

**Sedimentology, Stratigraphy, and Reservoir
Characterization of the Upper Jurassic Hanifa
Formation, Central Saudi Arabia**

BY

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A Dissertation Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

In

Geology

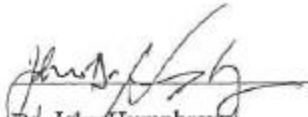
May, 2022

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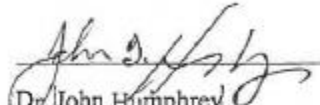

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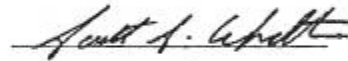

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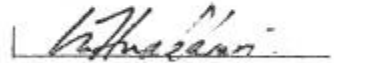
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2022

[To Gaddora, Ammona, and the rest of the gange]

ACKNOWLEDGMENTS

I'd want to thank the CPG and KFUPM for allowing me to complete my doctoral studies. Throughout writing my dissertation, I've had a lot of help and encouragement. Thanks to Dr. Abdulaziz Al-Kaabi, the Dean of CPG, and Dr. Abdullatif Al-Shuhail, the previous head of Geosciences, for facilitating and sponsoring this study.

It is undoubtedly because of the guidance, encouragement, and support I received during my doctoral studies from Professor Michael Kaminski and his colleagues, Drs. Osman Abdullatif, Scott Wattam, and Mohammad Makkawi, I am writing this letter to express my deepest gratitude. It's appropriate to congratulate Dr. John Humphrey for his work as the department's elegant, professional chairman and his contribution as a thesis committee member. Because of Prof. Rudy Swennen's generosity of knowledge and wealth of experience, I consider myself tremendously fortunate to have worked with him throughout my academic study.

My research would not have been possible without the help of Moaz Salih and Jarrah Babiker. All gratitudes are extended to Dr. Dave Cantrel and Dr. Bob Lindsay for motivation and guidance in research ideas. Prof. Omer Elbadri, Dr. Ammar Adam, Dr. Hassan Eltom, Dr. Mohammed Yassin, Omar Radwan, Ammar Abdulmutalib, Abdallah Abdelkarim, and Mutasim Osman are thanked for their field and laboratory help.

Special thanks go to the Geoscience Department, Laboratory Technical Support & Services Department, and Center for Integrative Petroleum Research workers for assisting with sample preparation and data collection. Mr. Mushabbab Al Raqdi, Mr. Bandar Al-Otaibi, Mr. Eassa Abdullah, Mr. Elias Arif, Mr. Ahmed Al-Bahrani, Mr. Jeffrey Aquino, and Mr.

Alberto E. Lundang, in particular. You gave me the resources I needed to make the proper decision and finish my dissertation effectively.

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ABSTRACT

Full Name : [Mazin Abdelgadir Abdelrazig Bashri]
Thesis Title : [Sedimentology, Stratigraphy, and Reservoir Characterization of the Upper Jurassic Hanifa Formation, Central Saudi Arabia]
Major Field : [Geology]
Date of Degree : [May, 2022]

High-resolution (centimeter-scale) description and analysis of eight outcrop sections through the Oxfordian Hanifa Formation along a 535 km-long N-S transect in central Saudi Arabia are used to develop a comprehensive conceptual depositional model through time. The cumulative vertical thickness of the studied sections reaches 461 m. Nine sedimentary lithofacies are interpreted, which are grouped into four facies associations, i.e., I) outer-ramp association (FA1), II) mid-ramp association (FA2), III) inner-ramp grainy-facies association (FA3), and VI) inner-ramp reefal association (FA4). The outer-ramp association includes argillaceous carbonate mudstone (F1). The mid-ramp association includes intraclast rudstone (F2), skeletal sponge spiculitic wackestone/packstone (F3), and horizontally-laminated siltstone/claystone (F4). The grainy facies of the inner-ramp association includes cross-bedded skeletal quartz peloidal grainstone (F5) and trough cross-bedded calcareous sandstone (F6). In contrast, the inner-ramp reefal association includes reef-crest stromatoporoid/coral framestone (F7), gravel-dominated fore-reef floatstone (F8), and open back-reef oncoidal rudstone (F9). The lithofacies succession distinguishes two depositional phases, i.e., Phase 1 and Phase 2, corresponding lithostratigraphically to the middle Oxfordian Hawtah and late Oxfordian Ulayyah Members. Phase 1 represents deposition on a homoclinal carbonate ramp, whereas Phase

2 witnessed the transition from a grain-dominated carbonate ramp to a reef-bearing one, as indicated by reefal association (FA4). Hanifa Formation carbonate ramp evolution reflects coral reef expansion over the southern Neo-Tethys passive margin in the late Oxfordian. In the southern section of the studied transect, siliciclastic deposits are described for the first time from the Hanifa Formation (F4 and F6).

Sequence stratigraphy is considered one of the most powerful hydrocarbon exploration and development tools. Due to its muddy nature, a continuous motif characterizes the well logs of the Jurassic succession in general and the Oxfordian Hanifa Formation. This continuous pattern makes it difficult to identify and correlate stratigraphic units of different orders, especially in the absence of biostratigraphic data. A high-resolution sequence and chemostratigraphic framework are presented for the Oxfordian Hanifa Formation outcrops in central Saudi Arabia. A total of sixteen fourth-order sequences (seq 1 - seq 16) were interpreted using sequence stratigraphic principles and by observing the lithofacies change and the bounding surfaces between sedimentary packages of the studied outcrops. Moreover, the strata stacking pattern of the fifth-order sequences is used to capture the fourth-order sequences through a Fischer plot. The plot shows facies partitioning and a similar pattern to the global sea level curve. The dominant depositional sequence types show a shallowing upward pattern, starting with an outer ramp argillaceous carbonate mudstone (transgressive systems tracts (TST)) that change to mid- and inner-ramp lithofacies (highstand systems tracts (HST)). Shallowing upward siliciclastic sequences are described for the first time within the Hanifa Formation southward. The correlation between interpreted sequences was guided by elemental chemostratigraphy. Four chemostratigraphic divisions (C1, C2, C3, and C4) were interpreted following the vertical

variation of the major elements Si, Al, Ca, Mn, and Fe. The Mn chemical profile is lithology independent and highly correlatable between studied outcrops and subsurface data. The study provides a means for using strata stacking patterns to study the Hanifa Formation sequences and the elemental chemostratigraphy for regional correlation.

Sedimentology, sequence stratigraphy, lithofacies petrophysical characterization, and 3D geostatistical modeling were used to understand the Hanifa reservoir lithofacies analogs in Wadi Mawan, south of the capital Riyadh. The 5th-order sequence boundaries were used as horizons and the interpreted lithofacies as input data to create 3D lithofacies models. The lithofacies model matches the regional trend. Each lithofacies' porosity and permeability are proportionate. Intragranular, intergranular, burrow, moldic, and fracture porosity are the common porosity types in the studied samples. The transgressive systems tract mid-ramp lithofacies have intragranular, moldic, burrow, and fracture porosity. The inner-ramp peloidal grainstone has better reservoir quality than coral/stromatoporoid framestone in the highstand systems tract. The grainstone has intergranular and intragranular porosity, while the framestone has intergranular and burrow porosity. On the lithofacies model skeleton, 3D porosity and permeability models were developed. Porosity and lithofacies models correspond well, while permeability does not.

ملخص الرسالة

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عنوان الرسالة: التحليل الرسوبي والطبقي ودراسة خواص الصخور الخازنة للنفط في تكوين حنيقة من عمر الجوراسي الأعلى

التخصص: علوم الأرض

تاريخ الدرجة العلمية: مايو 2022

تم تحليل ثمانية مكاشف لمكون حنيقة من الجوراسي الأعلى بدقة ، و ذلك للحصول على نموذج شامل و عالي الدقة يصف تطور البيئة الترسيبية أثناء فترة الأوكسفورديان. تمتد هذه المكاشف عبر قطاع اقليمي يصل طوله الى 535 كلم بسمك عمودي يصل الى 461 م . تم تفسير تسع سحن رسوبية صخرية و ضمها في أربع مجموعات من التجمعات السحنية: مجموعة المنحدر الجبيري الخارجي، مجموعة المنحدر الجبيري الأوسط، مجموعة المنحدر الجبيري الداخلي، و مجموعة المنحدر الداخلي المحتوية على السحن الرسوبية للشعب المرجانية، مجموعة المنحدر الخارجي تتضمن : (1) سحنة الطين الفتاتي الجبيري، تتكون مجموعة المنحدر الأوسط من (2) سحنة الردستون المتكون من الكتل الصخرية، (3) سحنة الواكستون/ياكستون المتكون من الفتات العضوي و ابر الاسفنج السيليكية، (4) صخور الطين الفتاتي المترقق، أما المنحدر الداخلي فيتكون من (5) سحنة الصخور الجبيرية الحبيبية ذات التطبيق المتقاطع والمحتوي على حبيبات الكوارتز والبيلويد، (6) الحجر الزملي الكلسي ذو التطبيق المتقاطع الحوضي، (7) سحنة الحجر الجبيري المرجاني ، (8) سحنة فتات الحجر الجبيري المرجاني المتكون في مقدمة الشعاب المرجانية، (9) صخور الرودستون المتكونة في من حبيبات الأونكويد خلف حزام الشعب المرجانية. تتوزع هذه السحن الرسوبية عموديا لتكون طورين رسوبيين على طول متكون حنيقة بما يميز كلا من عضوي حوطة و عليا، يتكون حوطة من بيئة منحدر جبيري ذو انحدار بسيط و متساوي ، بينما يتكون عليا من بيئة منحدر جبيري مشابه غير أنه يحتوي على الشعاب المرجانية.

تعتبر دراسة التتابعات الصخرية من أقوى السبل لإستكشاف النفط و تطوير حقوله، تتميز صخور العمر الجوراسي بعدم تغيير أنماط قياسات الآبار فيها و ذلك لطبيعتها الطينية، مما يجعل المقارنة بين تكويناتها صعبا خصوصا في حال غياب بيانات المستحاثات من تلك التكوينات. تم دراسة طبقات متكون حنيقة بدقة عالية بما في ذلك نوعية الأسطح الفاصلة بين الطبقات في مكشفات بوسط المملكة العربية السعودية، درست التتابعات الطباقية من الدرجة الخامسة بدقة و تم استعمال مخطط فيشر للتعرف على التتابعات من الدرجة الرابعة. بإستخدام مبادئ علم التتابعات الطباقية والإلمام بأنواع السحن الرسوبية السائدة وتغيراتها وبالإضافة لمخطط فيشر تم التعرف على ستة عشر تتابعا " طباقيا " ، أظهر مخطط فيشر ما يسمى بالتمايز السحني، حيث يحتوي كل جزء من المخطط على نوع معين من السحن الرسوبية، عموما أظعر مخطط فيشر تشابها كبيرا مع تغير مستوى سطح البحر أثناء فترة الأوكسفورديان، أظهرت التتابعات الطباقية لمكون حنيقة ميلا" الى ضحالة سحنها الى الأعلى بالإنتقال من سحن المنحدر الخارجي (والتي تكون الصخور المتكونة أثناء تقدم البحر) للمنحدر الأوسط و الداخلي (لتكون صخور مستوى البحر العالي)، تم وصف التتابعات الفتاتية وذلك لأول مرة في متكون حنيقة، تمت المضاهاة بين التتابعات المفسرة بالاستعانة بالتتابعات الكيميائية لمكون حنيقة، تم تفسير أربعة تتابعات كيميائية طباقية في متكون حنيقة بناء على التغيرات العمودية فعناصر السيليكون والألومنيوم والكالسيوم و المنجنيز و الحديد، يتغير عنصر المنجنيز بصورة مستقلة عن التغير الصخري لذا تمت مقارنته مع بيانات الآبار، هذه الدراسة أثبتت فعالية استخدام التتابعات الطباقية في فهم التطور الرسوبي وكذلك استخدام الطباقية الكيميائية للمضاهاة على نطاق اقليمي.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Due to many factors, carbonate reservoirs are relatively more complicated than their siliciclastic counterparts (Ahr, 2008). When formed, carbonate sediments are mainly autochthonous, shaped by different biological, chemical, and physical processes. They are mainly composed of skeletal grains with many different origins and morphological characteristics and non-skeletal grains such as ooids, pisoids, lime mud, and cement that are rarely found in recent siliciclastic. Physical processes also play a role in the formation of carbonate sediments, just like siliciclastics, by forming non-skeletal grains in addition to different bedforms.

Secondly, carbonate's mineralogical composition is chemically considered relatively unstable and susceptible to diagenetic alterations. Different diagenetic processes in various environments affect the carbonate minerals and cause them to be dissolved, cemented, recrystallized, and replaced more extensively than siliciclastic (Moore, 1989). Moreover, carbonate reservoirs are more likely to be diagenetically fractured than siliciclastic reservoirs (Ham and Pray, 1962). A principal difference is that carbonates are more controlled in terms of grain types and mineralogy by climate than siliciclastics (Schlager,

2005). In summary, the petrophysical properties of carbonate reservoirs are controlled by a higher number of parameters, starting from the rock composition and the diagenetic history, which could start from the moment of deposition until the time that the sample was taken (Choquette and Pray, 1970). In addition, fracture patterns may change with different stress directions in the studied field and may influence the diagenetic pathways and petrophysical properties.

Modern analogs of carbonate reservoirs show a relatively wide range of spatial homogeneity in their petrophysical properties in different depositional environments. Moreover, they display a positive correlation between the primary characteristics of the sediments (e.g., grain size and sorting) and the hydrodynamic energy associated with their deposition (Incze, 1998). Petrophysically, modern analogs typically show a negative correlation between their texture, porosity, and permeability, i.e., the finest sediments have the highest porosity values and the least permeability (Tucker, 2001). This correlation is not typically applied in carbonates because of the effect of diagenesis; the porosity and permeability are commonly more independent of grain size and textural characteristics (Enos and Sawatsky, 1981; Flugel, 2010).

The geologic definition and understanding of the variability in reservoir parameters is a prerequisite for accurate potential reservoir characterization and modeling. The initial geologic conceptual models are important; they help to understand the reservoir heterogeneity and represent the base for which the following reservoir geostatistical models and simulations can be built (Pyrzcz and Deutch, 2014). For a long time, outcrops have typically been used to build representative subsurface reservoirs. The outcrop analogs

provide detailed 2-D and 3-D vision for sedimentary facies and diagenetic overprints, better than subsurface and modern analogs (Grammer et al., 2004).

The sedimentary cycles, or group of cycles, are potentially significant from a reservoir characterization perspective since they are the base of any geologic model built from outcrop to be used as subsurface analog. Consequently, once a detailed interpretation of these cycles is done on outcrops (sequence stratigraphy), the petrophysical analysis could be done on the cycles' beds and provide the basic dataset needed to correlate, model, and predict the continuity and efficiency of reservoir zones. Outcrops may provide a more spatial comprehensive view of the lithofacies and the reservoir quality than the subsurface datasets, partially because of the large inter-well distances. So, porosity and permeability measurements on outcrops could be done in a cycle/sequence base and then used to study the different pore-throat systems. The pore-throat systems could build fluid-flow scenarios in reservoir simulation models (Pyrch and Deutsch, 2014). Although the different stratigraphic interpretations and lateral and vertical facies relations deduced from the outcrop analogs are powerful tools that can be used as a template for subsurface correlation, a question is always raised about how much these stratigraphic and diagenetic variations from the outcrop are comparable to their subsurface analogs (Grammer et al., 2004).

Sequence stratigraphy is an effective approach to establishing a spatial and chronological framework of depositional environments' elements, which helps reconstruct paleogeography. It may enhance the lithology and facies predictability far from control points. Understanding the sequence stratigraphic framework is useful in displaying sedimentary bodies' geometrical relationships and architecture. In addition, it can be used to interpret depositional events through space and time. Sequence stratigraphic

interpretation is highly improved if integrated with detailed sedimentary facies analysis and sedimentary processes understanding because they are the base of understanding the variation within the sequence. This combination could identify stratal stacking patterns and the key surfaces criteria, which are sometimes hardly separable. In summary, the sequence stratigraphy and sedimentology provide the skeleton that can be used for further spatial studies of reservoirs' characteristics (Catuneanu et al., 2011).

The link between reservoir characterization and sequence stratigraphy is strong since the reservoir dimensions and its petrophysical properties' heterogeneity, in the scale of cores and outcrops, strongly control hydrocarbons migration pathways. In addition, one major factor which plays a principal role in defining these pathways within the reservoir is diagenesis, which is somehow predictable to some extent depending on principles of sequence stratigraphy (Zecchin and Catuneanu, 2013).

The Hanifa Formation is composed of an over 100 m thick carbonate succession, deposited at the western margin of the equatorial Neo-Tethys passive margin basin during the mid-late Oxfordian (Late Jurassic). Lithostratigraphically the sediments of the Hanifa Formation can be subdivided into two members: the Hawtah Member, which is overlain by the Ulayyah Member (Vaslet et al., 1983). In terms of the petroleum system, the Ulayyah Member is a major hydrocarbon reservoir in the Jurassic succession, and it is in contiguity with rich intra-shelf basinal source rock. It is overlain by the sediments of the Jubaila Formation that represent its main seal (Hughes et al., 2008). The Hanifa Formation exposures in central Saudi Arabia follow the same pattern as those of the Jurassic succession outcrops (Ziegler, 2001) (Figure 1.1).

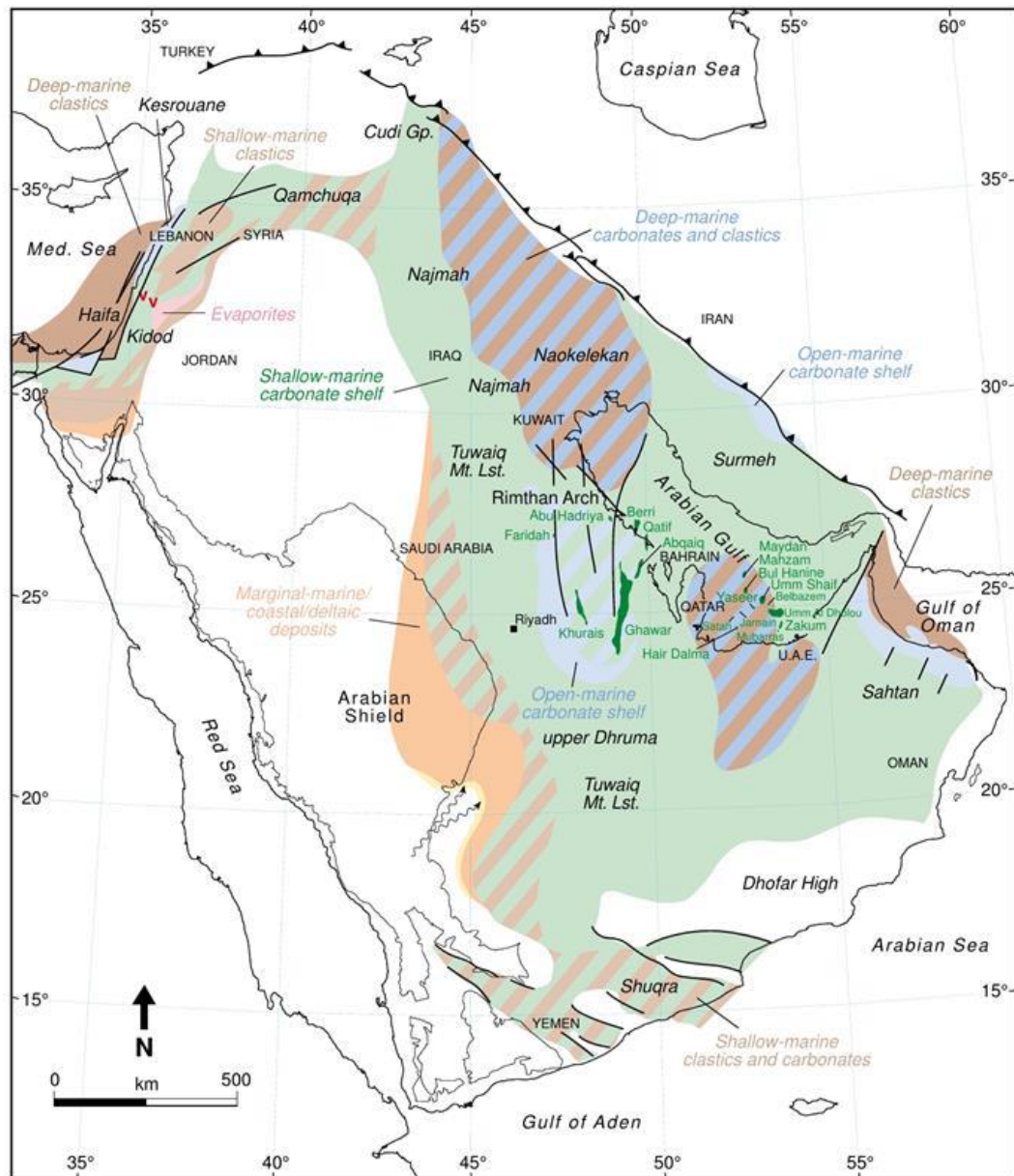


Figure 1.1: Paleoenvironments of the Arabian Plate during Callovian-Oxfordian stages. From Ziegler (2001).

1.2 Problem Statement

The main parameters that should be well understood when exploring important reservoirs are their variations in lithofacies and depositional environments. In addition, the diagenetic history, their position in a sequence stratigraphic framework, and the stratal stacking pattern will be important. The petrophysical properties vary following the lithological and diagenetic variations within the sequence stratigraphic model. So, it is important to fully understand the reservoir's high-frequency cycles on outcrops, which could be challenging in the subsurface, especially when core control is limited. These cycles describe the geometry, continuity, and thickness variation of reservoir equivalent units through the stratigraphic succession. Consequently, the definition of this cyclicity in different stratigraphic sections and correlating them to each other give a regional sense of the reservoir properties variation. Outcrop analogs can be a powerful tool in delineating the stratigraphic boundaries and deciphering the internal lateral and vertical variation in facies (Grammer et al., 2004).

The Hanifa Formation represents an important part of the Jurassic succession of Saudi Arabia along the Arabian Plate. It is one of the major reservoirs in the Shaqra Group and is characterized by organic-rich source rock intervals (Alsharhan and Magara, 1994). It is composed of different pore types and sizes that will affect the efficiency of reservoir units. Moreover, the reservoir units are intensively bioturbated, which increases the heterogeneity. All previously mentioned characteristics make the Hanifa Formation one of the complex formations in the Shaqra Group, containing highly variable depositional facies (in terms of water depth and sedimentological processes). Due to the stratigraphic

importance of the Hanifa Formation as a chronostratigraphic unit that represents different sedimentological and oceanographic conditions in a short vertical range, and because of its economic importance, a deep understanding of its sedimentological and stratigraphic characteristics is essential (Fallatah and Kerans, 2018).

1.3 Motivation

To study the Hanifa Formation subsurface reservoir, a very well understanding of its lithofacies, sedimentary environments, and sequence stratigraphy of outcrops should be reached. The outcrops help decipher the lithologic spatial variations in a 3-D view, which assists in understanding and assessing facies and flow units heterogeneity. Furthermore, assessing the variability of the petrophysical characteristics (porosity, permeability, pore throat geometry, sorting & types) and its relation to the facies variations and the stratal stacking pattern is also an essential step in reservoir modeling (Grammer et al., 2004).

The Hanifa Formation was defined as a member of the Tuwaiq Mountain Formation by Steineke (1937) and has drawn the attention of many geologists. Most of these studies concentrated on building a bio- and lithostratigraphic framework (Arkell et al., 1952; Powers et al., 1966; Powers, 1968; Vaslet et al., 1983; Manivit et al., 1985). Other studies discussed the structural framework of this formation within the Jurassic belt in Saudi Arabia (Al-Husseini, 2000; Ziegler, 2001). Sedimentologists targeted the outcrops of the formation generically, either describing the details of one of the components of the formation or describing the details of the formation in local sections (Okla, 1983, 1986; Moshrif, 1984). Paleontologists also studied the Hanifa Formation and contributed to the general understanding of the stratigraphy (El-Asa'ad, 1991; Hughes, 2004; Hughes et al.,

2008; Alkhayl, 2021). Recently, some detailed stratigraphical studies were carried out on the Hanifa Formation (Eltom et al., 2017; El-Sorogy et al., 2018; Fallatah and Kerans, 2018). The denominator of all previous studies is that they all targeted the Hanifa Formation in the central part of the Jurassic outcrop belt around its type locality. Hughes et al. (2008) proposed a rimmed-shelf carbonate platform as a depositional model for the Hanifa Formation, which conflicts with Fallatah and Kerans (2018), who discussed a carbonate ramp model and recommended more detailed facies analysis and sedimentological studies to be carried on to decipher this ambiguity.

The differentiation between the types of carbonate platforms in ancient successions is a must. The carbonate rimmed-shelves and the carbonate ramps have their own stratigraphic characteristics. The bathymetry and its interaction with the hydrodynamic system, represented by the waves and tides, make the sedimentary facies accumulate in predictable patterns and arrangements, which is important in reservoir units' spatial predictability. This importance also appears because the facies boundaries may coincide with non-reservoir and reservoir strata boundaries. In other words, the boundary between high and low porosity and permeability, whether these properties are original and depositionally-controlled or diagenetically facies-selective (Ahr, 2008). In addition, no detailed reservoir characterization studies were carried out on reservoir units in the Hanifa Formation (the Ulayyah Member), except for Elzain (2015), who targeted the Ulayyah Member in the Jebel Abakkayn.

1.4 Objectives and Scope of Work

This study intends to describe, investigate and characterize the Hanifa Formation in Central Saudi Arabia in terms of:

- 1) Sedimentary facies analysis using micro and macro features in an attempt to solve the current ambiguity in the literature on the carbonate platform type that the Hanifa Formation represents. Was it a carbonate ramp with a gentle slope or a rimmed-shelf platform model? This ambiguity would impact understanding the reservoir architecture in the 3-D view because it is different in each carbonate depositional model.
- 2) Sequence stratigraphy and stratal stacking pattern to use it as a chronostratigraphic basis for a correlation between studied outcrops and those studied previously (e.g., Eltom et al., 2017; Fallatah and Kerans, 2018; Hughes et al., 2008)
- 3) To characterize the upper section of the Ulayyah Member as reservoir equivalent geologically and petrophysically (porosity, permeability). It would start by estimating the visual porosity from thin sections and describing the different types of pores, and then the porosity and permeability will be measured from plugs. These measurements will be associated with petrographic and textural descriptions to classify the reservoir into defined mappable flow units with control of lithofacies.

The following step is to work in the unstudied southern part of the Jurassic outcrop belt to correlate it with the central sections. The extension of the study area would help understand the lateral facies change and the possible carbonate model variation and could add new facies that have never been described. The sequential Gaussian simulation is a powerful

tool that helps understand the spatial variation and predict properties that have been modeled in unstudied areas by filling in the gap between the studied sections statistically. The process starts with real data collected from the outcrops, studying their variability through variograms, then moves to the geostatistical model. Finally, it returns to the outcrops to ensure that the model properly deciphered the property's heterogeneity. The final objective is to quantify all previous observations and interpretations and geostatistically study their spatial distribution and variation.

1.5 The Study Area

The Hanifa Formation crops out along the whole of the Jurassic Shaqra Group belt. The study will start with the central area around Riyadh with the Riyadh-Makkah road cut as a base section since it contains most of the formation's sequences. Then, the main focus will be on the unstudied southern flank of the belt between the Riyadh-Makkah road-cut section and the As Sulayyil section (Figure 1.2).

1.6 Literature Review

1.6.1 Geologic Setting of the Study Area

The Amar continental collision occurred during the Neoproterozoic (640–620 My) when the Ar Rayn microplate moved westward and collided with the Arabian Shield through the Amar Suture zone in the N-S trend (Al-husseini, 2000; Alsharhan and Nairn, 2003) (Figure 1.3). In the late Proterozoic, extensional stress affected the whole area, caused by the



Figure 1.2: Google map image showing the studied outcrops (red stars) and transect.

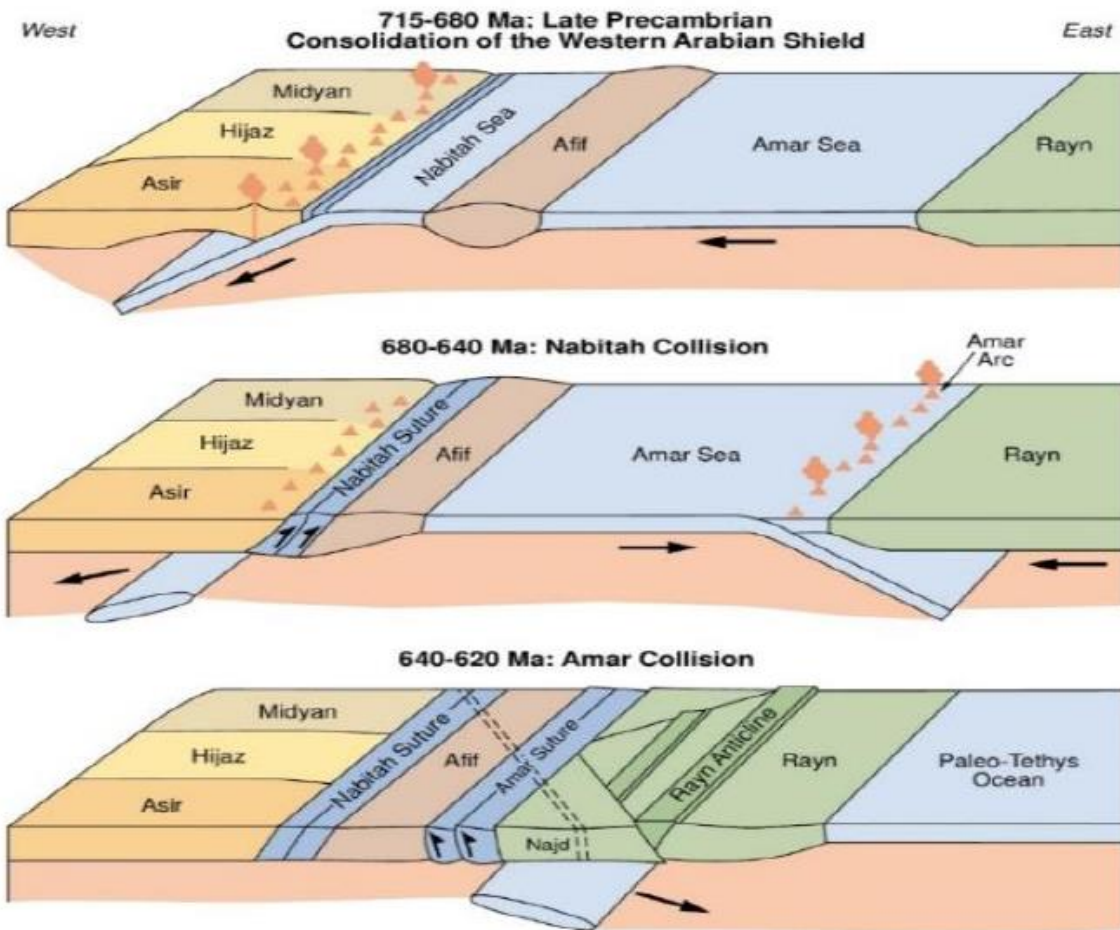


Figure 1.3: The tectonic history of the late Proterozoic Arabian Shield. From Al-Husseini (2001).

emplacement of an A-type granite. The ancient folds formed by the first collision steered the formation of new structures; the limbs of existing folds were faulted, and the crests remained high and formed horsts. The in-between grabens were filled with clastics, evaporites (salt), and carbonates (Al-husseini, 2000). Subsequently, the horsts and folds became giant structures that trapped hydrocarbons (e.g., Ghawwar Field) (Al-husseini, 2000). During Late Permian, the Neo-Tethys ocean was created following a major rifting event in the eastern part of the Arabian Plate (Al-Jallal, 1995). In dominance deposition intervals, the newly formed ocean witnessed an interchange between siliciclastics, evaporites, and shallow marine carbonates (Ziegler, 2001) (Figure 1.4). During the last stages of this intrusion-related extension, the Najd fault and rifting system showed a series of intracontinental rift basins with a NE-SW trend (Blasband et al., 2000).

Because of plate tectonic rearrangements, the location of the Arabian Plate was continuously changing throughout the Precambrian and the Phanerozoic (Figure 1.5). Following (Konert et al., 2001), the Arabian Plate was approximately in an equatorial latitude position, around 80° to the west of its current attitude during the Neoproterozoic. Passing the Proterozoic-Cambrian boundary, the Arabian Plate moved southward in an anticlockwise mode of motion till it reached its maximum location to the south in the Late Ordovician, which was a glacial period (Abu-Ali et al., 1991). Then, it gradually moved clockwise in a northern direction and entered another glaciation period in the Late Carboniferous- to Early Permian (Vaslet, 1989; Senalp and Al-Duaiji, 2001). It reached a position near the equator during the Jurassic (Murris, 1980; Le Nindre et al., 2003). According to Handford et al. (1988) and Al-Husseini (1997), wide accumulations of shallow marine carbonates occupied the Arabian Plate during the Jurassic, and these sediments formed a sequence of deposits that are now named “the Shaqra Group”.

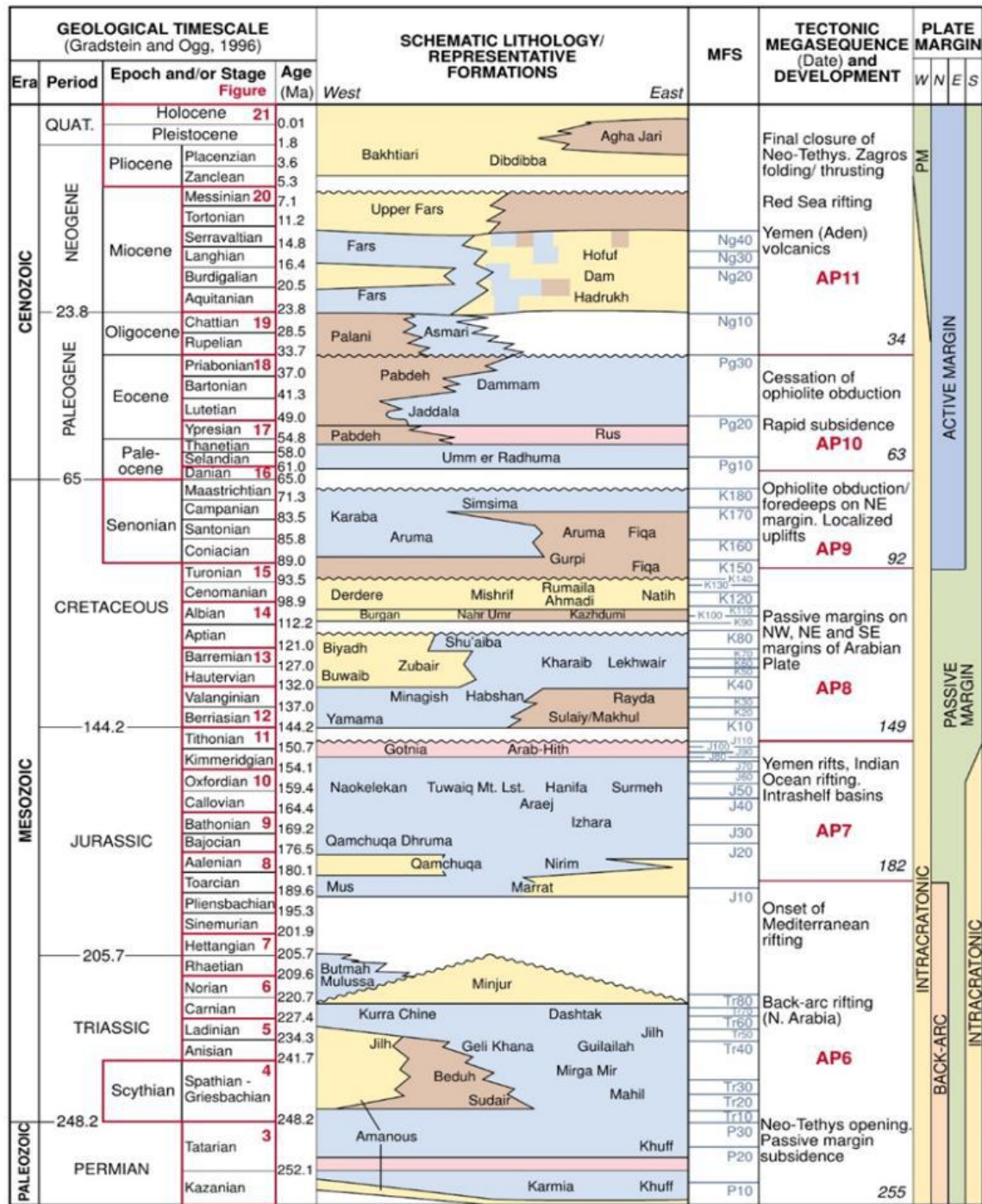


Figure 1.4: Arabian Plate stratigraphic column from Late Permian to Holocene. From Ziegler (2001).

During the late Callovian to Oxfordian, a general sea-level lowstand was recorded (Haq et al., 1988). However, a wide carbonate deposition occurred in shallow marine environments, in addition to deep marine environments that occurred in newly formed intrashelf basins in the Arabian Plate (Haq et al., 1988), e.g., Ras Al Khaimah, Rub' Al Khali, Arabian Basin in central Arabia and the Gotnia Basin. A large amount of organic-rich shales was deposited in those basins under anoxic conditions (e.g., Hanifa Formation) (Bordenave and Burwood, 1990). The four basins mentioned above were formed due to the reactivation of some of the Hercynian tectonic structures (Ziegler, 2001).

1.6.2 Shaqra Group

The Jurassic Shaqra Group represents the most significant stratigraphic unit in the Arabian Plate since it contains the largest hydrocarbon reservoirs in the area (Enay et al., 1987). It comprises seven formations, starting from the oldest: the Marrat, Dhurma, Tuwaiq Mountain, Hanifa, Jubaila, Arab and Hith Formations (Figure 1.6). These formations contain twelve different reservoir zones starting at the base with Marrat, followed by the Farida, Shares, Lower Fadhili, Upper Fadhili, Hadriya, Hanifa, Arab-D, Arab-C, Arab-B, Arab-A, and Manifa members (Enay et al., 1987; Hughes, 2004; Powers et al., 1966; Steineke and Bramkamp, 1952) (Figure 1.6).

During the Toarcian, the sediments of the Marrat Formation were unconformably deposited over the sediment of the Triassic Minjur Formation. The Marrat Formation comprises siliciclastics, evaporites, and carbonates that increase toward the top. A major transgression occurred during the Bajocian, following a hiatus during the Aalenian, which resulted in the deposition of the Dhurma and Tuwaiq Mountain Formations sediments. The sediments

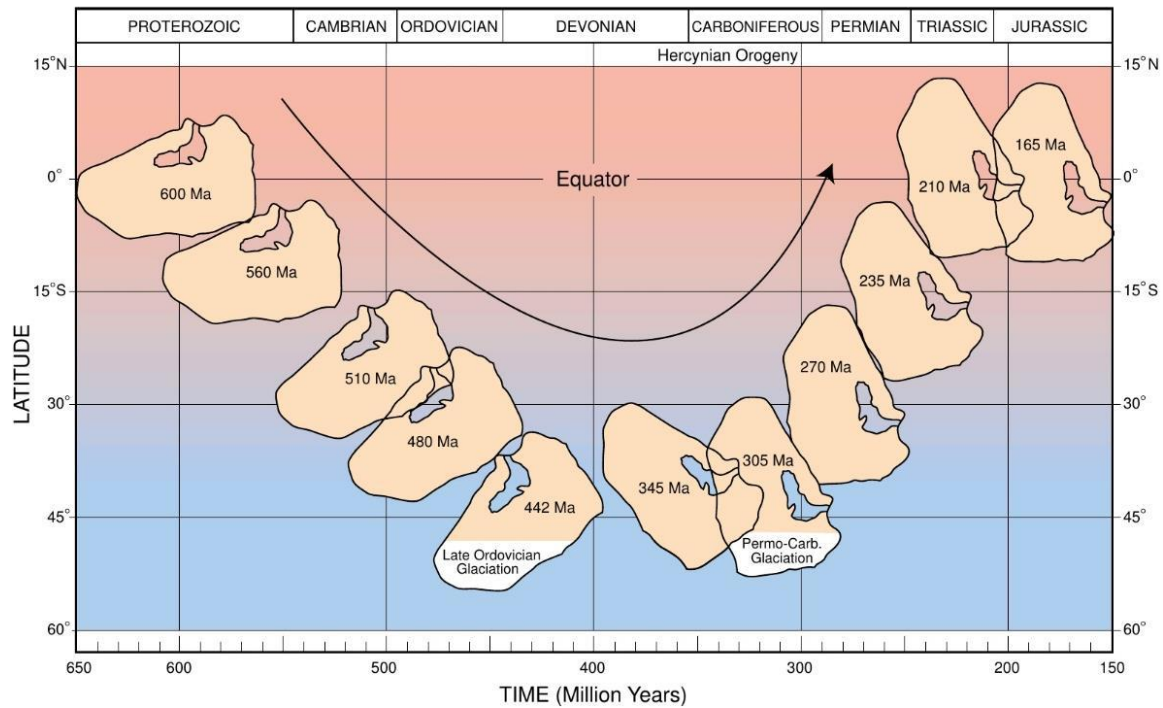


Figure 1.5: Paleolatitude of the Arabian Plate since the Late Proterozoic till the Jurassic. From Konert et al. (2001).

showed a high deposition rate in response to an increased tectonic subsidence rate (Le Nindre et al., 2003). A disconformity marks the boundary between the Dhurma and Tuwaiq Mountain formations. The proposed age for Tuwaiq Mountain Formation is from late Bajocian to Callovian (Alsharhan and Nairn, 2003).

The Hanifa Formation, Oxfordian in age, was subdivided by Vaslet et al. (1983) into two members: the Hawtah and the Ulayyah. Both show a shallowing-upward succession with high-frequency cycles and cycle sets related to the eustatic rise and subsidence (Sharland et al., 2001; Hughes et al., 2008). The upper part of the Ulayyah Member shows an aggrading and prograding oolitic grainstone succession representing the Hanifa reservoir (McGuire et al., 1993).

The sediments of the Jubaila Formation rest unconformably on the sediments of the Hanifa. They are mainly composed of subtidal wackestones and packstones, with derived coral heads from the Hanifa Formation. Generally, the Jubaila Formation sediments become intensively bioturbated upward (El-Asmar et al., 2015). It represents a Kimmeridgian transgressive event that resulted in the deposition of organic-rich fine carbonates forming the lower part of the formation (Alsharhan and Nairn, 2003). The Arab and Hith Formations are composed of interbedded carbonates and evaporites representing a series of transgressive-regressive depositional events in restricted conditions that lasted for 5 My (Sharland et al., 2001; Hughes, 2004).

1.6.3 Hanifa Formation

Hanifa Formation was firstly defined in outcrop by Max Steineke (1937) as an upper member of the Tuwaiq Mountain Formation. Steineke and Bramkamp, 1952, formally

raised the stratigraphic rank of Hanifa to a formation. It was named as Hanifa Formation by Powers et al. (1966) after the Wadi Hanifa, which is the type locality of the formation. The formation age, the main lithologic characteristics, and the lithostratigraphic boundaries with the underlying Tuwaiq Mountain and the overlying Jubaila formations were delineated by Powers et al. (1966). Lithostratigraphically, the Hanifa Formation was subdivided into two members: Hawtah and Ulayyah (Vaslet et al., 1983). Many studies targeted deciphering the paleoenvironments in which the sediments of the Hanifa Formation were deposited but restricted themselves to a series of limited regional interpretations that resulted in an approximation of the carbonate platform zonation and shoreline delineation (Murriss, 1980; Al-Husseini, 1997; Ziegler, 2001) (Figure 1.1 and 1.7). Different facies belts and associations were proposed, including restricted and open shelf lagoons, shoal & fore-shoal, coral & stromatoporoid reefs, and open marine (El-Sabbagh et al., 2017).

Droste (1990) described a laminated dark intra-shelf organic-rich calcareous mudstone with scattered anhydrite in the Qatar subsurface and mentioned its importance as one of the major source rocks in the Arabian Plate. The Oxfordian strata were described in terms of biostratigraphy and paleoenvironments by Hughes (2004) and Hughes et al. (2008) (Figures 1.8 & 1.9).

Le Nindre et al. (1990), Sharland et al. (2001), Mattner and Al-Husseini (2002), and Hughes (2004) studied the sequence stratigraphic framework of the Shaqra Group. They proposed that the Hawtah and Ulayyah members are equivalent to two third-order sequences in the Arabian Plate stratigraphy. Moreover, the Hawtah Member was subdivided into five fourth-order sequences and Ulayyah Member into seven.

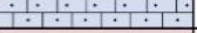
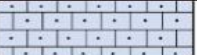
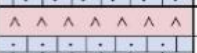
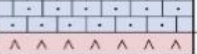
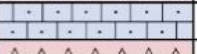
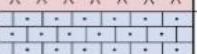
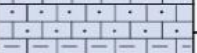
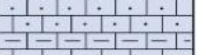
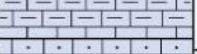
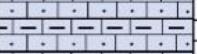
Stratigraphy			Formation	Member	Lithology	Reservoir
JURASSIC	UPPER	Portlandian	Hith			Manifa
						
		Arab	Arab	Arab-A		Arab-A
				Arab-B		Arab-B
				Arab-C		Arab-C
				Arab-D		Arab-D
		Kimmeridgian	Jubaila	J2		
				J1		
		Oxfordian	Hanifa	Ulayyah		Hanifa
				Hawtah		
						
	MIDDLE	Callovian	Upper Dhurma	T3/ Daddiyah		Hadriyah
				T2/ Maysiyah		Upper Fadhilli
				T1/ Baladiyah		
				Hisyan		
				Atash		Lower Fadhilli
		Bathonian			Non deposition	

Figure 1.6: Lithostratigraphy of the Jurassic Shaqra Group and the equivalent subsurface reservoirs. From Hughes (2004).

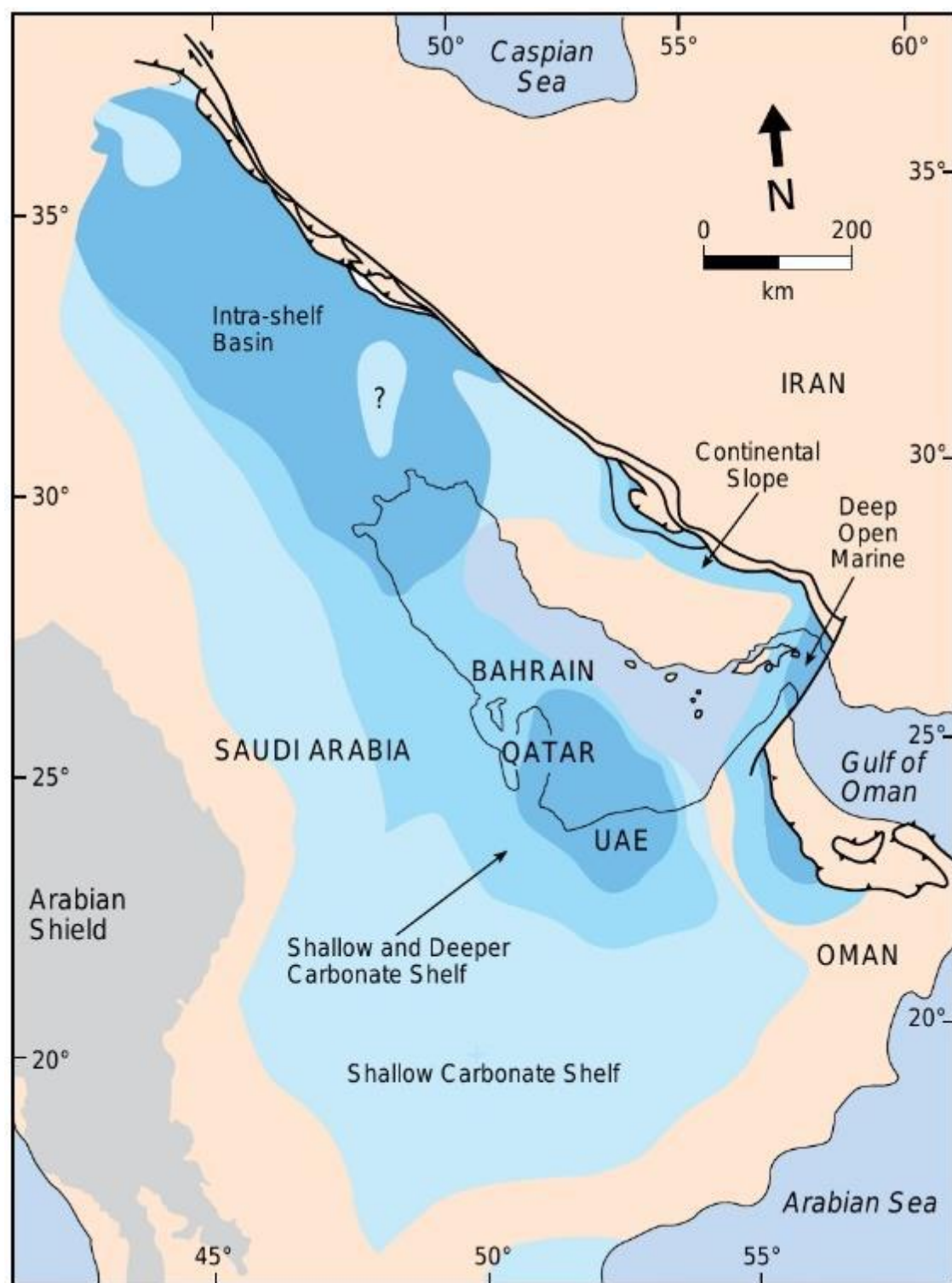


Figure 1.7: Interpreted paleogeography of the Middle East during Oxfordian-Kimmeridgian. From Murris (1980).

The Hawtah Member is 57 m thick and is middle Oxfordian in age. This age assignment was based on the occurrence of *Paraceoceras* aff. *arduennense*, *P. macrum* and *P. aff. hexagonum* nautiloids (Tintant, 1987), as well as the occurrence of *Euaspidoceras cf. catena perarmatum* ammonites (Vaslet et al., 1983; Enay et al., 1987). The Ulayyah Member is 71 m thick and shows a grainier texture than the sediments of the Hawtah. It is late Oxfordian in age. This age assignment was based on the occurrence of the benthic foraminifera *Alveosepta jaccardi* (Manivit et al., 1985; Hughes, 2004) and *Paracenoceras* aff. *sulcatum* ammonites (Tintant, 1987).

1.6.4 Reservoir Characterization

Reservoir characterization could be defined as studying a reservoir's three-dimensional spatial distribution of petrophysical properties (Lucia, 1999). Earlier studies on carbonate reservoirs were conducted by paleontologists and sedimentologists, who targeted the reef deposits as the main reservoir type. During the 1950's, the study of recent carbonates of the Bahamas by the group of Robert Ginsburg showed the importance of sedimentology and petrography of these modern deposits and the ability to use them as analogs for ancient systems. Simultaneously, Gus Archie elucidated that carbonate reservoirs could be described and characterized the same as siliciclastic; through their petrophysical parameters instead of being blindly described as "reefs". Subsequently, Murray (1960), Lucia and Murray (1967), and Roehl (1967) had a head start in linking the petrophysical properties of carbonate rocks to their sedimentation mode and petrography through detailed core geological and petrophysical studies. The 3-D distribution of carbonate reservoirs' petrophysical properties within constructed facies and diagenetic models was the principal method of reservoir characterization during the 1970s and 1980s.

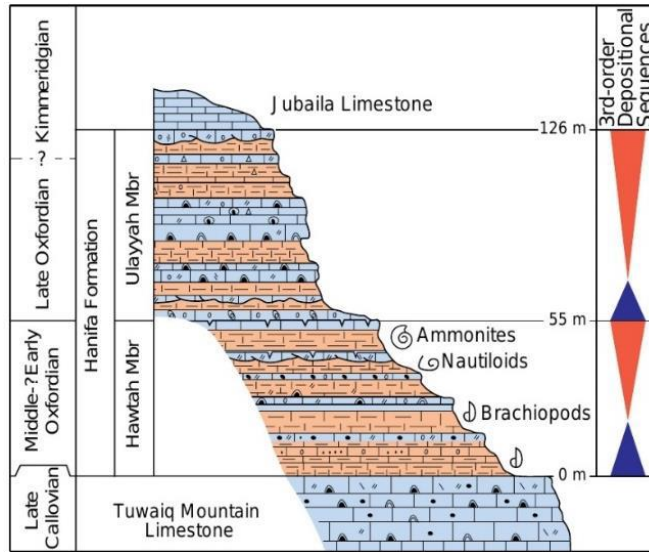


Figure 1.8: Hanifa Formation lithostratigraphy and chronostratigraphy. From Hughes (2008).

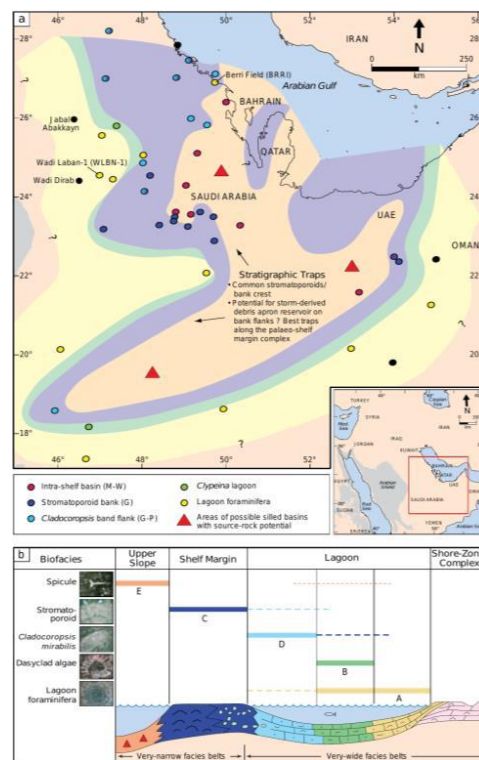


Figure 1.9: Paleoenvironmental interpretation of Hanifa Formation subsurface cores based on a detailed micropaleontological study, showing the geographic distribution of the shoreline complex, the lagoon, the shelf break, and the upper slope depositional environments (Hughes et al., 2008)

This research primarily focuses on characterizing the Hanifa Formation outcrops' equivalent reservoir units and developing three-dimensional lithofacies and petrophysical analogs for subsurface reservoir models and development plans. New subsurface reservoir zones can be discovered using these outcrop models, which mirror the Hanifa reservoir's architecture and flow units.

1.7 Methodology

The following chart (Figure 1.10) shows the main methods and steps applied in this research:

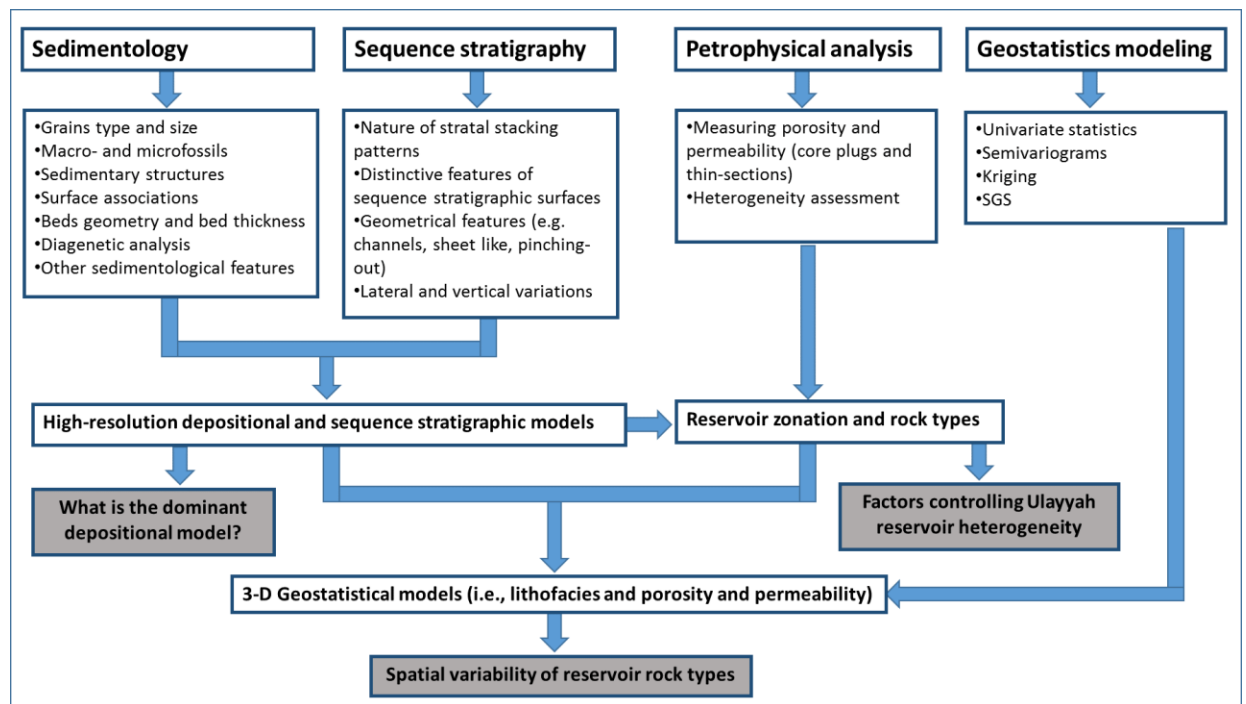


Figure 1.10: The workflow to accomplish the research objectives.

CHAPTER 2

FACIES ANALYSIS AND DEPOSITIONAL MODEL FOR THE OXFORDIAN HANIFA FORMATION, CENTRAL SAUDI ARABIA

Abstract

High-resolution (centimeter-scale) description and analysis of eight outcrop sections through the Oxfordian Hanifa Formation along a 535 km-long N-S transect in central Saudi Arabia are used to develop a comprehensive conceptual depositional model through time. The cumulative vertical thickness of the studied sections reaches 461 m. Nine sedimentary lithofacies are interpreted, which are grouped into four facies associations, i.e., I) outer-ramp association (FA1), II) mid-ramp association (FA2), III) inner-ramp grainy-facies association (FA3), and VI) inner-ramp reefal association (FA4). The outer-ramp association includes argillaceous carbonate mudstone (F1). The mid-ramp association includes intraclast rudstone (F2), skeletal sponge spiculitic wackestone/packstone (F3), and horizontally-laminated siltstone/claystone (F4). The grainy facies of the inner-ramp association includes cross-bedded skeletal quartz peloidal grainstone (F5) and trough cross-bedded calcareous sandstone (F6). In contrast, the inner-ramp reefal association includes reef-crest stromatoporoid/coral framestone (F7), gravel-dominated fore-reef floatstone (F8), and open back-reef oncoidal rudstone (F9). The lithofacies succession

distinguishes two depositional phases, i.e., Phase 1 and Phase 2, corresponding lithostratigraphically to the middle Oxfordian Hawtah and upper Oxfordian Ulayyah Members, respectively. Phase 1 represents deposition on a homoclinal carbonate ramp, whereas Phase 2 witnessed the transition from a grain-dominated carbonate ramp to a reef-bearing one, as indicated by reefal association (FA4). The Hanifa Formation carbonate ramp evolution reflects coral reef expansion over the southern Neo-Tethys passive margin in the late Oxfordian. In the southern section of the studied transect, siliciclastic deposits are described for the first time from the Hanifa Formation (F4 and F6).

Keywords

Homoclinal carbonate ramp; Reef-bearing carbonate ramp; Siliciclastics; Reef facies association; Oxfordian Hanifa Formation

2.1 Introduction

The geometry of a carbonate platform could be controlled partially by the biological components of the carbonate depositional system, which is controlled, in turn, by climate, water chemistry, light penetration, salinity, nutrition level, siliciclastic input, water agitation level, and the tectonic setting of the sedimentary basin. These elements have long been a focus of academic and industrial research because of the high number of parameters involved and how they continuously interact (Wilson, 1975; Crevello et al., 1989; Schlager, 2005; Markello et al., 2008; Kelley et al., 2020). The two most abundant carbonate platform geometries in the geologic record are rimmed-shelf and homoclinal ramps (Ahr, 1973; Tucker, 1985; Burchette and Wright, 1992; James and Kendall, 1992; Pomar, 2001; Ahr, 2008; Flügel, 2010). Differentiating between these two carbonate settings in ancient successions is significant because their facies belts grow in predictable patterns and

configurations; therefore, the reservoir and source rock facies developed differently (Lucia, 1995; Ahr, 2008). Consequently, lithofacies analysis is an indispensable step in hydrocarbon exploration. However, a depositional model interpretation is not straightforward, and good quality, large-scale outcrops (dip-oriented) and/or seismic data are typically required to establish the geometry.

The Mesozoic shallow-water carbonate succession of the Arabian Plate represents the southern Neo-Tethys' passive margin. The succession includes the world's largest and most prolific conventional hydrocarbon reservoirs (Konert et al., 2001). The Upper Jurassic Hanifa Formation is an economically significant lithostratigraphic unit in the Jurassic Shaqra Group in the Middle East. It contains both potential source rocks of organic-rich basinal mudstones (Carrigan et al., 1995; Cantrell et al., 2014; Al Ibrahim et al., 2017) as well as shallow-water non-skeletal grainstone facies with good conventional hydrocarbon reservoir characteristics (Alsharhan and Magara, 1994; Hughes et al., 2008). Therefore, the sedimentology and stratigraphy of the Hanifa Formation need to be well understood to work out successful exploration and development plans, either as a conventional subsurface reservoir, source rock, or unconventional petroleum system. Conceptual depositional models can detect fine-scale temporal and spatial sedimentological heterogeneities. Static reservoir models and 3-D volumetric lithofacies percentage estimations may be improved by including these heterogeneities (Grammer et al., 2005; Labourdette et al., 2008).

Many previous sedimentological studies focused on paleoenvironmental reconstructions for the Late Jurassic members of the Hanifa Formation, representing a shallow-marine carbonate succession deposited on the western flank of the passive continental margin of

the Neo-Tethys Ocean. Outcrop and subsurface investigations in central Saudi Arabia and the Middle East oil fields, respectively, suggest that shoreline to carbonate platform succession reflects the typical depositional setting (Powers et al., 1966; Murris, 1980; Okla, 1983; Moshrif, 1984; Okla, 1986; Droste, 1990; Al-Husseini, 1997; Ziegler, 2001; Eltom et al., 2017; El-Sorogy et al., 2018; Fallatah and Kerans, 2018). Furthermore, biostratigraphical studies have contributed to the general understanding of the stratigraphy of the formation (El-Asa'ad, 1991; Hughes, 2004; Hughes et al., 2008; Hughes, 2018; Énay and Mangold, 2021). Moshrif (1984), Droste (1990), and Hughes et al. (2008) proposed a rimmed-shelf carbonate platform depositional model based on subsurface lithofacies and biofacies characterizations. They interpreted the Hanifa Formation as part of a wide semi-continuous stromatoporoid bank (rim) surrounding an enclosed intra-shelf basin where organic-rich source rocks were deposited which were covered by a younger evaporite succession. This model contrasts with Fallatah and Kerans (2008), which discussed a gently sloping carbonate ramp model. For these reasons, the present study focused on the Hanifa Formation outcrops to refine the depositional models proposed in previous studies. The Hanifa Formation exposures were described over a wide area of the Jurassic outcrop belt in Saudi Arabia and interpreted in terms of its sedimentological characteristics and depositional environments.

2.2 Geological Setting

2.2.1 Tectonics

The study area in central Saudi Arabia represents a shallow Late Jurassic epeiric sea on the western side of the Neo-Tethys Ocean, underlain by the Arabian Shield basement rocks. During the Late Precambrian, the ArRayn microplate shifted westward and collided with

the Arabian shield, forming folds in addition to the N-S trending Al Amar Suture Zone (Al-Husseini, 2000; Alsharhan and Nairn, 2003). The Late Proterozoic concluded with a vast NW–SE intrusion-related expansion (Blasband et al., 2000). Ancestral folds were faulted, and their crests stayed high, forming sets of horsts and grabens. The folds formed over horsts later became huge hydrocarbon traps (e.g., Ghawwar Field) (Al-Husseini, 2000).

Western Pangaea witnessed extensive continental rifting and crustal stretching and weakening during the late Early Permian. This period split the Cimmerian continent from Gondwana, resulting in the development of the Neo-Tethys Ocean at the cost of the Paleotethys Ocean (Al-Jallal, 1995; Stampfli and Borel, 2002; Figure. 2.1A). During the Early and Middle Jurassic, the eastern Mediterranean passive margin developed in the northern part of the Arabian Plate (Ziegler, 2001). The Late Jurassic witnessed the Indian-African plate separation, characterized by a marine transgression affecting the Arabian passive continental margin (Sharland et al., 2001; Ziegler, 2001; Figure. 2.1B). During the late Callovian to middle Oxfordian stages, the continuous subsidence produced three main intra-shelf basins east of the Arabian Plate (Murriss, 1980; Énay et al., 1987; Droste, 1990; McGuire et al., 1993; Al-Husseini, 1997). However, multiple episodes of tectonic instability occurred in the Jurassic, which may have been linked to subsidence resistance and few large-scale uplifts (Le Nindre et al., 2003). The intra-shelf basins were formed potentially in connection with the rejuvenation of major N-S basement faults, which resulted in a set of basins bounded by uplifted horsts. Eastward, in addition to bordering the intra-shelf basins, the horsts represented the far east Arabian Plate margin, where sediments prograded eastward (toward the Neo-Tethys basin) and westward into the intra-shelf basins (Vahrenkamp et al., 2015). However, shallow in-situ carbonate growth,

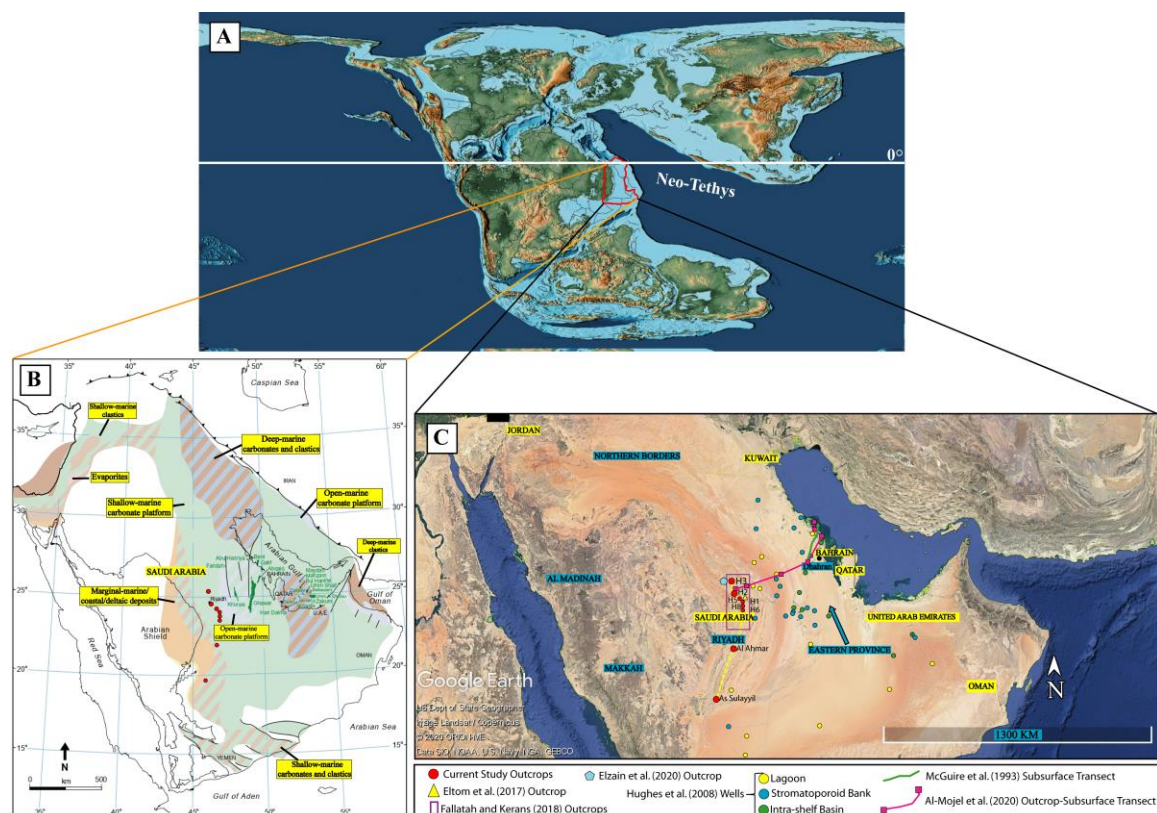


Figure 2.1: Geographic and geologic maps of the study area. A) The Oxfordian paleogeographic map showing the equatorial position of the Arabian Plate (drawn in red) as a continental passive margin of the Neo-Tethys Ocean (from Scotese, 2013). B) Paleofacies map of the early Late Jurassic in the Arabian Plate showing the spatial lithological variation through this epicontinental sea. The studied outcrop locations are marked by solid red circles (modified from Ziegler, 2001). C) Google Earth image, showing the studied transect (yellow dashed line) with the locations of the measured section (solid red circles), in addition to the available locations of previous studies.

associated with the Callovian and Oxfordian marine transgressions may be responsible for forming relatively deep intra-shelf basins (Gravestock et al., 2021). Wide accumulations of shallow marine carbonates occurred on the Arabian Plate during the Jurassic, and these sediments formed a sequence of deposits named "the Shaqra Group" (Vaslet et al., 1988; Al-Husseini, 1997; Handford et al., 2002).

2.2.2 Stratigraphic Background

Steineke (1937) originally described the Hanifa Formation as the top part of the Tuwaiq Mountain Formation in an unpublished paper. Later, Steineke and Bramkamp (1952) defined Hanifa as an independent stratigraphic formation. The Hanifa Formation is named after Wadi Hanifa, which is the type locality of the formation (Powers et al., 1966). The Hanifa Formation was subdivided into the Hawtah and Ulayyah members (Vaslet et al., 1983; Figure. 2.2). The Hawtah Member is 57 m thick, consisting of clayey and skeletal carbonates, and is middle Oxfordian in age. This age assignment was based on the occurrence of *Paraceoceras* aff. *arduennense*, *P. macrum* and *P. aff. hexagonum* nautiloids (Tintant, 1987), as well as the occurrence of *Euaspidoceras* cf. *catena perarmatum* ammonites (Vaslet et al., 1983; Énay et al., 1987). The Ulayyah Member is 71 m thick and possesses more skeletal and non-skeletal grainstones and coral/stromatoporoid boundstones than the sediments of the Hawtah Member. It is assigned a late Oxfordian age based on the occurrence of the benthic foraminifera *Alveosepta jaccardi* (Manivit et al., 1985; Hughes, 2004, Hughes, 2018) and *Paracenoceras* aff. *sulcatum* ammonites (Tintant, 1987).

Stratigraphy			Formation	Member
Jurassic	Upper	Tithonian	Hith	
			Arab	A
		B		
		C		
		D		
		J2		
		J1		
		Kimmeridgian	Jubaila	
	Oxfordian	Hanifa	Ulayyah	
			Hawtah	
Middle	Callovian	Tuwaiq Mt.	T1-T3	
		Dhurma	D1-D7	
	Bathonian			



Targeted Interval

Targeted Interval

Figure 2.2: Middle to Upper Jurassic lithostratigraphic succession of central Saudi Arabia (modified from Hughes, 2004).

2.3 Methodology

Sedimentary lithofacies are classically described based on lithology variations, textures, sedimentary structures, fossil content, and stacking pattern. The interpretations presented in this study are based on eight measured outcrop sections (H1, H2, H3, H5, H6, H8, Al Ahmar, and As Sulayyil) of the Oxfordian Hanifa Formation, along a 535 km-long transect in central Saudi Arabia (Figure. 2.1C; Appendix A). The thickness of the studied sections ranges from 113 m to 15 m, whereas the distance between them ranges from 56 km to 321 km. The vertical stratigraphic sections were drawn using Easy Core software and studied at high resolution at a centimeter scale. A total of 587 samples were slabbed, polished, and scanned using an Epson Perfection V700 scanner.

Moreover, 138 thin sections were prepared and impregnated with blue-dyed epoxy. The thin sections were photomicrographed using a polarizing microscope with an attached Olympus UC30 digital camera. The textural classification was based on Dunham (1962) and its amended version of Embry and Klovan (1971). The bioturbation intensity was estimated based on the bioturbation index proposed by Knaust (2012). Furthermore, mudstone chips and whole muddy sample powder were analyzed using scanning electron microscopy and X-ray diffraction techniques. Carbonate, silicate, and clay minerals were identified using an X'Pert3 Malvern Pananalytical system. Sample holders with a 20-mm square size were used to hold the powdered samples. For a broad variety of minerals, the scan range was set at 10 to 90°.

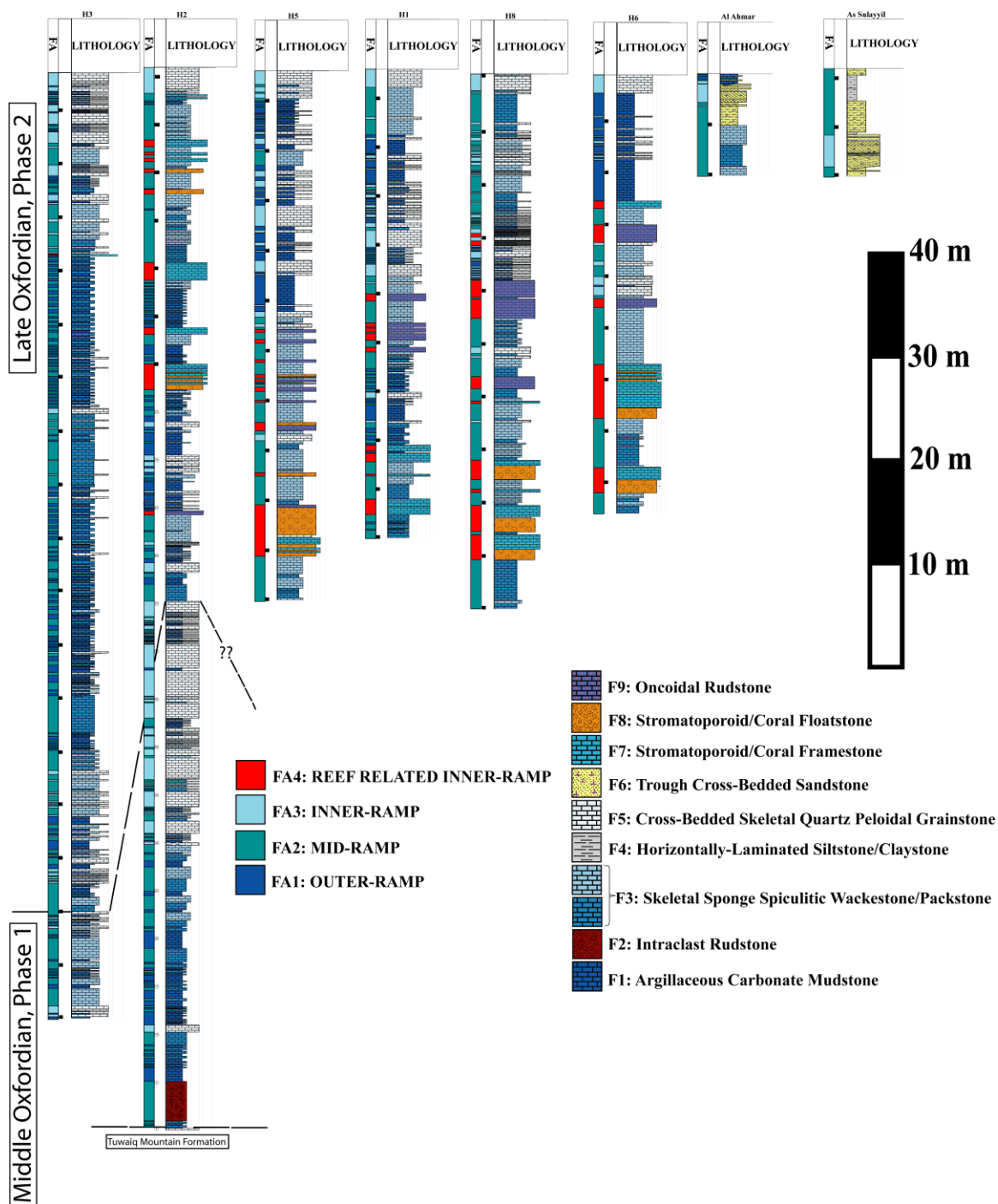


Figure 2.3: Sedimentological logs of the studied outcrops containing the described sedimentary lithofacies and facies associations.

2.4 Results

2.4.1 Facies Description

Facies analysis carried out in the Hanifa Formation allowed distinguishing nine lithofacies, labeled F1 to F9, reflecting different depositional environments (Figure. 2.3). Argillaceous carbonate mudstone (F1): Beds thicknesses range from a few centimeters to decimeters. F1 is interbedded with massive sponge spiculitic wackestone (F3) (Figure. 2.4A). It is represented by brown massive/laminated argillaceous carbonate mudstone (Figure. 2.4B). It contains small scattered bivalves and brachiopods. Thin sections reveal scattered monaxon and triaxon sponge spicules (Figure. 2.4C), and SEM analysis shows platy detrital and elongated lath-shaped authigenic illite (Figure. 2.4D). XRD analysis shows the dominance of calcite (88.3%) and the existence of quartz (7.3%), kaolinite (1.9%), illite (0.8%), muscovite (1.6%) as well as montmorillonite and magnetite (both 0.1%).

Intraclastic rudstone (F2): This facies interval has a thickness of 5.2 m of bedded and channelized deposits. It comprises a basal zone of well-bedded intraclastic rudstone (Figure. 2.4E) with an erosive base (average bed thickness of 0.5 m). The intraclasts consist of massive carbonate mudstone and sponge spiculitic wackestone. They are rounded to sub-rounded in shape, range in size from 1 to 12 cm, and show a general fining upward trend (Figure. 2.4F). The bedded rudstone is cut by a set of intercalated channels, filled, similarly, with intraclasts rudstone (Figure. 2.4G). The intraclasts in the channelized bodies are coarser than those in the bedded section; their diameter ranges from 5 to 25 cm. F2 is found only at the base of section H2, in the middle of the studied transect, stratigraphically below F1, and in contact with the uppermost beds of the older Tuwaiq Mountain Formation (TMF) (Figure. 2.3).

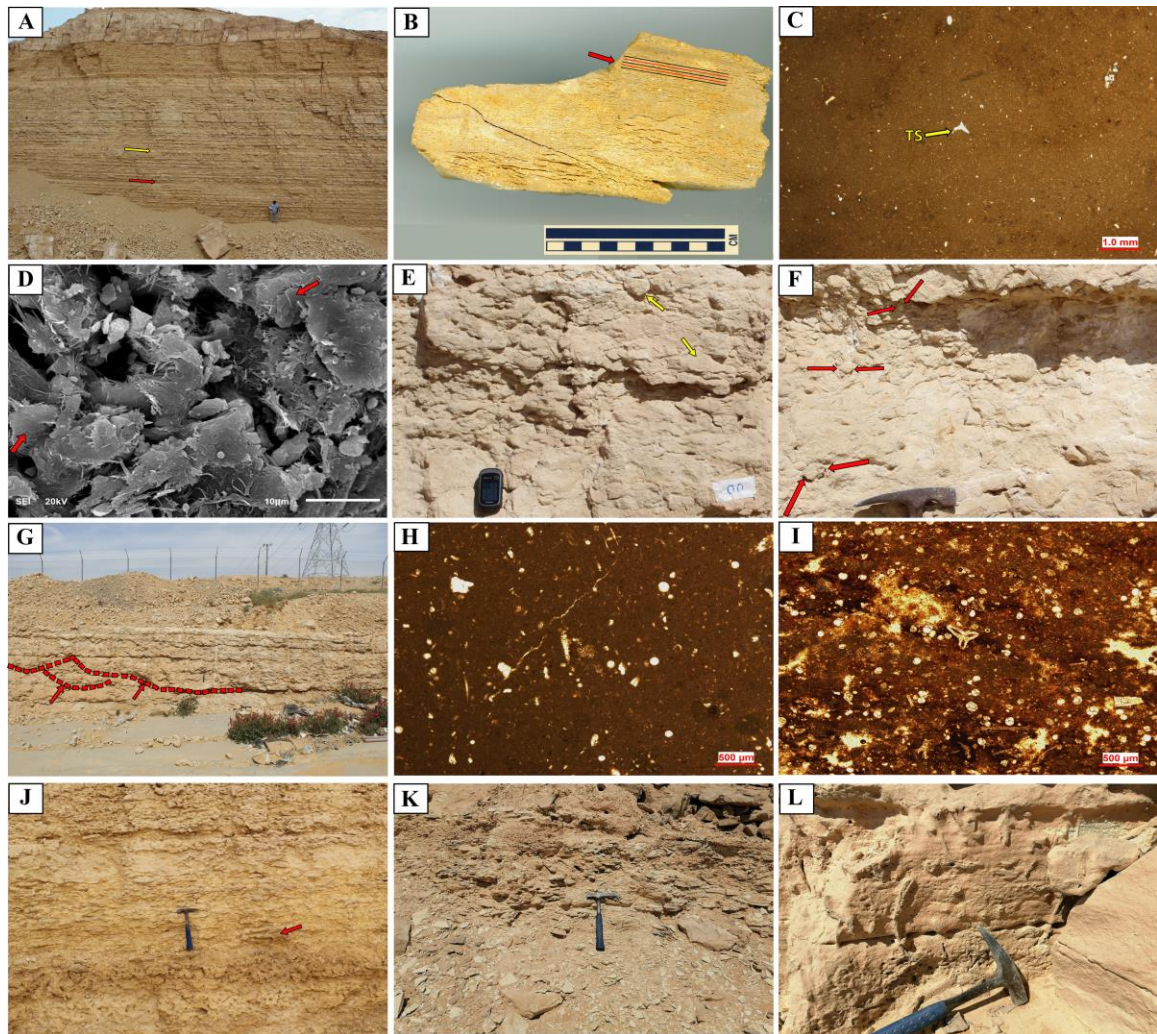


Figure 2.4: Macro and microphotographs of the mid-ramp to outer-ramp lithofacies; F1 (A, B, C & D), F2 (E, F & G), F3 (A, H, I & J) and F4 (K & L). A) High frequency interbedding between brown argillaceous carbonate mudstone beds (F1) (red arrow) and beige massive sponge spiculitic wackestone beds (F3) (yellow arrow). **B)** Vertical slab of F1 argillaceous carbonate mudstone, with traces of horizontal lamination (arrow). **C)** Thin section microphotograph of F1 with scattered monaxon and triaxon sponge spicules (TS, yellow arrow). **D)** SEM image of F1 illustrating the existence of platy detrital (red arrows) and filamentous and lath-shaped authigenic illite. **E)** Intraclasts (arrows) in the rudstone texture of F2. **F)** Finning upward pattern through F2 (intraclasts are shown between red arrows). **G)** Interbedding between horizontally-bedded intraclast rudstone with erosive base and channelized one (red dashed line and arrows). **H)** Thin section microphotograph showing the sponge spiculitic wackestone of the lower part of F3. **I)** F3 packstone thin section image demonstrating the dominance of monaxon and triaxon sponge spicules (note the preserved internal canals of the spicules in the middle of the image) in an organic-rich matrix. **J)** Intensive bioturbation (bioturbation index = 5) with complex branching *Thalassinoides* burrows in F3 (red arrow). **K)** Outcrop photo of fissile and massive white claystone beds of F4. **L)** Horizontal lamination and *Skolithos* burrows in the top of calcareous siltstone of F4.

Sponge spiculitic wackestone/packstone (F3): The beds are white to beige, range in thickness from 15 to 80 cm, have a massive appearance, or are intensively bioturbated. The depositional texture of F3 ranges from wackestone to packstone. F3 is an interbedding between these textures, with the wackestone more commonly found in the lower part of the lithofacies beds. F3 beds are laterally continuous within all studied outcrops (Figure. 2.4A). They overly and are often interbedded with F1 and underlie cross-bedded quartz skeletal peloidal grainstone (F5). Thin sections show the existence of monaxon siliceous sponge spicules in the wackestone (Figure. 2.4H). The packstone shows a more organic-rich matrix with monaxon and triaxon siliceous sponge spicules (Figure. 2.4I). The associated fossils in F3 are foraminifera (*Kurnubia palastiniensis* Henson 1948), bivalves, and echinoid spines. The bioturbation of F3 beds is intense (bioturbation index 4-5), so no other sedimentary structures were preserved (Figure. 2.4J). However, traces of cross-bedding are noticed in contact with F5 grainstone but are completely hindered by bioturbation. The main observed trace fossils are *Thalassinoides* burrows.

Horizontally laminated siltstone/claystone (F4): It comprises massive beds of fissile white claystone (Figure. 2.4K) and passes upwards into a brown to green siltstone. The siltstone is horizontally laminated and shows *Skolithos* ichnofossil at the upper part of its beds (Figure. 2.4L). The siltstone beds stratigraphically overlie the claystone and underlie the trough cross-bedded sandstone of F6.

Cross-bedded skeletal quartz peloidal grainstone (F5): Two main sub-facies are defined based on the bedding style and abundance of grains components; F5a and F5b. The bedding style of F5a shows laterally continuous beds with a constant thickness (Figure. 2.5A), whereas F5b beds show thickness heterogeneity and lenticular bedding (Figure. 2.5B).

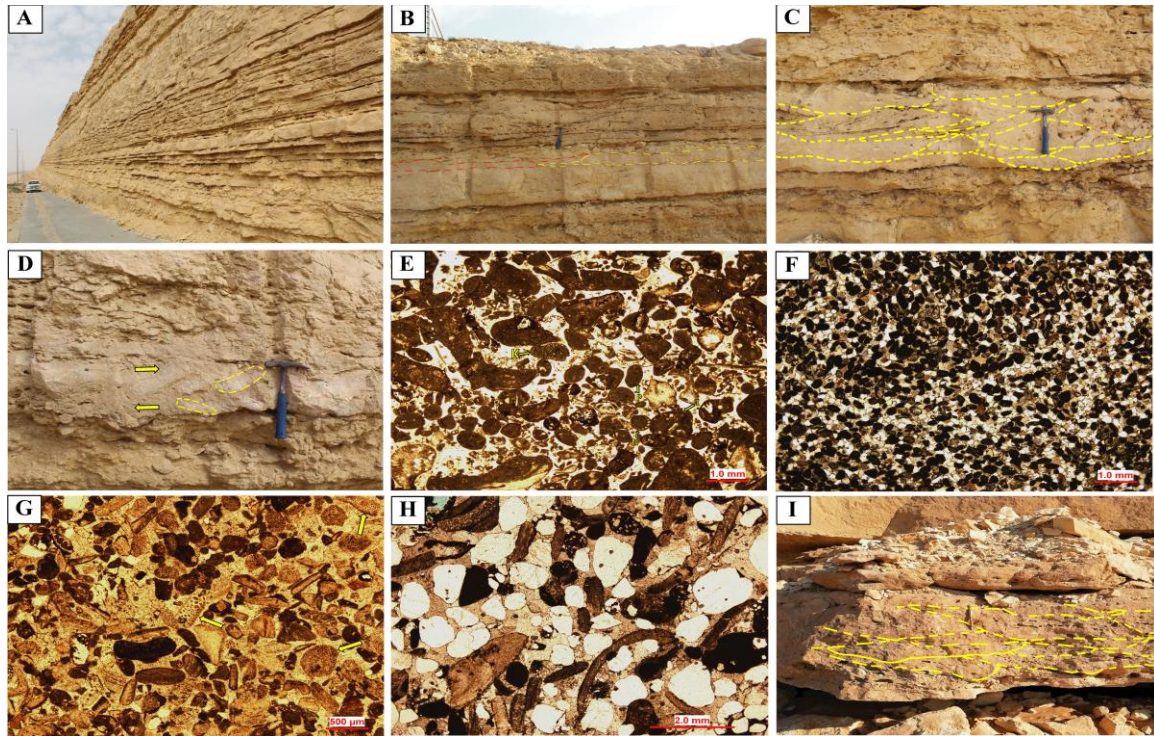


Figure 2.5: Macro and micro features of inner-ramp lithofacies F5 (A, B, C, D, E, F & G) and F6 (H & I). A) Outcrop photograph showing the lateral continuity of F5a isopachous beds. B) Outcrop photograph showing bedding thickness heterogeneity and interfingering beds of F5b (dashed red and yellow lines follow thin bed boundaries of F5b). Note the channelization (indicated by hammer). C) Trough cross-bedding in peloidal grainstone facies (F5). D) Herringbone cross-bedding in F5 demonstrated by stromatoporoid imbricated heads (dashed lines). The yellow arrows show the paleocurrent directions. E) Thin section displaying the first sub-facies of F5 (F5a): grainstone texture with peloids (P), and skeletal grain dominance (*Kurnubia palastiniensis* (K), *Nautiloculina oolithica* (N)) and intraclasts (I). F) Second sub-facies of peloidal grainstone facies (F5b) is dominated by well-sorted fine quartz grains and peloids. G) Thin section image showing transported fragments of inner lagoon dasyclad algae *Pseudoclypeina distomensis* (arrows) in a high-energy skeletal peloidal grainstone of F5. H) Thin section image of calcareous sandstone of F6 displaying well-rounded coarse quartz grains, lithic peloids, and bivalves. I) Small scale trough cross-bedding (yellow dashed lines) in F6.

Beds' thicknesses range from 10 to 150 cm. F5a dominates over F5b and is found through the whole section of Hanifa Formation, often associated with F3. Alternatively, F5b associates the reefal and oncoidal facies (F7 and F9, respectively) and is found in all studied sections but only in the upper part of the Hanifa Formation. F5 displays planar and trough cross-bedding (Figure. 2.5C) and imbricated stromatoporoid intraclasts (Figure. 2.5D). F5 comprises intraclasts, skeletal grains, sub-rounded fine quartz grains, and peloids with variable percentages. Two main abundances of these four components are noticed (F5a and F5b). The first type (F5a) shows more skeletal grains (*Kurnubia palastiniensis*, *Nautiloculina oolithica* (Mohler, 1938), echinoid spines, bivalves) and intraclasts versus quartz grains (Figure. 2.5E). The second type (F5b) is composed of very well-sorted fine quartz grains (Figure. 2.5F) and contains scattered fragments of dasyclad algae *Pseudoclypeina distomensis* (Figure. 2.5G). Peloids are common grains in both sub-facies and are coarser in F5a than in F5b.

Trough cross-bedded sandstone (F6): F6 is characterized by moderately sorted coarse calcareous sandstone. It consists of well-rounded coarse quartz grains with scattered bivalve and lithic peloids (Figure. 2.5H). The sandstone shows planar and trough cross-bedding (Figure. 2.5I). F6 is associated with the laminated siltstones of F4 and is only found in the southern sections (Al Ahmar and As Sullayil).

Coral-stromatoporoid framestone (F7): The framestone is characterized by in situ colonies of hemispherical scleractinian corals (Figure. 2.6A) and stromatoporoid (Figure. 2.6B). The framestone build-ups are massive, forming laterally continuous biostromes of outcrop scale and reaching a thickness of 2.6 m. The dominant coral form is hemispherical heads with diameters ranging from 10 cm to 43 cm. The identified coral species are *Kobyastrea*

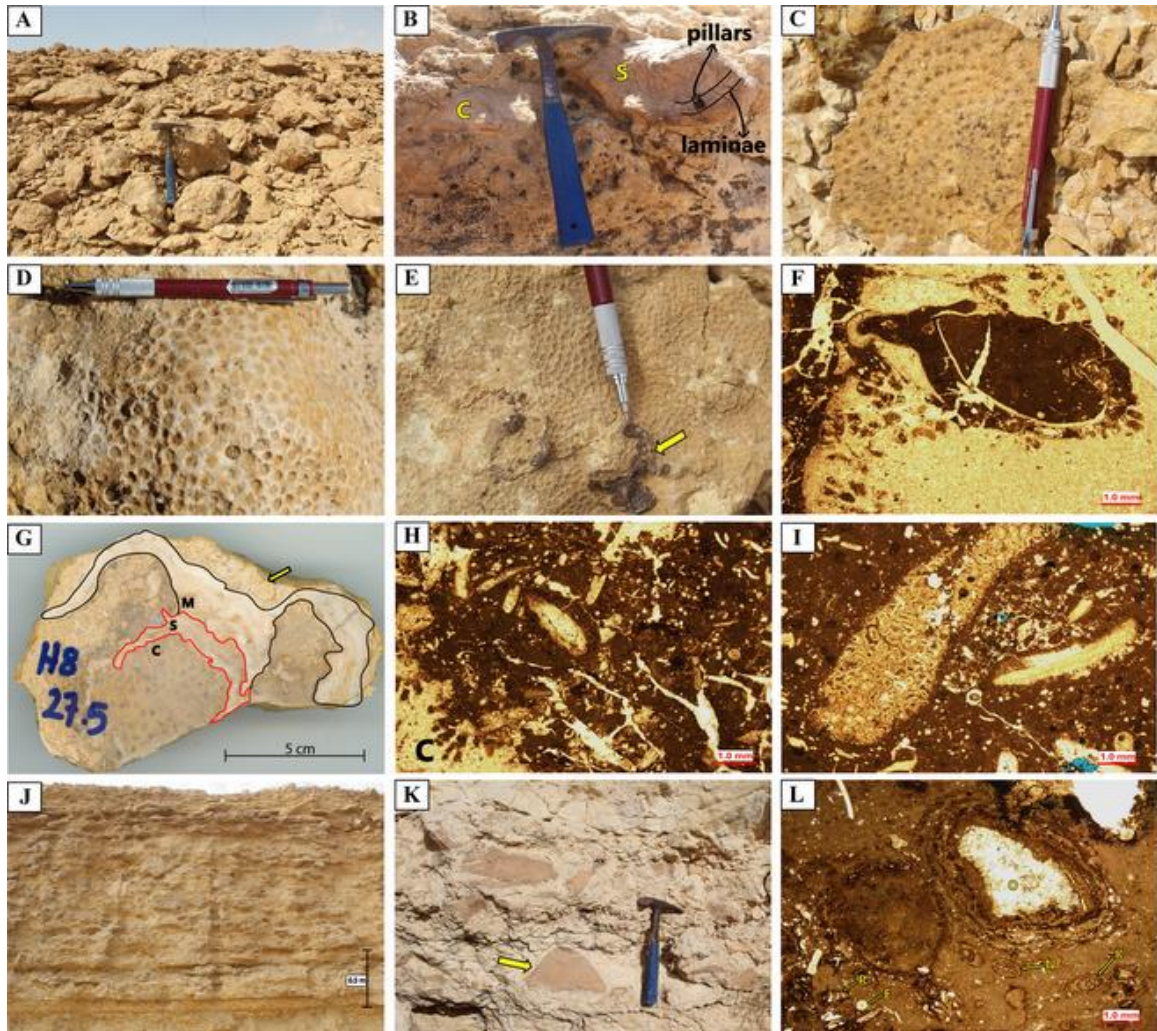


Figure 2.6: Sedimentary features of Phase 2, mid to inner-ramp coral/stromatoporoid reefal lithofacies F7 (A, B, C, D, E, F, G, H, and I) and F8 (J, K, and L): A) Outcrop photo of an in-situ colony of hemispherical scleractinian corals biostrome. B) Stromatoporoid (S) and coral head (C) together in a matrix of oncoidal grainstone (note the laminae and pillars of the stromatoporoid head). C) *Kobyastrea lomontiana* (Etallon 1864) coral with distinctive astraeoid corallites arrangement. D) *Stylina regularis* (Fromentel, 1867) coral species with radial septa, low relief corallite walls, and cerioid arrangement. E) *Actinastrea bernensis* (Koby, 1880-1890) with cerioid corallite arrangement, radial septa, and prominent separating walls. Note the encrusting oysters (arrow). F) Thin section showing micro boring by bivalve through the body of the coral. G) Rock slab of F7 showing multistage encrustation over the coral head (C) by stromatoporoid (S) and then by microbial crust (M) in oncoidal grainstone matrix (arrow). H) Thin section of F7 matrix demonstrating skeletal sponge spiculitic packstone. I) Skeletal packstone matrix of F7 with *Cladocoropsis mirabilis*. J) Outcrop image of F8 displaying horizontal beds of coral and stromatoporoid heads and head fragments, scattered over finer skeletal packstone matrix displaying a floatstone texture (vertical thickness of the roadcut is 3.7 m). K) Close-up outcrop image of F8 showing more allochthonous and less in-situ stromatoporoid heads (arrow). L) Thin section of F8 matrix showing mud-dominated packstone texture with oncoids (O), foraminifera (*Redmondoides lugeoni* (R), *Kurnubia palastiniensis* (K) and *Nautiloculina oolithica* (N)), and echinoid spines (E).

lomontiana (Etallon, 1864), *Stylina regularis* (Fromentel, 1867), and *Actinastrea bernensis* (Koby, 1880-1890) (Figure. 2.6C, D and E, respectively). The corals are bored by bivalves (Figure. 2.6F) and encrusted by oysters, stromatoporoid, and microbial crusts (Figures. 2.6E and G). The framestone has a matrix of either oncoidal peloidal grainstone (Figure. 2.6G), skeletal sponge spiculitic packstone (Figure. 2.6H), or scattered *Cladocoropsis mirabilis* (sponge) within skeletal packstone (Figure. 2.6I). Stromatoporoid-coral floatstone (F8): it is represented by a few scattered in situ and abundant allochthonous calcified demosponges (stromatoporoids) and coral heads, ranging in diameter from 7 to 50 cm, with a skeletal packstone matrix (Figure. 2.6J, K). The stromatoporoid-coral head debris is poorly sorted, the beds are massive, and the bedding planes are erosive, undulated, and poorly defined. The heads are slightly bored by bivalves, unlike the packstone matrix that is heavily burrowed and composed of sponge spicules, foraminifera (*Kurnubia palastiniensis*, *Nautiloculina oolithica*, *Redmondoides lugeoni* (Septfontaine 1977)), echinoid spines, peloids and scattered oncoid grains (Figure. 2.6L). F8 overlies F3 and underlies the F7 coral-stromatoporoid framestone and the F9 oncoidal rudstone.

Oncoidal rudstone (F9): F9 beds are 10 cm to 35 cm thick, massive, and have a rudstone texture with an erosive base and a high concentration of oncoids (Figure. 2.7A). The shape of the oncoids is controlled by the nucleus, i.e., ellipsoidal with bivalves and more spherical with foraminifera and aggregate (made of peloids and skeletal fragments) nucleus. Oncoids' diameter ranges from 1 to 3.5 mm (Figure. 2.7B). Thin section petrography shows the dominance of spongiostromate oncoids, where the cortex is laminated with sparitic patches or laminae (lamination type 2 & 3; Flügel, 2010); (Figure. 2.7C). However, fewer

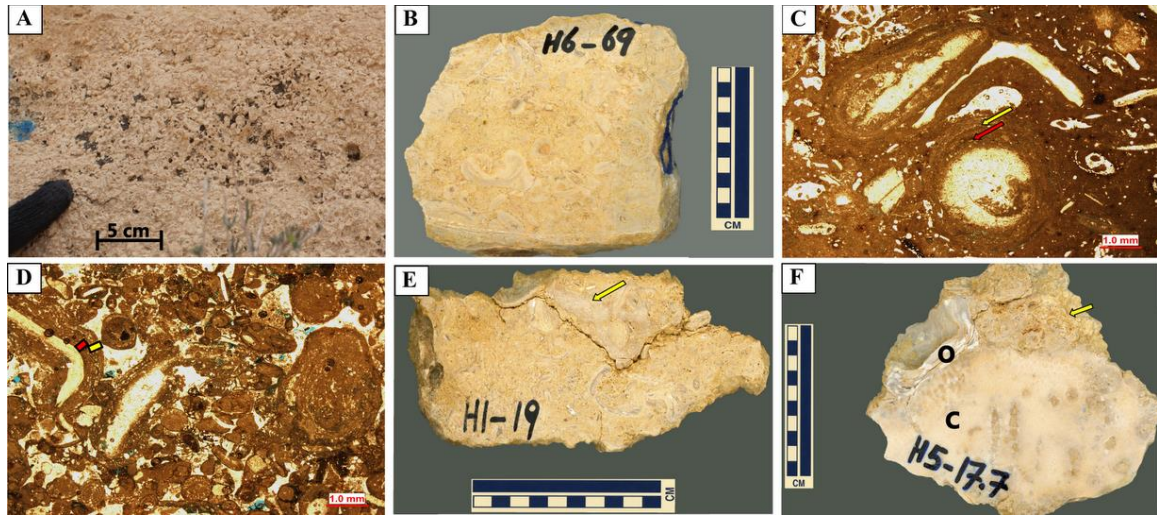


Figure 2.7: Oncoidal rudstone facies (F9): A) Outcrop image of massive, highly concentrated oncolitic rudstone bed. B) Rock slab image showing different shapes of oncoids (more spherical and ellipsoidal) with poor sorting. C) Spongiostromate oncoids with scattered sparite-filled patches (red arrow) and laminae (yellow arrow); (lamination type 2 and 3 (Flügel, 2010)). D) Porostromate oncoids formed by *Bacinella irregularis* (lamination type 5). Some oncoids are combination type (spongiostromate and porostromate) (red and yellow bars to the left). E) High microbial activity is noticeable in F9; note the encrusting *Girvanella* (arrow). F) Association of oncolitic rudstone (F9) (arrow) and coral (C). Note the encrusting oyster (O).

oncoids are encrusted by *Bacinella irregularis* (porostromate) (lamination type 5; Flügel, 2010; Peryt, 1981) (Figure. 2.7D). Combination forms and multistage formation of oncoids are also observed (Figure. 2.7D). Few cyanobacteria (*Girvanella*) either occur as independent colonies or coat skeletal peloidal aggregate grains (Figure. 2.7E). Associated grains include monaxon sponge spicules, foraminifera (*Kurnubia palastiniensis*, *Nautiloculina oolithica*), echinoid spines, peloids, intraclasts, gastropods, and micrite-enveloped grains that are highly cemented by sparite. F9 shows interbedding with cross-bedded peloidal grainstones (F5b) and is associated with the coral-stromatoporoid framestone (F7) as a matrix between coral hemispheroids (Figure. 2.7F).

2.4.2 Facies Interpretation

F1: The fine texture and massive appearance of F1 support a low-energy depositional environment. However, the horizontal lamination could result from lower plane bedform conditions resulting from the gravitational settlement of fine sediments in quiet water (Ashley, 1990). Fine quartz and clays indicate the input of a fine siliciclastic suspended load, which was transported and deposited in a relatively deeper environment. The Late Jurassic siliceous sponge spicules indicate deep and open marine conditions (Gammon and James, 2001; Hughes, 2004). Consequently, F1 is considered a deep outer-ramp deposit.

F2: The intraclast size and the rudstone texture of F2 beds with erosional surfaces indicate high-energy currents that ripped up early lithified clasts. The cut-and-fill structures, associated with coarser intraclasts, mark relatively higher energy conditions. The nature of the intraclasts (sponge spiculitic wackestone and massive mudstone) indicates a relatively deep marine environment. In addition to the normal grading, these criteria point towards

storm-generated currents that deposited mid-ramp gravel sheets and channel fills (Wignall and Twitchett, 1999; Handford et al., 2002).

F3: Low energy sedimentation is proposed for the wackestones of F3 lithofacies based on its texture, massive bedding, and the existence of the sponge spicules (Hughes et al., 2008; Flügel, 2010). Because no bioherms were detected in the examined sections in F3, the siliceous sponge spicules imply the presence of entirely disaggregated sponge colonies. Furthermore, since sponges are filter-feeders, they suggest low sedimentation rates required to develop sponge colonies (Krauter, 1998). Moreover, the association with mudstone beds of F1 confirms the deep marine conditions in a distal mid-ramp setting. The superimposition with packstones of F3 supports intermittent relatively shallower and higher-energy conditions. Still, sedimentation remains below the fairweather wave base because of the absence of sedimentary structures and diagnostic faunal assemblage. The high biodiversity in micro-fossils and the intensive bioturbation indicate open marine conditions (Taylor and Goldring, 1993) and suggest a gradual change from distal to proximal, mid-ramp setting (wackestone to packstone texture, respectively).

F4: The fine texture of the claystone and the horizontal lamination of F4 indicate overall low energy conditions, with net deposition out of suspension. The coarsening upward pattern from claystone to siltstone, the existence of *Skolithos* ichnofossil in the upper part of the siltstone beds, and the association of the overlying trough cross-bedded calcareous sandstone strongly suggest siliciclastic deposition below fairweather wave-base in a mid-ramp setting (MacEachern and Pemberton, 1992; Pemberton et al., 2012; Wesolowski et al., 2018).

F5: The planar and trough cross-bedding of both lithofacies F5a and F5b, in addition to the grainstone texture, with bedding constrained by erosive bases, indicate constant high energy conditions associated with waves. To interpret F5a lithofacies, firstly, the imbricated stromatoporoid intraclasts suggest a high-energy bidirectional flow (Gough, 2021). The absence of stratigraphically adjacent reef facies beds (F7) to F5a and the imbricated stromatoporoid intraclasts are interpreted by shallow marine patch reefs, eroded by waves and tidal currents. F5a overlies F3, and its skeletal packstone intraclasts show evidence of erosion of the relatively deeper facies. The laterally continuous bedding of F5a, with constant thickness, indicates the continuity of high energy conditions over a wide area. Therefore, the grainstone of F5a is interpreted to be deposited as sheet-like carbonate sand bodies in an inner-ramp setting (Burchette et al., 1990; Meyer and Price, 1993; Bauer et al., 2002, Flügel, 2010).

Concerning F5b, the associated reefal facies (F7) possibly played the role of an antecedent relatively high topography that formed subaqueous shoals (Rankey and Reeder, 2012; Harris et al., 2019). As the shoal's substrate, the reef high's spatial heterogeneity resulted in spatial hydrodynamic variability and wave currents' focus on narrow zones (Cruz and Eberli, 2019). Consequently, the morphology and size difference of the shoal bodies resulted in sets of amalgamated beds of variable thickness. The shoal banks developed due to the continuous wave action, which results in very well sorted quartz grains and peloids. The quartz grains are indicators of a nearby siliciclastic source. The dasyclad algae fragments indicate a shallow lagoonal source from back shoals (Hughes et al., 2008). In contrast, when the quartz peloidal grainstone of F5b lithofacies is compared with the skeletal peloidal grainstone (F5a), the beds of F5a are similar in terms of thickness but are

laterally more continuous and display more uniform bed thicknesses (i.e., sand sheets) (Figure. 2.5A, B).

F6: The calcareous sandstone with tractive-current structures (trough cross-bedding), the high degree of roundness, and the coarse size of F6 quartz grains indicate a multi-directional flow above the fairweather wave-base. Based on these criteria and the associated underlying claystone-siltstone facies (F4), F6 is interpreted as a proximal inner-ramp deposit (Walker and Plint, 1992; Dumas et al., 2005).

F7: The in situ massive hemispherical scleractinian coral and stromatoporoid heads in F7 indicate a reef-crest environment with moderate to strong wave energy (Karabiyikoğlu et al., 2005; Playton et al., 2010). The encrusting oysters with their sheet-like shells confirm the high energy conditions. The existence of stromatoporoids suggests extremely shallow warm water and a high-energy abrasive environment; favorable conditions for the Jurassic stromatoporoids. Moreover, the co-existence of corals and stromatoporoids in F7 indicates oligotrophic normal marine water (Leinfelder et al., 2005). Generally, the Jurassic scleractinian corals started to recover after the Permo-Triassic extinction and were in a young stage of a relationship with photosymbiotism. Therefore, unlike recent corals, Late Jurassic corals were adapted to mesotrophic conditions (Leinfelder et al., 2002; Leinfelder et al., 2005). However, in the studied sections, encrusting *Girvanella* shows that the southern Neo-Tethys Oxfordian corals of the Hanifa Formation could have harboured photosymbionts to survive the oligotrophic conditions in the shallow photic zone. The reefs and associated shoal environments pass laterally into each other since they exchange the stratigraphic position as the shallowest facies in the shallowing upward cycles of the Hanifa Formation. The framestone of F7 was deposited in a shallow typical marine environment

in the inner-ramp zone (Karabiyikoğlu et al., 2005). Although the reef crest zone, with domal coral heads, is laterally continuous and found in all studied sections, except in the Al-Ahmar and As-Sulayyil areas (southward) where siliciclastics dominate, they could represent reef patches in different locations and time intervals. A more detailed time correlation is needed to prove the reef continuity through the upper Oxfordian outcrops in central Saudi Arabia.

F8: Since some of the stromatoporoid heads show in situ growth position among the coral-stromatoporoid debris, these heads grew for a short time before becoming abraded by waves and suffocated by their debris (Leinfelder, 1992; Leinfelder et al., 2002). The allochthonous corals and stromatoporoids indicate the transportation of intra-formational gravels and boulders of collapsed reef framework by falling or sliding in an upper fore-reef environment (Riding et al., 1991; Hine et al., 1992; Ross, 1992; Drzewiecki and Simó, 2002; Playton et al., 2010). The randomly-oriented intraclasts, the petrographic similarity between F3 and the matrix of the floatstone (skeletal packstone), and the associated lithofacies all indicate a gravel-dominated fore-reef environment in intermediate conditions between the inner and mid-ramp (Playton et al., 2010).

F9: The rudstone texture of F9, the grainstone texture of the encasing sediment, and the intraclasts are high depositional energy indicators (Dahanayake, 1983; Flügel, 2010). Ellipsoidal to spherical morphology of the laminated oncolite surface shows a high degree of rolling on the sea bottom and hence a relatively high wave or current energy (Védrine et al., 2007; Flügel, 2010). The *Bacinella irregularis* micro-encruster on oncolites reflects relatively lower energy deposits with a low background sedimentation rate because of their slow growth (Dahanayake, 1977; Peryte, 1983, Leinfelder et al., 1993). Moreover,

Bacinella irregularis encrustation characterizes shallow marine environments with clear, oxygenated, normal-salinity water and oligotrophic conditions (Leinfelder et al., 1993; Dupraz and Strasser, 1999; Immenhauser et al., 2005). The low energy conditions probably led to the development of thin-walled cyanobacteria colonies (*Girvanella*), porostromate oncoid, or non-deposition. The multistage nature of many oncoids (Figure. 2.7D) indicates an oscillation in the hydrodynamism with intermittent high energy. The high abundance and diversity of fossil content support an open marine interpretation. The stratigraphic location of F9 regarding F7 shows that F9 likely corresponds to a shallow open lagoon deposit in an open back reef environment.

2.4.3 Facies Associations and Platform Evolution

The diverse sedimentological criteria of the Oxfordian Hanifa Formation studied outcrops have led to the recognition of four lithofacies associations: outer-ramp association (FA1), mid-ramp association (FA2), inner-ramp association (FA3), and inner-ramp association (reef-related association) (FA4). The vertical distribution of the lithofacies allowed to distinguish two main depositional phases, composed of different facies associations. These phases stratigraphically correspond to the Hawtah (middle Oxfordian) and Ulayyah (late Oxfordian) Members, respectively. The lithofacies of Phase 1 are comprised of F1, F2, F3, and F5a, whereas Phase 2 is formed of F1, F3, F4, F5 (a, b), F6, F7, F8, and F9. The gradual vertical change in facies, the bedding geometry, the absence of non-skeletal/skeletal shallow marine, high-energy barrier, and landward restricted facies characteristic of carbonate rimmed shelf settings support a homoclinal carbonate ramp depositional model for both Phase 1 and Phase 2. However, the reef-related facies association (FA4) in Phase 2 shows criteria of only partial restriction in the back-reef zone and without slope-related

facies criteria in the fore-reef zone, which indicates the dominance of the ramp depositional model, i.e., a reef-bearing carbonate ramp.

A homoclinal carbonate ramp system with neighboring depositional environments and facies belts was typical of Phase 1, with gradual lateral facies variations. The lower part of Phase 1 is dominated by outer-ramp depositional conditions (FA1). This part is better examined in sections H2 and H3, located in the center and north of the transect, and includes road cuts. The deepest facies of Phase 1 consists of an outer-ramp argillaceous carbonate mudstone of F1 that contains siliciclastic suspended load. The associated storm-related intraclast rudstone (F2) represents a mid-ramp facies (FA2) and is only found in section H2. Carbonate mudstone of F1 (FA1) gradually interbeds with the mid-ramp skeletal sponge spiculitic wackestone and packstone of F3 (FA2) in a shallowing upward pattern. The shallowest facies of Phase 1, which dominates its upper part, consist of cross-bedded skeletal peloidal grainstone (F5a) that gradually interbeds with and overly F3 and represents shallow high-energy inner-ramp sand sheets (FA3).

The main feature that distinguishes the two depositional phases of the Hanifa Formation, lithostratigraphically, is the presence of the reef-related facies association (FA4) in Phase 2 and the siliciclastic facies southward. The general absence of the coral reefs in southern Neo-Tethys during the middle Oxfordian is attributed to many factors. The heavy tropical rainfall could accelerate the influx of terrigenous mud, resulting in a scarcity of reefs in the low latitude zone (Parrish et al., 1982; Valdes and Sellwood, 1992). In the studied sections, the siliciclastic mud is evident in the outer-ramp carbonate mudstone (F1). However, the absence of counterpart shallow marine siliciclastic lithofacies in Phase 1 makes the tropical heavy rainfall scenario inapplicable to the Arabian Plate. The ramp platform configuration

could be another reason that causes reef destruction and reefal debris exportation (Leinfelder et al., 2002). The only index that could support this scenario is the stromatoporoid imbricated intraclasts in the peloidal grainstone (F5b). Nevertheless, no coral heads were found beside the stromatoporoid intraclasts. Finally, the poor development of coral reefs in Phase 1 could be due to the over-heated tropical water during the middle Oxfordian (Moore et al., 1992a; Moore et al., 1992b; Sellwood et al., 2000; Leinfelder et al., 2005) corresponding to a time of Oxfordian thermal maximum around the Neo-Tethys margins (Cecca et al., 2005).

The late Oxfordian Phase 2 outer and mid-ramp facies associations (FA1 and FA2, respectively) resemble those of Phase 1. They dominate the lower part of Phase 2 and gradually exhibit reduced representation upward. During Phase 2, the inner ramp is characterized by the onset of coral-stromatoporoid biostrome (F7) and their related facies (F8 and F9). The inner-ramp is distinguished by laterally continuous beds of cross-bedded skeletal peloidal sand sheets (F5a) and lenticular beds of quartz peloidal grainstone shoals (F5b). Southward, the mid-ramp and inner-ramp zones are represented by lower shoreface claystone/siltstone and upper shoreface trough cross-bedded sandstone, respectively. The presence of the coral reef could be attributed to the warm conditions during the late Oxfordian, which, however, was relatively cooler than the middle Oxfordian (Cecca et al., 2005). However, coral reefs are absent southward due to the high siliciclastic influx.

2.5 Discussion

2.5.1 Regional Depositional Model

The lithofacies analysis and reconstruction of the depositional environment of the Oxfordian Hanifa Formation was the scope of many research activities in various parts of

the Arabian Plate, either in outcrop or in the subsurface (Figure. 2.1C). In their study addressing the middle and late Oxfordian sedimentary record in Wadi Nisah, south of Riyadh city, Eltom et al. (2017) distinguished four facies associations of shallow carbonate ramp surrounding the Arabian intra-shelf basin facies. Fallatah and Kerans (2018) extended the studied area along an oblique transect and reached Wadi Birk, ~ 142 km south of Riyadh city. They also proposed a gently sloping carbonate ramp depositional model with open marine conditions for the Hanifa Formation. Elzain et al. (2020) analyzed the lithofacies of the late Oxfordian Ulayyah Member succession in the Jebel Abakkayn area, north of Riyadh, in the northwestern part of the Jurassic outcrop belt in Saudi Arabia. They presented ten lithofacies spread over three main facies belts, corresponding to outer-, middle- and inner-ramp zones.

On the other hand, El-Sorogy et al. (2018) targeted the Hanifa Formation in three outcrops north of the capital Riyadh. They recognized 14 lithofacies reflecting five associations: off-shoal, fore-shoal, shoal, back-shoal, and tidal flat. They proposed a rimmed carbonate platform setting with a well-developed lagoon. Al-Mojel et al. (2020) studied the lithofacies of the Upper Jurassic formations in the Arabian Plate based on fourteen outcrops. They correlated their studied sections with the subsurface using a gamma-ray log. They proposed a mud-dominated platform (inner lagoon) with oncoidal and peloidal shoals that grade subsurface into a back barrier and an open marine reef-bearing platform for the Hanifa Formation.

Droste (1990) used subsurface cores from Qatar to demonstrate the existence of an intrashelf basin. He interpreted organic-rich wackestone and mudstone in the Hanifa Formation as intrashelf basinal deposits, surrounded by shallow platform bioclastic

packstones and grainstones. Hughes et al. (2008) studied the biocomponents of the Ulayyah Member in detail, using cores from 41 wells in central and eastern Saudi Arabia (Figure. 2.1C). They proposed a rimmed shelf carbonate depositional model for the Hanifa Formation, with a well-developed lagoon. McGuire et al. (1993) and McGuire (2003) used 32 cores with 142 well logs and 200 wells, respectively, to study the upper Oxfordian Hanifa reservoir (Ulayyah Member) in the Berri field, 100 km north of Dhahran city (Figure. 2.1C). They proposed a depositional model corresponding to a mid to deep outer-ramp setting that grades into shallower mid- and inner-ramp skeletal peloidal grainstones, conglomerates, and small reefs. Al-Suwaidi et al. (2000) studied the subsurface Oxfordian succession in U.A.E, equivalent to the Hanifa Formation, using regional seismic lines, well logs, cores, and strontium isotope dating. They identified an outer shelf of organic-rich fine-grained carbonates, which grade into slope and shelf edge bioclastic packstone and grainstone and then into an inner shelf protected zone.

According to the current study, the middle Oxfordian Hawtah Member (Phase 1) corresponds to a homoclinal ramp, from inner to outer setting (Figure. 2.8A), with a lack of large barrier reef belts. However, the stromatoporoid intraclast imbrication in the skeletal peloidal grainstone lithofacies (F5a) (Figure. 2.5D) proves the existence of biogenic build-ups in Phase 1 at least as small patch reefs, in addition to the high-energy conditions that kept destroying them. Moreover, the herringbone cross-bedding of F5a indicates shallow sedimentation conditions (intertidal zone) (Gough, 2021) but without evidence of exposure.

During the late Oxfordian (Phase 2), the Ulayyah Member illustrates the evolution into a reef-bearing ramp model with a reefal facies association (FA4: F7, F8, and F9) developed

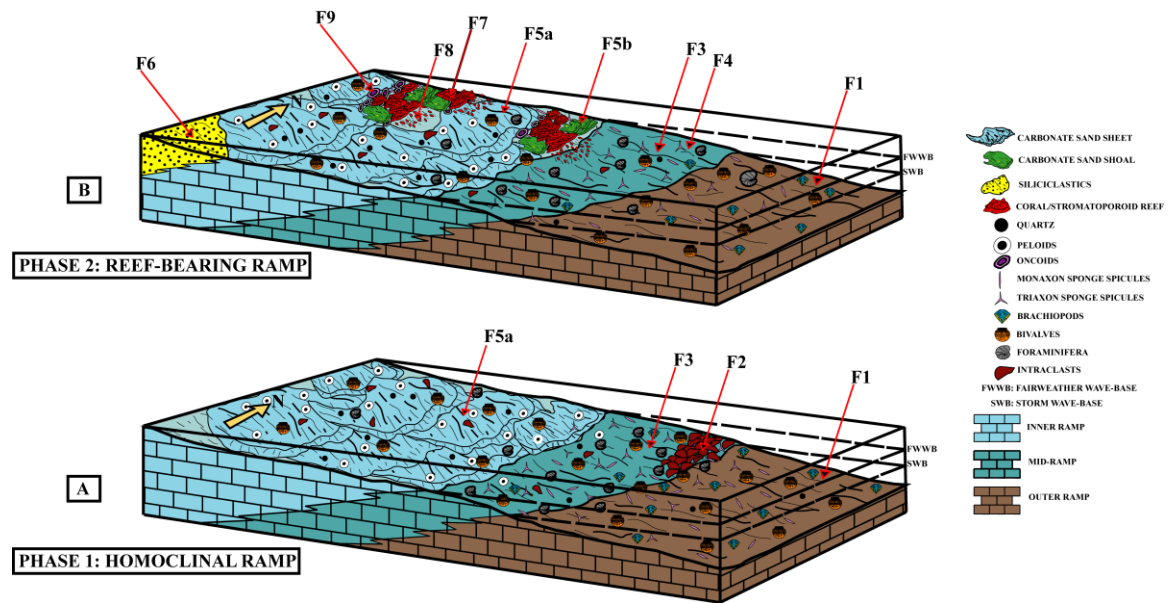


Figure 2.8: The three-dimensional depositional model of the Oxfordian Hanifa Formation outcrops in central Saudi Arabia illustrating different lithofacies distribution. A) Middle Oxfordian Hawtah Member with a homoclinal carbonate ramp model. B) Late Oxfordian Ulayyah Member, with a reef-bearing carbonate ramp model.

in the inner-ramp zone (Figure. 2.8B). Nevertheless, where reefal lithofacies are absent, Phase 2 resembles Phase 1, with a difference in the relative contributions of lithofacies. In Phase 2, evidence of a lagoon in the back-shoal zone is reflected by the scattered dasyclad algae *Pseudoclypeina distomensis* fragments in the associated quartz peloidal grainstones of F5b. The high energy criteria of F5b lithofacies indicates that the algae fragments are transported, and the lagoon environment was not fully protected. Moreover, the oncoidal rudstone lithofacies (F9), with encrusting *Bacinella irregularis* algae, confirms an open lagoon's clear, oxygenated and normal salinity water conditions in the back-reef zone. The vertical facies succession of the Hanifa Formation shows an overall shallowing upward pattern. In the lower part of each member (Hawtah and Ulayyah), the mid-ramp lithofacies overly the outer-ramp carbonate mudstone. This cyclicity continues upward with a gradual decrease in the outer-ramps lithofacies thickness and the gradual appearance of the inner-ramp lithofacies that cap the cycles.

2.5.2 Regional Controls on Oxfordian Ramps

It is clear that the majority of outcrop studies came up with carbonate ramp models (Eltom et al., 2017; Fallatah and Kerans, 2018; Elzain et al., 2020), whereas rimmed-shelf models were favored in subsurface studies (Droste, 1990; Al-Sawaidi et al., 2000; Hughes et al., 2008). This model might be justified by the location of the study area in each research related to the regional basin geometry. The outcrop studies mainly cover the gently sloping paleo-epeiric sea to the west, making a proper template for a homoclinal ramp to develop. However, this study proved that faint rimmed shelf criteria (reef front and back-reef) were noticed whenever reef facies were found in the upper Oxfordian Ulayyah Member. A comprehensive conceptual model is proposed with the enrollment of the basin's structural

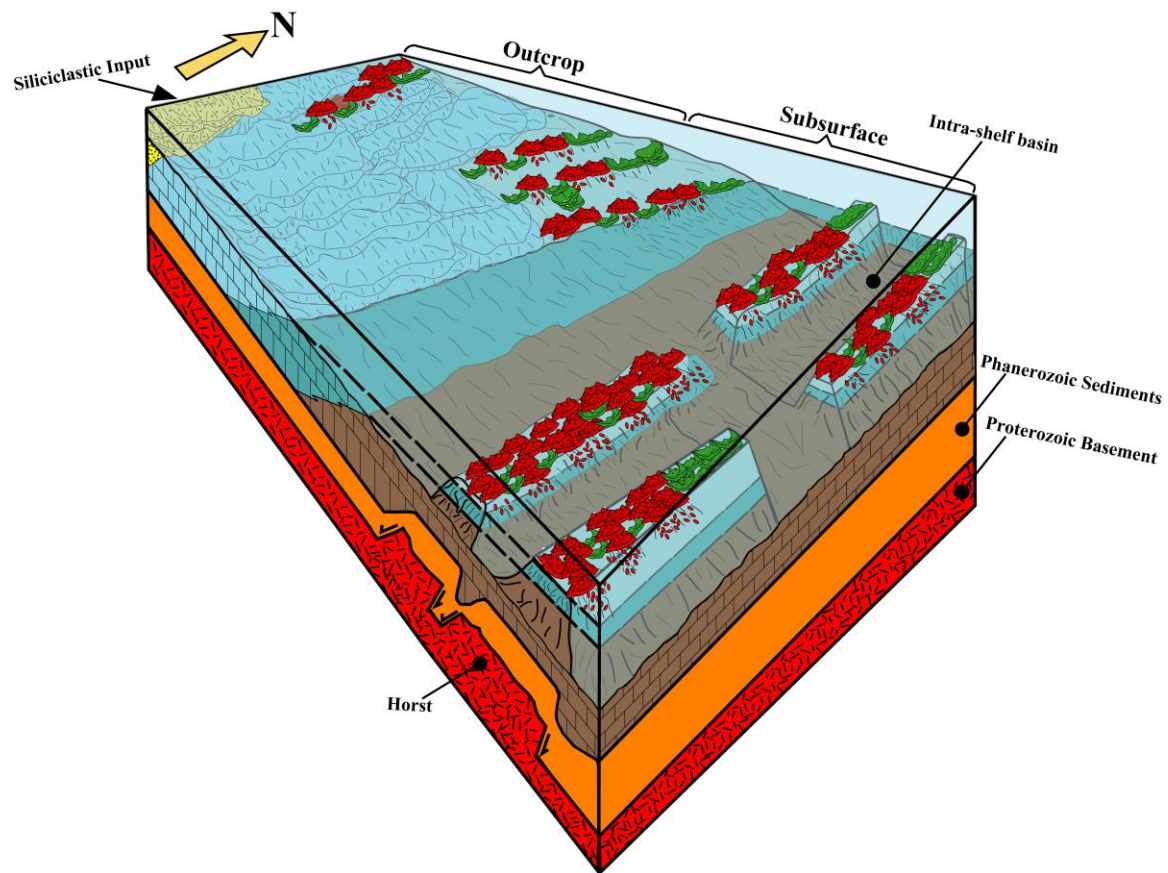


Figure 2.9: Three-dimensional conceptual depositional model representing the late Oxfordian Hanifa Formation in Arabian Plate. It covers the outcrop belt in the west and the subsurface section in the east (note the existence of paleo-highs (horsts) in the subsurface). For legend, refer to Figure 2.8.

evolution (Figure. 2.9). Toward the east, subsurface research on the Hanifa Formation (Droste, 1990; Al-Suwaidi et al., 2000; Hughes et al., 2008; Al-Mojel et al., 2020) mainly focused on the major anticlines that make the giant oilfields and the intra-shelf basins in-between. These structures were formed due to the Permo-Triassic reactivation of basement horsts (Wender et al., 1998; Alsharhan and Nairn, 2003; Carruba et al., 2006) and the triggering of subsurface salt diapirs (Edgell, 1996). They formed and controlled the subsequent succession characteristics and kinds of deposition (Edgell, 1992; Konert et al., 2001; Pollastro, 2003). The paleo-highs (horsts) have a general N-S trend (Perotti et al., 2011; Stewart, 2016; Stewart et al., 2016; Figure. 2.10A, B), where they created favorable conditions (i.e., light, waves, substrate, and shallow oxygenated water) for shelf-edge lithofacies to exist. This major paleo-highs (N-S) trend goes well with the Oxfordian subsurface maps of the Hanifa Formation rimmed shelf depositional model (Murriss, 1980; Droste, 1990; Al-Suwaidi et al., 2000; Hughes et al., 2008; Al-Mojel et al., 2020). The detailed subsurface work of McGuire et al. (1993) and McGuire (2003), which proposed a homoclinal carbonate ramp, does not contradict this general setting because his subsurface profile had a N-S trend parallel to the primary structures.

2.5.3 Siliciclastic Lithofacies

For the first time, a well-developed late Oxfordian shallow marine siliciclastic facies belt (F4 and F6) is documented in the southern section of the Jurassic outcrops: i.e., in the Al-Ahmar and As-Sulayyil areas. The late Early Jurassic was a period of thermal uplifting in the southern borders of the Arabian plate, synchronized with the initiation of the Indian Ocean (Sharland et al., 2001; Ziegler, 2001). This uplifting event created a siliciclastic sediment source in the western and southern areas. Siliciclastics have been found

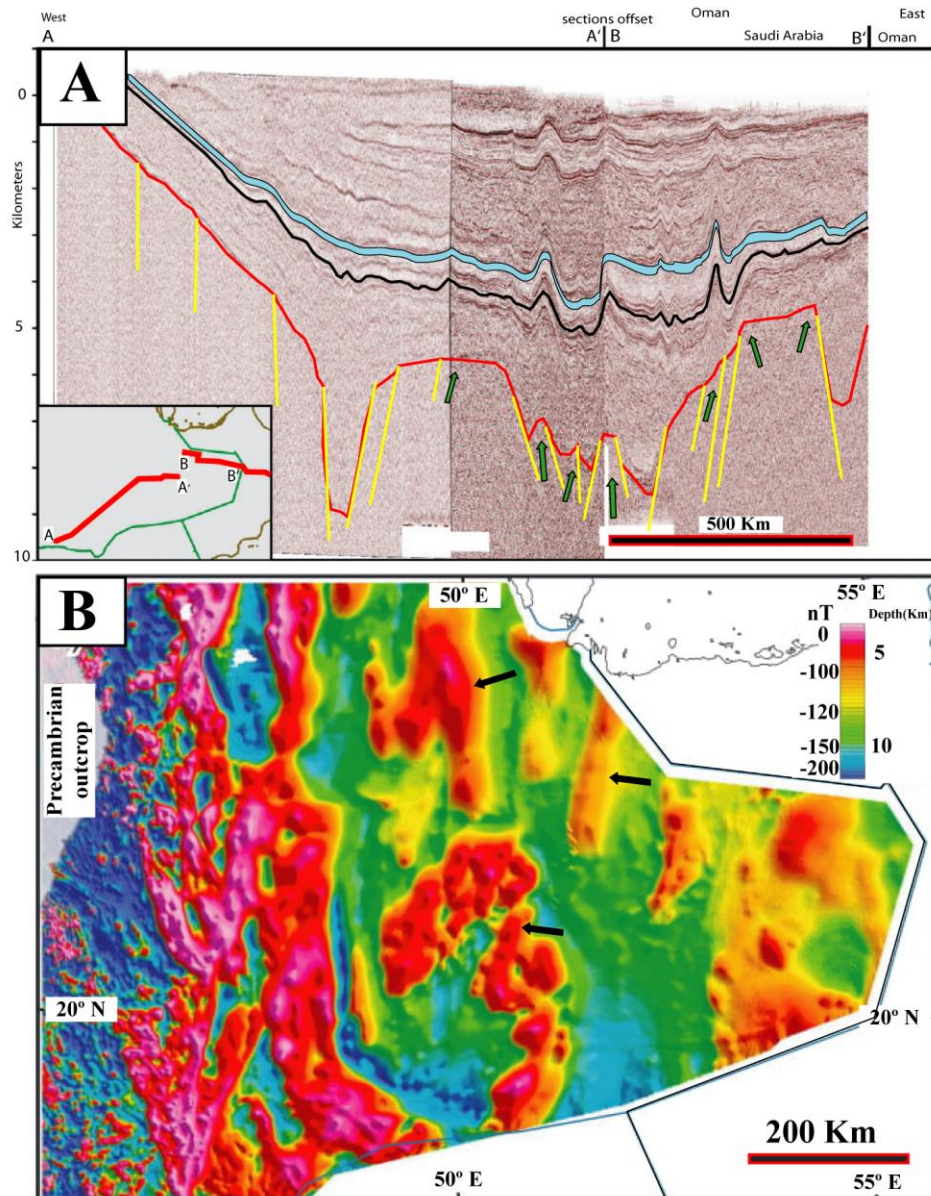


Figure 2.10: Hanifa Formation subsurface interpretation. A) A composite general E-W regional seismic section crossing the Arabian Plate and showing the whole Phanerozoic succession lying unconformably over the Proterozoic basement. The red line marks the basement top, and the basement faults are in yellow. A black line marks the Permo-Triassic boundary time-line, and the light blue interval indicates the studied interval. Note the paleo-highs (arrows), which were reactivated in the Permo-Triassic period (modified after Stewart et al., 2016). **B)** Interpreted depth of N-S trend Proterozoic basement highs (arrows) using aeromagnetic data. The top of those paleo-highs controlled the subsurface distribution oil reservoir intervals of late Oxfordian shallow marine coral/stromatoporoid reefs and shoals of peloidal grainstone lithofacies and the organic-rich source rock in the intra-shelf basins between the highs (modified after Stewart, 2016).

associated with carbonates in the late Early Jurassic Marrat Formation (Stewart et al., 2016; Farouk et al., 2018), the Middle Jurassic Dhurma Formation (Al-Aswad, 1995; Stewart et al., 2016; Al-Hussaini et al., 2019), and the Upper Jurassic Jubaila Formation (Al-Mojel et al., 2020). The Oxfordian Stage witnessed the Indian-Arabian Plate separation and the continuous development of the Yemen rifting-related uplifting (Davis et al., 2019). In addition to the dominant warm-humid climate (Cecca et al., 2005), this uplifting provided siliciclastic input from the southwestern direction. Consequently, a new potential reservoir zone could be added to the Hanifa reservoir system in the Ulayyah Member, represented by a coarse moderately-sorted upper shoreface calcareous sandstone. However, this potential reservoir is restricted to the southern section of the Jurassic belt and thus could be considered an exploration target in the Rub' Al-Khali Basin.

2.6 Conclusions

The Oxfordian depositional system of the southern Tethys was investigated through a high-resolution sedimentological study of eight outcrops of the Oxfordian Hanifa Formation along a 535 km-long curved transect through the Jurassic outcrop belt in Central Saudi Arabia. This study supports the finding that the carbonate homoclinal ramp depositional model can be used for both Hawtah and Ulayyah members of the Oxfordian Hanifa Formation outcrops. Nine sedimentary lithofacies (F1-F9) are defined and grouped into four associations (FA1-FA4) based on the dominant grain types, sedimentary structures, ichnofacies, depositional texture, bedding architecture, and lithofacies relationship. These lithofacies are interpreted to have been deposited in outer-ramp, mid-ramp, and inner-ramp depositional zones. Stratigraphically, two defined depositional systems (Phase 1 & Phase 2) are equivalent to the middle Oxfordian Hawtah and upper Oxfordian Ulayyah Members,

respectively. The two phases correspond to homoclinal ramp systems but with the development of large patch reefs in the second phase. Reef-related carbonate sand shoals were established with associated front and back-reef domains, marking faint carbonate shelf criteria that may resemble the development of shelf morphologies in subsurface distal zones of the Hanifa system towards the east. However, the outcrop depositional system of Phase 2 is still defined as a reef-bearing homoclinal ramp. Although the global distribution of coral reefs during the middle Oxfordian, the conditions for coral reef growth in the Hawtah Member were quite unfavorable, possibly due to the overheated tropical water in the southern Neo-Tethys. Mainly sourced from the south, inner-ramp coarse calcareous sandstones and mid-ramp horizontally laminated siltstone and massive claystone are described for the first time from the Hanifa Formation, in the southern section of the Jurassic outcrop belt of Saudi Arabia. The siliciclastic lithofacies add a potentially new upper Oxfordian reservoir, especially in the Rub' Al-Khali Basin.

CHAPTER 3

Sequence and Chemostratigraphy of the Oxfordian Hanifa

Formation, central Saudi Arabia

Abstract

Sequence stratigraphy is considered one of the most powerful hydrocarbon exploration and development tools. A continuous pattern characterizes the well logs of the Jurassic succession and the Oxfordian Hanifa Formation in central Saudi Arabia, particularly due to its muddy nature. This continuous pattern makes identifying and correlating stratigraphic formations and members difficult, especially in the absence of biostratigraphic data.

A high-resolution sequence and chemostratigraphic frameworks are presented based on the Oxfordian Hanifa Formation outcrops in central Saudi Arabia. The studied outcrops extend over a 535 km long transect and represent a total cumulative thickness of 430 m of the stratigraphic sections of the Oxfordian outcrop belt in central Saudi Arabia. A total of sixteen fourth-order sequences (seq. 1-seq. 16) were interpreted using sequence stratigraphic principles and by observing lithofacies changes and bounding surfaces between sedimentary packages of eight outcrops. Moreover, the strata stacking patterns of the fifth-order sequences are used to capture the fourth-order sequences by applying a Fischer plot. The plot shows facies partitioning and an overall pattern similar to the global sea level curve. The dominant depositional sequence types show shallowing upward patterns, starting with an outer ramp argillaceous carbonate mudstone (transgressive

systems tracts (TST)) that changes into mid- and inner-ramp lithofacies (highstand systems tracts (HST)). Shallowing upward siliciclastic sequences are described for the first time within the Hanifa Formation southward outcrops. The correlation between interpreted sequences was also refined by elemental chemostratigraphy. Four chemostratigraphic divisions (C1, C2, C3, and C4) were interpreted following the vertical variation of the major elements Si, Al, Ca, Mn, and Fe. Chemostratigraphic correlation of the studied outcrops with a well in east Saudi Arabia enables subsurface subdivision at high resolution. Based on the predominance of the outer- and mid-ramp lithofacies, a westward extension of the Arabian Intrashelf Basin is suggested in the northern section of the examined transect. Due to the interpreted deep depositional conditions, the coral/stromatoporoid reefal lithofacies are poorly developed northward. However, they dominate the HST southward rather than the inner-ramp grainstone until they represent the border with the younger Jubaila Formation in Wadi Mawan (H6). The siliciclastic sequences dominate the southern end of the investigated transect, which results in the disappearance of the reefal lithofacies association. The study provides a means for using strata stacking patterns to study the Hanifa Formation sequences, and the elemental chemostratigraphy for regional correlation.

3.1 Introduction

Stratigraphic sequences are packages of sedimentary rocks bounded by stratigraphic surfaces with distinctive strata stacking patterns (Catuneanu, 2019). The stratal stacking patterns arise from the interaction of sedimentation and accommodation space creation rates. In sedimentary successions, the change in these patterns is used to identify the sequence stratigraphic surfaces. The definition of stratigraphic sequences and their

bounding surfaces allows for reconstructing the depositional history within sedimentary basins since they are considered time-lines that describe certain events (Catuneanu, 2006; Embry, 2009; Catuneanu et al., 2011). The sequence stratigraphic investigation of a basin fill is an effective tool in hydrocarbon exploration and development. It allows lithofacies prediction and the definition of sedimentary bodies' architecture and their correlation (Catuneanu, 2006; Slatt, 2006; Zecchen and Catuneanu, 2013). However, integrating multiple data sets with various resolutions is required to observe the entire spectrum of stratigraphic complexity as it evolves at different scales. In this context, a chemostratigraphic approach could complement a sequence stratigraphy approach. Chemostratigraphy is a geochemical correlation method that uses inorganic geochemical data. It offers many potential variables (chemical elements) that go beyond the boundary of lithology, age, and depositional environment (Craigie, 2018).

One of the most significant hydrocarbon reserves in the world relates to the Jurassic succession of the Arabian Plate, particularly in Saudi Arabia, where several production zones are found. The Oxfordian Hanifa Formation is economically important, containing a conventional hydrocarbon reservoir in its upper section and an unconventional reservoir and source rock in its lower part (Murriss, 1980; Alsharhan and Magara, 1994; Cantrell et al., 2014). This research aims to document the vertical and lateral lithofacies variation of the Hanifa Formation outcrops to study its sequence development to create a regional correlation framework. An integrative objective is to use inorganic geochemical data to build an elemental chemostratigraphic framework, to support the regional correlation of interpreted sequences. Due to the “continuous” nature of the well logs (gamma-ray, neutron, density, and sonic logs), chemostratigraphy could be a particularly effective tool

for correlating the Middle and Late Jurassic succession within the Arabian Plate. This correlation role is particularly in the absence of core material from which cuts may be used to get geochemical data (Craig, 2015).

3.2 Regional Geological Setting

The breakup of Pangea and the formation of the Neo-Tethys during the Late Permian affected the northern part of the Arabian Plate. This breakup accelerated during the Jurassic (Sharland et al., 2001). Thermal subsidence may have been the primary process in the north, with sediment load becoming a more significant factor in the south (Sharland et al., 2001; Ziegler, 2001). As a result of major subsidence processes, intra-shelf basins started to form during the Toarcian and later during the Callovian and middle Oxfordian, east of the Arabian Plate (Murriss, 1980; Énay et al., 1987; Droste, 1990; Al-Husseini, 1997). During the Late Jurassic, a complete separation occurred between the Arabian and Indian Plate, associated with major marine transgressions (Ziegler, 2001).

The Hanifa Formation forms the basal part of the Late Jurassic succession of the Arabian Plate (Manivit et al., 1990) (Figure. 3.1). It overlies the Callovian Tuwaiq Mountain Formation (TMF), paraconformably with a Lower Oxfordian hiatus (Le Nindre in Kadar et al., 2015). The Kimmeridgian Jubaila Formation caps the Hanifa Formation disconformably (Powers et al., 1966). The Hanifa Formation comprises the middle Oxfordian Hawtah and the late Oxfordian Ulayyah Members (Vaslet et al., 1983; Hughes, 2004). On average, about 60m thick, Hawtah Member comprises clayey and skeletal carbonates, whereas on the average of 70 m thick, the Ulayyah Member comprises more grainy beds with calcareous algae, corals, and stromatoporoids (Hughes et al., 2008).

According to the geological time scale of Gradstein et al. (2012), the duration of the Hanifa Formation reaches 5.5 million years (My). In contrast, it reaches 4.86 My based on the Arabian Plate Orbital Stratigraphic framework (APOS) (Al-Husseini and Mathews, 2005; Al-Husseini et al., 2006). The estimated duration time suggests that the Hawtah and Ulayyah Members correlate to third-order sequences (Hughes et al., 2008).

Globally, the Jurassic period witnessed a general rise in sea level that reached a climax during the Kimmeridgian-Tithonian interval. However, multiple second-order sea-level highs were recorded, including an Oxfordian-Kimmeridgian one (Haq, 2018). Furthermore, a major sea-level fall associated with the late Callovian cooling phase is recorded in the Arabian Plate. The sea level fall extended and resulted in an Early Oxfordian hiatus (Tremolada et al., 2006; Cantrell et al., 2014). However, the global Oxfordian sea level rise coincided with an increased subsidence rate and the formation of intra-shelf basins (Droste, 1990). This marine transgression resulted in a wide deposition of shallow and deep marine carbonates (Figure. 3.2). A maximum flooding surface (MFS J50) of the middle Oxfordian age is proposed in the upper section of the Hawtah Member of the Hanifa Formation (Sharland et al., 2001).

Age		Formation	Member	Study Interval
Upper Jurassic	Kimmeridgian	Jubaila	J2	
			J1	
	Oxfordian	Hanifa	Ulayyah	
			Hawtah	
		Hiatus		
Mid Jurassic	Callovian	Tuwaiq Mt	T3	
			T2	
			T1	
		Dhruma	Hisyan	
			Atash	

Figure 3.1: The Middle to Upper Jurassic lithostratigraphic succession of the Arabian Plate showing the study interval (modified from Hughes, 2004).

3.3 Materials and Methods

The current research investigates eight outcrops of the Oxfordian Hanifa Formation in central Saudi Arabia (Figure. 3.2), with a total cumulative thickness of 430 m. The outcrops are distributed over a N-S transect over a total distance of 535 km. The thickest section (110.5 m) is named H2, which lies west of Riyadh city through the Riyadh-Makkah road cut. The lithofacies analysis of the studied succession was done by Bashri et al. (2022, in press; Table 1), representing the database for the sequence stratigraphic interpretation. The buildup of the sequence stratigraphic framework and the identification of stratigraphic bounding surfaces is done following the stratigraphic concepts described by Catuneanu et al. (2011). Sequence identification is based on lithofacies variation and their recurrence through sedimentary cycles, their transitional pattern (gradual or abrupt), and the change of the strata stacking patterns that marks the key surfaces. Since no low stand systems tract (LST) could be interpreted in the studied sections of the Hanifa Formation, sequence boundaries (SB) coincide with transgressive surfaces (TS). The sequence boundaries associate the abrupt change from shallow to relatively deep depositional setting with a change in the strata stacking pattern from a thinning to a thickening upward succession, marking the transgressive systems tract (TST). Each sequence's maximum flooding surface (MFS) is interpreted conceptually in the middle of the relatively deepest lithofacies beds.

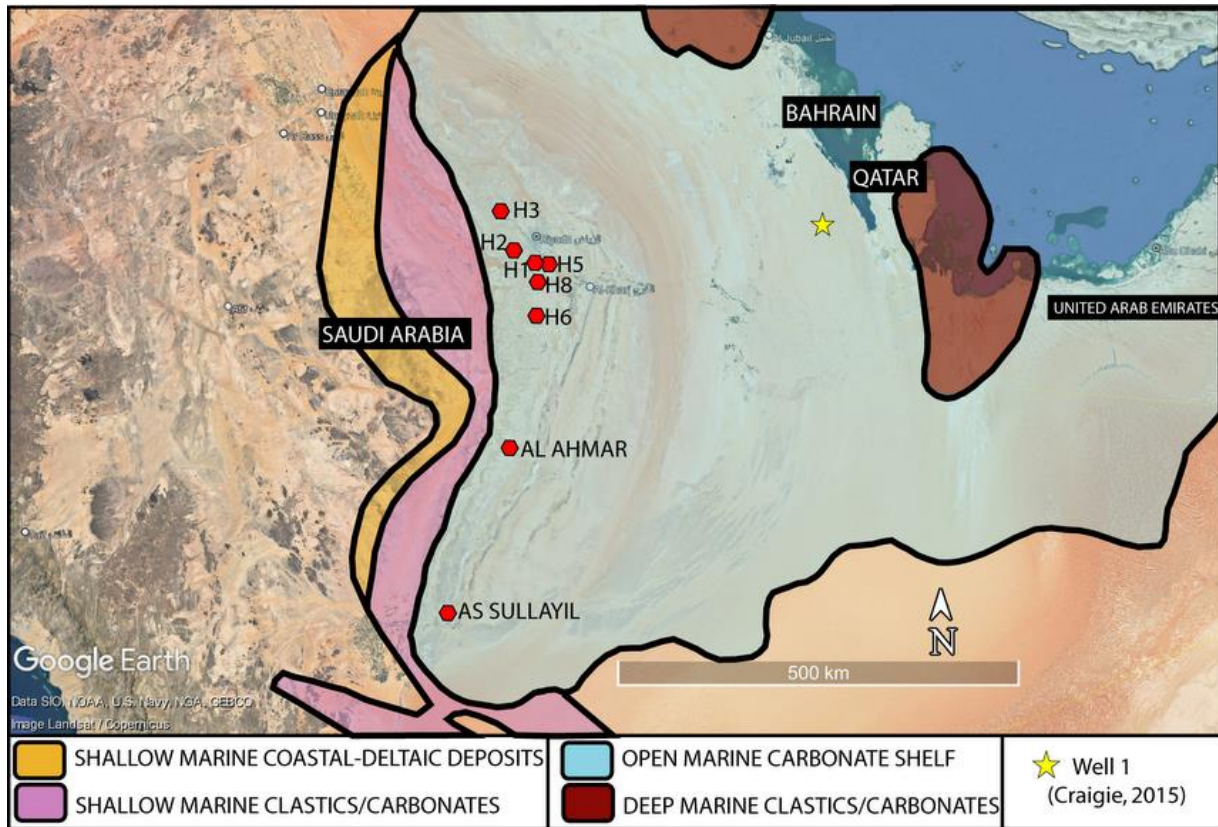


Figure 3.2: Interpreted paleogeographic map of the Arabian Plate during the Oxfordian stage (modified from Ziegler, 2001), with the locations of the studied outcrops (red hexagons) and the subsurface well of Craigie (2015) that is correlated with the outcrops data (yellow star).

Table 3.1: Summary of interpreted sedimentary facies of the Oxfordian Hanifa Formation (Bashri et al., 2022; in press)

Lithofacies	Description	Depositional process	Facies association	Depositional environment
F1: Argillaceous carbonate mudstone	Massive/laminated carbonate mud with illite content. Scattered brachiopods and bivalve and sponge spicules	Fine suspended-load (carbonate with less siliciclastic) gravitational settling, associated with benthic organisms	Outer ramp (FA1)	Offshore/basinal carbonate
F2: Intraclast rudstone	Bedded and channelized massive rudstone with mudstone and sponge spiculitic wackestone intraclasts	Storm currents depositing gravel sheets and channel-fill	Mid ramp (FA2)	Storm bed carbonate
F3: Skeletal sponge spiculitic wackestone/packstone	Monaxon, triaxon and tetraaxon sponge spicules, Kurnubia palastiniensis, bivalves, echinoderm spines and peloids. Wackestone and packstone texture. Occasional intensive bioturbation.	Benthic skeletal bed-load deposition in low-moderate energy conditions		Carbonate lower shoreface
F4: Horizontally laminated siltstone/claystone	Massive white claystone to horizontally-laminated green siltstone with skolithos trace fossils.	Calm conditions resulted in gravitational settling of suspended-load of silty quartz grains and clay sediments		Siliciclastic lower shoreface
F5: Cross-bedded quartz peloidal grainstone	Trough and herringbone cross bedding, grains imbrication, grainstone texture, the domination of peloids with either skeletal or quartz grains associated with different bedding geometries	Uni-, bi-, and multi-directional subaqueous dunes of skeletal, quartz and peloid grains. Deposition of widely extended sand sheets, in addition to shoals by strong waves	Inner ramp (FA 3)	Carbonate upper shoreface
F6: Trough cross-bedded sandstone	Keystone vugs, low angle trough cross bedding, calcareous coarse sandstone, well-rounded quartz grains, bivalves and peloids	Multi-directional siliciclastic sand dunes in high energy waves conditions		Siliciclastic upper shoreface
F7: Floatstone	Coral and stromatoporoid heads floating on skeletal packstone matrix, absence of sedimentary structures	Falling, slumping and sliding of reef-related fragments	Inner ramp (Reef association) (FA4)	Gravel-dominated fore-reef
F8: Stromatoporoid /Coral framestone	Unstratified in situ scleractinian corals hemispheroids and stromatoporoid, the matrix is of skeletal sponge spiculitic wacke/packstone or oncoidal peloidal grainstone	In situ coral and stromatoporoid growth in a high energy wave zone, with associated symbiotic community		Reef crest
F9: Oncoidal rudstone	Ellipsoidal and more rounded oncoids with skeletal and intraclasts nucleus, dominant spongiostromate with less porostromate oncoids and combination type in rudstone texture	Microbial encrustation, waves abrasion in intermittent high energy open marine conditions		Open reef-flat/back-reef

Although the disagreement over their efficiency, Fischer plots remain a valuable graphical tool to show how accommodation space has changed over time (Fischer, 1964; Read and Goldhammer, 1988; Sadler et al., 1993). A Fischer plot was constructed for section H2 since this road cut represents the thickest and the best exposure of the Hanifa Formation among the studied sections. The plot is constructed as a cumulative deviation from the mean cycle thickness versus the number of cycles (with 113 cycles for the current study) (Sadler et al., 1993). The fifth-order interpreted sequences are used in the Fischer plot to identify fourth-order sequences. Conceptually, the rising limbs of the plot are formed by thick cycle packages that deviate positively from the mean cycle thickness. In contrast, the falling limbs of the plots are formed by thin cycle packages that deviate negatively from the average cycle thickness, reflecting a long-term decrease in accommodation space.

From five sections (H3, H2, H5, H1, and H8), 349 fresh rock samples, with a vertical sampling resolution of 0.5 to 1 m, were ground using a granite grinder and analyzed using an M4 TORNADO Micro X-ray Fluorescence. The analyzer uses the spot mode for detection, with multiple spots for each sample. Three points were chosen on a smooth surface of 30g of each sample with a detection time of 120 seconds for each spot. The weight % of 22 elements was measured in each spot and averaged automatically. Even though 22 elements were included in the dataset, the chemostratigraphic correlation scheme is based on the vertical variation of five major elements, namely Si, Al, Ca, Mn, and Fe. Microsoft Excel software was used to plot the chemostratigraphic data, whereas Adobe Illustrator CS software drew the stratigraphic sections and correlation schemes. Finally, a subsurface geochemical log of one well was adopted from the published work of Craigie (2015) for correlation (Figure. 3.2).

3.4 Results and Discussion

3.4.1 Sequence Stratigraphy

The interpreted transect extends in an oblique N-S direction, mainly parallel to the depositional strike. The sequence stratigraphic architecture of the Hanifa Formation is represented by a second-order sequence that is split into two third-order sequences (Hughes et al., 2008). In the current study, the composite section of Hanifa Formation outcrops reaches an average thickness of 135 m, with 55m for the Hawtah Member (the lower third-order sequence) and 80 m for the Ulayyah Member (the upper third-order sequence). The depositional environment of the studied outcrops is dominated by a homoclinal carbonate ramp in the lower third-order sequence that changes to a coral/stromatoporoid reef-bearing homoclinal ramp in the upper third-order sequence (Table 3.1) (Bashri et al., 2022; in press).

3.4.2 Depositional Sequences Architecture

Six characteristic depositional cycle architectures have been identified based on the vertical variation of Hanifa Formation lithofacies (Figure. 3.3A-F). All sequence types show a general coarsening and shallowing upward pattern. The first type is found only in the lowermost part of the Hanifa Formation. It is composed of an intraclast rudstone storm bed (F2) that shows a fining upward in size of intraclasts and has been cut by channels at the top with an intraclast rudstone fill (Figure. 3.3A). The second cycle type (Figure. 3.3B) is the most abundant in the Hanifa Formation. It shows a dominance of an outer ramp argillaceous carbonate mudstone lithofacies (F1) at the base and a cap of a mid-ramp massive sponge spiculitic wackestone (F3). Type 2 sequence architecture dominates the TST of the third-order sequences. The third type resembles the previous type in the cycle

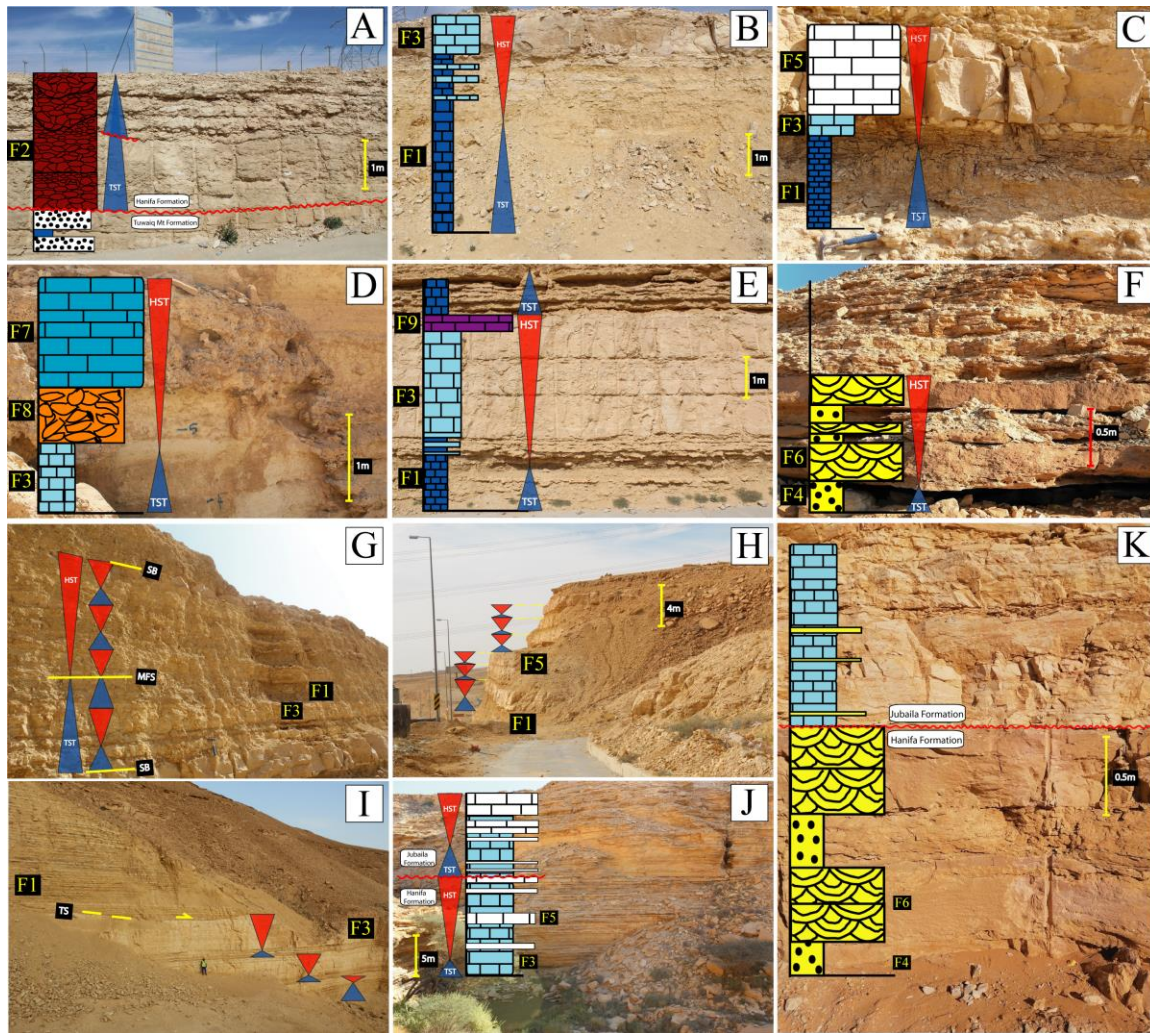


Figure 3.3: Outcrop observations used in the sequence stratigraphic interpretation. (A-F) Depositional sequences architecture of the Hanifa Formation. A) Type 1 depositional sequence composed of storm beds of finning upward bedded and channelized intraclast rudstone (F2). It unconformably overlies the late Callovian Tuwaiq Mountain Formation and represents the intensive initial transgression events of the Hanifa Formation. B) Depositional sequences of type 2, showing a base of an outer-ramp argillaceous carbonate mudstone (F1), capped by a mid-ramp sponge spiculitic wackestone (F3). C) Type 3 sequence architecture showing a change from outer- (F1) to mid- (F3) to inner-ramp lithofacies with a cap of cross-bedded peloidal grainstone (F5). D) Depositional sequence of type 4, capped by reef crest coral/stromatoporoid framestone (F7), overlying fore-reef reef-debris floatstone (F8), and mid-ramp sponge spiculitic wackestone of F3. E) Type 5 sequence architecture with a cap of inner-ramp oncolitic rudstone (F9). F) Type 6 siliciclastic-dominated sequences to the south (Al Ahmar and As Sulayyil sections) showing a change from mid-ramp claystone and siltstone (F4) to an inner-ramp trough cross-bedded coarse calcareous sandstone (F6). G) strata stacking pattern of depositional cycles of type 2. Note the flipping from thickening to thinning upward pattern, reflecting a corresponding decrease in the accommodation space. H) Two fourth-order sequences of type 3, with a general thinning upward pattern marking the approach of the third-order sequence boundary. I) Transgressive outer-ramp carbonate mudstone onlapping the mid-ramp wackestone capped cycles. J) The third-order sequence boundary between the Oxfordian Hanifa and the Kimmeridgian Jubaila Formation is captured by the strata stacking patterns change. K) The Hanifa-Jubaila boundary in the Al Ahmar section, showing the sharp contact between calcareous siliciclastic lithofacies of Hanifa and a mixed siliciclastic-carbonate system of Jubaila.

base and is capped by an inner ramp cross-bedded quartz skeletal peloidal grainstone lithofacies (F5) (Figure. 3.3C). Depositional cycles of type 3 are more common in the upper sections of the lower and upper third-order sequences of the Hanifa Formation.

The depositional architectures of types 2, 3, 4, and 5 are similar to those described by Fallatah and Kerans (2018). The fourth depositional architecture type is only found in the upper third-order sequence (Ulayyah Member). It is composed of mid-ramp massive sponge spiculitic wackestone beds (F3) at the base, which are overlain by an inner-ramp coral/stromatoporoid forereef and reef crest lithofacies (F7 and F8, respectively; (Figure. 3.3D). The fifth cycle type is found only within the upper third-order sequence of the Hanifa Formation. It is represented by argillaceous carbonate mudstone (F1) at the base that shallows upward into mid-ramp sponge spiculitic wackestone (F3) and inner-ramp back reef oncolitic rudstone (F9) (Figure. 3.3E). The final depositional cycle type is found only in the upper third-order sequence and in the southern section of the studied transect (Al Ahmar and As Sullayil sections) (Figure. 3.1). It shows a transition from mid-ramp siliciclastic claystone and siltstone (F4) to a cap of an inner-ramp trough cross-bedded coarse calcareous sandstone (F6) (Figure. 3.3F).

3.4.3 Strata Stacking Patterns

Besides the lithofacies variation, the strata stacking pattern (Figure. 3.3G, H) and its representation by the Fischer plot (Figure. 3.4) are used for sequence identification. The observed strata stacking patterns of the studied sections are in the resolution of fifth- and

fourth-order sequences. The depositional cycles of types 1 and 2 show a base of an upward thickening pattern, with gradual domination of the argillaceous carbonate mudstone lithofacies (F1), which soon got capped by the mid-ramp sponge spiculitic wackestone (F3) (Figure. 3.3G). This change in lithofacies abundance is associated with the flipping of strata stacking pattern from thickening to thinning upward. A similar pattern is observed in the upper section of both third-order sequences of the Hanifa Formation, but with different internal depositional architecture; types 3, 4, 5, and 6 (Figure. 3.3H). The fifth-order repetition of these binary strata stacking patterns marks the fourth-order sequence boundaries.

On the Fischer plot (Figure. 3.4), the leftward drift is associated with the overall thickening upward strata stacking pattern and indicates a long-term increase in the created accommodation space. On the other hand, the right-hand side drift in the plot indicates an overall fall in accommodation space creation rate, where thinning-upward patterns prevail. The general pattern of the created Fischer plot of the Hanifa Formation matches the high-frequency middle and late Oxfordian global sea level curve of Haq (2018) (Figure. 3.4). However, due to the difference in sedimentation mode and rate between different lithofacies, a facies partitioning pattern has emerged, i.e., certain parts of the Fischer plot are characterized by certain lithofacies (Tucker and Garland, 2010). Where the global sea level curve strongly matches the Fischer plot, then the depositional cycles are dominated by both types 1 and 2, where the deposition via accumulation of benthic heterotrophs in addition to the gravitational settling of suspended load processes prevail. Type 3 depositional architecture shows a more serrated pattern that could be interpreted by erosion via high energy depositional currents or by less accommodation space creation rate at the

HST of the 3rd order sequences. Finally, the reefal facies association shows fewer strata stacking pattern responses to the created accommodation space; they show a sharp negative departure from mean cycle thickness, either for slow growth rate or intensive erosion.

3.4.4 Sequence Stratigraphic Interpretation

The Riyadh-Makkah road cut (H2) has been used as a reference section, showing a set of high-frequency sequences. The field observations, strata stacking patterns, bounding surfaces, and lithofacies associations allowed the construction of a high-resolution sequence stratigraphic framework based on the studied sections. Two third-order sequences were interpreted, reflecting a shift between outer-, mid-, and inner-ramp conditions.

The first third-order sequence is only observed in sections H2 and H3 northward. This sequence corresponds to the middle Oxfordian Hawtah Member and comprises seven fourth-order sequences (seq. 1-seq. 7) (Figure. 3.4). The oldest fourth-order sequence has a lower sequence boundary (SB) that matches the unconformity with the late Callovian Tuwaiq Mountain Formation. This sequence is composed entirely of storm beds of intraclast rudstone (F2), representing an intense marine transgression event. The cyclicity and the channelization indicate that the initial transgression occurred in more than one phase. Seq. 2, 3, and 4 are dominated by depositional sequences of type 2, where the TST extends till the mid part of the argillaceous carbonate mudstone.

In contrast, the mid-ramp sponge spiculitic wackestone dominates the HST. The MFS of seq. 3 represents the MSF of the third-order sequence and coincides with the regional MFS

of J50 (Sharland et al., 2001). The HST of the first third-order is dominated by fourth-order sequences of type 3, with a general thinning upward pattern.

The second third-order sequence in the H2 section is composed of seven fourth-order sequences dominated by depositional sequences of type 3 (seq. 8 and seq. 14), type 4 (seq. 10, 11, 12, and 13), and type 5 (seq. 9). A sharp lithofacies change is observed from thick cross-bedded peloidal grainstone beds (F5), that dominate the HST of the first third-order sequence, to an outer-ramp thick carbonate mudstone (F1). This change marks the transgression of the second third-order sequence and the boundary with the late Oxfordian Ulayyah Member. The MFS of the second third-order sequence lies in the middle of seq. 10.

The bedding planes of all studied sections are flat and horizontal. They show no distinctive clinoform geometries, except in section H3, northward, where transgressive bed sets show onlapping on the lower sequences (Figure. 3.3I). Although the lithofacies analysis shows a high degree of shallowness, a total absence of subaerial exposure indicators is noticeable in all orders of sequences. The boundary between the Hanifa and the Kimmeridgian Jubaila Formations is marked lithostratigraphically by the absence of the inner-ramp reef lithofacies association. However, the change in strata stacking patterns could still capture the boundary, even with the absence of reefal lithofacies and the dominance of type 3 sequences in both formations (Figure. 3.3J). In the southward Al Ahmar and As Sullayil sections, the boundary between Hanifa and Jubaila corresponds to a flip from calcareous siliciclastic lithofacies to a mixed siliciclastic-carbonate system that characterizes the Jubaila Formation (Figure. 3.3k).

3.4.5 Chemostratigraphy

3.4.5.1 Elements Used in Chemostratigraphic Units Definition

Geochemical analysis was carried out for 22 elements in this study, but only five major elements were used to build a chemostratigraphic framework (Si, Al, Ca, Mn, and Fe). The rest of the elements show no pattern by reaching a false zero value that shows that the element mainly has very low abundance, often below the tool detection limit. The coexistence of Si, Al, and Fe associated with a decrease in Ca abundance indicates siliciclastic input, specifically clay minerals. In contrast, the independent increase in Si shows detrital quartz phases (Craigie, 2016). The Manganese profile shows a distinctive pattern and is chosen for correlation with subsurface data from Craigie (2016) for the same stratigraphic interval. Mn concentrations are often high around the oxic-anoxic boundary; in suboxic conditions. Strong Mn leaching caused by reducing conditions enriches the bottom sea water with dissolved Mn^{2+} . However, after mixing with oxygenated water, Mn^{2+} oxidation may occur through autocyclic reactions and/or microbial metabolism (Calvert and Pedersen, 1993; Wirth et al., 2013; Craigie, 2015). Thus, mixing anoxic water along the suboxic zone is often linked with increased Mn oxi/hydroxides precipitation. However, the sediment content of Mn could be of detrital origin associated with siliciclastic elemental affinities (Jarvis et al., 2001) or be an early or late diagenetic product (Johnson et al., 2016).

3.4.5.2 Chemostratigraphy VS Litho and Sequence Stratigraphy

The present chemostratigraphic framework is built based on the changes in the profiles of detrital input elemental affinities in addition to Mn. The chemostratigraphic units of the

reference section H2 and their correlation with subsurface data of Craigie (2015) are illustrated in Figure (3.5). In his research, Craigie (2015) studied the chemostratigraphy of Middle and Upper Jurassic Formations in five wells and used a hierarchical order for chemostratigraphic units comprised of zones, subzones, and divisions. He classified the Hanifa Formation as the subzones C3-3 and the lower part of C4-1a within the chemostratigraphic zone C3. In the current study, the chemostratigraphic units (C1, C2, C3, and C4; ascending stratigraphic order) are considered divisions in those subsurface subzones. The general trend of the interpreted chemostratigraphic divisions is observed subsurfacely (Figure. 3.5). C1 yields lower Mn than in C2, with a wide sharp peak in the middle of the division of Si, Al, and Fe associating a drop in Ca, which indicates an increase in clay minerals abundance and coincides with the third-order MFS J50. The lower part of C1 shows an increase of Mn associated with the increase of Si, Al, and Fe and the drop of Ca that indicates a detrital source. C2 division shows a slight increase in Mn than C1, with more oscillation in Al, Si, and Fe against Ca content. The slight increase of Mn at the top of C2 is of a detrital source. This division characterizes the HST of the first third-order sequence.

The C3 division is distinguished at the base by a gradual increase in Mn, coupled with clay minerals affinities (high Si, Al, and Fe with a drop in Ca contents). This elemental behavior characterizes the boundary between Hawtah and Ulayyah Members, i.e., the boundary between the two third-order sequences of the Hanifa Formation. This SB is transgressive, and the Mn peak indicates a relatively deep sub-oxic zone approach. Toward the top of C3, low concentrations of all elements, except Ca, with fewer variations are noticeable. Only the basal part of C4 is observed in section H2. It shows the highest values of Mn with sharp

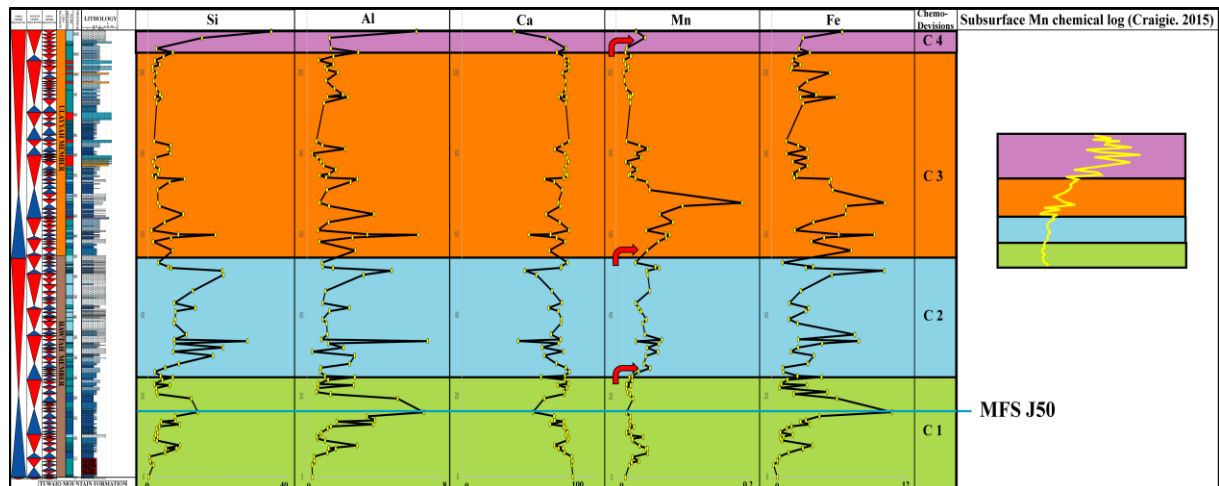


Figure 3.5: Chemostratigraphic divisions (C1, C2, C3, and C4) of the Hanifa Formation in section H2, based on the vertical variation of the weight % of the major elements Si, Al, Ca, Mn, and Fe. The MFS J50 (Sharland et al., 2001) coincides with a major drop in carbonate production (Ca) and a siliciclastic clay deposition (increase in Si, Al, and Fe). The adopted subsurface Mn log from chemostratigraphic subzone C3-3 of Craigie (2015) is on the right-hand side. Although the difference in thickness, the general trends are still correlatable with how chemostratigraphic divisions could be interpreted subsurfically and the lithostratigraphic units; the sharp increment in the Mn log between C2 and C3 marks the Hawtah/Ulayyah boundary.

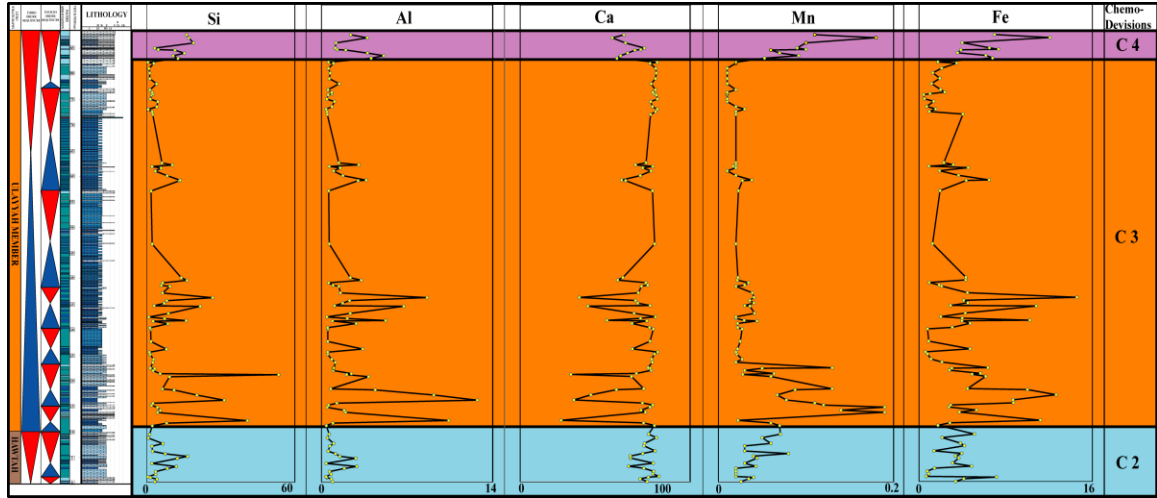


Figure 3.6: Chemostratigraphic divisions of the H3 section to the north. Lithofacies of H3 are muddier in texture; however, the chemostratigraphic divisions C2, C3, and the base of C3 are still correlatable.

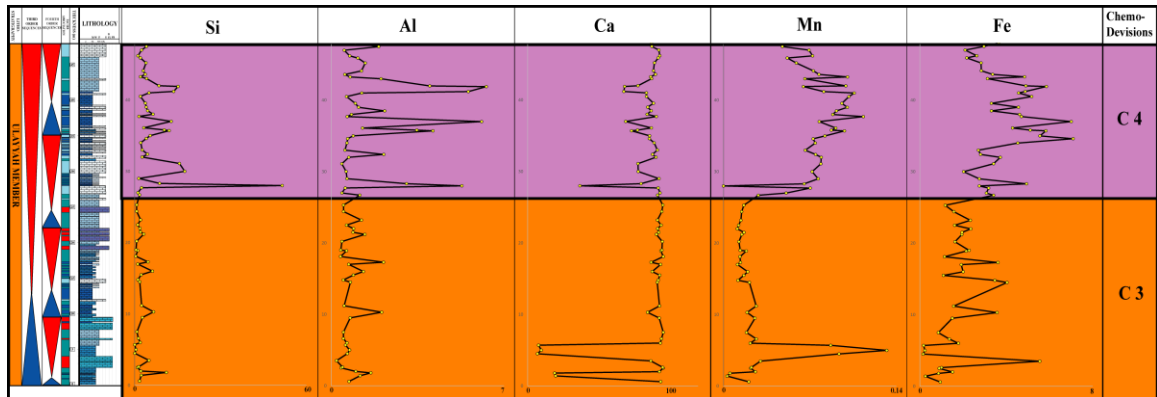


Figure 3.7: Chemostratigraphic divisions of section H1 in Wadi Nisah show the presence of C3 and C4 only (the Ulayyah Member).

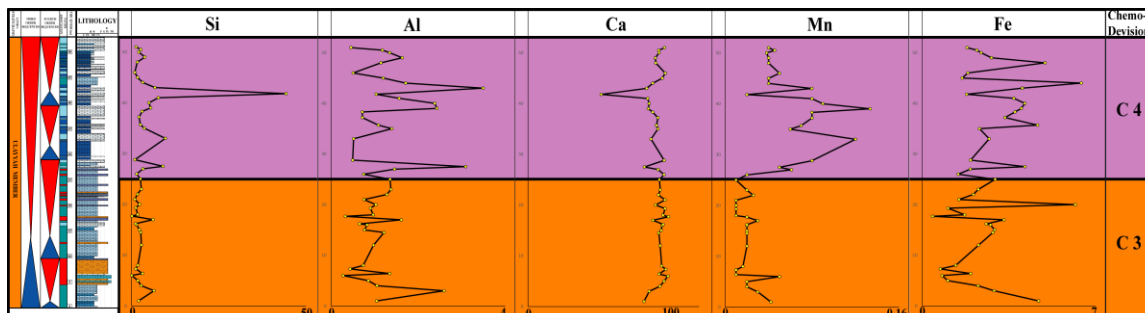


Figure 3.8: Chemostratigraphic divisions are proposed for section H5, with divisions C3 and C4 marking the Ulayyah Member.

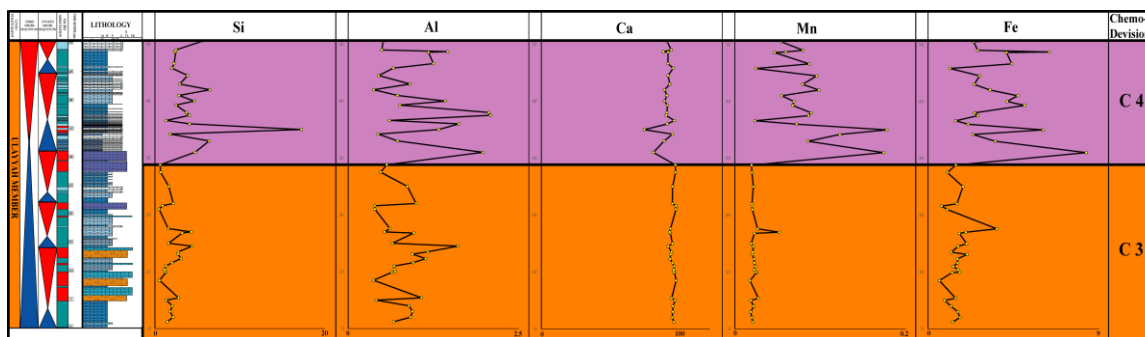


Figure 3.9: Chemostratigraphic criteria of C3 and C4 divisions in section H8 in Wadi Al Ain correlate to the Ulayyah Member beds.

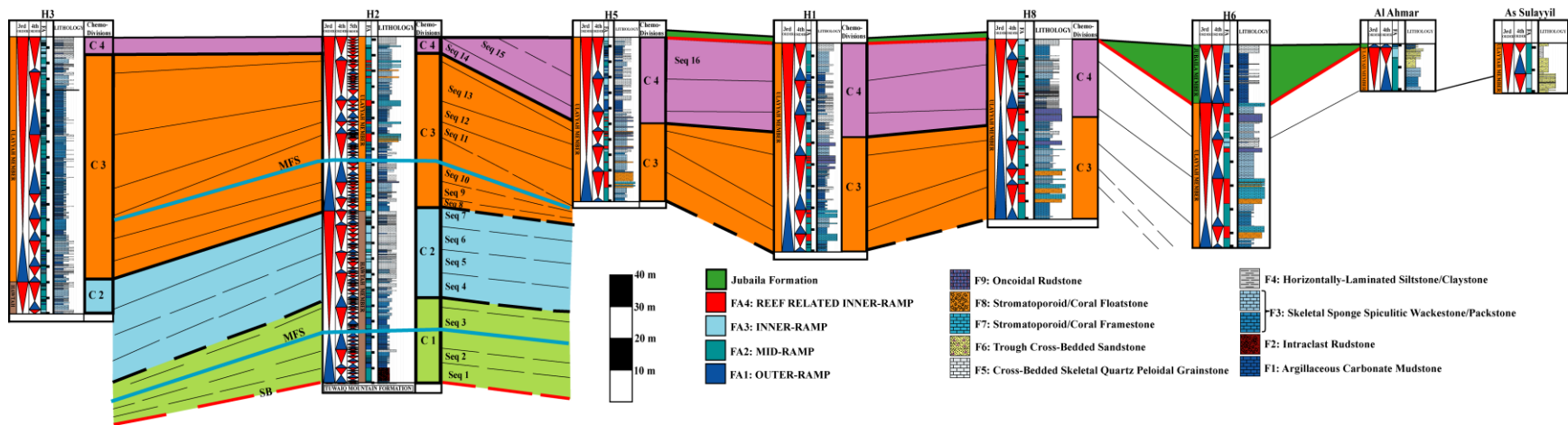


Figure 3.10: Regional correlation of the stratigraphic sequences (Seq 1-Seq 16) guided by the chemo divisions' correlation in the studied outcrops with the aid of the Hanifa - Jubaila boundary as a marker surface.

peaks of siliciclastic input affinities. The divisions C2, C3, and the base of the C4 could be observed in section H3 (Figure. 3.6), whereas only C3 and C4 divisions are found in sections H1, H5, and H8 (Figures. 3.7, 3.8, and 3.9, respectively).

Although the large distance between the studied outcrops and the well, the chemostratigraphic divisions are still correlatable (Figure. 3.10). Due to poor exposure, sections H6, Al Ahmar, and As Sulayyil have not been included in the chemostratigraphic approach. However, the Hanifa-Jubaila boundary represents a useful surface for correlation.

3.4.5.3 Regional correlation

The studied sections of the Hanifa Formation show that it undergoes a noticeable lateral and vertical lithofacies change regionally (Figure. 3.11). The interpreted fourth-order sequences of the first third-order sequence (the Hawtah Member, seq. 1-seq. 7) are only found in the northern part of the studied transect (H2 and H3 sections). This third-order sequence shows a shallowing upward lithofacies pattern, gradually changing from outer-ramp lithofacies at the TST to mid- and inner-ramp lithofacies at the HST. The correlation of the HST of the first third-order sequence between H2 and H3 sections shows a more grainy texture in H2 than in the correlated fourth-order sequences in H3, where mid-ramp wackestone dominates. The correlation between H2 and H3 in the second third-order sequence (the Ulayyah Member, seq. 8- seq. 14) shows inner-ramp reef-related lithofacies association in the HST of the fourth-order sequences in H2. In contrast, the reefal lithofacies are only found as thin layers in H3. The reef- and grainstone-dominated HST of H2 sequences is correlated to the outer- and mid-ramp lithofacies in the HST of H3. Those mudstone and wackestone lithofacies dominate most of the H3 section. The Jurassic

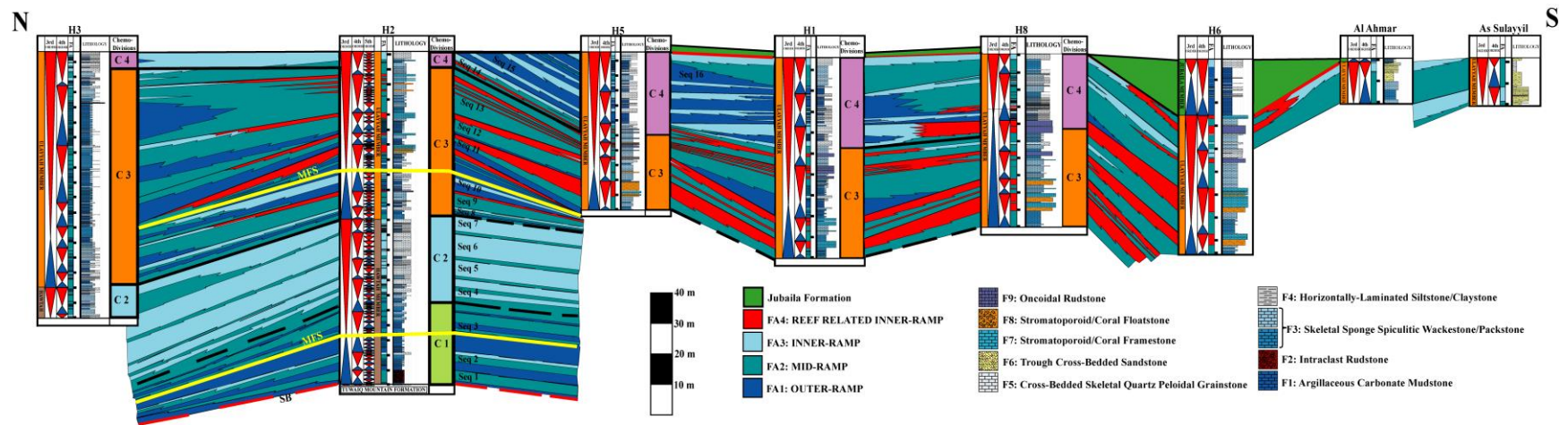


Figure 3.11: Lateral profile showing the regional lateral facies change of the Oxfordian Hanifa Formation outcrops in central Saudi Arabia

outcrop belt in Saudi Arabia is considered the western rim of the Arabian Intrashelf Basin that extends from the Rimthan Arch in the north to the empty quarter in the south (Murris, 1980a; Énay et al., 1987, Droste, 1990; Ziegler, 2001; Hughes et al., 2008). The Oxfordian Hanifa outcrops are proposed to represent relatively higher energy, shallow lithofacies that prograde eastward into the Arabian Intrashelf Basin (Wilson, 2020). Moreover, the paleolatitudes show equatorial conditions (Al-Husseini 1997; Ziegler, 2001), with strong, persistent easterly winds that result in energy levels that increase northward (Torsvisk and Cocks, 2016; Wilson, 2020). The dominance of the outer-ramp argillaceous carbonate mudstone (F1) and the mid-ramp sponge spiculitic wackestone (F3) in the H3 section could be explained by a westward extension of the northern section of the Arabian Intrashelf Basin.

The reef-related inner-ramp facies association appears in the HST of the lower fourth-order sequences of the Ulayyah Member in the reference section H2 (Fig 11). The coral /stromatoporoid lithofacies show much less abundance to the north of the studied transect (H3), only as thin layers with smaller coral heads. The correlation of H2 and H3 with the other sections revealed that the inner-ramp reef-related lithofacies association dominates southward, with higher representation in the top section of the Ulayyah Member rather than the HST peloidal grainstone. However, the most southern sections (Al Ahmar and As Salayyil) show total disappearance of the reef-related lithofacies and dominance of mid- to inner-ramp siliciclastics. The geographical restriction of reefal lithofacies could be attributed to relatively deep depositional conditions northward and the siliciclastic input from the south.

3.5 Conclusion

High-resolution sequence stratigraphic interpretation was established for the Oxfordian Hanifa Formation outcrops in central Saudi Arabia. The lithofacies variation, the bounding surfaces, and the strata stacking patterns helped to build the sequence stratigraphic framework. The sections show overall shallowing upward sequences with six distinct sequence types. A total of sixteen fourth-order sequences were interpreted within the two third-order sequences of the Hanifa Formation. Southward, shallow marine siliciclastic sequences are described for the first time in the Hanifa Formation and are correlatable to the carbonate sequences in the north. Although the large distance between the studied outcrops and the subsurface adapted well, elemental chemostratigraphy represented a powerful correlation tool. Moreover, chemostratigraphy allowed the delineation of the third-order sequence boundary that coincides with the lithostratigraphic boundary between Hawtah/Ulayyah Members. Combining the identified lithostratigraphic boundaries, the interpreted sequences, and the new chemostratigraphic divisions allows the construction of a powerful correlation theme that could be used subsurfacely.

CHAPTER 4

Integration of sequence stratigraphy and petrophysical models in reservoir characterization, Upper Oxfordian Hanifa reservoir outcrop analog, Central Saudi Arabia

Abstract

The geological and petrophysical assessment of outcrop analogs for hydrocarbon reservoirs becomes one of the most important steps in reservoir characterization. The late Oxfordian Ulayyah Member outcrop analog for the Hanifa reservoir was studied in high resolution to build high-resolution geological and petrophysical models to capture its fine geologic characteristics. Sedimentology and sequence stratigraphic principles were integrated with lithofacies petrophysical characterization and 3D geostatistical modeling to understand the geological controls on the reservoir lithofacies analogs. Ten outcrops were investigated in Wadi Mawan in central Saudi Arabia. The interpreted lithofacies included an outer-ramp argillaceous carbonate mudstone, mid-ramp skeletal wackestone/packstone, inner-ramp skeletal peloidal grainstone, and inner-ramp coral/stromatoporoid framestone. These lithofacies are distributed in two fourth-order regressive sequences capped by the boundary between Hanifa and the Kimmeridgian Jubaila Formation boundary. 3D lithofacies models were constructed using the sequential indicator simulation algorithm (SIS) using the fifth-order sequence boundaries as horizons and the interpreted lithofacies as input data. They were evaluated geologically and statistically. A single realization was chosen to be used for reservoir simulation. The lithofacies model shows a lithofacies distribution similar to the regional lithofacies trend. The measured porosity and permeability values show a general proportional relationship for each lithofacies. The main porosity types are

intragranular, intergranular, burrow, moldic, and fracture porosity. The mid-ramp lithofacies in the transgressive systems tract shows the best reservoir quality with intragranular, moldic, burrow, and fracture porosity. The inner-ramp peloidal grainstone shows better reservoir properties than the coral/stromatoporoid framestone in the highstand systems tract, with intergranular and intragranular porosity types in the grainstone, and intragranular and burrow porosity types in the matrix of the framestone. The constructed 3D porosity and permeability models were built on the skeleton of the previously built lithofacies model. The porosity model correlates well with the lithofacies model, whereas the permeability shows a more complex relationship.

4.1 Introduction

Petrophysical properties of carbonate reservoirs are controlled by geological processes (depositional and diagenetic) in the three-dimensional space (Lucia, 2007). Carbonate hydrocarbon reservoirs are problematic because of the heterogeneity of their petrophysical properties, which are influenced by various factors (de Almeida, 2010). It's difficult and multidisciplinary to model carbonate reservoirs since their models should include geology, petrophysics, and flow characteristics (Ziegel et al., 1996, Da Costa e Silva et al., 1997). Therefore, geology, stratigraphy, and petrographic description are required to develop a reservoir model. In the following step, the petrophysical simulations of a reservoir rock are guided by the previously constructed lithofacies models (Soares, 2001, Mata-Lima, 2008, Emery and Silva, 2009). However, subsurface reservoir characterization and development projects face the problem of the large inter-well spacing that rises the correlation uncertainty between reservoir units.

Outcrop models have traditionally been used to develop proxies for subsurface reservoirs, particularly when the core material is scarce. Using outcrop analogs helps to understand the lithofacies distribution and sequence stratigraphy interpretation. This advantage is due to the 3-D view, the better characterization of stratigraphic surfaces and sedimentary features, and the ability to observe the lithofacies' lateral continuity at a short distance (Grammer et al., 2004). When paired with a diagenesis analysis, 3-D outcrop measurements may be able to anticipate the location and quality of possible reservoir lithofacies. The late Oxfordian Hanifa succession is significant economically due to its proximity to the Arabian Intrashelf organic-rich source rock and the efficient regional seal that makes it a good hydrocarbon reservoir and source rock at the same time (Alsharhan

and Magara, 1994; Hughes et al., 2008). However, a lateral and vertical heterogeneity of the reservoir units is noticeable. The heterogeneity is related to paleotopography and the post-Hanifa provincial erosion (Awwad, 2016; Al Ibrahim et al., 2017; Fallatah, 2019). When been correlated to the nearest oilfield, 150km east of the Jurassic outcrop belt, the fourth- and fifth-order sequences of the Hanifa reservoir are found to be correlatable to those in the outcrops (Fallatah, 2019). Therefore, the Hanifa exposures represent an opportunity to study the lateral lithofacies variation in a high resolution and inter-well spacing to enhance our understanding of the Hanifa reservoir zone, which is difficult to conduct subsurfacely.

The main objective of this research is to characterize the equivalent reservoir units of the Hanifa Formation outcrops and construct three-dimensional lithofacies and petrophysical analogs, to be utilized for subsurface reservoir simulations and development plans. These outcrop models could resemble the Hanifa reservoir architecture and flow units' characteristics, which help to explore new reservoir zones in the subsurface.

4.2 Geological setting:

4.2.1 Depositional paleoenvironment and paleogeography

The accelerated fragmentation of Pangea during the late Triassic-early Jurassic caused a rifting event in the north of the Arabian Plate (Sharland et al., 2001). These tectonics caused subsidence northward, whereas a high sedimentation rate triggered subsidence southward (Murriss, 1980, Enay et al., 1987, Droste, 1990, Al-Husseini, 1997). The propagation of the extensional events southward resulted in the formation of multiple intrashelf basins. The Arabian Intrashelf Basin was formed in the center of Saudi Arabia and most of the Arabian Gulf area eastward (Murriss, 1980, Droste, 1990, Sharland et al., 2001), with a southward

extension in Rub' al Khali (Hughes et al., 2008). These extensional events were associated with major transgressions of the Neo-Tethys Ocean (Haq, 2008). The transgression was coupled with tropical paleolatitudes (Konert et al., 2001), resulting in a wide carbonate deposition in the epeiric sea on the Arabian Plate.

The Early Oxfordian witnessed an extension of the late Callovian cooling event that caused a hiatus and an unconformity between the late Callovian Tuwaiq Mountain Formation and the middle Oxfordian Ulayyah Member of the Hanifa Formation (Figure. 4.1) (Tremolada et al., 2006; Cantrell et al., 2014). However, more restricted conditions prevailed during this lowstand. They caused the sedimentary record to continue in the deep section of the Arabian Intrashelf Basin as microbial and organic-rich laminated carbonate mudstone representing the beginning of the widely extended Oxfordian source rock (Wilson, 2020). Later, the middle Oxfordian witnessed a major marine transgression associated with subsidence propagation. This transgression expanded the Intrashelf deep lithofacies and the deposition of a shallow marine carbonate succession on the shallow epeiric sea (Droste, 1990). The dominance of the ramp depositional environment (Sharland et al., 2001; Fallatah and Kerans, 2018; Bashri et al., 2022 (in press)) with a low accommodation space caused a significant progradation of the reservoir equivalent shallow marine lithofacies toward the Intrashelf Basin.

4.2.2 Petroleum Geology of the Hanifa Reservoir

The middle Oxfordian Hawtah Member is dominated by organic-rich carbonate mudstone with a total organic carbon (TOC) range of 4% to 14% (Carrigan et al., 1995). This source

Age	Formation	Member	Reservoir
Kimmeridgian	Jubaila	J2	Arab-D
		J1	
Oxfordian	Hanifa	Ulayyah	Hanifa
		Hawtah	
Calloviaian	Tuwaiq Mountain	T3	Hadriyah
		T2	
		T1	Upper Fadhili

Figure 4.1: Lithostratigraphy and hydrocarbon reservoir zones of the Middle and Upper Jurassic surrounding the Hanifa Formation. The Hanifa reservoir is highlighted in green and is correlated to the upper Oxfordian Ulayyah Member (Modified after Hughes, 2004).

rock feeds most of the Jurassic and Cretaceous reservoirs via upward and downward migration (Moore et al., 1998; Cantrel et al., 2014). The late Oxfordian Ulayyah Member represents the reservoir zone in the Hanifa Formation in most of the gigantic oil fields in the Arabian Plate. The Hanifa reservoir represents shallow marine lithofacies deposited around the rims of the Arabian Intrashelf basin (Wilson, 2020). In the Abqiaq field, the reservoir facies are dominated by highly porous mud-rich carbonates, with microporosity up to 32% and permeability less than 10 mD (Grover, 1993). In the Berri field, the reservoir lithofacies are low porosity skeletal wackestone, porous skeletal packstone, grainstone, and coral/stromatoporoid boundstone (Kompanik et al., 1993). Alsharhan and Magara (1995) stated that the permeability of the Hanifa reservoir is greatly enhanced where oil and calcite-filled vertical fractures associate stylolite-rich reservoir zones. The Hanifa reservoir in offshore Abu Dhabi shows more than 20% porosity values and high permeability of more than 1000 mD due to the enhancement by meteoric dissolution (Al-Suwaidi and Aziz, 2002). Hughes et al. (2008) used a detailed micropaleontology investigation to delineate the reservoir lithofacies of the stromatoporoid banks and grainstone shoals in the Arabian Intrashelf Basin's flanks. They proposed a southward basin extension and new potential reservoir zones in the Rub' al Khali basin.

4.3 Methodology

The study area (1.4 km²) is located in Wadi Mawan, approximately 69 km south of Riyadh City (Figure. 4.2). Ten outcrops were investigated and described in a high resolution, with a maximum distance between two sections of 2.1 km. The outcrops represent an exposure of

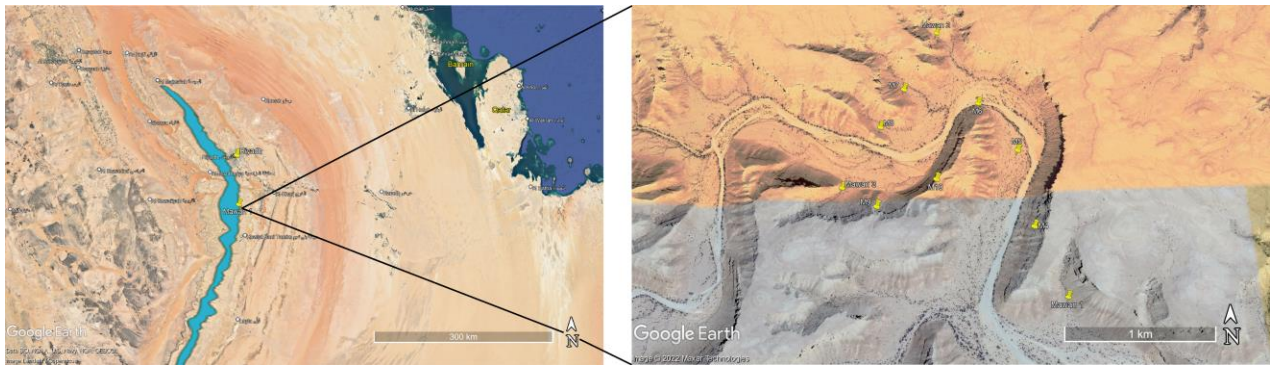


Figure 4.2: Google Earth image showing the study area in Wadi Mawan, central Saudi Arabia, and the distribution of the studied outcrops.

the upper section of the late Oxfordian Ulayyah Member, with a contact with the Kimmeridgian Jubaila Formation at the top. In order to reach the high-resolution aim, the outcrops were selected based on the quality of the exposure throughout the Wadi and the short distance between the sections.

The outcrops were investigated through field observation, hand specimens, slabs, and thin sections to interpret the depositional processes and environment. The slabs were described using a binocular microscope, whereas thin sections were described by Olympus optical petrographic microscope equipped with high-definition cameras. The described lithofacies were compared to those interpreted by Bashri et al. (2022, in press), and a lateral correlation between studied sections was done. The strata stacking patterns and the interpreted paleobathymetry guided the sequence stratigraphic interpretation through all outcrops. A 3D lithofacies geostatistical model was created using the sequence stratigraphic surfaces as horizons and the vertical lithofacies as input data. Semivariograms were calculated using Petrel software to characterize the spatial variability, and the sequential indicator simulation (SIS) algorithm was used to build the lithofacies model.

The different types of visual porosity of different lithofacies were characterized qualitatively using thin sections petrography. The samples were obtained perpendicular to the bedding planes. A water-cooled, 1.5-inch diameter diamond drilling bit was used to obtain the plugs. The porosity was measured using Helium expansion PORG-200 porosimeter, whereas the permeability was measured using PMI gas permeameter. The maximum, the minimum, the mean, and the standard deviation of porosity and permeability were calculated for each lithofacies. Those values were assigned to each lithofacies in the

original data of the lithofacies model, representing the base for the petrophysical models built using the sequential Gaussian simulation (SGS) algorithm.

4.4 Results and Discussion

4.4.1 Sedimentology and Sequence Stratigraphy

The described sections of the Ulayyah Member could be classified into four main lithofacies (Figure. 4.3). The interpreted depositional environment for each lithofacies was correlated to Bashri et al. (2022, in press). Those lithofacies are outer-ramp argillaceous carbonate mudstone, mid-ramp sponge spiculitic skeletal wackestone/packstone, inner-ramp skeletal peloidal grainstone, and inner-ramp coral/stromatoporoid framestone. The argillaceous mudstone is massive, brown in color, and contains siliciclastic clay content, brachiopods, and bivalves. It represents an open marine basinal lithofacies with calm depositional conditions. The skeletal wackestone is highly interbedded with skeletal packstone layers and contains siliceous sponge spicules, echinoderms, bivalves, peloids, and foraminifera. Based on the coarser texture and the associated facies, relatively higher energy mid-ramp depositional conditions are proposed. The grainstone lithofacies overlies the packstone beds with erosional contact. It shows trough cross-bedding and contains bivalves, foraminifera, scattered quartz grains, and peloids. When found interbedded with the reef-related lithofacies, the grainstone is interpreted as inner-ramp carbonate sand sheets and shoals (Bashri et al., 2022, in press). The coral/stromatoporoid lithofacies caps the packstone beds and shows lateral interfingering with the peloidal grainstone lithofacies. The matrix between the scleractinian coral hemispheroids and stromatoporoid heads is of skeletal wackestone/packstone texture. The coral/stromatoporoid biostromes represent a

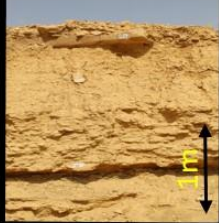
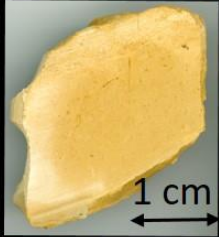
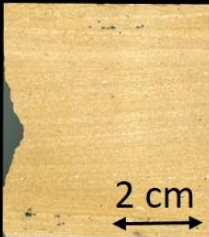
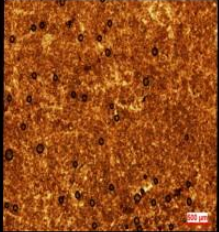
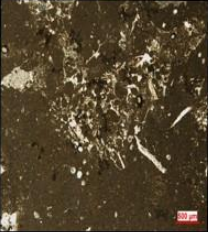
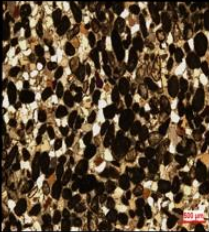
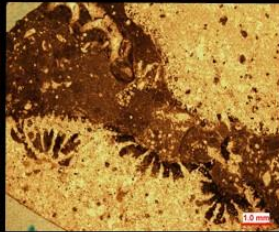
FACIES	Argillaceous carbonate mudstone	Massive skeletal wacke/packstone	Skeletal peloidal grainstone	Coral/ stromatoporoid framestone
KEY ATTRIBUTES	Massive to laminated, dark brown to paige, clay content brachiopods,	Massive, burrowed, skeletal sponge spiculitic wacke/ packstone	Cross bedding, foraminifera, mollusks, quartz grains	Coral heads, stromatoporoids, skeletal packstone or oncolitic matrix
OUTCROP				
SLAB				
THIN SECTION				

Figure 4.3: The major features of the interpreted lithofacies in the studied outcrops.

reef-crest and fore-reef depositional environment in the inner-ramp zone.

The interpreted lithofacies are arranged in shallowing upward cycles. The stratigraphic sequences are interpreted based on the variation of lithofacies and strata stacking patterns (Figure. 4.4). The studied sections represent the upper section of the youngest third-order sequence of the Hanifa Formation (Hughes et al., 2008). Two fourth-order sequences were interpreted in all studied sections (Figure. 4.5). The lower sequence shows a gradual upward lithofacies change starting from outer-ramp argillaceous mudstone that represents a transgression event and is considered a transgressive systems tract (TST). A general regression is interpreted when the mid-ramp skeletal wackestone/packstone overlies the transgressive mudstone. The top of the first sequence is dominated by coral/stromatoporoid framestone lithofacies representing the highstand systems tract (HST) and a basinward progradation of inner-ramp lithofacies over the mid-and the outer-ramp facies. This general lithofacies succession is repetitive through the fifth-order sequences and makes the general frame of the lower fourth-order sequence with less mudstone and more reefal facies upward. The fifth-order sequences of the lower sequence show an upward thinning pattern (Figure. 4.4) and are correlatable through all studied sections with minimal differences in beds' thickness (Figure. 4.5).

The upper fourth-order sequence starts with a transgression, indicated by thin beds of outer-ramp argillaceous carbonate mudstone, which is not found in all sections; some sections start with mid-ramp facies overlying the HST reefal facies of the lower sequence. The interpreted paleobathymetry shows a relative shallowness with the dominance of the skeletal peloidal grainstones upward, representing the HST. The strata of the grainstone

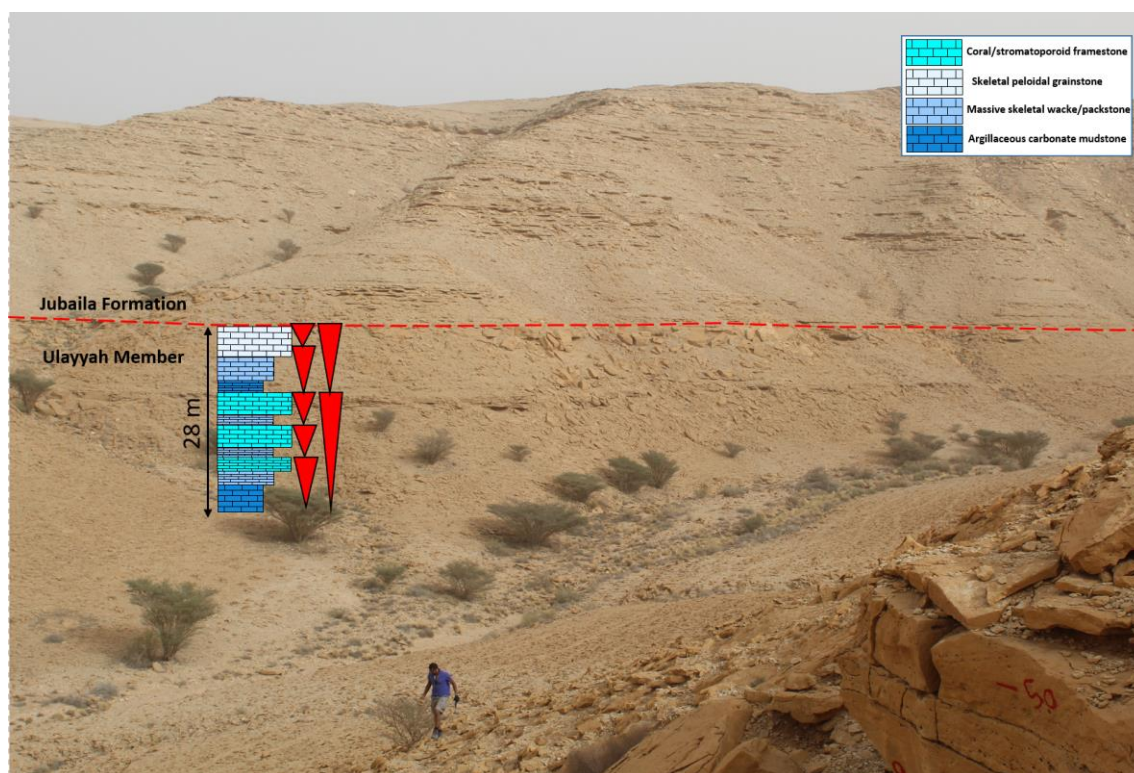


Figure 4.4: A field photo showing the exposure of the last two fourth-order sequences of the late Oxfordian Ulayyah Member and its contact with the Kimmeridgian Jubaila Formation.

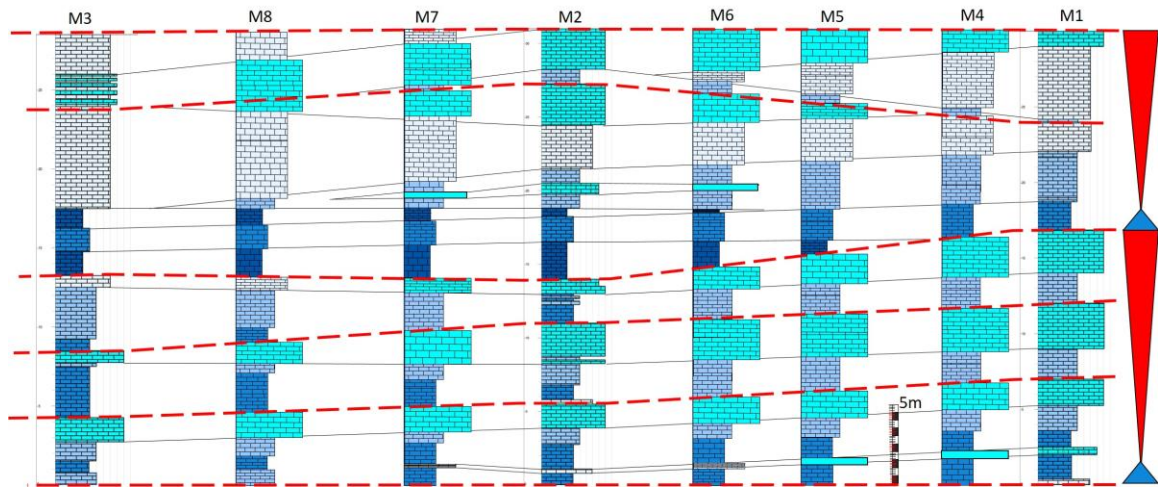


Figure 4.5: A correlation scheme between the interpreted lithofacies in eight of the ten studied outcrops. The lithofacies are distributed in five thinning and shallowing fifth-order sequences upward with marine flooding surfaces between them. Note the interfingering between the mid- and outer-ramp transgressive lithofacies in the TST and between the inner-ramp grainstone and reefal lithofacies in the HST.

show a thinning upward stacking pattern, in addition to a high level of interbedding and interfingering with coral/stromatoporoid framestone in some sections. The upper sequence is capped in all sections with the boundary between Hanifa and Jubaila Formations. The lower and upper fourth-order sequences are subdivided into three and two fifth-order sequences, respectively, and they are correlatable through all studied sections (Figure. 4.5)

4.4.2 Lithofacies Modeling

The 3D geostatistical lithofacies model was created using the stochastic sequential indicator simulation (SIS) with a total area of 1.4 km². The model is constructed of cells with dimensions of 0.5 m X 0.5 m, with a maximum vertical thickness of 29 m. Vertically, the model is subdivided into 205 layers to capture vertical lithofacies heterogeneity. The sequence stratigraphic model (Figure. 4.5) is the foundation of the lithofacies model, with the fifth-order SB being chosen as horizontal horizons in the model. Consequently, the model is subdivided into five zones with six horizons. Five semivariograms were calculated with a horizontal lag distance of 1500 m because it gives good coverage for the distributed pairs through the studied sections. The lag distance was chosen based on the distance between the studied outcrops, which resembles that of Al-Khalifa and Makkawi (2002), who studied the facies-porosity relationship of the Hanifa reservoir in the Berri oilfield. A value of 0.3 m was assigned as a lag distance for the vertical semivariograms to capture the high-resolution lithofacies variation.

Ten realizations, which are models that honor the original data and have equal probabilities, were constructed using the original lithofacies data. These realizations were evaluated statistically and geologically before being used for characterization.

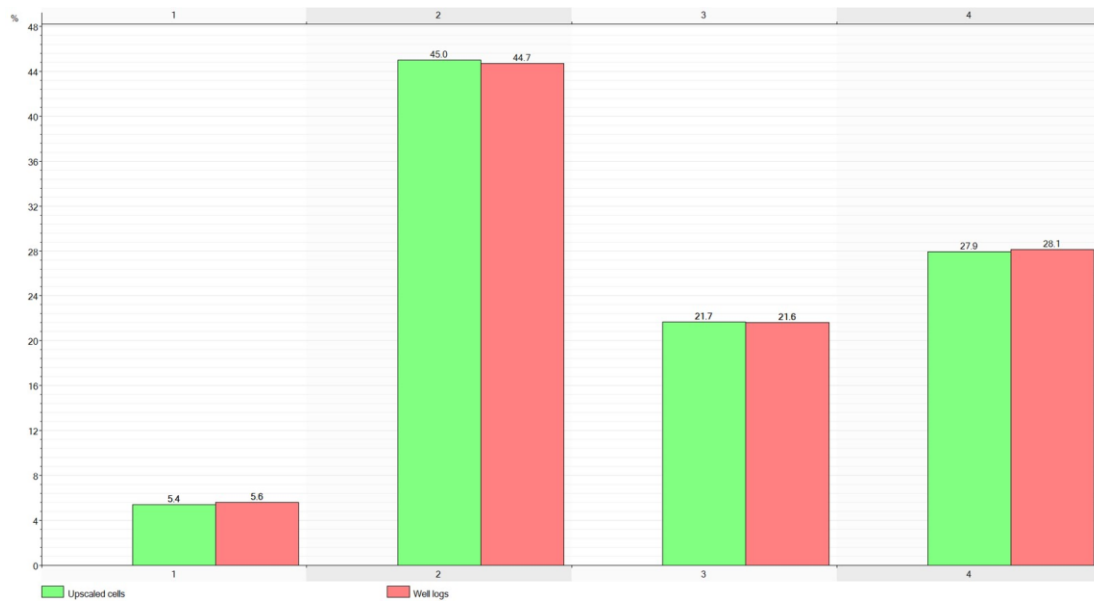


Figure 4.6: Comparison of histograms representing the lithofacies original true data (upscaled) and those resulting from sequential indicator simulation (SIS) modeling algorithm (well logs). Note the similarity between the true and simulated values. 1: Argillaceous carbonate mudstone, 2: Massive skeletal wackestone/packstone, 3: Skeletal peloidal grainstone, 4: Coral/stromatoporoid framestone.

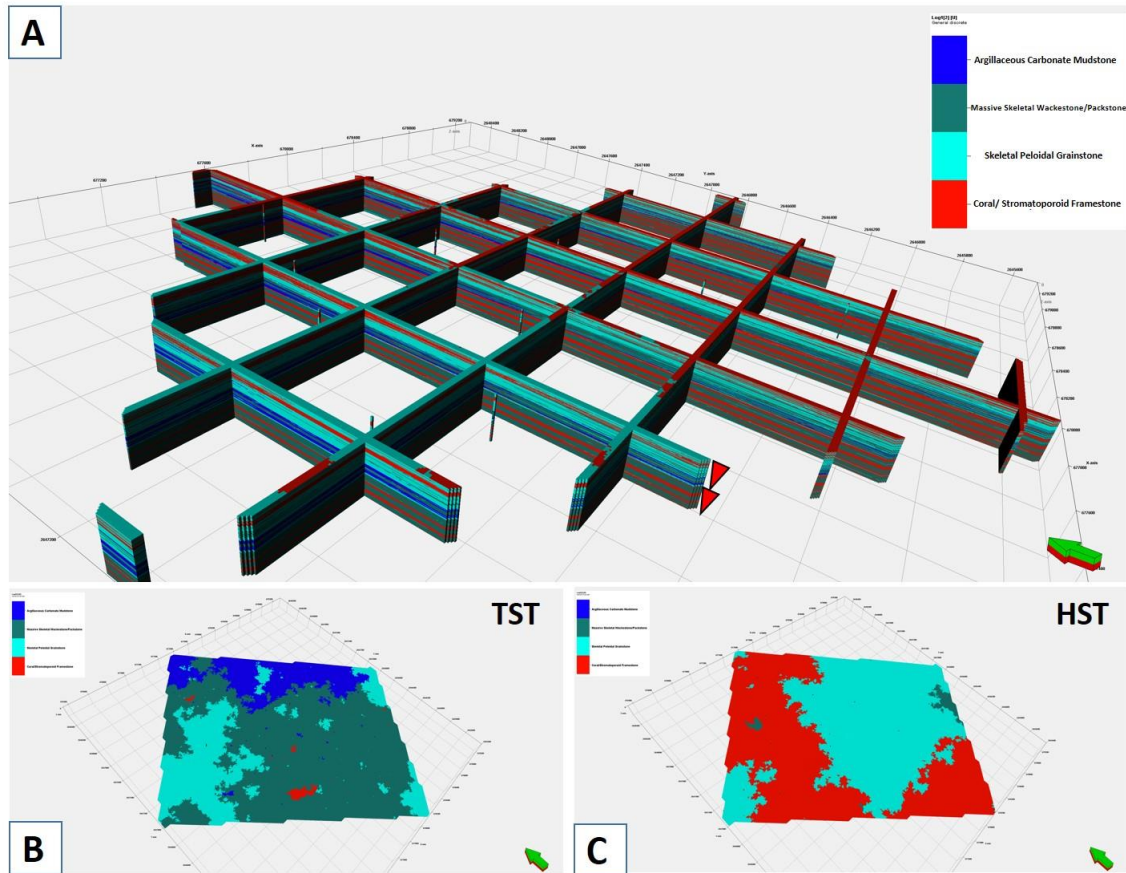


Figure 4.7: 3D lithofacies model. A) Fence diagram of the lithofacies model, view from the southwest, with a vertical exaggeration $\times 66$. The interpreted lithofacies show two shallowing upward sequences (red triangles). The lower sequence approximately lacks the out-ramp mudstone, with a reef-dominated HST. Note the lateral facies change between the inner-ramp reefal and grainstone in the HST of the upper sequence. B) Horizontal slice in the TST of the upper sequence showing the transgression of the outer-ramp muddy lithofacies from the east, the retrogradation of the inner-ramp grainstone, and the drowning of the reefal lithofacies. C) Horizontal slice from the HST of the upper sequence showing the flourishing of the reefal lithofacies with approximately NE-SW strike that resembles the general basinal setting and spread of the peloidal grainstone.

The statistical evaluation included comparing the univariate statistics of the original data and those for the simulated one. The best fitting realization was chosen for characterization (Figure. 4.6). The constructed lithofacies model clearly distinguishes the two interpreted fourth-order sequences (Figure. 4.7A). The lower sequence shows a TST dominated by a mid-ramp massive skeletal wackestone/packstone lithofacies. In contrast, the HST is dominated by the coral/ stromatoporoid reefal lithofacies. In low resolution, the general view of the lower sequence resembles that of Elzain et al. (2020), who proposed a layer cake model. The upper sequence begins with a TST of an outer-ramp carbonate mudstone, covered with the mid-ramp packstone. The HST shows the existence of the peloidal grainstone shoals interfingering in small and large scales with the reefed facies. Horizontal slices of the upper sequence's TST show a general deepening in the NE direction (Figure. 4.7B), where the transgression most probably came from. The proposed transgression direction goes well with the general basin setting. The reefal lithofacies are less observed in the TST, whereas the peloidal grainstone shoal lithofacies show relatively better representation. This scarcity could be attributed to a slower growth rate of the coral/stromatoporoid than the accumulation rate of the carbonate sand shoals and the relative sea level rise that most corals were drowned. However, the HST (Figure. 4.7C) shows the rapid flourishing of the coral/stromatoporoid framestone that formed N-S trending reefs, with lateral facies changing with the peloidal grainstone observed in the 3D view (Figure. 4.7A).

4.4.3 Petrophysical Modelling

Although the similarity in the interpreted lithofacies between outcrops and the subsurface Hanifa Reservoir in the near oilfields, the measured porosity and permeability generally show lower values than those of the reservoir published in the literature. However, porosity and permeability show a moderate proportional relationship, with a correlation coefficient of 0.63 (Fig 8A). The skeletal peloidal grainstone has a maximum porosity value of 16% and a generally low permeability (maximum of 0.8 mD). The dominant porosity types are intergranular (Figure. 4.8B) and intragranular and moldic porosity, mainly in skeletal grains (Figure. 4.8C). The moldic porosity could be formed due to the dissolution of skeletal grains by meteoric water in the vadose zone. In some samples, the dissolution exceeds the skeletal grains and creates irregular vuggy porosity (Figure. 4.8C). However, the saturated meteoric solutions played a negative role by cementing all previous porosity types and producing highly cemented grainstone samples with poor reservoir properties (Figure. 4.8D).

The mid-ramp skeletal wackestone/packstone lithofacies shows a wider range of porosity and permeability than the inner-ramp grainstones. The porosity measurements reach 19.72%, with a maximum permeability of 4.8 mD. The moldic porosity type dominates the wackestone/packstone lithofacies (Figure. 4.8E). This lithofacies is intensively bioturbated, and the burrows are occasionally filled with relatively coarser sediments that exhibit both moldic and intergranular porosity types (Figure. 4.8F). The burrows are of *Thalassinoides* ichnotaxa and reach an intensity of more than 50%. Eltom et al. (2021) studied these burrow patterns and petrophysical properties, and they proposed an enhancement of

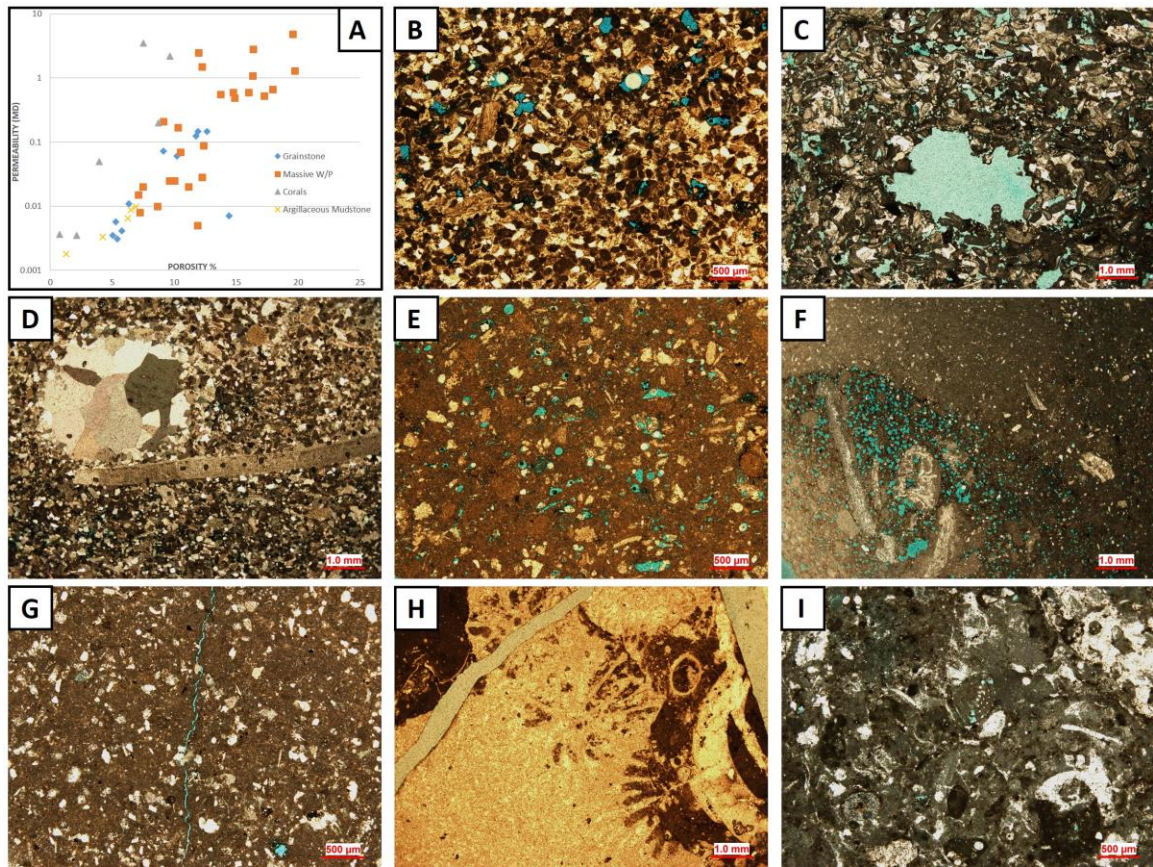


Figure 4.8: Petrophysical characterization of interpreted lithofacies. A) Porosity-permeability cross plot. However, the generally low measured porosity and permeability values show a proportional relationship with a moderate correlation coefficient of 0.63. The mid-ramp massive skeletal wackestone/packstone relatively shows the highest porosity and permeability. B) Intergranular and intragranular porosity in an inner-ramp skeletal peloidal grainstone. C) A grainstone thin section microphotograph showing the high dissolution of the skeletal grains (intragranular and moldic porosity) could continue and form a vuggy porosity. D) Thin section photomicrograph of a skeletal peloidal grainstone showing a later stage blocky calcite cementation that fills the intergranular and vuggy pores in a meteoric environment. E) Intragranular and moldic porosity in a mid-ramp skeletal packstone. Note the dissolution of the sponge spicule (with circular cross-section) and the bivalve shells. F) Thin section photomicrograph of a mid-ramp skeletal wackestone with burrow porosity. The coarse filling of the burrow shows intergranular and moldic porosity. G) Skeletal packstone thin section photomicrograph with intragranular and fracture porosity. H) A thin section photomicrograph of inner-ramp coral framestone. A high degree of cementation and micritization characterize the coral heads and the associating bores. Note the highly cemented corallites. I) A thin section photomicrograph of the skeletal peloidal matrix between the coral heads with intragranular porosity type.

reservoir properties due to their existence. However, the burrows' fill is sometimes cemented or filled with finer sediments with no visual porosity. This heterogeneity could explain this lithofacies' wide range of porosity and permeability measurements. The third type of porosity is a fracture porosity with less presence than previous types (Figure. 4.8G). However, the fracture porosity is proven effective in enhancing the subsurface Hanifa reservoir by rising the permeability values to more than 1000 mD (Al-Suwaidi and Aziz, 2002).

The reefal lithofacies represents productive reservoir zones in the Hanifa reservoir (Kompanik et al., 1993). However, it shows low porosity and permeability values, a maximum of 9.64% and 3.5 mD. The coral heads show intensive cementation and micritization of the corallites and internal bores (Figure. 4.8H). This cementation could be of early marine diagenesis origin due to the continuous action of waves (Lightly, 1985). The matrix between coral heads is burrowed (with less degree than the mid-ramp packstone) and shows intragranular porosity (Figure. 4.8I).

The 3D porosity and permeability models are built on the frame of the previously constructed lithofacies 3D model. A general correlation between lithofacies and petrophysical models is done to study their distribution relationship (Figure. 4.9). The lithofacies model shows more continuous beds in the lower sequence (Figure. 4.9A) and less abundance of the peloidal grainstone lithofacies. Therefore, a slice of the upper sequence is chosen to study the lithofacies-petrophysical properties relationship since it contains all interpreted lithofacies and shows more interfingering between the interpreted reefal and shoal environments (Figure. 4.9B). The 3D porosity model shows a good

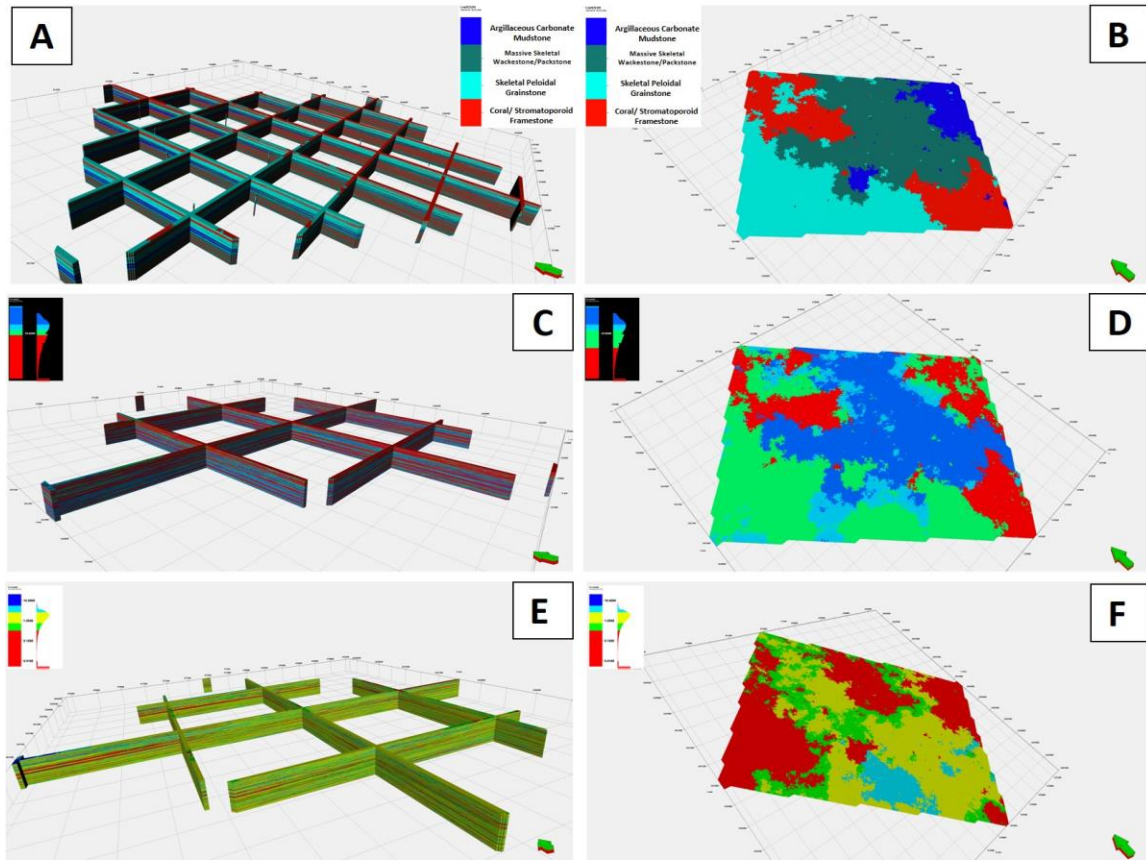


Figure 4.9: Comparison between the constructed 3D lithofacies, porosity, and permeability models. A) Fence diagram of the lithofacies model showing the spatial distribution of the interpreted lithofacies. Note the locations of the originally studied outcrops inside the fence diagram. **B)** A 2D horizontal slice from the upper sequence of the lithofacies model showing the spatial lithofacies distribution. A general NW-SE trend is observed for the reefal facies. The outer- and mid-ramp lithofacies dominate eastward, with a transgressive tongue passing through the reef body till it reaches the peloidal grainstone lithofacies. **C)** Fence diagram of the 3D porosity model. The relatively high values are colored in blue, whereas the lowest values are colored in red. Vertically, the porosity values resemble the cyclicity of the lithofacies where the reef-dominated HST of the lower sequence is distinctive with low porosity zones. The TST shows higher porosity values in both sequences. The HST of the upper sequence shows lateral change to relatively higher porosity values following the lateral facies change from reefal to grainstone lithofacies. **D)** A 2D slice of the porosity model with the same vertical position as the lithofacies slice in figure B. The low porosity values follow the spatial distribution of the reefal and outer-ramp muddy lithofacies. In contrast, the moderate and relatively higher porosities follow the same patterns of the peloidal grainstone and the mid-ramp wackestone/packstone, respectively. **E)** Fence diagram of the 3D permeability model. The values are vertically segregated, with the lowest values distinguishing the HST framestone of the lower sequences and the overlying transgressive mudstone of the upper sequence (the red bands in the Middle). The other lithofacies show better permeability values (yellow and green colors), but they are hardly distinguished. **F)** A 2D permeability model slice with the same vertical position as the previous porosity and lithofacies slices. A high degree of heterogeneity is noticeable with a moderate degree of qualitative distinction (the spatial distribution of lithofacies) and a high degree of quantitative spatial randomness.

correlation with the lithofacies model regarding vertical distribution (Figure. 4.9C). In both interpreted sequences, relatively low porosity zones extend laterally following the coral/stromatoporoid biostromes. Intermediate to relatively higher porosity is noticed in the HST of the upper sequence where carbonate sand shoals dominate over reefs. The mid-ramp skeletal wackestone/packstone lithofacies shows better continuity of relatively higher porosity values in the TST of both interpreted sequences. In the 2D view, a good relationship could be observed between the modeled aerial distribution of lithofacies (Figure. 4.9B) and the porosity distribution (Figure. 4.9D). The transgressive argillaceous carbonate muddy lithofacies in the east show relatively low porosity values with patches of intermediate values related to interbedding with mid-ramp wackestones. The transgressive outer- and mid-ramp lithofacies are distributed in a general E-W trend that cuts through a N-S trending reef (Figure. 4.9B). This distribution could be explained by a wide transgression concentrated through channels cutting through the reef bodies. This facies pattern correlates to a similar porosity distribution, where relatively high values are found following the mid-ramp facies that cut the relatively low values assigned to the reefal facies belt (Figure. 4.9D). Wide intermediate porosity values are found westward associated with the distribution of the peloidal grainstone facies. A relatively higher porosity is observed in the reefal facies where it interfingers with the grainstones. The higher value could be attributed to the coarser matrix and the burrows' fill in the reefal beds. Eventually, the constructed lithofacies-based porosity model shows a good vertical and lateral definition of the potential reservoir zones. This result comports with the findings of Al-Khalifa and Makkawi (2002). They integrated the subsurface facies data with the

porosity data from well logs and produced geostatistical models that represent the lateral and vertical reservoir heterogeneity.

The 3D permeability model generally shows lower values in the lower sequence than those in the upper sequence (Figure. 4.9E). Moreover, the reef-dominated HST has lower values than the mid-ramp packstone-dominated TST. The upper sequence shows relatively higher permeability values than the lower sequence in TST and HST. This difference could be related to the existence of the grainstone facies. The horizontal aerial permeability distribution shows more complexity than the porosity when correlated with the lithofacies distribution (Figure. 4.9F). The argillaceous carbonate mudstone continues to show the least values in petrophysical properties. The mid-ramp wackestone/packstone and inner-ramp grainstone lithofacies show a random distribution of permeability values. Except for the suggested westward extending channel linked to a low permeability zone of grainstone, the mid- and inner ramp facies have relatively low values. The highest permeability values are found southward in the interfingering zone between the mid-ramp and inner ramp grainstone. The reef facies is distinguished qualitatively from other lithofacies zones by a high internal quantitative heterogeneity. The high heterogeneity of the spatial permeability distribution could be attributed to the high mud content in the facies that works as bafflers, both internally and between the beds. Moreover, the intensive micritization, the small pore size, and their isolation with a finer matrix (intragranular and moldic porosity types) play a negative role in permeability development.

4.5 Conclusion

Outcrop analogs of hydrocarbon reservoirs are one of the most significant phases in reservoir characterization. A late Oxfordian Ulayyah Member outcrop analog for the

Hanifa reservoir was examined in high resolution to create high-resolution geology and petrophysical models. Sedimentology and sequence stratigraphy were combined with lithofacies petrophysical characterization and 3D geostatistical modeling to comprehend reservoir lithofacies analogs. Ten outcrops were investigated in central Saudi Arabia: an outer-ramp argillaceous carbonate mudstone, mid-ramp skeletal wackestone/packstone, inner-ramp skeletal peloidal grainstone, and inner-ramp coral/stromatoporoid framestone represent the main lithofacies. These lithofacies form two fourth-order regressive sequences topped by the Hanifa-Kimmeridgian boundary. By employing fifth-order sequence boundaries as horizons and interpreted lithofacies as input data, 3D lithofacies models were generated using the sequential indicator simulation technique (SIS). They were assessed geologically and statistically, and a single realization was selected to be utilized for reservoir modeling. The lithofacies model matches the regional trend. Porosity and permeability are predictive for each lithofacies. Intragranular, intergranular, burrow, moldic, and fracture porosity are common. Mid-ramp lithofacies has intragranular, moldic, burrow, and fracture porosity. Inner-ramp peloidal grainstone has greater reservoir qualities than coral/stromatoporoid framestone in the highstand systems tract. The grainstone has intergranular and intragranular porosity, whereas the framestone has intragranular and burrow porosity. On the lithofacies model skeleton, 3D porosity and permeability models were developed. The porosity model correlates well with the lithofacies model, but permeability has a more complicated connection.

CHAPTER 5

CONCLUSION

A 535 km long curving transect over the Jurassic outcrop area in Central Saudi Arabia was used to research the Oxfordian depositional system of the southern Tethys. This analysis supports adopting the carbonate homoclinal ramp depositional model for the Oxfordian Hanifa Formation outcrops. These associations (FA1-FA4) are characterized by prominent grain types, sedimentary structures, ichnofacies, depositional texture, bedding architecture, and lithofacies. These lithofacies were deposited in outer-ramp, mid-ramp, and inner-ramp zones. They correspond to the middle Oxfordian Hawtah and late Oxfordian Ulayyah Members, respectively. The two stages correlate to homoclinal ramp systems. However, the second phase develops enormous patch reefs. Carbonate sand shoals formed with front and rear reef domains, resembling the evolution of shelf morphologies beneath distal zones of the Hanifa system towards the east. Phase 2's outcrop depositional system is still a reef-bearing homoclinal ramp. Despite the middle Oxfordian's worldwide dispersion of coral reefs, the circumstances for reef building in the Hawtah Member were probably unfavorable, presumably owing to the southern Neo-Tethys' warm tropical water. An inner-ramp coarse calcareous sandstone and a mid-ramp horizontally laminated siltstone and massive claystone are reported from the Hanifa Formation in Saudi Arabia's Jurassic outcrop area. Siliciclastic lithofacies adds a new late Oxfordian reservoir in the Rub' Al-Khali Basin.

The Oxfordian Hanifa Formation outcrops in central Saudi Arabia were sequence stratigraphically interpreted. The variation of lithofacies, boundary surfaces, and strata stacking patterns helped form the sequence stratigraphic framework. The sections demonstrate general shallowing upward sequences with six unique sequence types. Sixteen fourth-order sequences were interpreted in the Hanifa Formation's two third-order sequences. The Hanifa Formation contains shallow marine siliciclastic strata correlating to the northern carbonate series. Despite the enormous distance between the examined outcrops and the subsurface, elemental chemostratigraphy has shown to be an effective technique for correlation. Delineation of the third-order sequence boundary between Hawtah/Ulayyah Members was also made possible by chemostratigraphy. A significant correlation theme may be created by combining the discovered lithostratigraphic borders, interpreted sequences, and new chemostratigraphic divisions.

Outcrop analogs of hydrocarbon reservoirs are one of the most significant phases in reservoir characterization. The late Oxfordian Ulayyah Member outcrop analog for the Hanifa reservoir was examined in high resolution to create high-resolution geology and petrophysical models. Sedimentology and sequence stratigraphy were combined with lithofacies petrophysical characterization and 3D geostatistical modeling to comprehend reservoir lithofacies analogs. Ten outcrops were investigated in central Saudi Arabia: an outer-ramp argillaceous carbonate mudstone, mid-ramp skeletal wackestone/packstone, inner-ramp skeletal peloidal grainstone, and inner-ramp coral/stromatoporoid framestone represent the main lithofacies. These lithofacies form two fourth-order regressive sequences topped by the Hanifa-Kimmeridgian boundary. By employing fifth-order sequence boundaries as horizons and interpreted lithofacies as input data, 3D lithofacies models were generated using the sequential indicator simulation technique (SIS). They were assessed geologically and statistically, and a single realization was selected to be utilized for

reservoir modeling. The lithofacies model matches the regional trend. Porosity and permeability are predictive for each lithofacies. Intragranular, intergranular, burrow, moldic, and fracture porosity are common. Mid-ramp lithofacies has intragranular, moldic, burrow, and fracture porosity. Inner-ramp peloidal grainstone has greater reservoir qualities than coral/stromatoporoid framestone in the highstand systems tract. The grainstone has intergranular and intragranular porosity, whereas the framestone has intragranular and burrow porosity. On the lithofacies model skeleton, 3D porosity and permeability models were developed. The porosity model correlates well with the lithofacies model, but permeability has a more complicated connection.

Appendices

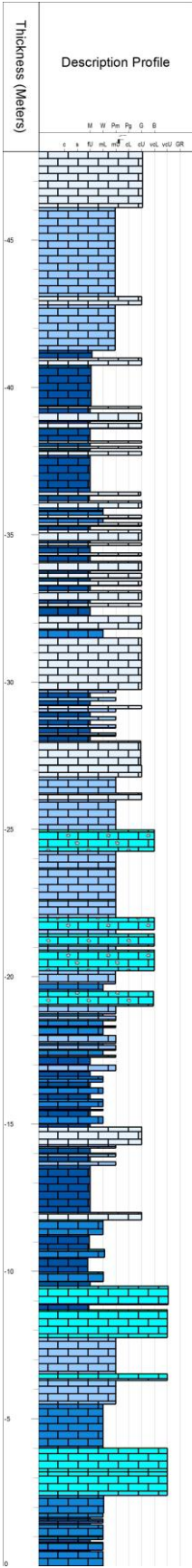
Appendix A: Vertical sedimentary sections and localities

Key for Appendix A:

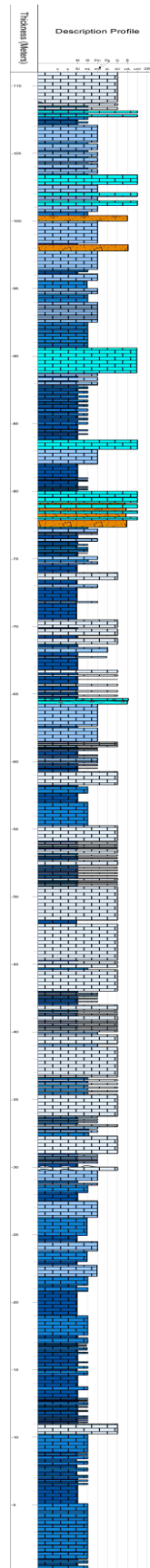
M	Carbonate mudstone
W	Wackestone
Pm	Mud-dominated packstone
Pg	Grain-dominated packstone
G	Grainstone
B	Boundstone
C	Claystone
S	Siltstone
F	Fine sandstone
mL/mU	Medium sandstone
cL/cU	Coarse sandstone
vcL/vcU	Very coarse sandstone
GR	Gravel

Section Name: H1

Coordinates: (24.210931°N,
46.716382°E)

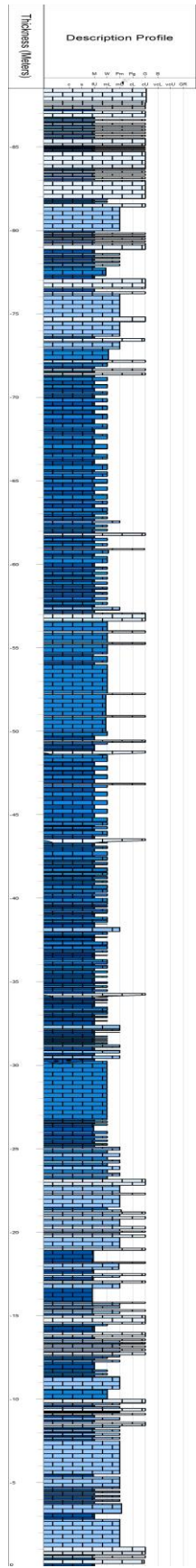


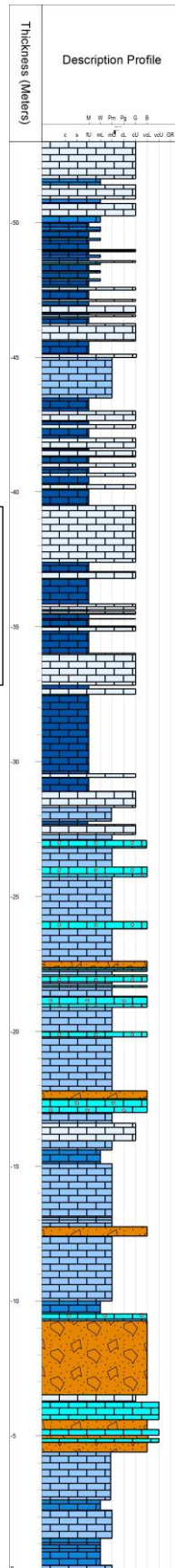
Section Name: H2
Coordinates: (24.527797°N,
46.393832°E)



Section Name: H3

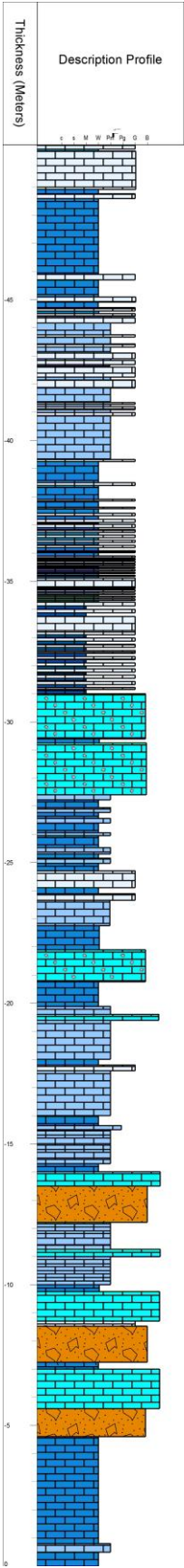
Coordinates: (24.965801°N,
46.215935°E)





Section Name: H8

Coordinates: (24.098278°N,
46.694556°E)



References

- Abu-Ali, M. A., Franz, U. A., Shen, J., Monnier, F., Mahmoud, M. D., Chambers, T. M., 1991. Hydrocarbon generation and migration in the Paleozoic sequence of Saudi Arabia. In SPE Middle East Oil Show. Society of Petroleum Engineers.
- Ahr, W.M., 1973. The Carbonate Ramp: An Alternative to the Shelf Model. In: Trans. Gulf Coast Association of Geol. Soc., 23rd Annual Convention, pp. 221–225.
- Ahr, W.M., 2008. Geology of Carbonate Reservoirs: The Identification, Description, and Characterization of Hydrocarbon Reservoirs in Carbonate Rocks. John Wiley and Sons, pp 1–227.
- Al Ibrahim, M.A., Sarg, J.F., Hurley, N., Cantrell, D.L., Humphrey, J.D., 2017. Depositional environments and sequence stratigraphy of carbonate mudrocks using conventional geologic observations, multiscale electrofacies visualization, and geochemical analysis: The case of the Tuwaiq Mountain and Hanifa Formations in a basinal setting, Saudi Arabia. AAPG Bull. 101 (5), 683–714.
- Alsharhan, A.S., Magara, K., 1994. The Jurassic of the Arabian Gulf Basin: Facies, depositional setting and hydrocarbon habitat. Pangea: Global Environments and Resources, Mem. 17, 397–412.
- Alsharhan, A.S., Nairn, A.E.M., 2003. The geological history and structural elements of the Middle East. In: Alsharhan, A.S., Nairn, A.E.M., Sedimentary basins and petroleum geology of the Middle East. Elsevier, Amsterdam, pp. 15–63.

- Ashley, G.M., 1990. Classification of large-scale subaqueous bedforms: a new look at an old problem. *J. Sediment. Petrol.* 60 (1), 160–172.
- Amaefule, J. O., Altunbay, M., Tiab, D., Kersey, D. G., & Keelan, D. K., 1993. Enhanced reservoir description: using core and log data to identify hydraulically (flow) units and predict permeability in uncored intervals/wells. In SPE annual technical conference and exhibition. Society of Petroleum Engineers (SPE paper 26436).
- Arkell, W.J., 1952. Jurassic ammonites from Jebel Tuwaiq, central Arabia. *Royal Society of London Philosophical Transactions, Series B* 36, 241-313.
- Awwad, S., 2016. The Arab D – Hanifa Reservoir Communication: Stratigraphic Solutions to Engineering Problems. AAPG Datapages/Search and Discovery, Article #90254. 12th Middle East Geosciences Conference & Exhibition, Bahrain.
- Al-Aswad, A.A., 1995. Middle Jurassic non-marine siliciclastic facies in southern central Saudi Arabia. *J. African Earth Sci.* 20 (3–4), 253–262.
- Al-Hussaini, A., Steel, R.J., Melvin, J., Olariu, C., Ertug, K., Hooker, N., 2019. New evidence of regressing and transgressing Jurassic siliciclastic coastlines within the Dhurma Formation in Northern Central Arabia, Saudi Arabia. *Sediment. Geol.* 379, 114–137.
- Al-Husseini, M.I., 1997. Jurassic sequence stratigraphy of the western and southern Arabian Gulf. *GeoArabia* 2 (4), 361–382.
- Al-Husseini, M.I., 2000. Origin of the Arabian Plate Structures: Amar Collision and Najd Rift. *GeoArabia* 5, 527–542.

- Al-Husseini, M.I., Matthews, R. K., 2005. Arabian Orbital Stratigraphy: Periodic second-order sequence boundaries. *GeoArabia*, v. 10, no. 2, p. 165-184.
- Al-Husseini, M.I., Matthews, R.K., Mattner, J., 2006. Stratigraphic note: Orbital-forcing calibration of the Late Jurassic (Oxfordian-early Kimmeridgian) Hanifa Formation, Saudi Arabia. *GeoArabia*, 11, no. 1, 145-149.
- Al-Jallal, I., 1995. The Khuff Formation: its regional reservoir potential in Saudi Arabia and other Gulf countries; depositional and stratigraphic approach: In: M.I. Al-Husseini (Ed.), *Middle East Petroleum Geosciences Conference, GEO'94*. Gulf PetroLink, Bahrain. 1, 103–119.
- Al-Khalifah, M., Makkawi, M., 2002. The impact of data integration on geostatistical porosity modelling: A case study from the Berri field, Saudi Arabia. *Journal of Petroleum Geology*, 25(4), 485–498.
- Al-Mojel, A., Razin, P., Dera. G., 2020. High-resolution sedimentology and sequence stratigraphy of the Oxfordian-Kimmeridgian, Hanifa, Jubaila and Arab outcrops along Jabal Tuwaiq, Central Saudi Arabia. *J. African Earth Sci.* 165, 103803.
- Al-Suwaidi, A.S., Taher, A.K., Alsharhan, A.S., Salah, M.G., 2000. Stratigraphy and Geochemistry of Upper Jurassic Diyab Formation, Abu Dhabi, U.A.E. In: Alsharhan, A.S., Scott, R.W., (Eds.), *Middle East Models of Jurassic/Cretaceous Carbonate Systems*. SEPM (Society for Sedimentary Geology), Spec. Publ. 69, pp. 249–271.

- Al-Suwaidi, A. S., Aziz, S. K., 2002. Sequence stratigraphy of Oxfordian and Kimmeridgian shelf carbonate reservoirs, offshore Abu Dhabi. *GeoArabia*, 7(1), 31–44.
- Bauer, J., Kuss, J., Steuber, T., 2002. Platform environments, microfacies and systems tracts of the upper Cenomanian - Lower Santonian of Sinai, Egypt. *Facies* 47, 1–26.
- Blasband, B., White, S., Brooijmans, P., Boorder, H.D.E., Visser, W., 2000. The late Proterozoic extensional collapse in the Arabian – Nubian Shield. *J. Geol. Soc. London*. 157, 615–628.
- Boada, E., Barbato, R., Porras, J. C., & Quaglia, A., 2001. Rock Typing: Key Approach for Maximizing Use of Old Well Log Data in Mature Fields, Santa Rosa Field, Case Study. In *SPE Latin American and Caribbean Petroleum Engineering Conference*. Society of Petroleum Engineers.
- Bordenave, M. L., Burwood, R., 1990. Source rock distribution and maturation in the Zagros orogenic belt: provenance of the Asmari and Bangestan reservoir oil accumulations. *Organic Geochemistry* 16 (1–3), 369–387.
- Burchette, T. P., Paul Wright, V., Faulkner, T. J., 1990. Oolitic sand body depositional models and geometries, Mississippian of southwest Britain: implications for petroleum exploration in carbonate ramp settings. *Sediment. Geol.* 68(1–2), 87–115.
- Burchette, T. P., Wright, V. P., 1992. Carbonate ramp depositional systems. *Sediment. Geol.* 79(1–4), 3–57.

- Cantrell, D.L., Nicholson, P.G., Hughes, G.W., Miller, M.A., Buhllar, A.G., Abdelbagi, S.T., Norton, A.K., 2014. Tethyan petroleum systems of Saudi Arabia. AAPG Mem. 106, 613–639.
- Carrigan, W.J., Cole, G.A., Colling, E.L., Jones, P.J., 1995. Geochemistry of the Upper Jurassic Tuwaiq Mountain and Hanifa Formation Petroleum Source Rocks of Eastern Saudi Arabia. In: Katz, B.J. (Ed.), *Petroleum Source Rocks*. Springer, Heidelberg, pp. 67–87.
- Carruba, S., Perotti, C.R., Buonaguro, R., Calabró, R., Carpi, R., Naini, M., 2006. Structural pattern of the Zagros fold-and-thrust belt in the Dezful embayment (SW Iran). *Geol. Soc. Am. Special Paper* 414, 11–32.
- Catuneanu, O., 2006. *Principles of Sequence Stratigraphy*. Elsevier, Amsterdam (375 pp).
- Catuneanu, O., Galloway, W. E., Kendall, C. G. S. C., Miall, A. D., Posamentier, H. W., Strasser, A., Tucker, M. E., 2011. *Sequence Stratigraphy: Methodology and Nomenclature*. *Newsletters on Stratigraphy* 44(3), 173–245.
- Cecca, F., B.M. Garin, D. Marchand, B. Lathuiliere and A. Bartolini 2005. Palaeoclimatic control of biogeographic and sedimentary events in Tethyan and peri-Tethyan areas during the Oxfordian (Late Jurassic). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 222, p.10-32.
- Chehrizi, A., Rezaee, R., & Rahimpour, H., 2011. Pore-facies as a tool for incorporation of small-scale dynamic information in integrated reservoir studies. *Journal of Geophysics and Engineering*, 8(2), 202.

- Choquette, P. W., Pray, L. C., 1970. Geologic nomenclature and classification of porosity in sedimentary carbonates. The American Association of Petroleum Geologists Bulletin 54(2), 207–250.
- Cortez, O. D., & Corbett, P. W. M. (2005). Time-lapse production logging and the concept of flowing units. In SPE Europec/EAGE Annual Conference. Society of Petroleum Engineers (SPE paper 94436.).
- Craigie, N. W., 2015. Applications of chemostratigraphy in Middle Jurassic unconventional reservoirs in eastern Saudi Arabia. *GeoArabia*, 20(2), 79–110.
- Craigie, N., 2018. Principles of Elemental Chemostratigraphy. *Advances in Oil and Gas Exploration and Production* (196 pp).
- Crevello, P.D., Wilson, J.L., Sarg, J.F. and Read, J.F., 1989. Controls on Carbonate Platform and Basin Development. *SEPM*, Tulsa, Oklahoma, 405 pp.
- Cruz, F.E.G., Eberli, G.P., 2019. Co-existence of skeletal and ooid shoals as a result of antecedent topography—Cat cay shoal complex, Bahamas. *Depos. Record* 5 (3), 451–468.
- Da Costa E Silva, A., Soares, A., Almeida, J. A., Ramos, L., & Carvalho, J., 1999. A multi-step approach for modelling oil reservoir lithologies and petrophysical attributes based on the integration of geostatistics and geology. *Geostatistics Wollongong 96 - Proceedings of the Fifth International Geostatistics Congress, Wollongong, Australia*. 327–338.

- Dahanayake, K., 1977. Classification of oncoids from the Upper Jurassic carbonates of the French Jura. *Sediment Geol* 18:337–353
- Dahanayake, K., 1983. Depositional Environments of Some Upper Jurassic Oncoids. In *Coated Grains* (pp. 377–385). Springer Berlin Heidelberg.
- Davis, R.B., Simmons, M.D., Jewell, T.O., Collins, J. 2019. Regional Controls on Siliciclastic Input into Mesozoic Depositional Systems of the Arabian Plate and Their Petroleum Significance. In: AlAnzi, H.R., Rahmani, R.A., Steel, R.J., Soliman, O.M. (Eds). *Siliciclastic Reservoirs of the Arabian Plate*. AAPG Mem. 116, 103–140.
- de Almeida, J. A., 2010. Stochastic simulation methods for characterization of lithoclasses in carbonate reservoirs. *Earth-Science Reviews*.
- Droste, H., 1990. Depositional cycles and source rock development in an epeiric intra-platform basin: the Hanifa Formation of the Arabian Peninsula. *Sediment. Geol.* 69 (3–4), 281–296.
- Drzewiecki, P.A., Simó, J.A., 2002. Depositional processes, triggering mechanisms and sediment composition of carbonate gravity flow deposits: Examples from the Late Cretaceous of the South-Central Pyrenees, Spain. *Sediment. Geol.* 146 (1–2), 155–189.
- Dumas, S., Arnott, R.W.C., Southard, J.B., 2005. Experiments on oscillatory-flow and combined-flow bedforms: implications for interpreting parts of the shallow-marine sedimentary record. *J. Sediment. Res.* 75, 501–513.

- Dunham, R.J., 1962. Classification of carbonate rocks according to depositional textures. AAPG Bull. 1, 108–121.
- Dupraz, C., Strasser, A., 1999. Microbialites and micro-encrusters in shallow coral bioherms (Middle to Late Oxfordian, Swiss Jura Mountains). *Facies* 40, 101–130.
- Edgell, H.S., 1992. Basement tectonics of Saudi Arabia as related to oil field structures. *Basement Tectonics 9: Australia and Other Regions. Proc. Conference, Canberra, 1990.* 169–193.
- Edgell, H.S., 1996. Salt tectonism in the Persian Gulf Basin. In: Aslop, G.I., Blundell, D.J., and Davison, I., (Eds.), *Salt tectonics: Geological Society of London Spec. Publ. 100*, p. 129–151.
- El-Asa'ad, G.M.A., 1991. Oxfordian hermatypic corals from central Saudi Arabia. *Geobios* 24 (3), 267–287.
- El-Asmar, H. M., Assal, E. M., El-Sorogy, A. S., Youssef, M., 2015. Facies analysis and depositional environments of the Upper Jurassic Jubaila Formation, Central Saudi Arabia. *J. Afr. Earth Sci.* 110, 34-51.
- El-Sabbagh, A. M., El-Hedeny, M. M., Mansour, A. S., 2017. Paleoecology and paleoenvironment of the Middle-Upper Jurassic sedimentary succession, central Saudi Arabia. *Proceedings of the Geologists' Association.* 128 (3), 340-359
- El-Sorogy, A., Al-Kahtany, K., Almadani, S., Tawfik, M., 2018. Depositional architecture and sequence stratigraphy of the Upper Jurassic Hanifa Formation, central Saudi Arabia. *J. African Earth Sci.* 139, 367–378.

- Eltom, H.A., Rankey, E.C., Cantrell, L.A., Hasiotis, S.T., Gonzalez, L.A., 2017. Impact of upwelling on Heterozoan, biosiliceous and organic-rich deposits: Jurassic (Oxfordian) Hanifa Formation, Saudi Arabia. *J. Sediment. Res.* 87, 1–24.
- Eltom, H. A., Gonzalez, L. A., Hasiotis, S. T., Rankey, E. C., Cantrell, D. L. (2018). Paleogeographic and paleo-oceanographic influences on carbon isotope signatures: Implications for global and regional correlation, Middle-Upper Jurassic of Saudi Arabia *Sediment. Geol.*, 364, p. 89-102
- Eltom, H. A., Alqubalee, A., Yassin, M. A., 2021. Potential overlooked bioturbated reservoir zones in the shallow marine strata of the Hanifa Formation in central Saudi Arabia. *Marine and Petroleum Geology*, 124.
- Elzain, H.E., Abdullatif, O., Senapathi, V., Chung, S.Y., Sabarathinam, C., Sekar, S., 2020. Lithofacies modeling of Late Jurassic in upper Ulayyah reservoir unit at central Saudi Arabia with inference of reservoir characterization. *J. Pet. Sci. Eng.* 185, 106664.
- Embry, A.F., Klovan, J.E., 1971. A Late Devonian Reef Tract on the Northeastern Banks Island, Northwest Territories. *Bull. Can. Pet. Geol.* 19 (4), 730–781.
- Embry, A.F., 2009. *Practical Sequence Stratigraphy*. Canadian Society of Petroleum Geologists.
- Énay, R., Le Nindre, Y.M., Mangold, C., Manivit, J., Vaslet, D., 1987. The Jurassic of Central Saudi Arabia: New Data on Lithostratigraphy, Paleoenvironments, Ammonite Faunas, Ages and Correlations. *Geobios*, 20, 13–65.

- Énay, R., Mangold, C., 2021. Jurassic ammonites from Central Saudi Arabia (Jebel Tuwaiq and adjacent areas). *Rev. Paléobiol.* 40 (1), 1–197.
- Enos, P., Sawatsky, L. H., 1981. Pore networks in Holocene carbonate sediments. *Journal of Sedimentary Research* 51(3), 961–985.
- Emery, X., Silva, D. A., 2009. Conditional co-simulation of continuous and categorical variables for geostatistical applications. *Computers and Geosciences*, 35(6), 1234–1246.
- Fallatah, M.I., Kerans, C., 2018. Stratigraphic evolution of the Late Jurassic Hanifa Formation along the Tuwaiq Escarpment, Saudi Arabia: Evidence for a carbonate ramp system. *Sediment. Geol.* 363, 152–180.
- Fallatah, M., 2019. Subsurface Stratigraphy Problem Resolved from Outcrop Stratigraphy: A Case Study from the Late Jurassic Hanifa Formation, Saudi Arabia. The 11th International Petroleum Technology Conference, China.
- Farouk, S., Al-Kahtany, K., El-Sorogy, A., El-Motaal, E.A., 2018. High-frequency cycles and sequence stratigraphy of the lower Jurassic Marrat Formation, central Saudi Arabia. *Mar. Pet. Geol.* 98, 369–383.
- Fischer, A. G., 1964. The Lofer cyclothems of the Alpine Triassic. In D.F. Merriam (ed.) *Symposium on Cyclic Sedimentation*. State Geological Survey of Kansas Bulletin, 1, 107-149.
- Flügel, E., 2010. *Microfacies of Carbonate Rocks: Analysis, Interpretation and Application*. Springer-Verlag, New York, 996 pp.

- Francesconi, A., Bigoni, F., Balossino, P., Bona, N., Marchini, F., Cozzi, M., 2009. Reservoir Rock Types Application-Kashagan. In SPE/EAGE Reservoir Characterization & Simulation Conference (SPE paper 125342).
- Frank, S., Narayanan, R., Hansen, P., Allen, D. F., Albrechtsen, T., Steinhardt, H., Rose, D. A., 2005. Carbonate rock typing using NMR data: a case study from the Al Shaheen field, offshore Qatar. (IPTC paper 10889) International Petroleum Technology Conference.
- Gammon, P.R., James, N.P., 2001. Palaeogeographical influence on Late Eocene biosiliceous sponge-rich sedimentation, Southern Western Australia. *Sedimentology* 48 (3), 559–584.
- Ghedan, S. G., 2007. Dynamic rock types for generating reliable and consistent saturation functions for simulation models. In SPE/EAGE Reservoir Characterization and Simulation Conference. Society of Petroleum Engineers.
- Gomes, J. S., Ribeiro, M. T., Strohmenger, C. J., Naghban, S., Kalam, M. Z., 2008. Carbonate reservoir rock typing-the link between geology and SCAL. In Abu Dhabi International Petroleum Exhibition and Conference. Society of Petroleum Engineers (SPE paper 118284).
- Gough, A., 2021. Sedimentary Structures. *Encyclopedia of Geology* (Second Edition), Academic Press, pp. 787–808.
- Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M., 2012. The Geologic Time Scale 2012. Elsevier, pp. 1144.

- Grammer, G. M., Harris, P. M. M., Eberli, G. P., 2004. Integration of outcrop and modern analogs in reservoir modeling: Overview with examples from the Bahamas. AAPG Memoir, (80), 1–22.
- Gravestock, C., Simmons, M., Van Buchem, F., Davies, R.. 2021. Challenging Middle Eastern Stratigraphic Misconceptions—An Example for Creation and Infill of the Gotnia Basin. 82nd EAGE Annual Conference & Exhibition.
- Grover, G. A., 1993. Abqaiq Hanifa reservoir: geologic attributes controlling hydrocarbon production and water injection. In Proceedings of the Middle East Oil Show. 2, 113–118.
- Gunter, G. W., Finneran, J. M., Hartmann, D. J., & Miller, J. D., 1997. Early determination of reservoir flow units using an integrated petrophysical method. In SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers (SPE paper 38679).
- Ham, W. E., Pray, L. C., 1962. Modern concepts and classifications of carbonate rocks. Classification of carbonate rocks. American Association of Petroleum Geologists Memoir 1, 2-19.
- Handford, C.R., Cantrell, D.L., Keith, T.H., 2002. Regional facies relationships and sequence stratigraphy of a supergiant reservoir (Arab-D member), Saudi Arabia. In: Sequence-stratigraphic models for exploration and production: 22nd Annual Bob F. Perkins Gulf Coast Section SEPM Foundation Research Conference, Houston, Texas. 8, 539–563.

- Haq, B. U., Hardenbol, J., Vail, P. R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. SEPM Special Publication 42, 71-107.
- Haq, B. U., 2018. Jurassic sea-level variations: A reappraisal. *GSA Today*, 28(1), 4–10.
- Harris, P.M., Diaz, M.R., Eberli, G.P., 2019. The formation and distribution of modern ooids on Great Bahama Bank. *Ann. Rev. Mar. Sci.* 11, 491–516.
- Hine, A.C., Locker, S.D., Tedesco, L.P., Mullins, H.T., Hallock, P., Belknap, D.F., Gonzales, J.L., Neumann, A.C., Snyder, S.W., 1992. Megabreccia shedding from modern, low-relief carbonate platforms, Nicaraguan rise. *Geol. Soc. Am. Bull.* 104 (8), 928–943.
- Hollis, C., Vahrenkamp, V., Tull, S., Mookerjee, A., Taberner, C., Huang, Y., 2010. Pore system characterisation in heterogeneous carbonates: An alternative approach to widely-used rock-typing methodologies. *Marine and Petroleum Geology*, 27(4), 772–793.
- Hughes, W., 2004. Middle to Upper Jurassic Saudi Arabian carbonate petroleum reservoirs: Biostratigraphy, micropalaeontology and palaeoenvironments. *GeoArabia* 9 (3), 79–114.
- Hughes, W., Varol, O., Al-Khalid, M., 2008. Late Oxfordian micropalaeontology, nannopalaeontology and palaeoenvironments of Saudi Arabia. *GeoArabia* 13 (2), 15–46.
- Hughes, W., 2018. A new thin-section based micropaleontological biozonation for the Saudi Arabian Jurassic carbonates. *Micropaleontology* 64, 331–364.

- Immenhauser, A., Hillgärtner, H., van Betum, E., 2005. Microbial-foraminiferal episodes in the Early Aptian of the southern Tethyan margin: ecological significance and possible relation to oceanic anoxic event 1a. *Sedimentology* 52:77–99.
- Incze, M. L., 1998. Petrophysical properties of shallow-water carbonates in modern depositional and shallow subsurface environments. *Dissertation Abstracts International*, 60 (6), Section: B, 2577; 405 p.
- James, N.P., Kendall, A.C., 1992. Introduction to carbonate and evaporite facies models. In: Walker, R.G., James, N.P. (eds.): *Facies models. Response to sea level change*. GAC, 265-276.
- Kadar, A.P., De Keyser, T., Neog, N., Karam, K.A., Le Nindre, Y.M., Davies, R.B., 2015. Calcareous nanofossil zonation and sequence stratigraphy of the Jurassic System, onshore Kuwait. *GeoArabia* 20 (4), 125-180.
- Karabiyikoğlu, M., Tuzcu, S., Çiner, A., Deynoux, M., Örcen, S., Hakyemez, A., 2005. Facies and environmental setting of the Miocene coral reefs in the late-orogenic fill of the Antalya Basin, western Taurides, Turkey: Implications for tectonic control and sea-level changes. *Sediment. Geol.* 173 (1–4), 345–371.
- Kelley, B. M., Lehrmann, D. J., Yu, M., Jost, A. B., Meyer, K. M., Lau, K. V., Altiner, D., Li, X., Minzoni M., Payne, J. L., 2020. Controls on carbonate platform architecture and reef recovery across the Palaeozoic to Mesozoic transition: A high-resolution analysis of the Great Bank of Guizhou. *Sedimentology*, 67(6), 3119–3151.

- Kompanick, G. S., Heil, R. J, Al-Shammari, Z. A., Al-Shammary, M. J., 1993. Geological Modeling for Reservoir Simulation: Hanifa Reservoir, Berri Field, Saudi Arabia. SPE paper 25580.
- Knaust, D., 2012. Methodology and techniques. In: Knaust D, Bromley, R.G. (Eds.), Trace fossils as indicators of sedimentary environments. *Developments in Sedimentology* 64, 245–271.
- Konert, G., Afifi, A.M., Al-Hajri, S.A., Droste, H.J., 2001. Paleozoic stratigraphy and hydrocarbon habitat of the Arabian plate. *GeoArabia*, 6 (3), 407–442.
- Krauter, M., 1998. Ecology of siliceous sponges: Application to the environmental interpretation of the Upper Jurassic sponge facies (Oxfordian) from Spain. *J. Iber. Geol*, 24, 223-239.
- Labourdet, R., Hegre, J., Imbert, P., Insalaco, E., 2008. Reservoir-scale 3D sedimentary modelling: Approaches to integrate sedimentology into a reservoir characterization workflow. *Geol. Soc. Spec. Publ*, 309, 75–85.
- Leinfelder, R. R., 1992. A modern-type Kimmeridgian reef (Ota Limestone, Portugal): implications for Jurassic reef models. *Facies* 26:11–34.
- Leinfelder, R. R., Nose, M., Schmid, D.U., Werner, W., 1993. Microbial crusts of the Late Jurassic: composition, palaeoecological significance and importance in reef construction. *Facies* 29:195–230.

- Leinfelder, R. R., Schmid, D. U., Nose, M., Werner, W., 2002. Jurassic reef patterns-the expression of a changing globe. In: Kiessling, W., Flügel, E., Golonka, J., (eds) Phanerozoic reef patterns, SEPM Special Publication, vol 72, Tulsa. pp. 465–520.
- Leinfelder, R. R., Schlagintweit, F., Werner, W., Ebli, O., Nose, M., Schmid, D. U., Hughes, G. W., 2005. Significance of stromatoporoids in Jurassic reefs and carbonate platforms-concepts and implications. *Facies* 51:287–325.
- Le Nindre, Y., Manivit, J., Manivit, H., Vaslet, D., 1990. Stratigraphie sequentielle du Jurassique et du Cretace en Arabie Saoudite. *Bulletin de La Societe Geologique de France*, 6(6), 1025–1034.
- Le Nindre, Y.M., Vaslet, D., Le Métour, J., Bertrand, J., Halawani, M., 2003. Subsidence modelling of the Arabian Platform from Permian to Paleogene outcrops. *Sediment. Geol.* 156 (1–4), 263–285.
- Lonoy, A., 2006. Making sense of carbonate pore systems. *AAPG Bulletin* 90(9), 1381–1405.
- Lucia, F. J., Murray, R. C., 1967. Origin and distribution of porosity in crinoidal rock. In 7th World Petroleum Congress.
- Lucia, F.J., 1995. Rock-fabric/petrophysical classification of carbonate pore space for reservoir characterization. *AAPG Bull.* 79 (9), 1275–1300.
- Lucia, J., 1999. *Carbonate Reservoir Characterization*. Springer.
- Lucia, F. J., 2007. *Carbonate Reservoir Characterization An Integrated Approach*, Second Edition. *Journal of Petroleum Technology* (Vol. 55)

- MacEachern, J.A., Pemberton, S.G., 1992. Ichnological aspects of Cretaceous shoreface successions and shoreface variability in the Western Interior Seaway of North America. In: Pemberton, S.G. (Ed.), *Applications of Ichnology to Petroleum Exploration*. SEPM Core Workshop Notes 17, pp. 57–84.
- Manivit, J., Pellaton, C., Vaslet, D., Le Nindre, Y.M., Brosse, J.M., Fourniguet, J., 1985. Explanatory notes to the geologic map of the Wadi Al Mulayh Quadrangle, Kingdom of Saudi Arabia. *Geoscience Map GM-92C*, Scale, 1(250,000).
- Manivit, J., Le Nindre, Y.M., Vaslet, D., 1990. Histoire géologique de la bordure occidentale de la Plate-forme Arabe. Le Jurassique d'Arabie Centrale. *Documents de Recherches Géologiques et Minières*, Orleans. 194, 1-574.
- Markello, J.R., Koepnick, R.B., Waite, L.E., Collins, J.F., Lukasik, J., Simo, J.A., 2008. The carbonate analogs through time (CATT) hypothesis and the global atlas of carbonate fields—A systematic and predictive look at Phanerozoic carbonate systems. In: *Controls on carbonate platform and reef development* (Eds J. Lukasik and J.A. (Toni) Simo), *SEPM Spec. Publ.*, 89, 15–45.
- Mata-Lima, H. 2008. Reservoir characterization with iterative direct sequential co-simulation: Integrating fluid dynamic data into stochastic model. *Journal of Petroleum Science and Engineering*, 62(3–4), 59–72.
- Mattner, J., Al-Husseini, M., 2002. Essay: applied cyclo-stratigraphy for the Middle East E&P industry. *GEOARABIA* 7, 734–744.

- McGuire, M.D., 2003. Sequence stratigraphy of the Hanifa reservoir in Berri field, Saudi Arabia. AAPG Conference, Salt Lake City. Abstract (No. 78653).
- McGuire, M.D., Koepnick, R.B., Markello, J.R., Stockton, M.L., Waite, L.E., Kompanik, G.S., Al-Shammery, M., Al-Amoudi, M.O., 1993. Importance of sequence stratigraphic concepts in development of reservoir architecture in upper Jurassic Grainstones, Hadriya and Hanifa reservoirs, Saudi Arabia. In: Proceedings of the Middle East Oil Show. SPE of AIME. 1, 489–499.
- Meyer, F. O., Price, R.C., 1993. A new Arab-D depositional model, Ghawar field, Saudi Arabia. 8th Middle East Oil Show & Conference. SPE, Inc., Bahrain. 1, 465–474.
- Moore, C. H. 1989. Carbonate Diagenesis and Porosity. *Developments in Sedimentology* 46, 1-19
- Moore, G. T., Hayashida, D. N., Ross, C. A., Jacobson, S. R., 1992a. Paleoclimate of the Kimmeridgian/Tithonian (Late Jurassic) world: I. Results using a general circulation model. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 93, p. 113–150.
- Moore, G. T., Sloan, L. C., Hayashida, D. N., Umrigar, N. P., 1992b. Paleoclimate of the Kimmeridgian/Tithonian (Late Jurassic) world: II. Sensitivity tests comparing three different paleotopographic settings. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 95, p. 229–252.
- Moore, L. V., Gilbert, D. G., Al-Ateeqi, A. M., Al-Zuabi, Y., 1998. The Late Jurassic (Najmah) hydrocarbon system of West Kuwait (Abs.). *GeoArabia*, 3(1), 13, 1-132.

- Moshrif, M.A., 1984. Sequential development of Hanifa Formation (Upper Jurassic) paleoenvironments and paleogeography, Central Saudi Arabia. *J. Pet. Geol.* 7, 451–460.
- Murray, R. C., 1960. Origin of porosity in carbonate rocks. *Journal of Sedimentary Research*, 30(1), 59–84.
- Murris, R. J., 1980. Middle East: stratigraphic evolution and oil habitat. *AAPG Bull.* 64 (5), 597–618.
- Okla, S. M., 1983. Microfacies of Hanifa Formation (Upper Jurassic) in Central Tuwaiq Mountains. *J. Coll. Sci. King Saud Univ.* 14, 121–143.
- Okla, S. M., 1986. Litho- and microfacies of Upper Jurassic carbonate rocks outcropping in Central Saudi Arabia. *J. Pet. Geol.* 9, 195–206.
- Parrish, J. T., Ziegler, A. M., Scotese, C. R., 1982. Rainfall patterns and the distribution of coals and evaporites in the Mesozoic and Cenozoic. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 40, p. 67–101.
- Pemberton, S. G., MacEachern, J. A., Dashtgard, S. E., Bann, K. L., Gingras, M. K., Zonneveld, J. P., 2012. Shorefaces. In *Developments in Sedimentology*. 64, pp. 563–603. Elsevier B.V.
- Perotti, C.R., Carruba, S., Rinaldi, M., Bertozzi, G., Feltre, L., Rahimi, M., 2011. The Qatar–South Fars Arch Development (Arabian Platform, Persian Gulf): Insights from Seismic Interpretation and Analogue Modelling. In: Shattner, U. (Ed.), *New Frontiers in Tectonic Research - At the Midst of Plate Convergence*. Intech Open. pp. 325–352.

- Peryt, T.M., 1981. Phanerozoic oncoids—an overview. *Facies* 4:197–214.
- Peryt, T.M., 1983. Oncoids: a comment to recent developments. In: Peryt TM (ed) *Coated grains*. Springer, Berlin Heidelberg New York, pp 273–275.
- Playton, T.E., Janson, X., Kerans, C., 2010. Carbonate slopes. In: James NP, Dalrymple RW (eds) *Facies Models, GEOText 6. GAC, St John's, Newfoundland*. 4, 449–476.
- Pollastro, R.M., 2003. Total Petroleum Systems of the Paleozoic and Jurassic, Greater Ghawar Uplift and Adjoining Provinces of Central Saudi Arabia and Northern Arabian-Persian Gulf. *U.S. Geol. Surv. Bull.* 2202-H, 100 pp.
- Pomar, L., 2001. Types of carbonate platforms: A genetic approach. *Basin Res.* 13(3), 313–334.
- Powers, R., Ramirez, L., Redmond, C., Elberg, E., 1966. *Geology of the Arabian Peninsula Sedimentary Geology of Saudi Arabia*. U.S. Geol. Surv. Professional Paper 560-D, 127 pp.
- Powers, R.W., 1968. Saudi Arabia (Excluding the Arabian Shield). *Lexique Stratigraphique International III*, Paris. 171 p.
- Pyrz, M. J., Deutsch, C. V., 2014. *Geostatistical reservoir modelling*. Oxford university press.
- Rankey, E.C., Reeder, S.L., 2012. Tidal sands of the Bahamian archipelago. In: Davis, R.A., Dalrymple, R.W., (Eds.), *Principles of tidal sedimentology*. Springer, pp. 537–565.

- Read, J. F., Goldhammer, R. K., 1988. Use of Fischer plots to define third-order sea-level curves in Ordovician peritidal cyclic carbonates: *Geology*, 16, 895-899.
- Riding, R., Martin, J.M., Barga, J.C., 1991. Coral-stromatolite reef framework, Upper Miocene, Almería, Spain. *Sedimentology* 38 (5), 799–818.
- Roehl, P. O., 1967. Stony Mountain (Ordovician) and Interlake (Silurian) facies analogues of Recent low-energy marine and subaerial carbonates, Bahamas. *AAPG Bulletin* 51(10), 1979–2032.
- Ross, D.J., 1992. Sedimentology and depositional profile of a mid-Cretaceous shelf edge rudist reef complex, Nahal Ha'mearot, northwestern Israel. *Sediment. Geol.* 79 (1–4), 161–172.
- Sadler, P. M., Osleger, D. A., Montanez, I. P., 1993. On the labelling, length and objective basis of Fischer plots: *Journal of Sedimentary Petrology*, 63, 360-368.
- Salman, S. M., Bellah, S., 2009. Rock typing: An integrated reservoir characterization tool to construct a robust geological model in Abu Dhabi carbonate oil field. In *SPE/EAGE Reservoir Characterization & Simulation Conference*.
- Schlager, W., 2005. *Carbonate Sedimentology and Sequence Stratigraphy*. SEPM, Tulsa, Oklahoma, 200 pp.
- Scotese, C.R., 2013. Map Folio 35, Late Jurassic (Oxfordian, 158.4 Ma). *PaleoAtlas for ArcGIS, Triassic and Jurassic Paleogeographic, Paleoclimatic and Plate Tectonic Reconstructions*. PALEOMAP Project, Evanston, IL. 3.

- Sellwood, B. W., Valdes, P. J., Price, G. D., 2000. Geological evaluation of multiple general circulation model simulations of late Jurassic palaeoclimate. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 156(1–2), 147–160.
- Senalp, M., Al-Duaiji, A. A., 2001. Qasim Formation: Ordovician storm-and tide-dominated shallow-marine siliciclastic sequences, Central Saudi Arabia. *GEOARABIA* 6, 233–268.
- Sharland, P.R., Archer, R., Casey, D.M., Davies, R.B., Hall, S.H., Heward, A.P., Horbury, A.D., Simmons, M.D., 2001. Arabian Plate Sequence Stratigraphy. *GeoArabia Special Publication* 2, 371 pp.
- Skalinski, M., & Kenter, J. A. M., 2015. Carbonate petrophysical rock typing: integrating geological attributes and petrophysical properties while linking with dynamic behaviour. *Geological Society, London, Special Publications*, 406(1), 229–259.
- Slatt, R. M., 2006. Stratigraphic Reservoir Characterization for Petroleum Geologists, Geophysicists, and Engineers - Origin, Recognition, Initiation, and Reservoir Quality. *Developments in Petroleum Science* 61, 621–656.
- Soares, A. 2001. Direct sequential simulation and cosimulation. *Mathematical Geology*, 33(8), 911–926.
- Stampfli, G. M., Borel, G. D., 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. *Earth Planet. Sci. Lett.*, 196(1–2), 17–33.

- Steineke, M., Bramkamp, R.A., 1952. Mesozoic rocks of eastern Saudi Arabia. AAPG Bull. 36, 909
- Stewart, S.A., 2016. Structural geology of the Rub' Al-Khali Basin, Saudi Arabia. Tectonics 35, 2417–2438.
- Stewart, S.A., Reid, C.T., Hooker, N.P., Kharouf, O.W., 2016. Mesozoic siliciclastic reservoirs and petroleum system in the Rub' Al-Khali basin, Saudi Arabia. AAPG Bull. 100 (5), 819–841.
- Taylor, A.M., Goldring, R., 1993. Description and analysis of bioturbation and ichnofabric. J. Geol. Soc. Lond. 150 (1), 141–148.
- Tintant, H., 1987. Jurassic Nautiluses of Saudi Arabia. Geobios 20, 67–159.
- Tremolada, F., Erba, E., Schootbrugge, B. van de., Mattioli, E., 2006. Calcareous nannofossil changes during the late Callovian-early Oxfordian cooling phase. Marine Micropaleontology, v. 59, p. 197-209.
- Tucker, M.E., 1985. Shallow-marine carbonate facies and facies models. Geol. Soc. Lond. Special Publications, 18(1): 147-169.
- Tucker, M., 2001. Sedimentary Petrology: an Introduction to the Origin of Sedimentary Rocks. Oxford; Malden, MA: Blackwell Science.
- Tucker, M., Garland, J. (2010). High-frequency cycles and their sequence stratigraphic context: Orbital forcing and tectonic controls on Devonian cyclicity, Belgium. Geologica Belgica, 13(3), 213–240.

- Valdes, P. J., Sellwood, B. W., 1992. A palaeoclimate model for the Kimmeridgian. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 95, p. 47–72.
- Vahrenkamp, V. C., Van Laer, P., Franco, B., Celentano, M. A., Grelaud, C., Razin, P., 2015. Late Jurassic to Cretaceous Source Rock Prone Intra-Shelf Basins of the Eastern Arabian Plate – Interplay between Tectonism, Global Anoxic Events and Carbonate Platform Dynamics. Society of Petroleum Engineers (SPE).
- Vaslet, D., Delfour, J., Manivit, J., Le Nindre, Y.M., Brosse, J.M., Fourniquet, J., 1983. Geologic Map of the Wādī Ar Rayn Quadrangle, Sheet 23 H, Kingdom of Saudi Arabia. Deputy Ministry for Mineral Resources.
- Vaslet, D., Brosse, J. M., Breton, J. P., Manivit, J., Strat, P. Le., Fourniquet, J., Shorbaji, H., 1988. Explanatory notes to the geologic map of the Shaqra' Quadrangle, Kingdom of Saudi Arabia. Geoscience map GM-120C, scale 1:250,000, sheet 25H . Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. 29 p.
- Vaslet, D., 1989. Late Ordovician glacial deposits in Saudi Arabia: a lithostratigraphic revision of the Early Paleozoic succession. Professional Paper, Saudi Arabian Deputy Ministry for Mineral Resources 3, 13-44
- Védrine, S., Strasser, A., Hug, W., 2007. Oncoid growth and distribution controlled by sea-level fluctuations and climate (Late Oxfordian, Swiss Jura Mountains). *Facies* 53 (4), 535–552.

- Walker, R.G., Plint, A.G., 1992. Wave- and storm-dominated shallow marine systems. In R. G. Walker & N. P. James (Eds.), *Facies Models: Response to Sea Level Change*. St. John's: GAC. 219–238.
- Wender, L.E., Bryant, J.W., Dickens, M.F., Neville, A.S., Al-Moqbel, A.M., 1998. Paleozoic (Pre-Khuff) Hydrocarbon Geology of the Ghawar Area, Eastern Saudi Arabia. *GeoArabia* 3 (2), 273–302.
- Wesolowski, L.J.N., Buatois, L.A., Mángano, M.G., Ponce, J.J., Carmona, N.B., 2018. Trace fossils, sedimentary facies and parasequence architecture from the Lower Cretaceous Mulichinco Formation of Argentina: The role of fair-weather waves in shoreface deposits. *Sediment. Geol.* 367, 146–163.
- Wibowo, A. S., & Permadi, P., 2013. A Type Curve for Carbonates Rock Typing. In *IPTC 2013: International Petroleum Technology Conference* (IPTC paper 16663.).
- Wilson, J.L., 1975. *Carbonate Facies in Geologic History*. Springer-Verlag, New York, 471 pp.
- Wilson, A. O., 2020. Introduction to the jurassic arabian intrashelf basin. *Geological Society Memoir*, 53(1), 1–19.
- Wignall, P.B., Twitchett, R.J., 1999. Unusual intraclastic limestones in Lower Triassic carbonates and their bearing on the aftermath of the end-Permian mass extinction. *Sedimentology* 46 (2), 303–316.

- Ye, S.-J., & Rabiller, P., 2000. A new tool for electro-facies analysis: multi-resolution graph-based clustering. In SPWLA 41st annual logging symposium. Society of Petrophysicists and Well-Log Analysts.
- Zecchin, M., Catuneanu, O., 2013. High-resolution sequence stratigraphy of clastic shelves I: Units and bounding surfaces. *Marine and Petroleum Geology* 39(1), 1-25.
- Ziegel, E. R., Yarus, J., Chambers, R., 1996. Stochastic Modeling and Geostatistics. *Technometrics*, 38(4), 411.
- Ziegler, M.A., 2001. Late Permian to Holocene Paleofacies Evolution of the Arabian Plate and its Hydrocarbon Occurrences. *GeoArabia* 6 (3), 445–504.

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List of Publications

Bashri,M, Michael A. Kaminski, Osman Abdullatif, John Humphrey, Mohammed Makkawi, Rudy Swennen, Omer Ali, Ammar Adam, Moaz Salih, and Jarrah Babiker., 2022. Facies analysis and depositional model for the Oxfordian Hanifa Formation, Central Saudi Arabia. Marine and Petroleum Geology.

Bashri, M., Kaminski, M., Abdullatif, O., Humphrey, J., Makkawi, M., Swennen, R., Ali, O., Adam, A., Salih, M., Babiker, J., 2021. Sedimentary facies analysis and depositional environment modeling of the Oxfordian Hanifa Formation, central Saudi Arabia. 35th IAS Meeting of Sedimentology, June 2125, 2021, Prague, Czech Republic.

Moaz Salih, John J.G Reijmer, Ammar El Hussein, Mazin Bashri, Hassan Eltom, Hani Al Mukainah, and Michael A. Kaminski. "Controlling Factors on Petrophysical and Acoustic Properties of Bioturbated Carbonates:(Upper Jurassic, Central Saudi Arabia)". *Applied Sciences* 11, no. 11 (2021): 5019.