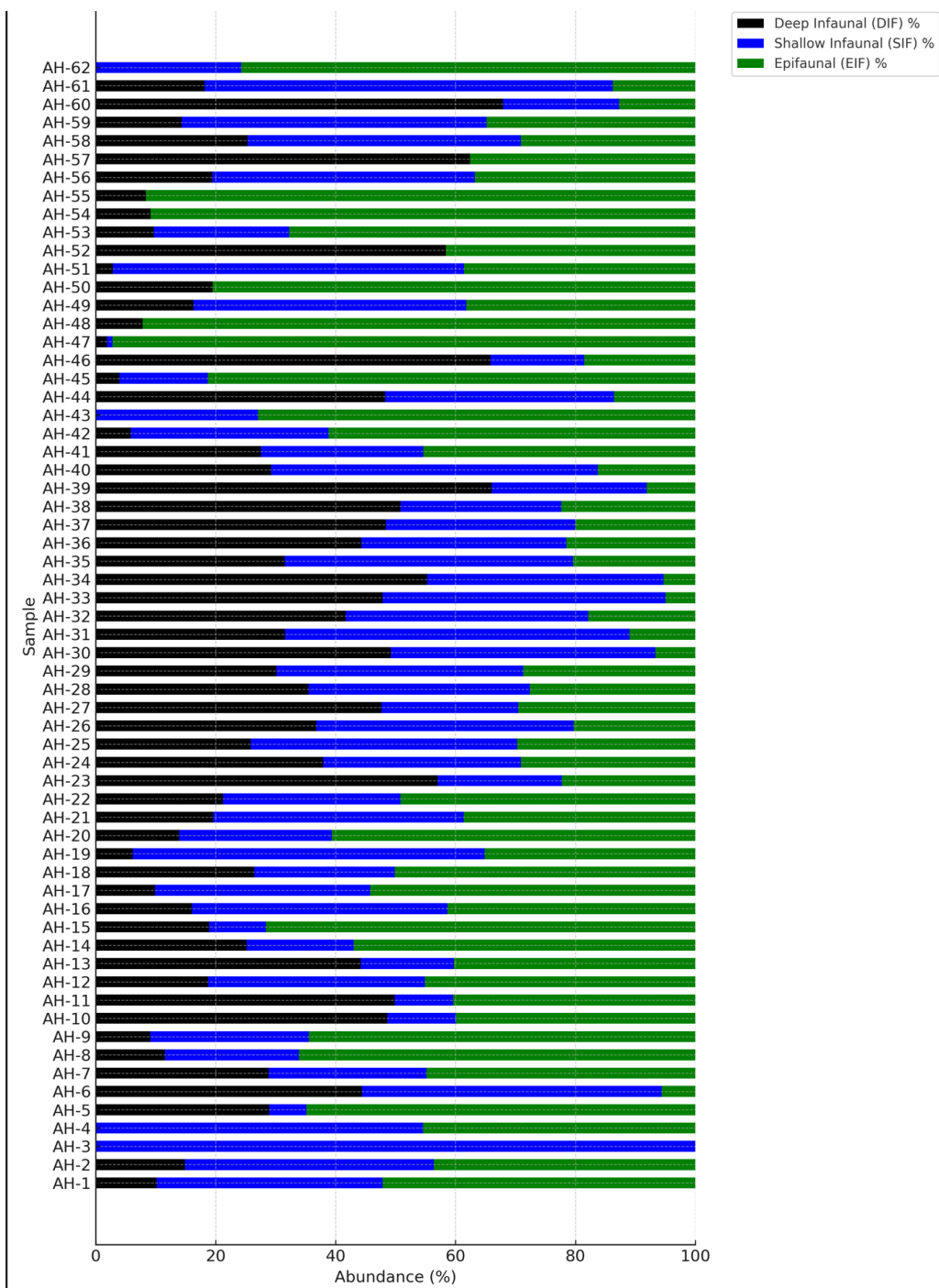


Figure 15: Normalized morphogroup distribution by sample (Equal bar height=100%)

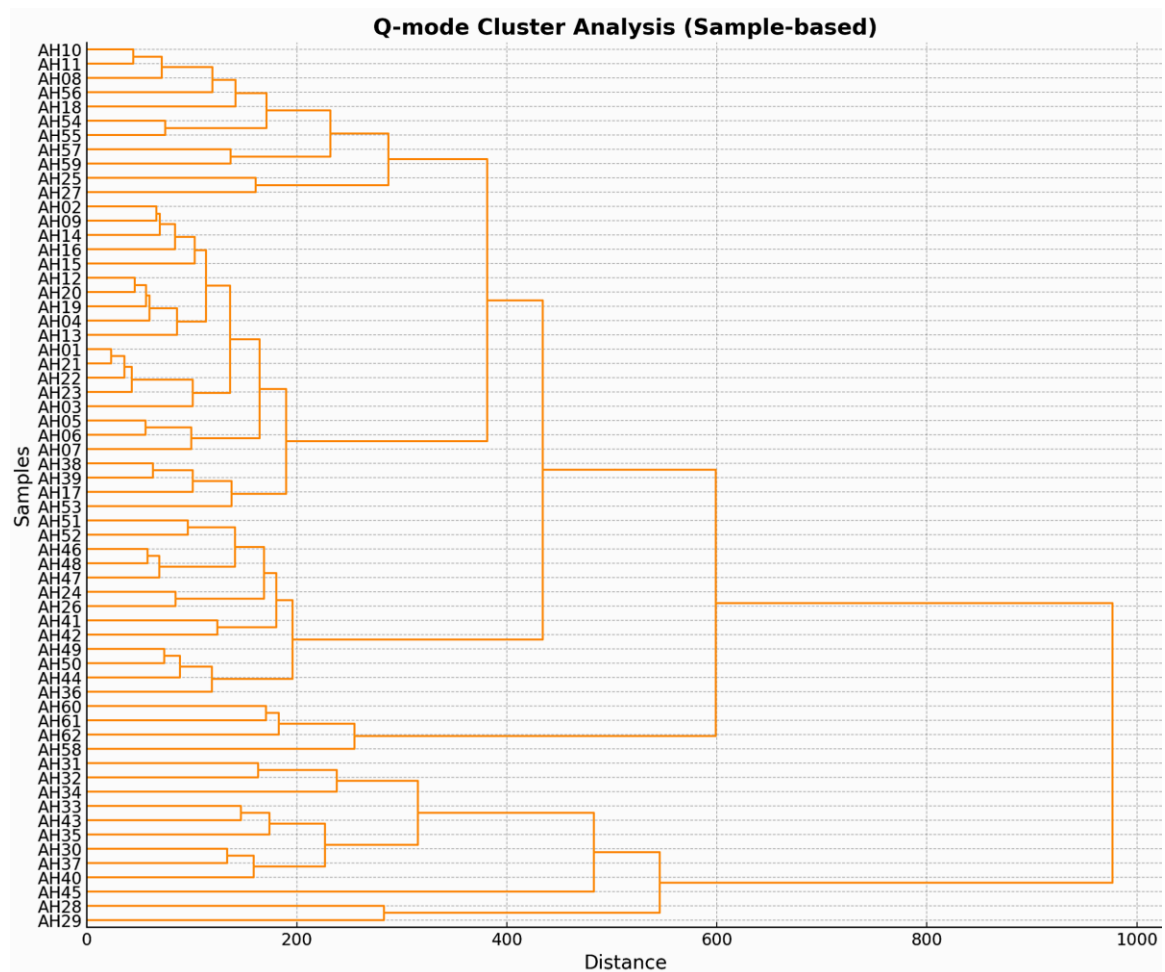


Figure 16 : A Sample-based (Q-mode) cluster analysis of foraminiferal assemblages.

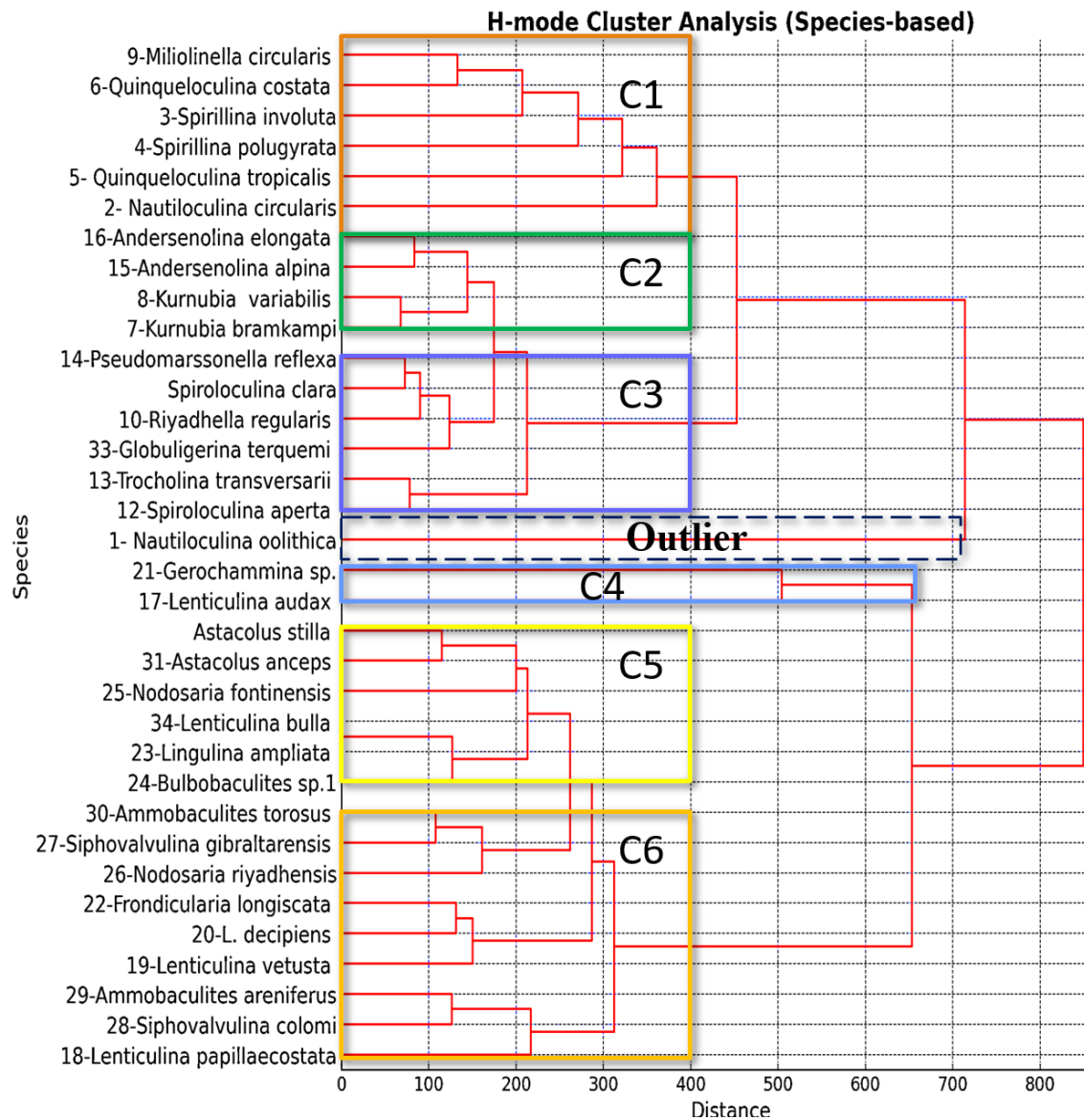


Figure 17: A species-based (H- cluster analysis).

These highlight depositional environment shifts and paleoenvironmental gradients across the D7 Unit, revealing transitions from shallow to deeper marine settings. Which aids in identifying stratigraphic markers, such as Maximum Flooding Surfaces (MFS), and supports the high-resolution sequence stratigraphic framework in the upper Ddruma Formation.

4.2.5 Paleobathymetric model

The paleobathymetric model for the Upper Dhurma Formation demonstrates a gradual depth progression along an epicontinental ramp. It begins with a complex zone (0–1 m), followed by very shallow lagoons (2–3 m) and shallow lagoons (3–5 m). These shallow environments are dominated by benthic calcareous epifaunal species. The deep lagoon (6–10 m) is colonized by mixed calcareous and agglutinated foraminifera shall and deep infaunal forms, reflecting reduced energy and oxygen levels.

The middle neritic zone with depth (20–50 m) also contains recurring shallow infaunal genera, indicating further oxygen depletion. In the outer neritic zone (50–100 m), calcareous and agglutinated deep infauna such as *Lenticulina*, *Lingulina*, *Siphovalvulina*, and *Ammobaculites* are observed. The intra-shelf basin (100–150 m), also records calcareous *Lenticulina*, *Nodosaria*, with agglutinated *Bulbobaculites*, *Gerochammina*, and planktic *Globuligerina*, indicating low-energy, oxygen-poor conditions typical of maximum flooding surfaces (MFS).

This synthetic conceptual model (Figure 20) reflects a dynamic sequence of transgressive-regressive cycles, capturing environmental and ecological transitions along the depositional ramp. The inferred depth ranges and classifications align with Hughes (2006) and general stratigraphic conventions for epicontinental ramp systems like the Dhurma Formation.

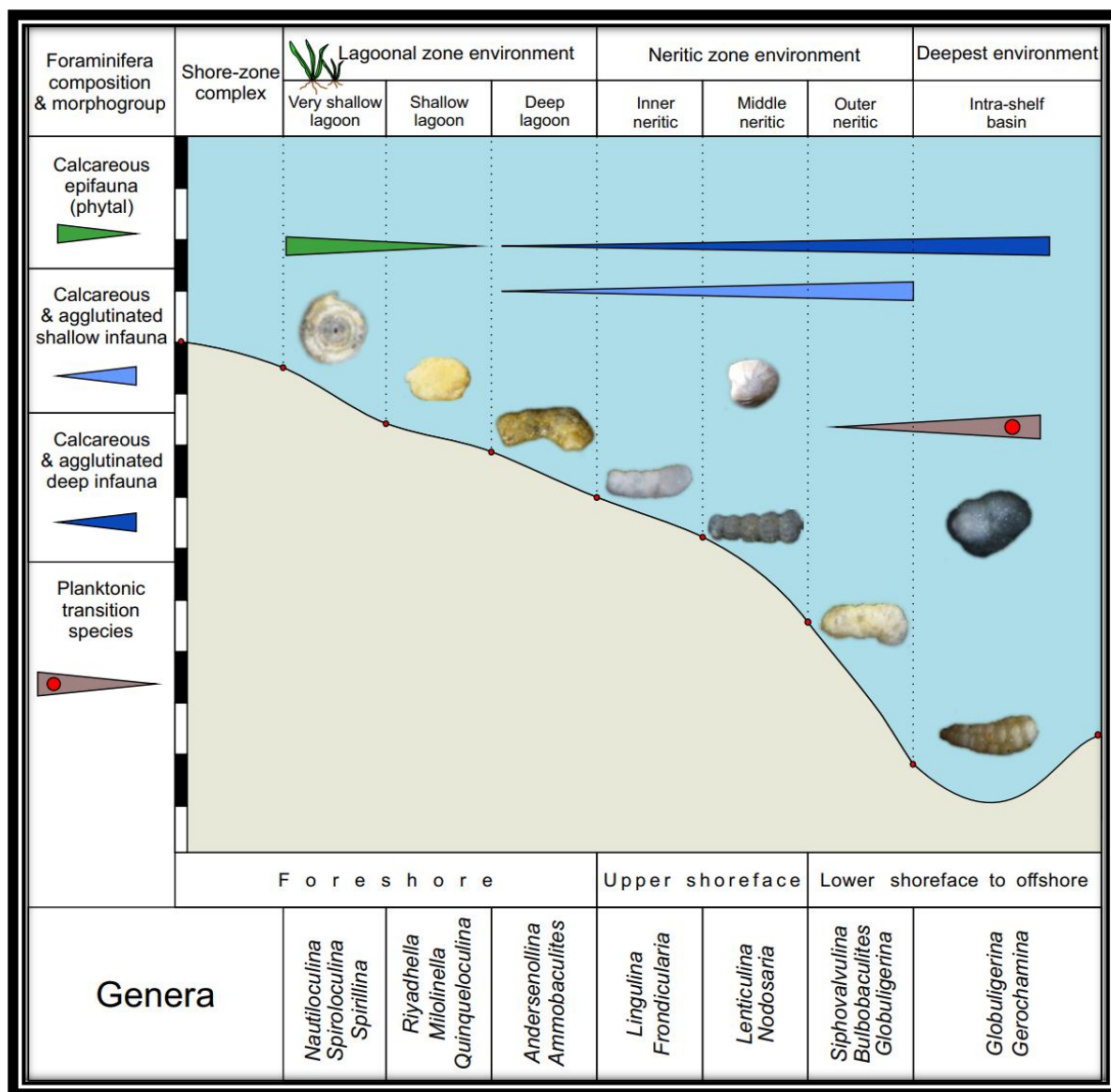


Figure 18: Conceptual Paleobathymetric Model of the D7 Unit (Atash and Hisyan Members)
Based on Foraminiferal Analysis.

Table 1: Identified calcareous and agglutinated morphogroups of 21 foraminifera genera, D7 unit (Atash and Hisyan Members)

Morphogroup Type	Genera	Life-form& Foraminifera composition	Environment	Reference
	<i>Nautiloculina</i>	Epifauna calcareous	Very shallow lagoon	Hughes,2004,2006
	<i>Spirillina</i>		shallow lagoon	Cushman, 1933; Reolid et al., 2019a; Ansari et al.2021
	<i>Quinqueloculina</i>		shallow lagoon	Reolid et al., 2019; Ansari et al.2021;
	<i>Kurnubia</i>		shallow lagoon	Hughes et al.2004
	<i>Riyadhella</i>		Very shallow lagoon	Hughes et al.2004,2006
	<i>Miliolinella</i>		shallow lagoon	Tyszka,1994; Ansari et al.2021
	<i>Spiroloculina</i>		Very shallow lagoon	Reolid et al. 2008
	<i>Trocholina</i>		Very shallow lagoon	Hughes,2004,2006
	<i>Paleomarrssonella</i>	Shallow infauna calcareous	Deep lagoon Inner neritic zone	Reolid et al., 2019a; Ansari et al.2021
	<i>Andersenolina</i>		Deep lagoon Inner neritic zone	Ansari et al.2021
	<i>Lingulina</i>		Deep lagoon Inner neritic zone	Reolid et al.2016,
	<i>Lenticulina</i>	Deep Infauna Calcareous	Middle -Intrashelf Basin	Reolid et al.2012a; Hughes,2004
	<i>Astacolus</i>		Middle -Intrashelf Basin	Tyszka,1994; Reolid et al. 2008,2019
	<i>Vaginulinopsis</i>		Middle -Intrashelf Basin	Reolid et al. 2008,2019
	<i>Frondicularia</i>		Middle -Intrashelf Basin	Tyszka,1994; Ansari et al.2021
	<i>Nodosaria</i>		Middle -Intrashelf Basin	Hughes,2004; Ansari et al.2021;
	<i>Ammobaculites</i>	Shallow Infauna Agglutinated	Deep lagoon to Inner neritic zone	Reolid et al.2012a;
	<i>Siphonvulvina</i>		Deep lagoon to Inner neritic zone	
	<i>Bulbobaculites</i>	Deep Infauna Agglutinated	Middle -Intrashelf Basin	Holbourn and Kaminski, 1995; Waskowska, 2014
	<i>Gerochammina</i>		Intra-shelf Basin	
	<i>Globuligerina</i>	Planktonic	Deep marine or basinal	Kaminski et al. 2018a; Gradstein et al. 2017

Table 2: Cluster Group Classifications for D7 Unit of the Upper Dhurma Formation

Cluster Group	Cluster group composition	Species	Ecological Niche	Environmental Interpretation
Cluster 1	Very Shallow Calcareous	<i>Nautiloculina oolithica</i> <i>Spirillina vivipara</i> <i>Trocholina sp.</i>	Shallow marine, well-oxygenated, high-energy carbonate-rich environments	Inner shelf/lagoonal settings during regression phases
Cluster 2	Shallow Calcareous	<i>Lenticulina rotulata</i> <i>Andersonolina alpina</i> <i>Trocholina sp.</i>	Shallow marine, moderate energy, carbonate sedimentation	Early transgressive phases, representing lagoonal or inner shelf environments
Cluster 3	Deep Calcareous	<i>Nodosaria radiculata</i> <i>Nodosaria riyadhensis</i> <i>Lenticulina sp.1</i> <i>Lingulina sp.</i>	Deeper inner shelf, oxygenated waters with calcareous-dominant sediments	Transition to deeper marine environments, marking peak transgression
Cluster 4	Deep Lagoon Agglutinated	<i>Ammobaculites sp.3</i> <i>Bulbobaculites sp.1</i> <i>Gerochammina sp.</i>	Tolerant of low-oxygen conditions, found in restricted or deeper lagoonal environments	Lagoonal to intra-shelf basin settings, indicating deeper water with fluctuating conditions
Cluster 5	Deep marine/Intra-Shelf Basins Agglutinated	<i>Ammobaculites sp.1</i> <i>Valvulina sp.</i> <i>Siphovalvulina sp.</i>	Deeper marine, oxygen-depleted zones, agglutinated species dominate	Represents maximum flooding surfaces, deeper intra-shelf basins during peak transgression
Cluster 6	Planktic/Transitional Species	<i>Globuligerina terquemi</i> , <i>Quinqueloculina sp.</i> , <i>Riyadhella regularis</i> , Samples	Open marine species with planktic forms, indicating fluctuating depths and nutrient-rich waters	Transitional environments marking open marine influence during peak transgressive phases

4.3 DISCUSSION

4.3.1 Foraminiferal composition and paleoenvironmental implications

The D7 Unit's stratigraphy displays a distinctive pattern in foraminiferal composition, reflecting a complex sequence of deepening and shallowing (T-R cycles). Calcareous

foraminifera dominate the lower section of the unit within the Atash Member, corresponding to samples (AH1–AH23) in the stratigraphic log (Figure 15, with significant representation of *Nautiloculina oolithica*, *Riyadhella arabica*, *Spirillina vivipara*, *Quinqueloculina* sp., *Milolinella* sp., and *Trocholina* sp., alongside agglutinated species like *Ammobaculites agglutinans* and *Siphovalvulina*. This assemblage reflects a very shallow, well-oxygenated inner shelf environment at the onset of a transgressive phase, suggesting the shallowest lagoonal conditions within the D7 Unit lower section.

Moving into the middle section, within the upper Atash Member and the base of the overlying Hisyan Member, there is an increase in agglutinated forms, including previously unreported species such as *Bulbobaculites* n.sp., and *Gerochammina* n.sp., along with the planktic species *Globuligerina terquemi* (Figure 20), marking peak transgression. Planktic species have been previously documented in the Middle Jurassic Dhurma Formation's middle section (basal D5) in Saudi Arabia (Kaminski et al., 2018a). This section represents the Maximum Flooding Surface (MFS), as indicated by the mixed presence of planktic, agglutinated, and calcareous forms such as *Frondicularia* sp., *Lenticulina rotulata* and *Nodosaria riyadhensis*, suggesting a deepening upward sequence (Figure 21) toward an outer shelf or intra-shelf basin setting. It is considered that many of the species from deep lagoon or shelf to bank environments may be present as storm-transported debris within intra-shelf basin biofacies (Hughes, 2004).

The unit's upper section, entirely within the Hisyan Member (AH54–AH62), shows a return to calcareous dominance (Figure 16) with minimal planktic species and reduced agglutinated forms (*Ammobaculites agglutinans* and *Siphovalvulina* sp), indicative of a shallowing upward sequence during the regressive phase. The dominance of species such

as *Nautiloculina oolithica*, *Spiroloculina* sp., *Spirillina vivipara*, *Kurnubia* sp., and *Trocholina* sp., in this section suggests a restricted lagoonal or inner shelf environment. These findings imply a regression sequence, reflecting restricted marine conditions with reduced open ocean influence. Overall, the Atash Member records a deepening upward trend, while the overlying Hisyan Member exhibits a shallowing upward trend, marking a full T-R cycle within the D7 Unit.

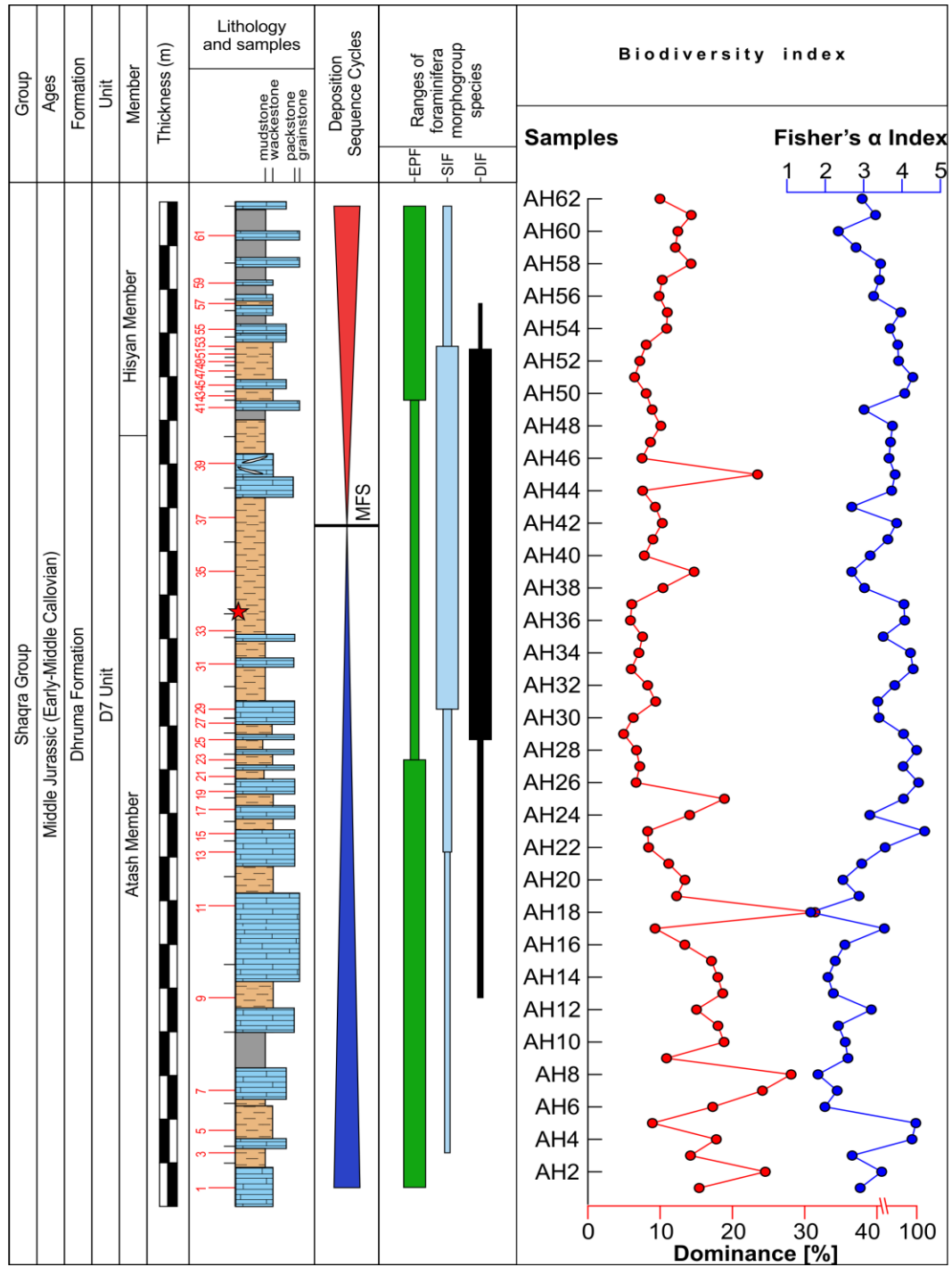


Figure 19: Depositional Sequence Stratigraphic Model Derived from Foraminiferal Morphogroup Analysis. It indicates the Position of the **MFS**

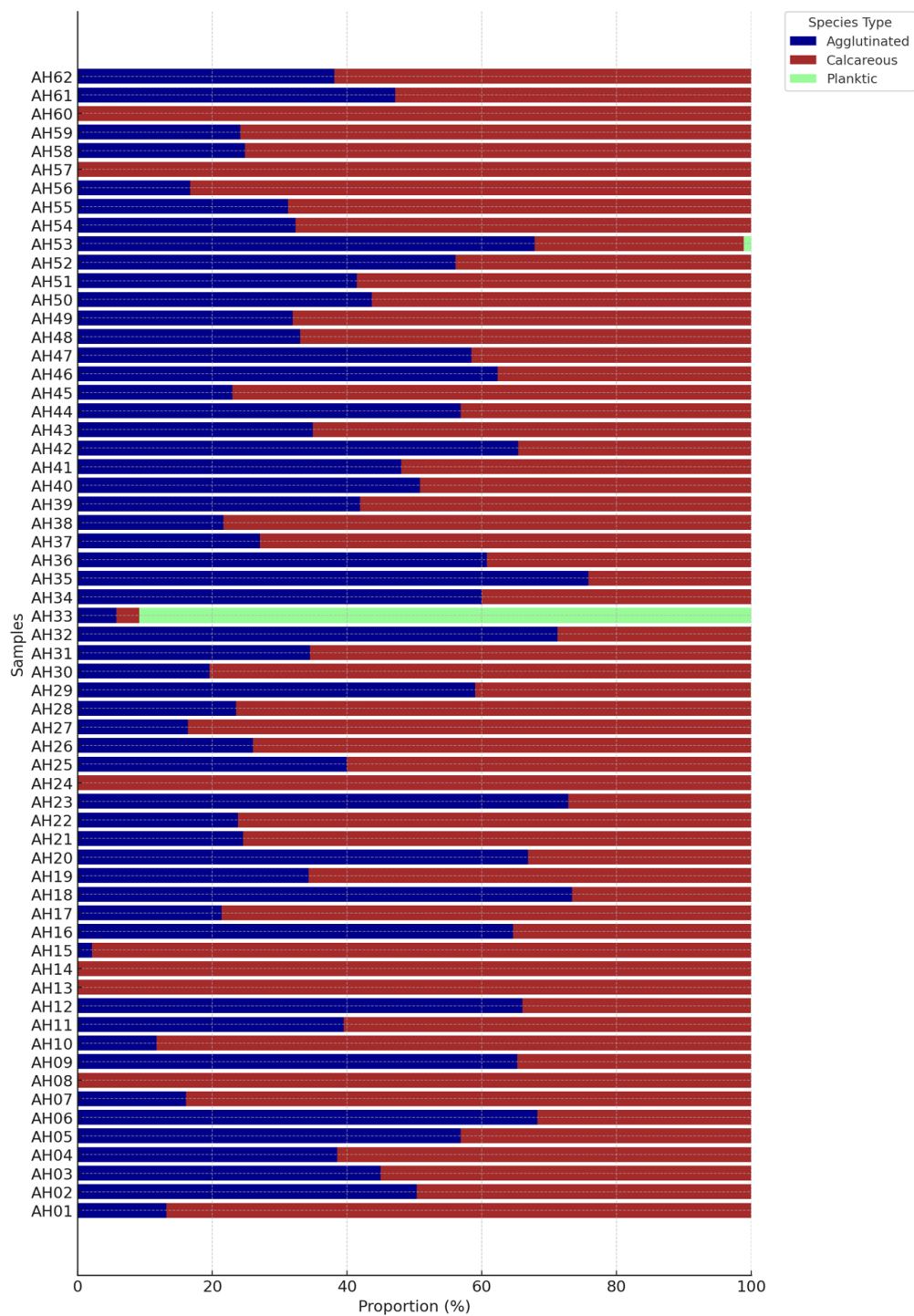


Figure 20: Stratigraphic distribution of calcareous, agglutinated and planktic foraminifera across the D7 unit

4.3.2 Morphogroup distribution and ecological impacts of T-R cycles

The morphogroup distributions across the D7 Unit reflect significant ecological niche shifts tied to sea-level fluctuations and changes in depositional settings. In the basal section, epifaunal species dominate (50%), indicating a high-energy, shallow lagoonal to inner shelf environment with well-oxygenated bottom waters. The presence of shallow infauna (30%) suggests moderate substrate variability, while the limited occurrence of deep infauna (Figure 21) points to episodic sedimentation or oxygenation changes, indicating marginal marine settings and stable shallower depths. In the intermediate section (Figure 17), shallow and deep infauna become more prevalent, aligning with greater substrate heterogeneity and variable oxygen levels, typical of outer or intra-shelf environments. This shift corresponds with the Maximum Flooding Surface (MFS) and peak transgression phase, where mixed morphogroups indicate a transition to deeper lagoonal or outer shelf settings.

A significant return to epifaunal dominance (60%) in the upper section (Figure 21) suggests shallowing conditions associated with a regressive phase, marking a transition back to restricted, inner shelf, or lagoonal environments. This morphogroup distribution pattern across the D7 Unit highlights the ecological impact of T-R cycles, illustrating a full transition from shallow inner shelf to deeper outer shelf and back to a restricted lagoonal setting (Figure 22).

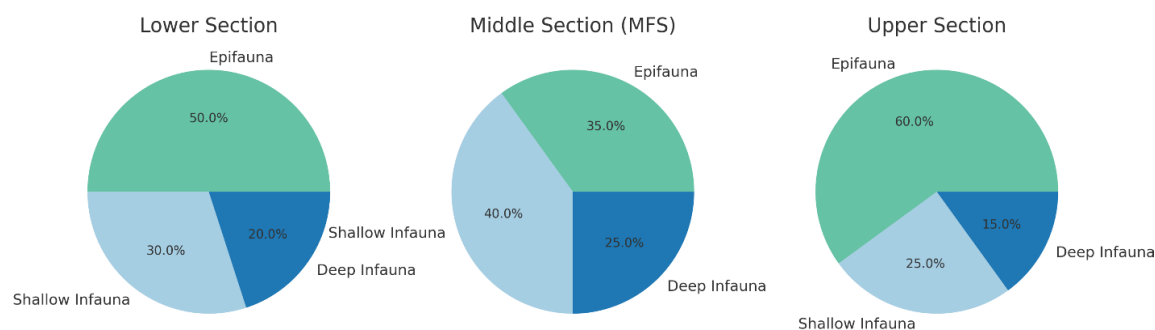


Figure 21: Morphogroup benthic species percentage distribution across the D7 unit (Atash and Hisyan Members).

4.3.3 Biodiversity, Clustering, and Paleoenvironmental Interpretation

Biodiversity indices in the upper Dhurma Formation support complex T-R sequences, with species richness highest in the middle interval (Fisher's alpha ~ 5.47) and lowest in the basal unit (~ 2.0) within the Atash Member. The upper portion, within the overlying Hisyan Member, shows moderate richness. High richness and low dominance in the middle section indicate environmental variability and nutrient availability during peak transgression, characteristic of outer shelf or intra-shelf basin settings. In contrast, moderate richness and dominance in the basal part suggest high-energy, well-oxygenated shallow marine conditions, while increased dominance in the upper section points to restricted marine settings with reduced open marine influence.

The sample and species-based cluster analysis (Figure 22) supports the sequence patterns in the D7 Unit's basal Atash and overlying Hisyan Members. The first cluster, dominated by calcareous epifaunal species, aligns with inner shelf to shallow lagoonal settings in the lower and upper parts, reflecting early transgressive and regressive phases. Mixed calcareous and agglutinated infaunal forms in the second and third clusters indicate deeper

lagoonal to outer shelf environments. The fourth and fifth clusters, dominated by deep infauna agglutinated species, suggest low-oxygen conditions in intra-shelf basin settings at the Maximum Flooding Surface (MFS). Cluster 6, containing planktic species, highlights open marine influence during peak transgression.

Biodiversity patterns and cluster groupings support the sequence stratigraphic framework of the D7 Unit, transitioning from a shallow lagoonal/inner shelf in the lower section to a peak transgressive intra-shelf basin in the middle, then back to a restricted lagoonal/inner shelf in the overlying member. This reflects complex T-R cycles in the upper Dhurma Formation.

4.3.4 Paleobathymetric and Sequence Stratigraphic Implications

The stratigraphic record of the Upper Dhurma Formation reveals a complex sequence of transgressive-regressive (T-R) cycles, providing valuable insights into Middle Jurassic sea-level dynamics in central Saudi Arabia. Foraminiferal assemblages, morphogroup distributions, and lithological trends across the D7 Unit collectively indicate deepening and shallowing successions within a sequence, reflecting depositional environments transitioning from shallow inner shelf to deeper intra-shelf basins and back.

In the basal section of the Atash Member (AH1–AH23), high dominance of calcareous epifaunal species, including *Nautiloculina oolithica* and *Spirillina vivipara*, reflects a shallow, high-energy marine environment consistent with a highstand systems tract (HST). This interval indicates progressively shallowing waters, with deposition in a well-oxygenated inner shelf setting (Murray, 1991; Katz et al., 2013).

The upper section (AH25–AH53) of the Atash Member and the base of the overlying Hisyan Member exhibit increased diversity of calcareous and agglutinated shallow and deep infauna, alongside planktic species such as *Globuligerina terquemi*, marking a transition to deeper water conditions. These trends correspond to a transgressive systems tract (TST), culminating in the maximum flooding surface (Figure 22). The MFS can be identified by the peak planktic abundances and heightened species diversity (Loutit et al., 1988; Browning et al., 1997). The presence of finer-grained marl deposits within this section further supports this interpretation.

The upper part of the Hisyan Member (AH54–AH62) shows a return to calcareous epifaunal dominance, accompanied by shallow infaunal forms, reflecting a return to shallower marine conditions. This shallowing-upward trend is indicative of a highstand systems tract (HST), transitioning into a regressive phase. These depositional patterns, characterized by rhythmic limestone and marl deposition, align with sedimentological models where transgressive systems fine upward and highstand systems coarsen upward (Posamentier et al., 1988; Katz et al., 2013).

The results refine the sequence stratigraphic framework for the Upper Dhurma Formation, highlighting the interplay of paleoenvironmental dynamics and sea-level fluctuations in shaping Jurassic depositional systems on the Arabian Shelf.

4.4 Conclusion and Implications

4.4.1 Conclusion

This chapter presents a detailed analysis of foraminiferal assemblages, morphogroup distributions, and sequence stratigraphy within the D7 Unit of the Middle Jurassic Upper Dhurma Formation in central Saudi Arabia. The findings reveal complex transgressive-regressive (T-R) cycles marked by a progression from shallow lagoonal to deeper intra-shelf basin environments and back to restricted marine settings. Through morphogroup analysis, biodiversity indices, and cluster analysis, this study identifies the Maximum Flooding Surface (MFS) and provides a high-resolution stratigraphic framework that captures ecological and depositional shifts within the formation. These insights deepen our understanding of Jurassic sea-level dynamics and contribute valuable data on paleoenvironmental conditions in the Arabian Shelf region.

4.4.2 Study Implications

Scientific and environmental implications

The study's findings are essential for advancing paleoenvironmental research and refining Middle Jurassic sequence stratigraphy in the Arabian region. By documenting morphogroup distributions and foraminiferal composition in relation to T-R cycles, this research improves interpretations of ancient marine ecosystems and provides a basis for reconstructing past sea-level changes. These paleoecological insights align with the United Nations Sustainable Development Goals (SDGs) on climate action (SDG 13) and life

below water (SDG 14), offering context for current environmental challenges by linking historical and modern marine conditions. Understanding these ancient sea-level patterns can inform predictive models for coastal resource management and environmental conservation.

Industry implications

By delineating the depositional environments and MFS within the Dhurma Formation, this study provides a model that can support subsurface correlation, aiding in the identification of potential hydrocarbon reservoirs. These findings are instrumental for the hydrocarbon industry, offering insights that support more precise exploration and sustainable development strategies within the Arabian Peninsula's energy sector.

CHAPTER 5

TAXONOMY AND SYSTEMATICS OF UPPER DHRUMA FORMATION

5.1 Introduction to results and discussion

This chapter presents the taxonomic and systematic analysis of 33 foraminiferal species representing 21 genera, extracted from 62 lithified limestone and marl samples of the upper Dhurma Formation in the Middle Jurassic of Central Saudi Arabia. These samples, collected from a well-exposed section at the Darma Quadrangle near the village of Haniya (approximately 82 km from Riyadh; Figure 3), were processed using acetic acid disaggregation. This technique enables three-dimensional observation and precise identification of foraminiferal morphology, offering a significant improvement over traditional thin-section methods, as demonstrated in previous studies (e.g., Kaminski et al., 2018; Malik et al., 2020).

The taxonomic composition revealed a diverse and well-preserved microfaunal assemblage, providing new insights into depositional environments, paleobiogeographic distributions, and evolutionary trends during the Jurassic. This study emphasizes three primary foraminiferal groups: calcareous, agglutinated, and planktonic taxa, each

contributing to our understanding of the ecological and sedimentological conditions in the Middle Jurassic of Saudi Arabia.

5.1.1 Calcareous Foraminifera

The calcareous foraminiferal assemblage is dominated by benthic species, including *Nautiloculina oolithica*, *Spirillina vivipara*, *Trocholina* sp., and *Quinqueloculina* sp., which thrive in high-carbonate environments typical of shallow, tropical marine platforms (Hughes, 2004). These taxa reflect a photic zone with sufficient light penetration. The presence of hyaline forms such as *Lenticulina rotulata* and *Nodosaria riyadhensis* possibly suggest well-oxygenated, stable substrate conditions.

5.1.2 Agglutinated Foraminifera

Agglutinated taxa, including *Ammobaculites agglutinans* and *Siphovalvulina* sp., form a smaller yet ecologically significant component of the assemblage. The presence of *Bulbobaculites* n.sp. and *Gerochammina* n.sp. in the Dhurma Formation suggests intermittent clastic input or dysoxic to anoxic conditions at the sediment-water interface, likely associated with deep lagoonal or restricted marine settings. These taxa are commonly linked to low-energy environments, restricted depositional settings, and fluctuating salinity.

Different species of *Bulbobaculites* have been documented in deep-water flysch-type shale deposits (Holbourn and Kaminski, 1995; Waśkowska, 2014) and shallow-water carbonates (Săşăran et al., 2016). *Gerochammina* is known to inhabit deeper settings, ranging from

the inner shelf to upper bathyal zones, particularly under conditions of elevated organic matter influx (Setoyama et al., 2013).

5.1.3 Planktonic Foraminifera

The planktonic component, represented by *Globuligerina* sp., provides an important paleontological and stratigraphic insight. Although rare (4.54%), its occurrence signifies intermittent connections to open marine conditions during transgressive phases. This suggests that the primarily benthic-dominated depositional system experienced periodic influxes from pelagic environments, aligning with the evolving planktonic foraminiferal assemblage during the Middle Jurassic of Saudi Arabia.

The presence of *Globuligerina* sp., was first documented in the basal marly unit (D5) of the intermediate Dhruma Formation in Central Saudi Arabia by Kaminski et al. (2018b), serving as a new marker for recognizing the J30 Maximum Flooding Surface (MFS) Sharland et al. (2001) in the region.

5.2 Taxonomic and Systematic Analysis

This section presents the taxonomic analysis of 33 identified species belonging to 21 genera, extracted from 62 indurated limestone and marl samples collected from the Atash and overlying Hisyan members (D7 unit). These assemblages represent a diverse and well-preserved microfaunal community, offering valuable insights into the depositional and paleoenvironmental dynamics of the Middle Jurassic in Central Saudi Arabia.

The classification of agglutinated foraminiferal species is based on the revised taxonomic framework proposed by Kaminski (2014). Calcareous foraminiferal species follow the

original classification scheme of Loeblich and Tappan (1987). Specimens illustrated in plates one to eleven accompany the descriptions and provide visual references for the taxonomic identifications.

Class FORAMINIFERA d'Orbigny 1826

Subclass TUBOTHALAMANA Pawlowski, Holzmann & Tyszka 1993

Suborder MILIOLINA Delage & Herouard 1896

Superfamily MILIOLINELLINAE Vella 1957

Family QUINQUELOCULINIDAE Cushman 1917

Genus *Miliolinella* Wiesner 1931

Miliolinella circularis (Bornemann, 1855)

Plate 1, figures 1a-b

Triloculina circularis BORNEMANN, 1855, v. 7, pt. 2, p. 349, pl. 19, figs. 4a–c.

Miliolinella circularis (Bornemann). – FAJEMILA et al. 2020, pl.45, pl. 16, fig. 6.

Remarks: This species is predominantly recorded in the basal section of the D7 Unit's Atash Member, with three specimens noted in the upper part of the overlying Hisyan Member, indicating a restricted lagoon or very shallow setting during regression. Javaux and Scott (2003) reported its occurrence in brackish water (1–2 m depth), backreef-reef areas (1–10 m), and nearshore lagoons (1–20 m) in Bermuda. The specimens are characterized by inflated chambers, a near-circular lateral outline, and slight compression, with some appearing tear-shaped in lateral view (Parker and Gischler, 2024).

Superfamily MILIOLACEA Ehrenberg 1839

Family SPIROLOCULINIDAE Wiesner 1920

Genus *Spiroloculina* d'Orbigny 1826

Type-species: *Spiroloculina depressa*, d'Orbigny, 1826

Plate 1, figures 2a-b

Spiroloculina aperta CUSHMAN and TODD 1944, p. 66, pl. 9, figs. 21-22. – PARKER and GISCHLER 2024, pl. 16, figs. 11-13.

Remarks: The specimens are exclusively observed in the basal section of the Atash outcrop within the studied D7 Unit of the Dhruma Formation. The test varies from slightly rounded to flat. The wall is calcareous, imperforate, and porcelaneous. The aperture is single, located at the end of the chamber, produced on a short neck, and possibly accompanied by a simple tooth.

Spiroloculina clara Cushman 1932

Plate 1, figures 3a-b

Spiroloculina clara CUSHMAN 1932, p. 40, pl. 10, figs 4-5. – CUSHMAN et al. 1954, p. 335, pl. 84, fig. 9. – DEBENAY 2012, p. 132.

Remarks: This specimen exhibits a highly compressed test shape with a concave periphery and chambers characterized by distinctively transparent walls.

Subfamily QUINQUELOCULININAE Cushman 1917

Genus *Quinqueloculina* d'Orbigny 1826

Quinqueloculina tropicalis Cushman 1924

Plate 1, figure 4

Quinqueloculina tropicalis CUSHMAN, 1924, p. 63, pl. 23, figs. 9, 10; pl. 9, fig. 6. – MAKLED and LANGER 2011, fig. 6, nos 15, 16.

Remarks: This species is most common in the basal D7 Unit of the Atash Member, indicating a very shallow to shallow lagoonal setting. Studies from the Lizard Island reef complex have noted its presence in shallow backreef environments, as well as in lagoonal and patch reef areas (Baccaert, 1987). The specimens exhibit a granular, dull surface and apertural features consistent with Cushman's illustration. In the studied Middle Callovian unit of Central Saudi Arabia, it is recorded at an interpreted paleobathymetric depth of approximately 2–3 meters. Debenay (2012) also documented *Q. tropicalis* in a shallow bay within the southwestern lagoon of New Caledonia, at depths ranging from 0 to 5 meters.

Quinqueloculina costata d'Orbigny, 1826

Plate 1, figure 5

Quinqueloculina costata D'ORBIGNY, 1826, p. 301, pl. 4, fig. 8.

Remarks: This species is common in the basal D7 Unit of the Atash Member, with four specimens recorded in the uppermost part of the overlying Hisyan Member, indicating a restricted lagoonal or shallow setting. It is circumtropical in distribution (Rao et al., 2018) and is often confused with *Q. poeyana* d'Orbigny, which is narrower, with a length three times its width. It has been reported from shallow waters in the Gulf of California at depths of 0.8 to 12 m (Brenner, 1962) and from Matsushima Bay (Matoba, 1970). Machado and Moraes (2002) recorded *Q. costata* in sediment samples from two distinct reef environments in Brazil: a broad shallow shelf dominated by strong currents and a narrow shelf influenced by wind-induced waves.

Subclass GLOBOTHALAMANA Pawlowski, Holzmann and Tyska 2013

Order LITUOLIDA Lankester 1885

Suborder NEZZAZATINA Kaminski 2004

Superfamily NEZZAZATACEA Hamaoui and Saint-Marc 1970

Family NAUTILOCULINIDAE Loeblich and Tappan 1985

Genus *Nautiloculina* Mohler 1938

***Nautiloculina oolithica* Mohler 1938**

Plate 2, figure 6

Nautiloculina oolithica MOHLER 1938, p. 19, pl. 4, figs. 1-3

Remarks: This is the most abundant specimens in the Upper Dhurma Formation and is widely distributed across Jurassic strata in Saudi Arabia. It is characteristic of open marine environments, including deeper shelf and lagoonal settings (Hughes, 2006, 2008), and is commonly associated with transgressive sequences, such as the J30 maximum flooding horizon within the D5 Unit (Kaminski et al., 2020). The test is free, lenticular in shape, planispirally enrolled, and involute. It consists of a globular proloculus followed by numerous small chambers per whorl that gradually increase in size. Sutures are radial to very slightly arched, and the wall is microgranular, calcareous, and agglutinated.

***Nautiloculina circularis* Said and Barakat, 1959**

Plate 2, figure 7

Nautiloculina circularis SAID and BARAKAT 1959, pl. 1, fig. 1. – DERIN and REISS 1966, figs. 70, 71, 83, 254, 263, 264, 271, 280, 283, 286–289, 309. ≠ AL-SAAD 2008, p. 8, pl. 1, figs. 4a–4b.

Remarks: This specimen shows lower abundance compared to the *N. oolithica* in the studied D7 Unit, with a considerable occurrence in the basal section of the overlying Hisyan member.

Suborder SPIRILLININA Hohenegger and Piller 1975

Family SPIRILLINIDAE Reuss and Fritsch 1861

Genus *Spirillina* Ehrenberg 1843

Type species: *Spirillina vivipara* Ehrenberg 1843

Spirillina involuta Antonova 1958

Plate 2, figures 8a-b

Spirillina involuta Antonova 1958, p. 65, pl. 4, fig. 1a, b

Remarks: Commonly observed in the basal Atash and topmost part of the overlying Hisyan Members of the D7 Unit, the test is free, planispiral, and rounded, consisting of a spherical proloculus followed by a tubular chamber forming five whorls. The wall is calcareous, semitransparent, and perforate, with slightly depressed spiral sutures. The aperture is represented by the open end of the tube. This species differs from *Spirillina kuebleri* Mjatluk (Antonova, 1958) by its involute coiling and a more rapid increase in the diameter of the tubular chamber.

Plate 2, figures 9a-b

Spirillina polygyrata GÜMBEL 1862, p. 214, pl. 4, fig. 11a–c. – BLANK 1990, p. 84, pl. 1, figs. 3–4.

Remarks: The identified *Spirillina* specimens from the studied D7 Unit, predominantly observed in the basal Atash outcrop and the upper part of the overlying Hisyan Member, closely align with the illustrations presented by Blank (1990) from southern Germany.

Family TROCHOLINIDAE Kristan-Tollman 1963

Subfamily TROCHOLININAE Kristan-Tollman 1963

Genus *Trocholina* Paalzow 1922

Type-species: *Involutina conica* Schlumberger 1898

Plate 3, Figures 10a-b

Trocholina transversarii Paalzow, 1932

Trocholina transversarii PAALZOW 1932, p. 141, pl. XI, figs. 8–10

Remarks: This specimen is highly recorded at base of the Atash member, and upper part of the overlying Hisyan member. They exhibit a conical, plano-convex to lenticular in shape. The aperture is noted at the end of a tubular chamber. The specimen is distinguished from *Neotrocholina* by having a thinner, imperforate wall, and in lacking the deeply fissured, canaliculated umbilical structure of the latter (Fig. 4.6). Late Triassic to Late Cretaceous (Norian to Cenomanian) (Plate 3.1, figs 6-7; Plate 4.1, figs 6-9; Plate 4.4, fig. 1).

Family LENTICULINIDAE Chapman, Parr and Collins 1934

Subfamily LENTICULININAE Chapman, Parr and Collins 1934

Genus *Lenticulina* Lamarck 1804

Type species: *Lenticulites rotulatus* Lamarck 1804

Lenticulina audax Loeblich and Tappan 1950

Plate 3, Figures 11a-b

Lenticulina audax LOEBLICH and TAPPAN 1950, pl. 11, figs. 18-21, p. 43. –

KALANTARI 1969, p. 34, pl. 11, figs. 30-33a, b, – BHAT 2016, pl. 16, fig. 3.

Remarks: The specimen recorded from the Upper Dhurma Formation, Middle Callovian, Central Saudi Arabia, closely resembles *Cristellaria diademata* but differs by being approximately one-third larger and having twice the number of chambers in the final whorl (Loeblich and Tappan, 1950b). It is consistent with the original description and matches specimens reported from the Callovian Fakirwari Dome, Gujarat, India, by Bhat et al. (2016).

Lenticulina cf. papillaecostata Bielecka and Styk, 1981

Plate 3, Figures 12a-b

Lenticulina papillaecostata BIELECKA and STYK 1981, p. 29, pl. 2, figs. 19, 20.

Cristellaria mamilligera Karrer. – BRÜCKMANN, 1904, pl. 3, fig. 17.

Remarks: The test is oval in outline, bilaterally flattened, with a sharp peripheral margin resembling a keel. It consists of seven to ten chambers, with raised sutures radiating from the center and papillate ornamentation restricted to the early stage of the last whorl. The wall is calcareous, and the aperture is either circular or radial. This species, most common in the Hisyan Member of the D7 Unit (Middle Callovian), differs from the type specimens described by Bielecka and Styk (1981) by the presence of raised sutures and papillate ornamentation limited to the early stage of the final whorl. Its most reported occurrences are from the Callovian of northwest Poland and the East European platform in Russia (Bielecka & Styk, 1981).

Lenticulina vetusta (d'Orbigny 1850)

Plate 4, Figures 13a-b

Cristellaria vetusta d'ORBIGNY 1850, pl. 1, fig. 267, p. 242.

Hemicristellaria vetusta (d'Orbigny). – SAID and BARAKAT 1958, pl. 1, fig. 28, p. 251, et syn.

Astacolus vetusta (d'Orbigny). – KALANTARI 1969, pl. 5, figs. 30-33, pl. 6, figs. 11-12a, b, p. 48, et syn.

Remark: The specimen from the Hisyan outcrop of the Upper Dhurma Formation resembles the original form described by d'Orbigny (1850). However, the uncoiled portion in the current specimen is comparatively shorter and wider.

Lenticulina decipiens (Wiśniowski 1890)

Plate 4, Figures 14a-b

Cristellaria decipiens WIŚNIEWSKI 1890, pl. 10, figs. 5a-b, 11a-b, p.222.

Lenticulina decipiens (Wiśniowski). – ALHUSSEIN 2014, pl. 5, fig. 3a-b, p. 74.

Remarks: Pandey and Dave (1993) noted that this species occupies an intermediate position between *Lenticulina polonica* (Wiśniowski, 1890) and *L. uhligi* (Wiśniowski, 1890). Unlike *L. polonica*, this species lacks the distinct semicircular ridge around the umbilicus, and its sutures are less elevated. A comparison with forms described by Pandey and Dave (1993) and Alhussein (2014) from the Jurassic of Kutch indicates they are closely similar.

Lenticulina decipiens (Wiśniowski). – ALHUSSEIN 2014, pl. 5, fig. 3a-b, p. 74.

Subfamily MARGINULININAE Wedekind 1937

Genus *Astacolus* de Montfort 1808

Lenticulina bulla (Lalicker 1850)

Plate 4, Figures 15a-b

Robulus bulla LALICKER 1850, pl. 1, fig. 5, p. 12.

Lenticulina bulla (Lalicker). – PANDEY and DAVE 1993, pl. 3, figs. 6-9,
pl. 4, figs. 1-5, p. 127. – ALHUSSEIN 2014, pl. 4, fig. 20, pl. 5, fig. 1, p. 73

Astacolus anceps (Terquem 1870)

Plate 5, Figures 16a-b

Cristellaria anceps TERQUEM 1870, pl. 9, figs. 11-21, p. 428.

Astacolus anceps (Terquem). – ALHUSSEIN 2014, pl. 6, fig. 5, p. 77,

Remarks: This specimen exhibits a highly compressed test shape with a concave periphery and chambers characterized by distinctively transparent walls. Subbotina et al. (1960), Bhalla and Abbas (1978), Bhalla and Talib (1991), and Alhussein (2014) documented similar forms from the Jurassic deposits of Kutch. However, this specimen differs in possessing slightly depressed sutures in its later developmental stages, resembling the Iranian form described by Kalantari (1969).

Vaginulinopsis stilla (Terquem 1866)

Plate 5, Figures 17a-b

Cristellaria stilla TERQUEM 1866, pl. 22, fig. 7, p. 517.

Astacolus stilla (Terquem). – KALANTARI 1969, pl. 3, figs. 3-5a, b, p. 47

Remarks: This specimen from the D7 Unit, Middle Calovian Hisyan Member, closely resembles the original species described by Terquem (1866) and those documented by

Said and Barakat (1958) from the Bajocian of Egypt, as well as by Kalantari (1969) from the Bajocian of Iran.

Subfamily LINGULININAE Ehrenberg 1838

Genus *Lingulina* d'Orbigny 1826

Type species: *Lingulina carinata* d'Orbigny 1826.

Lingulina cf. ampliata Loeblich & Tappan 1950

Plate 5, Figures 18a-b

Lingulina ampliata Loeblich & Tappan, 1950, p. 50, pl. 13, figs. 25-26.

Remarks: The specimen is small, with parallel sides and five chambers. The sutures between the last three chambers form an inverted V. The wall features very fine costae, with at least 10 on each side. It is common in the basal section of the Atash outcrop, with seven specimens recorded. This species differs from the type specimens described by Loeblich and Tappan (1950) in having fewer chambers and a larger final chamber.

Subfamily FRONDICULARIINAE Reuss 1860

Genus *Frondicularia* Defrance 1826

Type species: *Renulina complanata* Defrance, in de Blainville, 1824

Frondicularia longiscata Terquem, 1870

Plate 5, Figure 19

Frondicularia longiscata TERQUEM, 1870, p. 216, pl. 22, fig. 23

Paralingulina longiscata (Terquem). – COPESTAKE and JOHNSON, 2014, p. 185, pl. 8, figs. 24, 29, 35.

Ichthyolaria longiscata (Terquem). – TALIB et al. 2016, p. 263, pl. 2, fig. 1.

Remarks: Eight specimens were identified in both the Atash and Hisyan Members of the D7 Unit. The test is free, elongated, compressed, and rectilinear, with striate ornamentation and five chambers. Sutures are highly arched, and the calcareous wall is well-preserved. The aperture is terminal and positioned on a small neck. It also shows some resemblance to *Frondicularia franconica* Gümbel (1862) from the Callovian of Brora, Scotland, in general test morphology; however, the D7 specimen is distinct in its test shape and chamber arrangement. While it is similar in size and shape to *Frondicularia moellari* Uhlig (1883), the absence of surface striations differentiates it from *F. moellari*.

Order LAGENIDA Lankester 1885

Suborder LAGENINA Delage and Herouard 1896

Superfamily NODOSARIACEA Ehrenberg 1838

Family NODOSARIIDAE Ehrenberg 1838

Subfamily NODOSARIACEA Ehrenberg 1838

Genus *Nodosaria* Lamarck 1812

Type species: *Nautilus radícula* Linne 1758.

Nodosaria fontinensis Terquem 1870

Plate 6, Figures 20a-b

Nodosaria fontinensis TERQUEM 1870, p. 353, pl. 26, fig. 1. – BLANK 1990, p. 114, pl. 2, fig. 27

Remarks: Frequently observed in the middle section of the studied D7 Unit, particularly within the upper part of the Atash Member. The specimens identified in this study closely resemble the illustrations presented by Blank (1990) from southern Germany.

Nodosaria riyadhensis Youssef and El-Sorogy 2015

Plate 6, Figure 21

Nodosaria riyadhensis YOUSSEF and EL-SOROGY 2015, pl. 2, fig. 2

Remarks: The test is uniserial and rectilinear, with subglobular to ovate chambers. The wall is calcareous, hyaline, and perforate,

Genus *Kurnubia* Henson 1948

Type species: *Kurnubia palastiniensis* Henson 1948

Kurnubia bramkampii Redmond 1964

Plate 6, Figure 22

Kurnubia bramkampii REDMOND 1964, p. 253, pl. 1, figs. 1-3.

Remarks: The identified specimens align with the illustrations of the types provided by Redmond (1964).

Kurnubia variabilis Redmond 1964

Plate 6, Figures 23a-b

Kurnubia variabilis REDMOND 1964, p. 254, pl. 1, figs. 9-10.

Remarks: The specimen is recorded in the top section of the Hisyan outcrop. It is characterized by a small, elongate test with a distinct rounded end.

Order SPIRILLINIDA Gorbachik and Mantsurova 1980

Suborder INVOLUTINA Hohenegger and Piller 1977

Superfamily INVOLUTINOIDEA Butschli 1980

Family INVOLUTINIDAE Butschli 1980

Subfamily AULOTORTINAE Zaninetti 1984

Genus *Andersenolina* Neagu 1994

Type species: *Andersenolina bancilai* Neagu 1994

Andersenolina alpina (Leupold 1936)

Plate 7, Figure 27

Coscinodiscus alpinus LEUPOLD 1936, p. 610, pl. 18, figs. 1-8.

Andersenolina alpina (Leupold). – AL-DHUBAIB, 2010, p. 247, pl. 1, figs. 1-13.

Remarks: This species is mainly confined to the lower and middle sections of the basal Atash outcrop (D7 Unit), and exhibit high conical test. Dubaib (2010) identified it as a common occurrence in the intermediate formation's D6 Member.

Andersenolina elongata (Leupold 1936)

Plate 7, Figure 28

Coscinococonus elongatus LEUPOLD 1936, p. 617, pl. 18, figs. 12-14.

Andersenolina elongata (Leupold). – AL-DHUBAIB 2010, p. 247, pl. 1, figs. 14-18.

Remarks: This species is common in the basal part of the overlying Hisyan outcrop (D7 Unit). Al-Dhubaib (2010) documented its frequent occurrence in the D6 Member of the Dhurma Formation.

Suborder VERNEUILININA Mikhalevich and Kaminski 2004

Superfamily VERNEUILINACEA Cushman 1911

Family PROLIXOPLECTIDAE Loeblich and Tappan 1985

Genus *Riyadhella* Redmond 1965

Type species: *Riyadhella regularis* Redmond 1965

Riyadhella regularis Redmond 1965

Plate 7, Figures 24a-b

Riyadhella regularis REDMOND 1965. p. 138, pl. 1, figs. 32-34. – BANNER et al. 1991, p. 131, figs. 57–63 (with synonymy). – AL-DHUBAIB 2010, p. 247, pl. 1, figs. 1-13.

Remarks: This species is abundant in the Atash outcrop within the studied D7 Unit. A revised description of the species was provided by Banner et al. (1991), and this study adopts the proposed classification framework. The genus *Riyadhella* has also been reported from the Bajocian to Bathonian intervals in Siberia (Azbel et al., 1991). However, the wall structure of the Siberian specimens is noncalcareous, indicating that they should be classified under a different genus.

Suborder ORBITOLININA Kaminski 2004

Superfamily PFENDERINOIDEA Smout and Smugden 1962

Family PFENDERINIDAE Smout and Smugden 1962

Subfamily PSEUDOPFENDERININAE Septfontaine 1988

Genus *Siphovalvulina* Septfontaine 1988

Type species: *Siphovalvulina variabilis* Septfontaine 1988.

Siphovalvulina colomi BouDagher-Fadel, Rose, Bosence and Lord, 2001

Plate 7, Figures 25a-b

Siphovalvulina colomi BOUDAGHER-FADEL, ROSE, BOSENCE and LORD, 2001, p. 504, pl. 1, figs. 1-4.

Remarks: The test is elongate, transitioning from an initial trochospiral arrangement to triserial and then biserial, with up to five whorls of oviform chambers. The chambers rapidly enlarge and increase in height as they are added. Sutures are depressed, and the

aperture is basal, featuring a twisted siphonal canal connecting successive apertures (Septfontaine, 1988). It is primarily observed in marl samples from the middle section of the Atash outcrop and the basal part of the overlying Hisyan Member. It differs from *Siphovalvulina gibraltarensis* in being more elongated and less flaring in shape.

Siphovalvulina gibraltarensis BouDagher-Fadel, Rose, Bosence and Lord, 2001

Plate 7, Figures 26a-b

Siphovalvulina gibraltarensis BOUDAGHER-FADEL, ROSE, BOSENCE and LORD
2001, p. 65, pl. 1, fig. 6-11.

Eggerellina sp. COLOM, 1980, fig. 4, 64, 66, 75, 76.

Remarks: The test is widely flaring and lobulate in outline, trochospirally coiled with up to four whorls of chambers that rapidly enlarge. Each whorl consists of three chambers, and the sutures are depressed. The wall is agglutinated, imperforate, and microgranular, consistent with the description by Septfontaine (1988), who reported it as calcareous and microgranular. The aperture is basal and features a twisted siphonal canal connecting successive apertures.

Suborder TEXTULARIINA Delage and Herouard 1896

Superfamily CHRYSALIDINACEA Neagu 1968

Family PARAVALVULINIDAE Banner, Simmons and Whittaker 1991

Subfamily PARAVALVULININAE Banner, Simmons and Whittaker 1991

Genus *Pseudomarssonella* Redmond 1965

Type species: *Pseudomarssonella maxima* Redmond 1965

Pseudomarssonella reflexa Redmond 1965

Plate 8, Figures 29a-b

Pseudomarssonella reflexa REDMOND 1965, p. 136, pl. 1, fig. 19.

Remarks: This species is most common in the Atash Member of the studied D7 Unit. The test is elongate and conical, with broad sides diverging at a uniform rate. The initial portion forms a narrow cone composed of small, flat chambers that gradually increase in size. Chambers in the final whorl are slightly inflated, and the aperture is interiomarginal but indistinct. The wall is finely agglutinated. Redmond (1965) also reported this species as common in the middle part of the Middle Dhurma Formation in Saudi Arabia.

Family LITUOLIDAE de Blainville 1827

Subfamily AMMOMARGINULININAE Podobina 1978

Genus *Ammobaculites* Cushman 1910

Ammobaculites areniferus Nagy and Basov 1998

Plate 8, Figures 30a-b

Ammobaculites areniferus NAGY and BASOV 1998, pl. 3, figs. 7-18, p. 236. – BHAT 2016, pl. 5.14, fig. 9

Remarks: The specimen recorded from the Middle Callovian Dhurma Formation closely resembles *Ammobaculites areniferus* described by Nagy and Basov (1998) from the Kimmeridgian deposits of Spitsbergen. Nagy et al. (1990) highlighted the affinity of this species with *Reophax hounstoutensis*, originally described by Lloyd (1959) from the Kimmeridgian of Dorset. Both species share similarities in test outline, densely arranged chambers, and coarse wall texture. *A. areniferus* differs in having a pyriform final chamber with an aperture positioned on a distinct neck (Nagy and Basov, 1998). Subsequent

observations also revealed the presence of a small initial coil, supporting its assignment to the genus *Ammobaculites* (Nagy and Basov, 1998).

Ammobaculites coprolithiformis (Schwager 1867)

Plate 8, Figures 31a-b

Haplophragmium coprolithiforme SCHWAGER 1867, p. 654, pl. 34, fig. 3.

Ammobaculites coprolithiformis (Schwager). – SUBBOTINA, DUTTA

and SRIVASTAVA 1960, pl. 1, fig. 1a-b, p. 12. – ALHUSSEIN 2014, p. 62, pl. 1, fig.

10. – BHAT 2016, pl. 5.14, fig. 10

Remarks: The specimens of *Ammobaculites coprolithiformis* identified in the Hisyan Member of the Upper Dhurma Formation closely resemble those described by Schwager (1867) from the Bajocian of Württemberg. They also align with forms recorded by Gordon (1962, 1965, 1967) from the Upper Jurassic of England and Scotland. They are observed to be comparable to specimens reported by Subbotina et al. (1960), Bhalla and Talib (1991), and Alhussein (2014) from Kutch, as well as those from the Callovian Fakirwari Dome, India (Bhat et al., 2016). This species has been documented across the Lower, Middle, and Upper Jurassic globally, with abundant occurrences in the Oxfordian.

Suborder LITUOLINA Lankester 1885

Superfamily RECURVOIDOIDEA Alekseychik-Mitskevich 1973

Family AMMOBACULINIDAE Saidova 1975

Subfamily HAPLOPHRAGMIINAE Maync 1952

Genus *BULBOBACULITES* Maync 1952

***Bulbobaculites* n.sp.**

Plate 8, Figures 32-33, Plate 9, Figures 34-35

Remarks: *Bulbobaculites* n.sp. is characterized by its coarsely agglutinated wall, streptospiral coiling, and a distinct bulbous initial chamber. The species also exhibits an elongated test that may be slightly curved, with progressively enlarging chambers and a relatively large overall size, distinguishing it from other species within the genus.

Suborder VERNEUILININA Kaminski, 2004

Superfamily VERNEUILINOIDEA Cushman 1911

Family PROLIXOPLECTIDAE Loeblich and Tappan 1985

Genus *Gerochammina* Neagu, 1990

***Gerochammina* n.sp.**

Plate 9, Figures 36-37, Plate 10, Figures 38-40

Remarks: This form closely resembles *Gerochammina lenis* (Grzybowski) but differs by having an initial quadriserial and triserial stage with well-aligned chambers, rather than a trochospiral stage with four to five chambers, followed by a high trochospiral portion that becomes biserial. It also differs from *Karrerulina coniformis* (Grzybowski) by possessing a basal to areal aperture and a longer trochospiral portion. It has an initial triserial portion that is not triangular in cross-section.

Suborder MILIOLINA Delage & Herouard 1896

Order GLOBIGERINIDA Lankester 1885

Suborder GLOBIGERININA Delage and Hérouard 1896

Superfamily FAVUSELLOIDEA Longoria 1974, emend. Banner and Desai 1988

Family CONOglobigerinidae Simmons, Boudagher Fadel, Banner and Whittaker
1997

Genus *Globuligerina* Bignot and Guyader 1971, emend. Banner and Desai 1988

***Globuligerina* sp.**

Plate 11, Figures 41-42

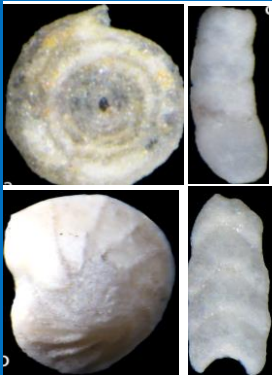
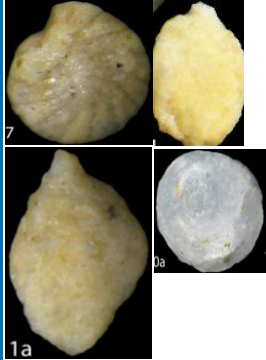
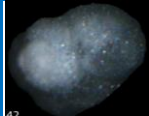
Globuligerina sp. KAMINSKI et al. 2018b, pl. 1, figs. 1a–4c; pl. 2, fig. 3.

Remarks: This appears to be the same species that was described from the Dhurma D5 Unit by Kaminski et al. (2018b). In this study it was only observed in two samples.

5.2.1 Classification and Systematic Framework of Foraminifera

The thirty-three analyzed foraminiferal species from the upper Dhurma Formation are classified into 21 genera. These are grouped into four categories based on their test composition and morphological characteristics (Table 4). This classification is critical for enhancing a detailed discussion on the taxonomic framework and its systematic implications in relation to biostratigraphy and depositional settings within the Middle Jurassic Dhurma Formation (Figure 22). A similar approach has been employed by Ansari et al. (2021) to interpret the depositional setting of the Middle to Late Jurassic at the Jhurio Dome, Kutch, Gujarat, India.

Table 3: Classification of identified foraminifera genera by test composition and morphological types. Group D-is a free-floating; thin, perforate test; indicative of open marine settings.

Group	Test Composition	Genera	E.g./Illustration
A	Hyaline Forms	<i>Spirillina</i> <i>Lingulina</i> <i>Lenticulina</i> <i>Nodosaria</i> <i>Frondicularia</i> <i>Andersonella</i> <i>Paleomarsonella</i> <i>Vaginulinopsis</i> <i>Astacolus</i>	
B	Porcelaneous calcareous	<i>Nautiloculina</i> <i>Riyadhella</i> <i>Kurnubia</i> <i>Trocholina</i> <i>Quinqueloculina</i> <i>Spiroloculina</i> <i>Milolinella</i>	
C	Agglutinated forms	<i>Ammobaculites</i> <i>Siphovalvulina</i> <i>Bulbobaculites</i> <i>Gerochammina</i>	
D	Planktic forms	<i>Globuligerina</i>	

5.3 Discussion

5.3.1 Taxonomic Framework and Systematic Implications

This study enhances the taxonomic framework of the Upper Dhurma Formation by documenting thirty-three foraminiferal species from nineteen genera (Table 4), indicating a complex depositional setting. The abundance of calcareous genera including *Nodosaria*, *Lenticulina*, *Frondicularia*, *Spirillina*, *Quinqueloculina*, *Trocholina*, *Spiroloculina*, and the deep-water taxa *Bulbobaculites* n.sp. and *Gerochammina* n.sp., as well as the planktic form (*Globuligerina*), highlights a complex range of paleoenvironmental conditions from shallow to open marine settings. *Gerochammina* was first described from the deep-water Carpathian flysch deposits (Neagu, 1990), and is associated with organic influx in inner shelf to upper bathyal environments (Setoyama et al., 2013), while species of *Bulbobaculites* have been reported from deep-water settings, including flysch-type shale deposits (Holbourn and Kaminski, 1995; Waśkowska, 2014). The occurrence of these taxa across the entire stratigraphic section, dominated by rhythmic deposits of limestone and marl (Figure 24), indicates periodic environmental fluctuations and organic-rich influxes within the Arabian epicontinental shelf.

The taxonomic analysis of foraminifera revealed new data, expanding the taxonomic record with essential deep-water indicators; complementing the established dominance of shallow-water benthic species (Kaminski et al., 2018a). This advancement refines the taxonomic framework of endemic Jurassic species and enhances the interpretation of high-resolution sequence stratigraphy in the region.

5.3.2 Biostratigraphy and Taxonomic Significance

The biostratigraphic utility of the identified foraminiferal assemblages lies in their potential to improve sequence stratigraphic correlations within the Middle Jurassic of the region. The presence of *Globuligerina* sp., in the Middle Callovian D7 Unit serves as a critical biostratigraphic marker for recognizing the J40 Maximum Flooding Surface (MFS) of Sharland et al. (2001) in central Saudi Arabia. It contributed to the recognition of the J30 Maximum Flooding Surface (MFS) of Sharland et al. (2001) in the region (Kaminski et al. 2018b).

The abundant occurrence of calcareous (*Frondicularia*, *Lenticulina*, *Nodosaria*) and agglutinated genera (*Siphovulvulina*, *Ammobaculites*, *Bulbobaculites*, *Gerochammina*) in the middle stratigraphic section of the D7 Unit, corresponding to the upper Atash Member and basal Hisyan Member, provides valuable indicators of peak transgression and deeper marine conditions. These observations further support the recognition of the maximum flooding surfaces (MFS) within the Middle Jurassic of Central Saudi Arabia based on their micropaleontological content.

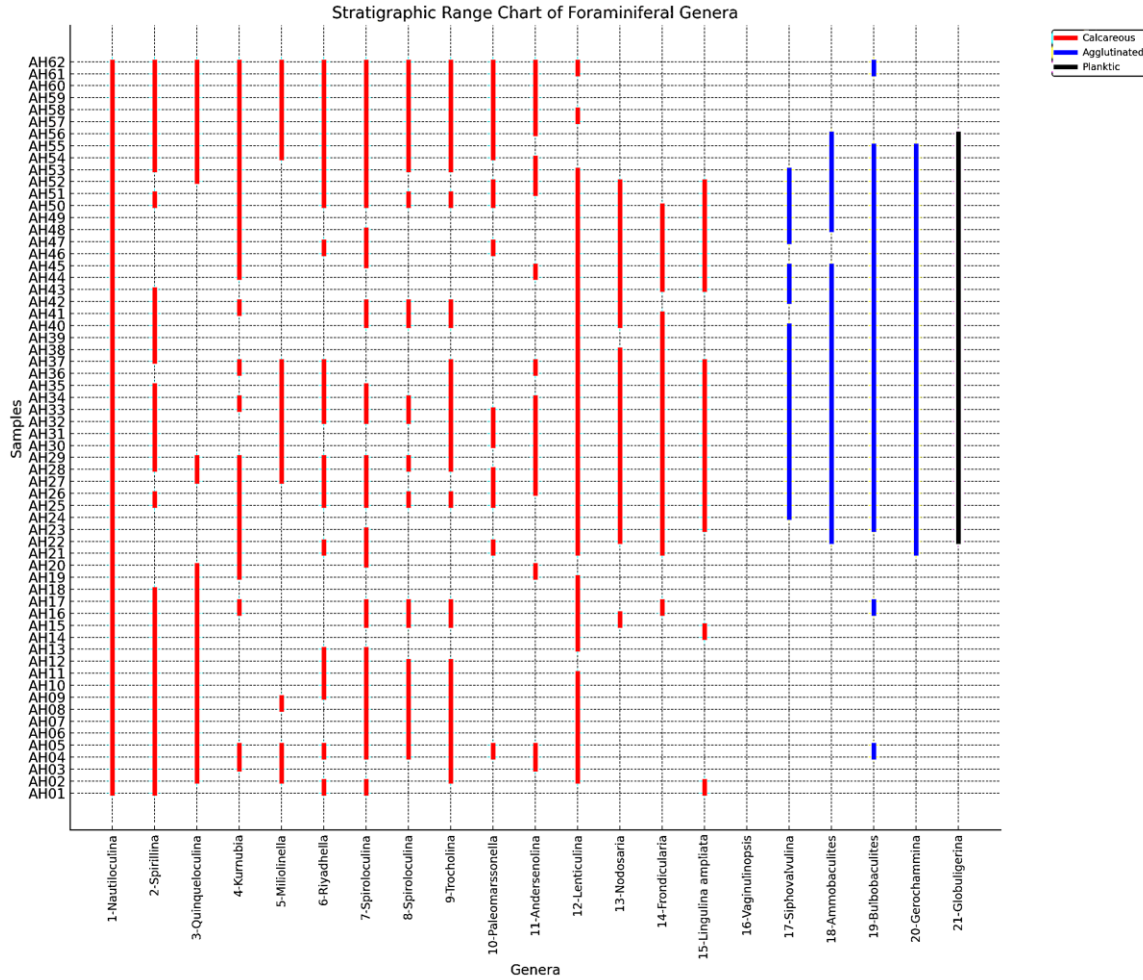


Figure 22: D7 unit stratigraphic ranges of foraminifera genera identified based on test composition.

CONCLUSION

The application of the acetic acid disaggregation method revealed previously unreported species, *Bulbobaculites* n.sp. and *Gerochammina* n.sp., from indurated carbonate and marl lithologies in the upper Dhurma Formation (Middle Jurassic). Although this study does not define biozones, the newly provided foraminiferal dataset has the potential to refine existing biozones, particularly those defined by Hughes (2018) and Al-Dhubaib (2010) for the Middle Jurassic Dhurma Formation, which were primarily based on thin-section analyses of outcrops.

The taxonomy and systematic analysis presented in this study provide a high-resolution framework for understanding the biodiversity and ecological dynamics of the D7 Unit. Morphogroup analysis undertaken in this study has the potential for identifying maximum flooding surfaces, and is therefore a powerful tool for understanding the regional sequence stratigraphy. The implications of this research extend beyond academia, offering valuable insights for the hydrocarbon industry and contributing to the global understanding of Jurassic epicontinental shelf environments.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

This chapter summarizes the key findings of the study, highlighting its contributions to the taxonomy, biostratigraphy, sequence stratigraphy, and paleobathymetry of the Middle Jurassic Dhurma Formation. The significance of these findings is discussed, and recommendations are provided to guide future research. The conclusions and recommendations highlight the broader implications of this study for geoscientific and environmental studies in the region.

6.2 Conclusion

The foraminiferal study of the upper Dhurma Formation, Middle Jurassic, Central Saudi Arabia revealed critical insights into taxonomy, biostratigraphy, sequence stratigraphy, and paleobathymetry, offering significant scientific and industrial contributions. A detailed analysis of the composition and morphogroup distributions of the 33 identified species delineated a complete transgressive-regressive (T-R) cycle within the D7 Unit, revealing a transition from shallow lagoonal environments to deeper intra-shelf basin settings during peak transgression, followed by a return to restricted marine conditions in the regressive phase.

The applied acetic acid disaggregation method improves upon traditional thin-section techniques by revealing previously undocumented deep-water taxa (*Bulbobaculites* n.sp. and *Gerochammina* n.sp.) and enabling three-dimensional analysis of foraminiferal assemblages. This is essential for interpreting paleoecological and paleoenvironmental conditions, reconstructing depositional sequences, and advancing high-resolution sequence stratigraphy in the region.

This study strongly aligns with the UN “SDG 13” (Climate Action), as it provides historical context for understanding modern climate dynamics and sea-level variations. It also supports goal “15” (Life on Land) by contributing valuable data for the preservation and interpretation of fossil biodiversity, including both physical fossil specimens and the scientific knowledge associated with them, thereby advancing efforts in ecological conservation and sustainable resource management. This is critical to fostering sustainable practices in managing natural and geological heritage in Saudi Arabia.

6.3 Recommendations

Further research is critical for foraminiferal studies, particularly in underexplored surface outcrops and stratigraphic intervals such as the D3, D4, and the type locality of the Dhurma Formation. Such research can refine the understanding of paleoecological and paleoenvironmental conditions, essential for high-resolution sequence stratigraphy. Detailed micropaleontological investigations of the formation’s siliciclastic deposits in northern central Arabia hold the potential to provide new data for enhancing correlations with Dhurma reservoir-equivalent outcrops in southern central Arabia and refining the

Middle Jurassic paleogeographic map. Previous studies only relied on sedimentological and stratigraphic techniques (Al-Hussaini et al., 2019).

The integration of micropaleontological, sedimentological, and high-resolution sequence stratigraphy studies, incorporating surface and subsurface outcrop data, is crucial for evaluating the proposed genetic relationship between the D7 Unit (Atash and Hisyan Members) and the lower Tuwaiq Mountain Formation (Hughes, 2004, 2006, 2018). Such interdisciplinary could refine lithological interpretations and enhance the understanding of their stratigraphic continuity.

The development of a comprehensive digital repository for taxonomic, stratigraphic, and paleoenvironmental data for the Jurassic formations of Saudi Arabia is strongly recommended. Such a resource would streamline data accessibility, promote interdisciplinary research, and drive further advancements in geosciences in the region.

Addressing these recommendations will allow future research to build upon this study's foundation, enhance our understanding of Middle Jurassic ecosystems, advance industrial applications, and contribute to environmental conservation in Saudi Arabia.

APPENDIX

Plate 1

Scale bar = 100 μm

1a-b: *Miliolinella circularis*

2a-b: *Spiroloculina aperta*

3a-b: *Spiroloculina clara*

4: *Quinqueloculina tropicalis*

5: *Quinqueloculina costata*

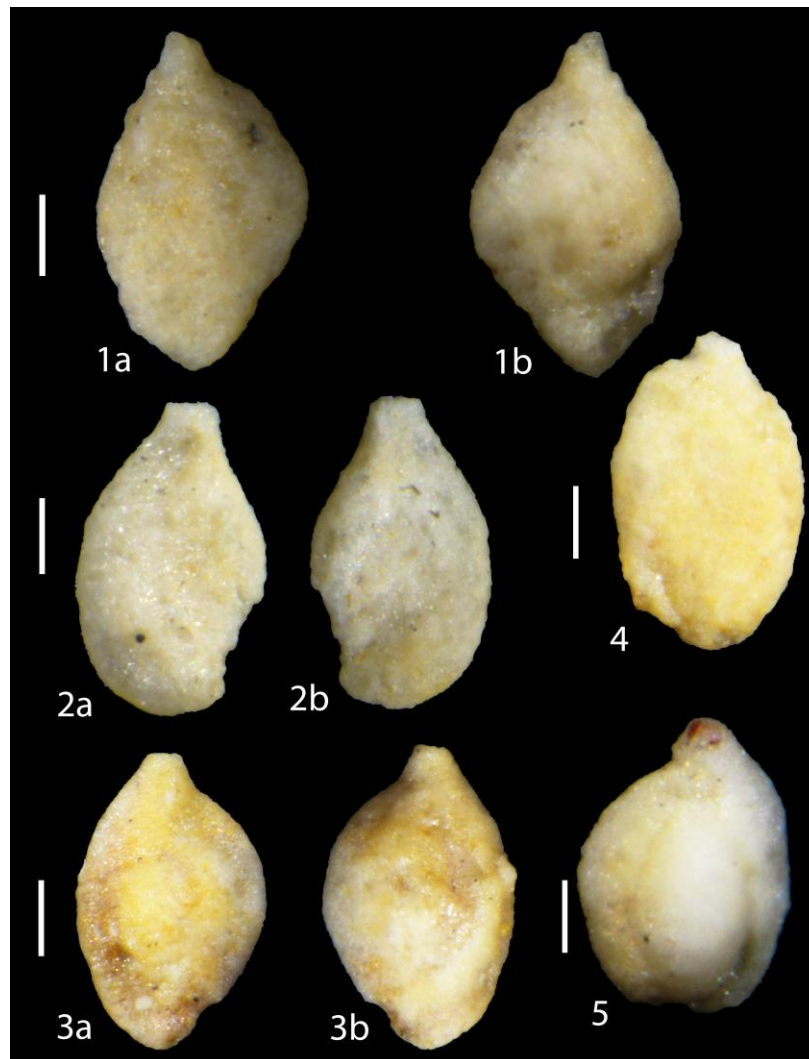


Plate 2

Scale bar = 100 μ m

6: *Nautiloculina oolithica*

7: *Nautiloculina circularis*

8a-b: *Spirillina involuta*

9a-b: *Spirillina polygyrata*

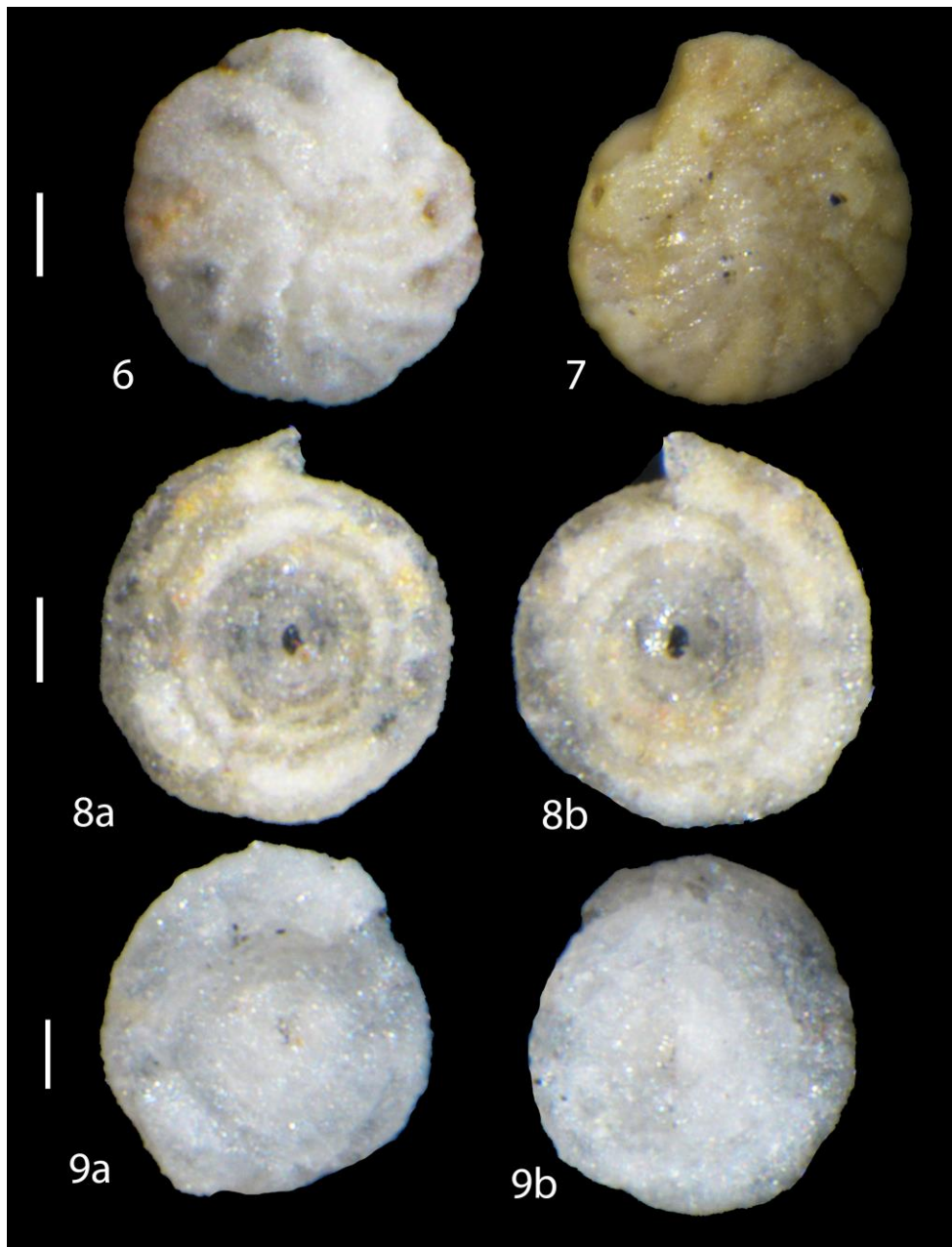


Plate 3

Scale bar = 100µm

10a-b: *Trocholina transversarii*

11a-b: *Lenticulina audax*

12a-b: *Lenticulina papillaecostata*

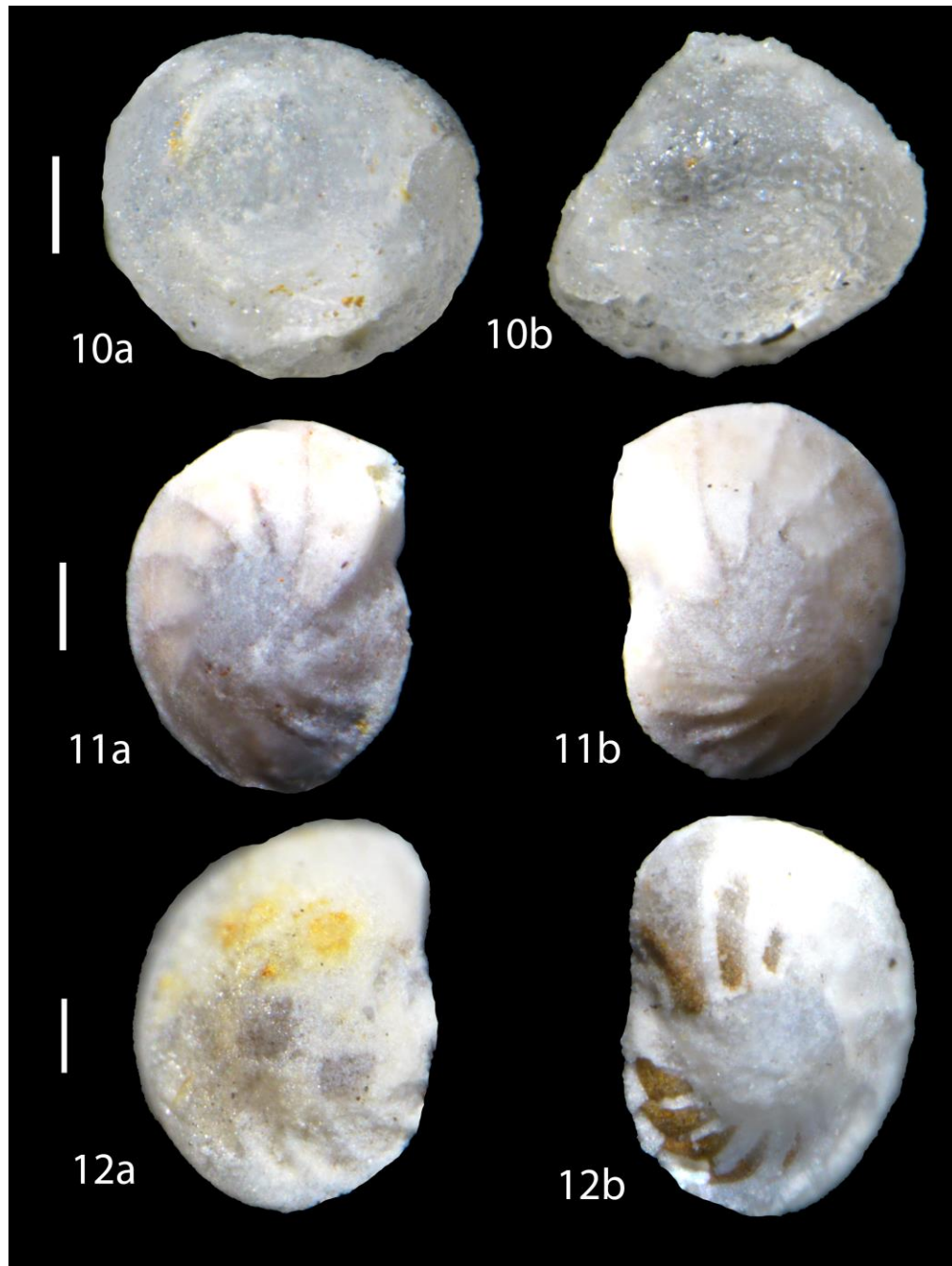


Plate 4

Scale bar = 100 μ m

13a-b: *Lenticulina vetusta*

14a-b: *Lenticulina decipiens*

15a-b: *Lenticulina bulla*

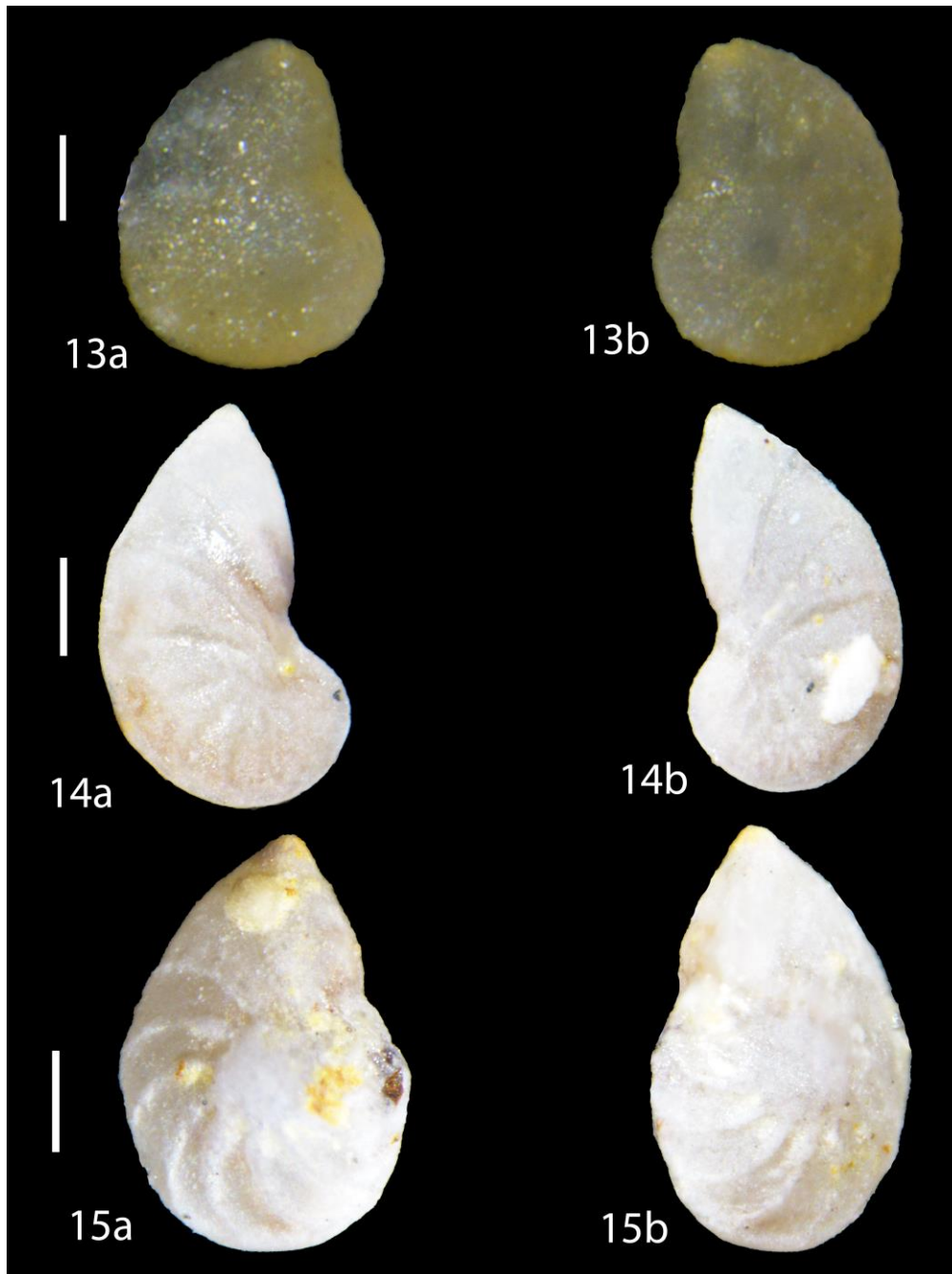


Plate 5

Scale bar = 100 μ m

16a-b: *Astacolus anceps*

17a-b: *Vaginulinopsis stilla*

18a-b: *Lingulina ampliata*

19: *Frondicularia longiscata*

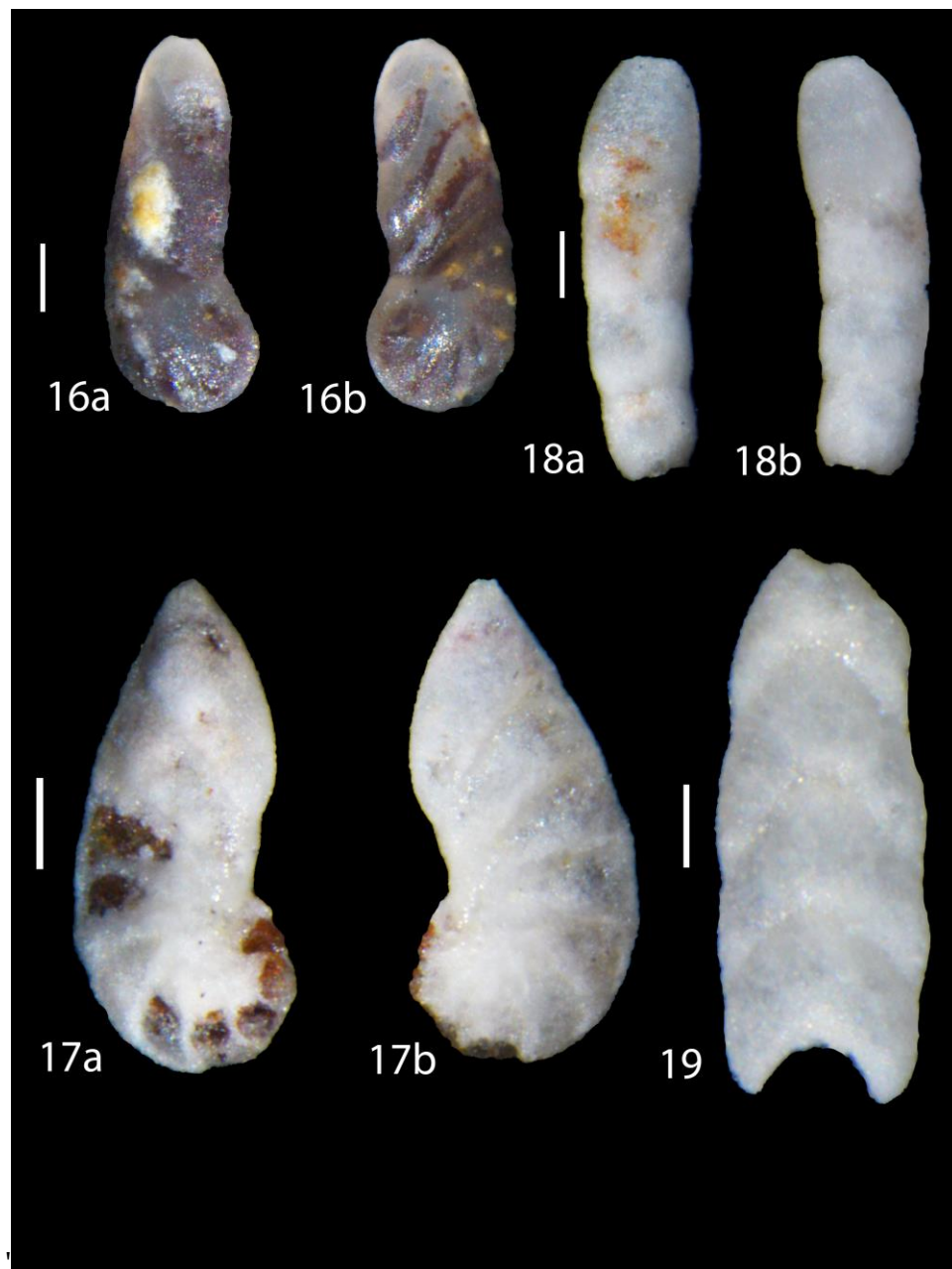


Plate 6

Scale bar = 100 μ m

20a-b: *Nodosaria fontinensis*

21: *Nodosaria riyadhensis*

22: *Kurnubia bramkampi*

23a-b: *Kurnubia variabilis*

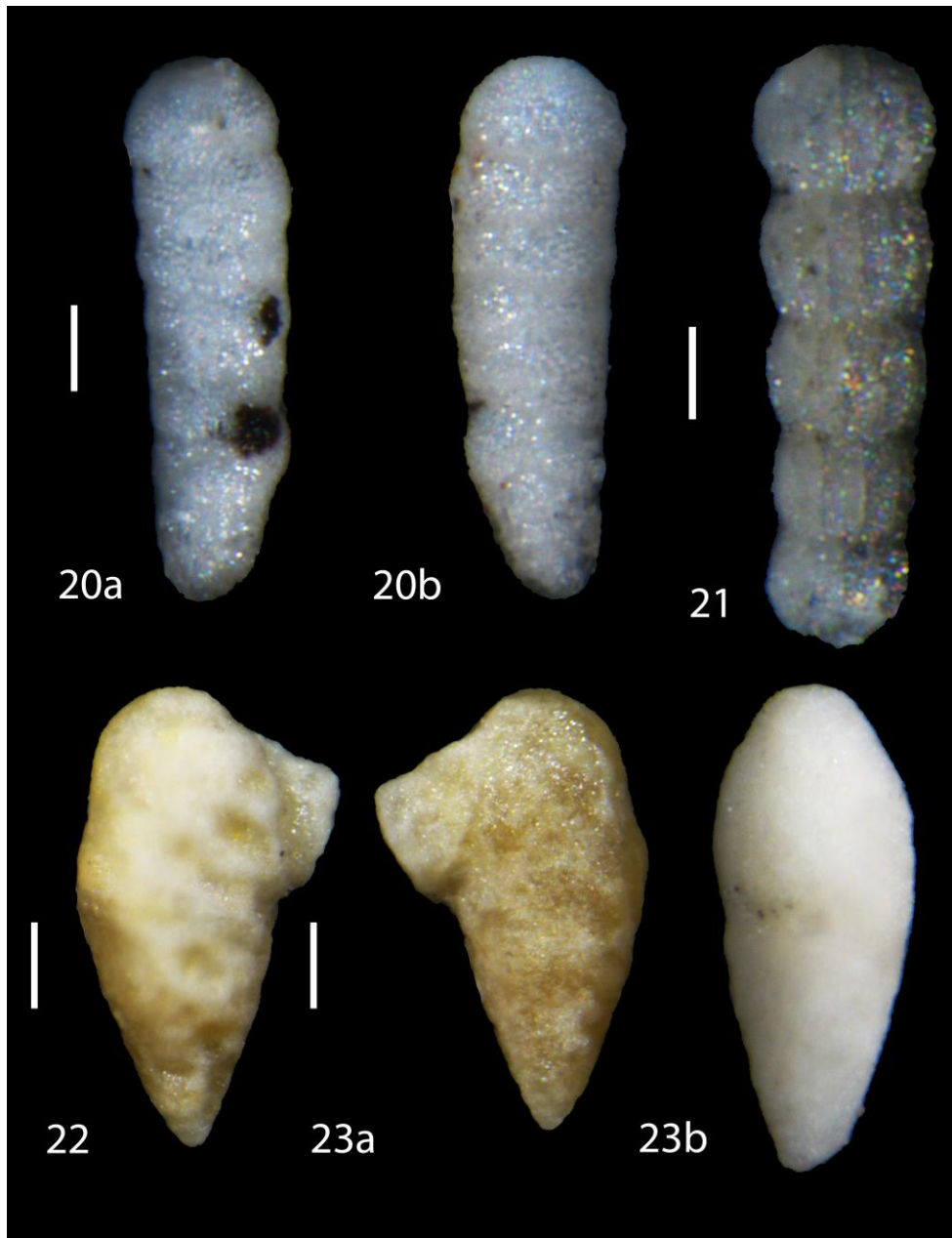


Plate 7

Scale bar = 100 μ m

24a-b: *Riyadhella regularis*

25a-b *Siphovalvulina gibraltarensis*

25a-b: *Siphovalvulina colomi*

27: *Andersenolina alpina*

28: *Andersenolina elongata*

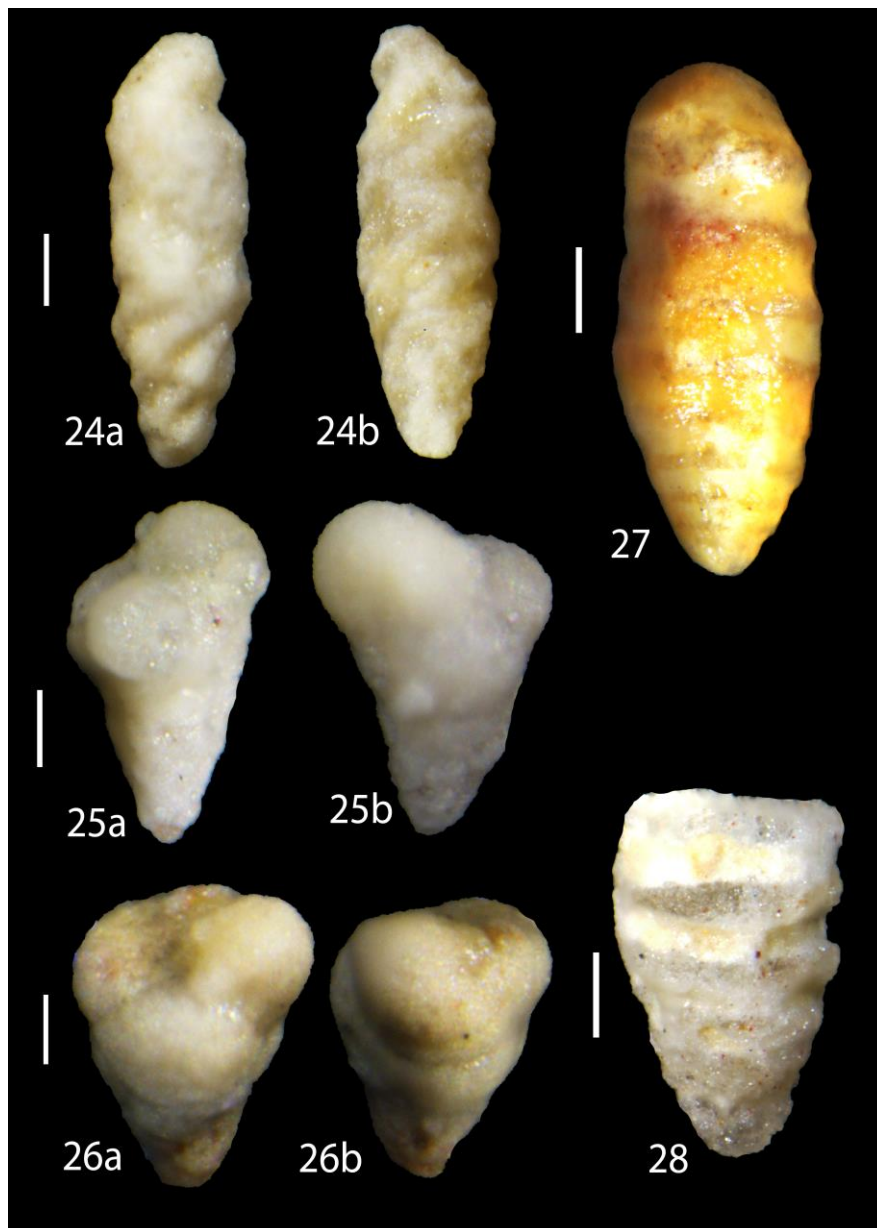


Plate 8

Scale bar = 100 μ m

29a-b: *Paleomarssonella reflexa*

30a-b *Ammobaculites areniferus*

31a-b: *Ammobaculites torosus*

32-33: *Bulbobaculites* n. sp

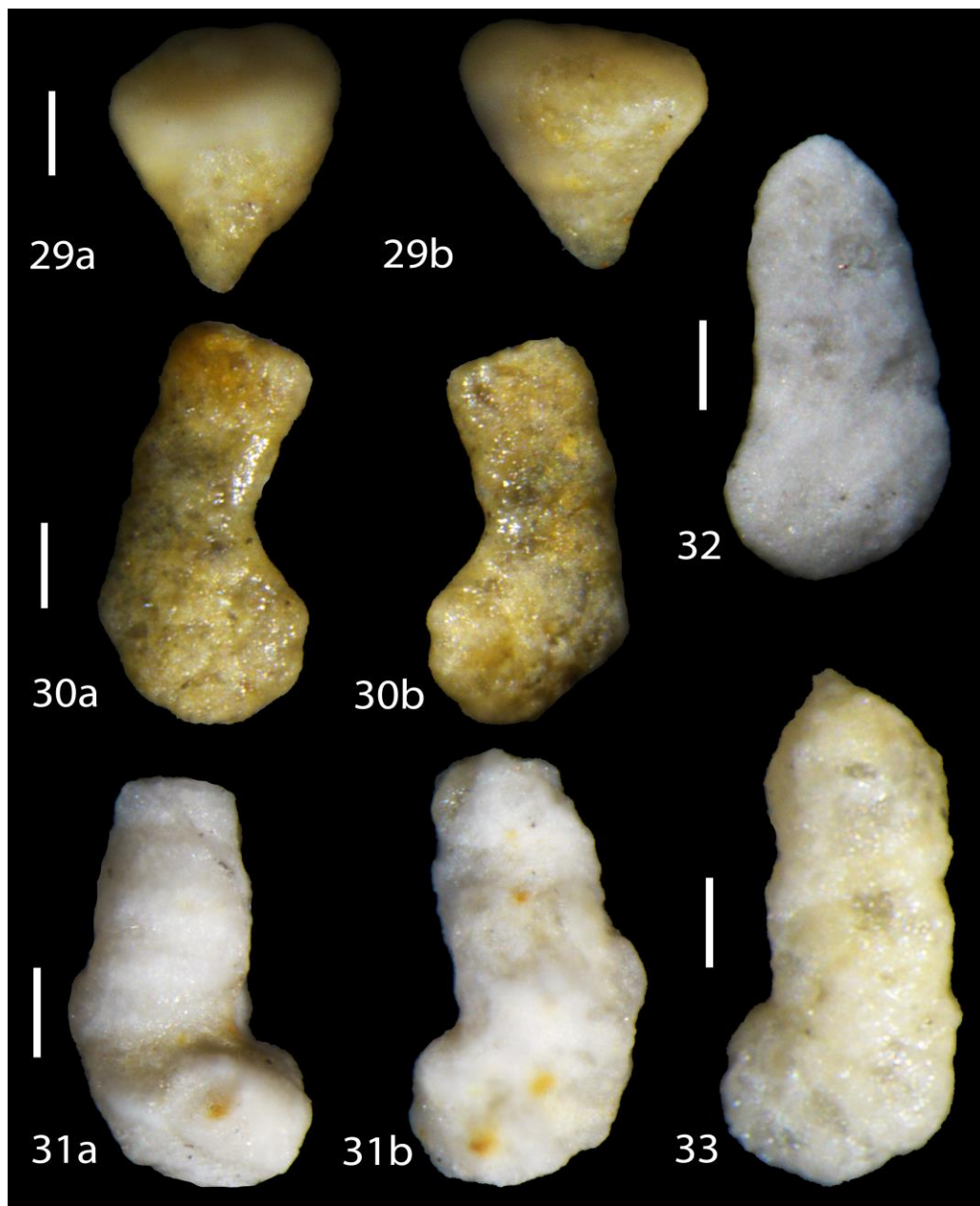


Plate 9

Scale bar = 100 μ m

34-35: *Bulbobaculites* n. sp.

36-37 *Gerochammina* n.sp.

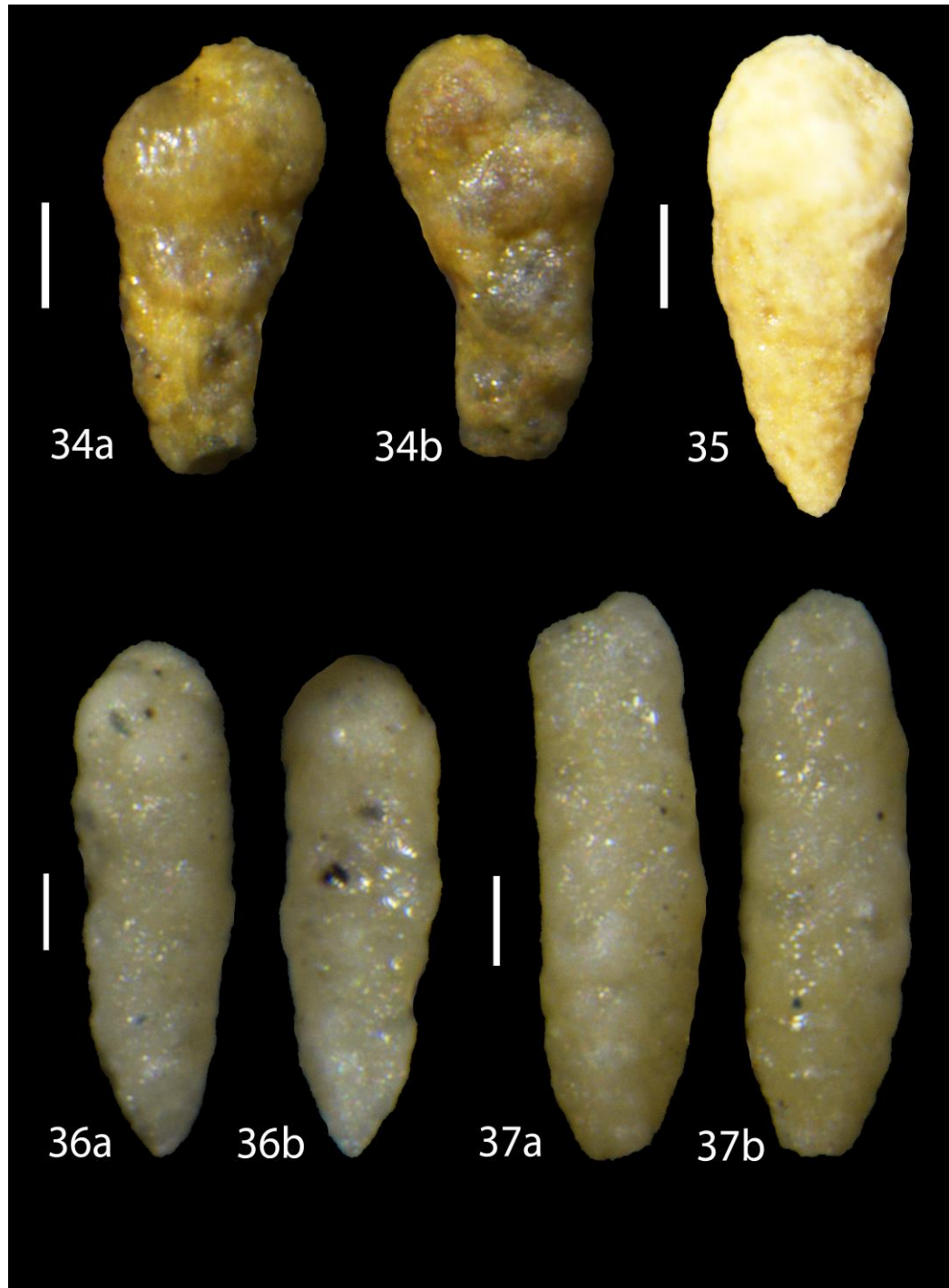


Plate 10

Scale bar = 100 μ m

38-40 *Gerochammina* n.sp.

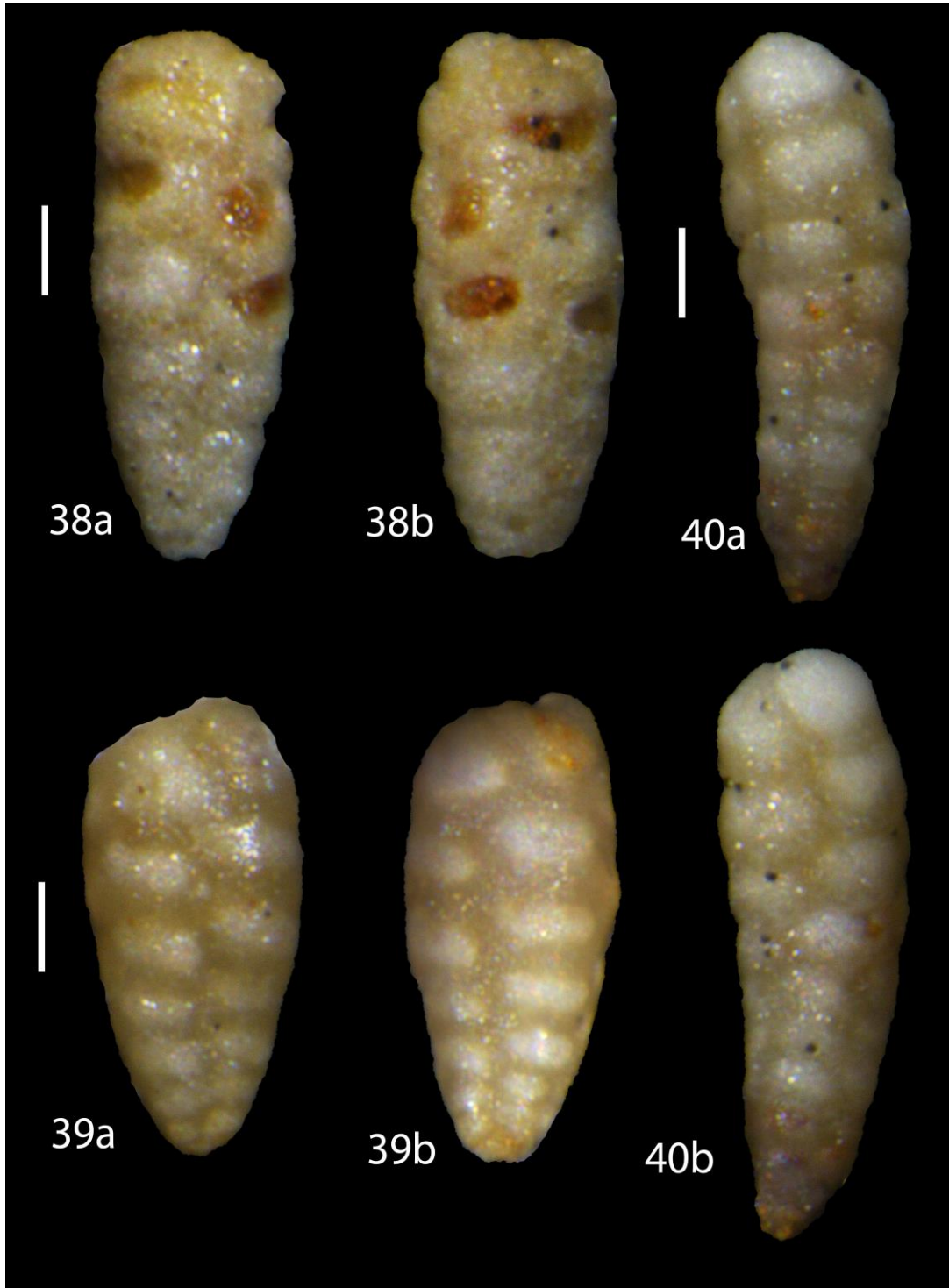
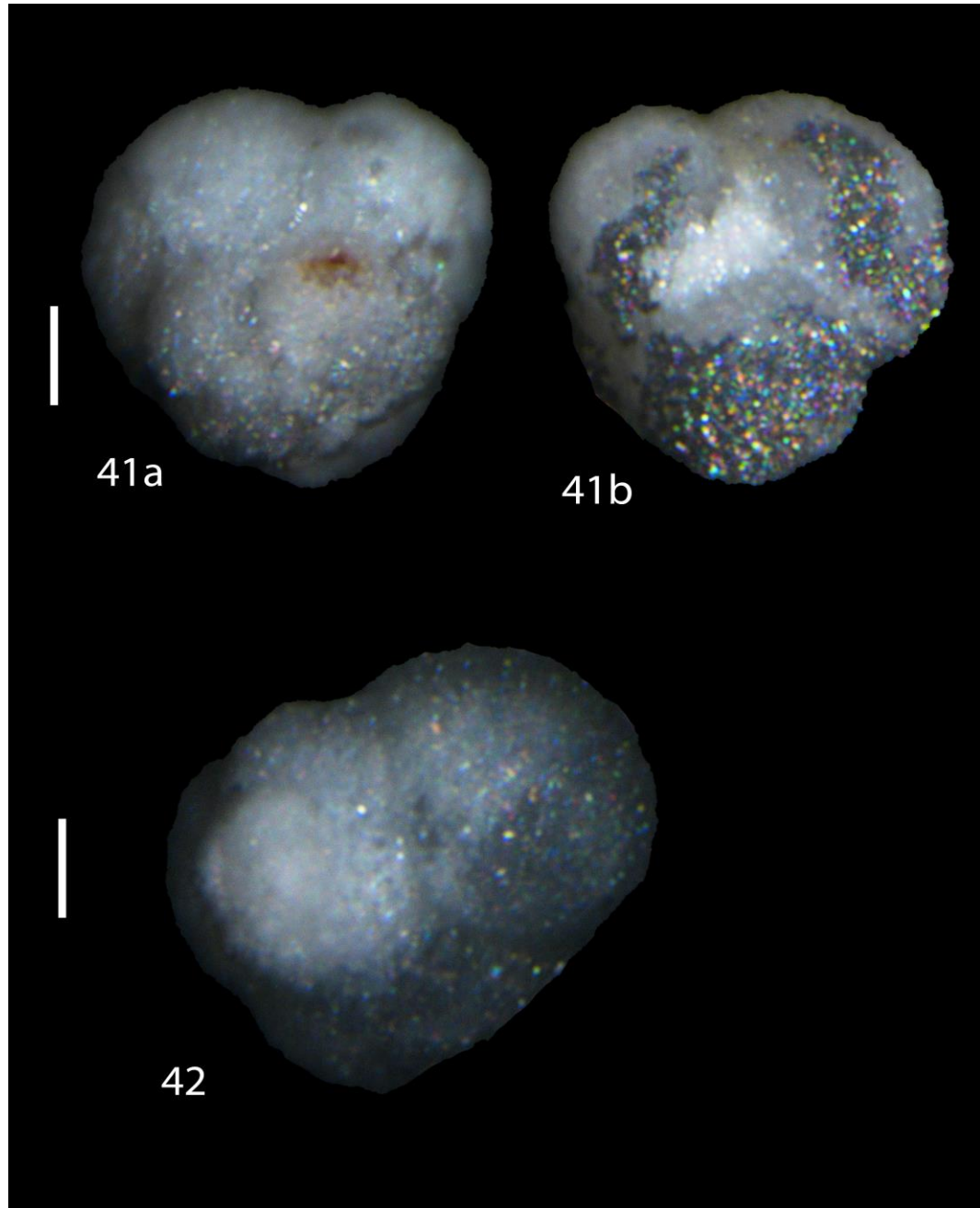


Plate 11

Scale bar = 100 μm

41- 42: *Globuligerina* sp.



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ABSTRACT/PUBLICATION:

1. Decadal Trends in Foraminiferology (Kaminski et al. 2023) – Contribution, methodology/sample preparation, Grzybowski Foundation Special Publication No. 27, 42 43-published, 2023.
2. Lion Mountain Landslide in Non-urbanized Terrain: Changing the Myth of Landslide Occurrence in Western Sierra Leone (Yusuf A. Lahai, Dauda Kamara & Chernoh Jalloh, 2020)-Contribution: field sample collection, preparation and analysis. Energy and Earth Science Vol. 3, No. 2, 2020
www.scholink.org/ojs/index.php/ees ISSN 2578-1359 (Print) ISSN 2578-1367.
3. *Bulbobaculites attashensis* n.sp., a new agglutinated foraminifera from the Middle Jurassic D7 Attash Member of the Dhurma Formation, Central Saudi Arabia. (Jalloh et al., 2024) - ASGP Journal (**under review**).

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