

**QUANTIFYING THE DYNAMICS OF MIXED SILICICLASTIC  
AND CARBONATE SYSTEM OF THE TOARCIAN MARRAT  
FORMATION, SAUDI ARABIA: INSIGHTS FROM 3D  
STRATIGRAPHIC FORWARD MODELING**

BY

**BAHARUDIN FAHMI**

A Thesis Presented to the  
**COLLEGE OF GRADUATE AND INTERDISCIPLINARY STUDIES**  
**KING FAHD UNIVERSITY OF PETROLEUM & MINERALS**

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the  
Requirements for the Degree of

**MASTER OF SCIENCE**

**In**

**GEOLOGY**

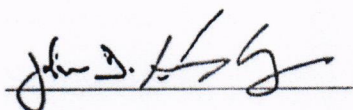
**MAY 2024**

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

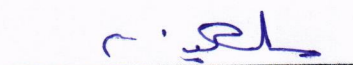
DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **BAHARUDIN FAHMI** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE MASTER OF SCIENCE IN GEOLOGY.**



Dr. John D. Humphrey  
Department Chairman



Prof. Suliman Saleh Al-Homidan  
Dean of Graduate Studies

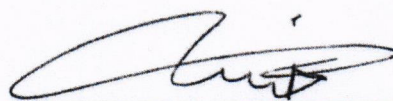
\_\_\_\_\_  
Date



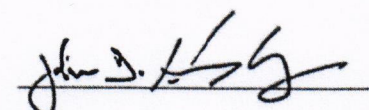
Dr. Ardiansyah Koeshidayatullah  
(Advisor)



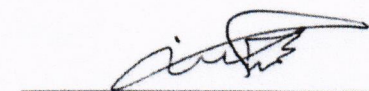
Dr. Korhan Ayranci  
(Internal Member)



Prof. Khalid Al-Ramadan  
(Internal Member)



Dr. John D. Humphrey  
(Internal Member)



Dr. Mahmoud Alnazghah  
(External Member)

I dedicate this to Allah the Most Gracious, the Most Merciful

© Baharudin Fahmi

2024

## **ACKNOWLEDGMENTS**

Praise be to Allah, we seek His help and His forgiveness. We seek refuge with Allah from the evil of our own souls and from our bad deeds. Whomsoever Allah guides will never be led astray, and whomsoever Allah leaves astray, no one can guide. I bear witness that there is no (true) God but Allah, and I bear witness that Muhammad is His slave and Messenger.

I would like to praise our creator, the creator of all beings, for which there is no power and no might except by Allah, for the realization of my master's degree undertook at King Fahd University of Petroleum and Minerals, Saudi Arabia.

Afterwards, I would like to thank King Fahd University of Petroleum and Minerals (KFUPM) for the financial support and the privilege to study and complete my master's at this prestigious University. This gratitude extends to President Dr. Muhammad M. Al-Saggaf, the Deans of Graduate Studies, Prof. Suliman Saleh Al-Homidan.

Gratitude is also towards the College of Petroleum and Geosciences (CPG) for facilitating academic growth and financial support. CPG, which is represented by the Dean Dr. Abdulaziz Obaid Al Kaab, Geoscience chairman, Dr. John Humphrey, and not least important, Dr. Sanlinn Kaka as graduate coordinator.

The importance of my thesis committee needs to be well acknowledged. First, Dr. Ardiansyah Koeshidayatullah as my main advisor, a lot of thanks is due for his acceptance as his student and for the opportunity to work on a wonderful and busy topic while giving excellent guidance. Most importantly, show a lot of patience throughout and there are no personal demands and high expectations placed upon you. Many thanks!

Not less important are Dr. Korhan Ayranci, Thank you for your valuable contributions and thought-provoking questions and discussions.

Dr. Mahmoud Alnazghah, Thank you for your valuable contributions and thought-provoking questions.

Prof. Khalid Al Ramadan and Dr. John D Humphrey, who have willingly accepted my request to be part of the committee member, despite their busy schedules and many thanks for their insight regarding analysis and input towards my manuscript.

Appreciation is due to my software technical support from Beicip Franlab Matthieu, Alberto, Florent, Lucie for their assistance in supporting and guiding tutorial software and resolving some software issues.

Appreciation is due to my colleagues Dr. Adhipa and Bang Sani and Mang Nanda for their valuable contributions and thought-provoking discussion.

Predict Research Group, I am blessed to have you all as my supporting system and a place for thought-provoking discussion.

This journey began with the unwavering encouragement and support of my parents for my education. I consider the various forms of support they have offered, particularly their prayers, to be pivotal in my academic achievements. While I aspire to repay them, I acknowledge that it may be nearly impossible. I also extend my heartfelt gratitude to my siblings and relatives for their prayers and generous support.

My peers in Geology, my partner in crime and my roommate, Faris, Daffa, and Diko, Nanda, Izzul, Dipta, Shouma consistently provide motivation and bring joy to my master's life.

The KFUPM-Indonesian community, which I cannot mention one by one, I am blessed your presence, and we experienced both ease and difficulty together while completing our individual programs.

Special gratitude is also warranted for Muhammad Sulhan Jauhari حفظه الله and my Indonesian friends in Dammam, whose weekend activities served as a significant substitute my family back in Indonesia.

I am thankful to my wife, who was there for me throughout my bad and busy time during master's program. I appreciate her support and love.

Finally, a special mention of gratitude for the rulers of this wonderful nation, the Kingdom of Saudi Arabia, King Salman, and Crown Prince Muhammad bin Salman may Allah preserve them.

# TABLE OF CONTENTS

|                                                     |       |
|-----------------------------------------------------|-------|
| ACKNOWLEDGMENTS .....                               | V     |
| TABLE OF CONTENTS .....                             | VIII  |
| LIST OF TABLES .....                                | XI    |
| LIST OF FIGURES .....                               | XII   |
| LIST OF ABBREVIATIONS .....                         | XV    |
| ABSTRACT.....                                       | XVI   |
| ملخص الرسالة.....                                   | XVIII |
| CHAPTER 1.....                                      | 1     |
| INTRODUCTION.....                                   | 1     |
| 1.1 Background .....                                | 1     |
| 1.2 Problem Statement .....                         | 4     |
| 1.3 Objective.....                                  | 4     |
| 1.4 Thesis Structure.....                           | 5     |
| CHAPTER 2.....                                      | 7     |
| LITERATURE REVIEW .....                             | 7     |
| 2.1 Study Area .....                                | 7     |
| 2.2 Geological Background.....                      | 8     |
| 2.3 Previous Studies.....                           | 13    |
| 2.4 Stratigraphic Forward Modeling Principles ..... | 17    |
| CHAPTER 3.....                                      | 22    |

|                                                                                                 |           |
|-------------------------------------------------------------------------------------------------|-----------|
| <b>ABSTRACT .....</b>                                                                           | <b>22</b> |
| <b>3.1 INTRODUCTION.....</b>                                                                    | <b>23</b> |
| <b>3.2 GEOLOGICAL SETTING .....</b>                                                             | <b>25</b> |
| <b>3.3 RESEARCH METHOD.....</b>                                                                 | <b>32</b> |
| 3.3.1 Dataset .....                                                                             | 32        |
| 3.3.2 Methodology .....                                                                         | 34        |
| 3.3.3 Data Preparation.....                                                                     | 35        |
| 3.3.4 Input Parameter .....                                                                     | 35        |
| 3.3.5 Model Calibration.....                                                                    | 46        |
| <b>3.4 RESULTS.....</b>                                                                         | <b>49</b> |
| 3.4.1 Best Fit Scenario for Marrat Formation .....                                              | 49        |
| 3.4.2 Sediment Proportion and Distribution .....                                                | 56        |
| 3.4.3 Simulated Model Validation .....                                                          | 59        |
| <b>3.5 DISCUSSION.....</b>                                                                      | <b>63</b> |
| 3.5.1 Testing Plausible Scenario for Best Fit Model in Marrat Formation .....                   | 63        |
| 3.5.2 Sequence Architecture and Lithology and Facies Distribution.....                          | 68        |
| 3.5.3 General Implications of the Model .....                                                   | 72        |
| <b>3.6 CONCLUSION .....</b>                                                                     | <b>73</b> |
| <b>3.7 ACKNOWLEDGEMENT .....</b>                                                                | <b>73</b> |
| <b>CHAPTER 4 .....</b>                                                                          | <b>75</b> |
| <b>ABSTRACT .....</b>                                                                           | <b>75</b> |
| <b>4.1 INTRODUCTION.....</b>                                                                    | <b>76</b> |
| <b>4.2 GEOLOGICAL FRAMEWORK .....</b>                                                           | <b>78</b> |
| <b>4.3 RESEARCH METHOD.....</b>                                                                 | <b>80</b> |
| 4.3.1 Input sensitivity parameter .....                                                         | 81        |
| <b>4.4 RESULTS.....</b>                                                                         | <b>84</b> |
| 4.4.1 Reference Model: Geometry and Lithology and Facies Distribution.....                      | 84        |
| 4.4.2 Global Sensitivity Analysis.....                                                          | 86        |
| <b>4.5 DISCUSSION.....</b>                                                                      | <b>87</b> |
| 4.5.1 Controls on Stratigraphic Architecture in The Marrat Formation.....                       | 87        |
| 4.5.2 Influence of Global and Regional Eustatic Sea Level (Accommodation space variations)..... | 89        |
| 4.5.3. Influence of Coefficient Transport to the Sequence Geometries .....                      | 90        |
| 4.5.4 Effect of Carbonate Production and Wave Action.....                                       | 94        |
| 4.5.5 Potential and limitations of the modeling.....                                            | 95        |

|                                               |            |
|-----------------------------------------------|------------|
| <b>4.6 CONCLUSION.....</b>                    | <b>96</b>  |
| <b>4.7 ACKNOWLEDGEMENT .....</b>              | <b>98</b>  |
| <b>CHAPTER 5.....</b>                         | <b>99</b>  |
| <b>CONCLUSIONS AND FUTURE DIRECTIONS.....</b> | <b>99</b>  |
| <b>REFERENCES.....</b>                        | <b>101</b> |
| <b>VITAE .....</b>                            | <b>122</b> |

## **LIST OF TABLES**

|                                                                                                                                            |    |
|--------------------------------------------------------------------------------------------------------------------------------------------|----|
| Table 1. Geological data are utilized for stratigraphic modeling and subsequently calibrated<br>to improve the accuracy of the model ..... | 32 |
| Table 2. Input parameters for initial deterministic scenario model.....                                                                    | 44 |
| Table 3. Uncertain range for the input parameters.....                                                                                     | 81 |

## LIST OF FIGURES

|                                                                                                                                        |    |
|----------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1. (A,B) Paleogeography map during the Early Jurassic period depicting the different depositional environments. ....            | 8  |
| Figure 2. General stratigraphic chart showing stratigraphic position of Marrat Formation and its overlain and underlain Formation..... | 11 |
| Figure 3. The schematic diagram shows the depositional environment of Marrat Formation.. ....                                          | 13 |
| Figure 4. The Simulated facies generated by stratigraphic forward modelling of Burgan-Kazhdumi. ....                                   | 17 |
| Figure 5. Schematic diagram of accommodation which refers to sum of eustasy and subsidence or sediment thickness and bathymetry.....   | 20 |
| Figure 6. (A,B) Paleogeography map during the Early Jurassic period depicting the different depositional environments.. ....           | 26 |
| Figure 7. General stratigraphic chart showing stratigraphic position of Marrat Formation and its overlain and underlain Formation..... | 28 |
| Figure 8. Outcrop photographs of Marrat Formation consist of upper Marrat member, middle Marrat member and lower Marrat member.. ....  | 29 |
| Figure 9. The conceptual model of the depositional environment of Marrat Formation..                                                   | 31 |
| Figure 10. Correlating sequence stratigraphy from surface to subsurface by utilizing gamma-ray logs. ....                              | 34 |
| Figure 11. A. Initial bathymetry cover the area from low land area, marginal area to shallow marine area. ....                         | 37 |
| Figure 12. The eustatic sea level curve. ....                                                                                          | 38 |

|                                                                                                                                      |    |
|--------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 13. Sediment class definition in stratigraphic forward model. ....                                                            | 40 |
| Figure 14. A. Carbonate production rate vs depth.. ....                                                                              | 41 |
| Figure 15. The global relationship between sediment discharge as a function of catchment<br>area and relief (R).....                 | 43 |
| Figure 16. The assessment of sediment supply within the Marrat Formation. ....                                                       | 44 |
| Figure 17. The general methodology employed in the study area. ....                                                                  | 48 |
| Figure 18. The simulated model in Lower Marrat member (183 Ma - 181.5 Ma).....                                                       | 51 |
| Figure 19. The simulated model in Middle Marrat member (181.5 Ma – 180.1 Ma).....                                                    | 53 |
| Figure 20. The simulated model in Upper Marrat member (180.1 Ma – 179.3 Ma). ....                                                    | 55 |
| Figure 21. The map view of the simulated model displays the distribution of sediment<br>proportions in a pie chart.....              | 57 |
| Figure 22. The map view of the best fit simulated model of lithology distribution and facies<br>distribution.....                    | 58 |
| Figure 23. Simulated model observed in dip section covering west to east area and oblique<br>strike covering north – south area..... | 60 |
| Figure 24. Observed lithology data observed in outcrop and well in Marrat Formation<br>versus simulated model.. ....                 | 61 |
| Figure 25. Observed isopach map generated from outcrop and well data in Marrat<br>Formation.....                                     | 62 |
| Figure 26. The plausible scenario model tested to see how the sediment supply and water<br>discharge filling the basin.....          | 66 |
| Figure 27. Scenario model incorporating subsidence testing (B) and without subsidence<br>testing (A).. ....                          | 68 |

|                                                                                                                               |    |
|-------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 28. (A) Stratigraphic section from northern to southern area based on observed outcrop data. ....                      | 71 |
| Figure 29. (A,B) Paleogeography map during the Early Jurassic period depicting the different depositional environments.. .... | 79 |
| Figure 30. The general methodology employed in the study area.. ....                                                          | 83 |
| Figure 31. The reference model of Marrat Formation. ....                                                                      | 85 |
| Figure 32. Results of the global sensitivity analysis in the study area.....                                                  | 86 |
| Figure 33. Global sensitivity analysis showing the most influential parameters. ....                                          | 87 |
| Figure 34. Regional sea level vs Global Sea level.....                                                                        | 90 |
| Figure 35. Summary of modeling result at 179.3 Ma.. ....                                                                      | 94 |
| Figure 36. The simulated model shows the response of different wave action in distributing the lithology.....                 | 95 |

## **LIST OF ABBREVIATIONS**

SFM : Stratigraphic Forward Modeling

RSM : Response Surface Modeling

# **ABSTRACT**

Full Name : Baharudin Fahmi

Thesis Title : Quantifying The Dynamics Of Mixed Siliciclastic And Carbonate  
System Of The Toarcian Marrat Formation, Saudi Arabia: Insights  
From 3d Stratigraphic Forward Modeling

Major Field : Geology

Date of Degree : May 2024

A mixed siliciclastic and carbonates system provides a unique opportunity to study the interaction of two competing systems, clastic influx and carbonate factories, in organizing a depositional system. The Toarcian Marrat Formation represents an ideal mixed carbonate-siliciclastic system developed under transgressive–regressive sequence. Despite extensive outcrop-based studies, understanding and quantifying the controlling processes behind the development of evolution of this mixed carbonate-clastic system is still a great challenge. Here, we performed a process-based stratigraphic forward modeling approach to unravel the interplay between different allogenic and autogenic factors contributing in the formation of different sequence architectures in the Marrat Formation. From the best-fit scenario, a more realistic reference model was developed, and calibrated. Our results reveal distinct aggradation–progradation geometries within the Marrat Formation that show a good agreement with the outcrop and subsurface observations. Furthermore, the accurate quantification of sediment supply enables a more precise spatial delineation of siliciclastic and carbonate distributions across the basin, particularly to capture along strike

variability. Sensitivity analysis indicates that sediment supply and carbonate production exert greater control compared to sea level changes on dictating the sedimentary architecture and dynamics. These findings offer valuable insights for mixed systems in enhancing regional understanding on the spatio-temporal heterogeneity of the Marrat Formation and aid in identifying potential petroleum reservoirs, subtle stratigraphic traps and informing exploration strategies by reducing the uncertainties.

Keywords: Marrat Formation, Mixed siliciclastic and carbonates, Stratigraphic Forward Modeling

## ملخص الرسالة

الاسم الكامل : بحر الدين فهمي

عنوان الأطروحة : القياس الكمي لديناميكيات النظام المختلط من الفلزات السيليسية والكربوناتية لتكوين مرات الطورسي،

المملكة العربية السعودية: رؤى من النمذجة الطبقيّة المستقبلية ثلاثية الأبعاد

المجال الرئيسي: الجيولوجيا

تاريخ الحصول على الدرجة : مايو 2024

يوفر النظام المختلط من فتات السيليكات والكربونات فرصة فريدة لدراسة التفاعل بين نظامين متنافسين، التدفق الفتاتي نظامًا مثاليًا مختلطًا من الكربونات Toarcian Marrat ومصانع الكربونات، في تنظيم نظام الترسيب. يمثل تكوين والسيليسيليكات تم تطويره في ظل تسلسل متجاوز - تراجعي. على الرغم من الدراسات المكثفة القائمة على النتوءات، فإن فهم وقياس عمليات التحكم وراء تطور هذا النظام المختلط من الكربونات الفتاتية لا يزال يمثل تحديًا كبيرًا. هنا، أجرينا نهجًا للنمذجة الطبقيّة المستقبلية القائمة على العملية لكشف التفاعل بين العوامل الخفيفة والذاتية المختلفة التي تساهم في تكوين أبنية تسلسلية مختلفة في تكوين مرات. ومن السيناريو الأفضل، تم تطوير ومعايرة نموذج مرجعي أكثر واقعية. تكشف نتائجنا عن أشكال هندسية متميزة للتدرج والتقدم داخل تكوين مرات والتي تظهر توافقًا جيدًا مع الملاحظات النتوءية وتحت السطحية. علاوة على ذلك، فإن التحديد الكمي الدقيق لإمدادات الرواسب يمكن من تحديد مكاني أكثر دقة لتوزيعات فتات السيليكات والكربونات عبر الحوض، لا سيما لالتقاط تباين الضربات. يشير تحليل الحساسية إلى أن إمدادات الرواسب وإنتاج الكربونات تمارس سيطرة أكبر مقارنة بالتغيرات في مستوى سطح البحر في إملاء البنية والديناميكيات الرسوبية. تقدم هذه النتائج رؤى قيمة للأنظمة المختلطة في تعزيز الفهم الإقليمي حول عدم التجانس المكاني والزمني لتكوين مرات والمساعدة في تحديد الخزانات النفطية المحتملة والمصادر الطبقيّة الدقيقة. وإرشاد استراتيجيات الاستكشاف عن طريق تقليل حالات عدم اليقين.

الكلمات المفتاحية: تكوين مرات، خليط من فتات السيليكات والكربونات، النمذجة الطبقيّة المستقبلية

# CHAPTER 1

## INTRODUCTION

### 1.1 Background

Mixed siliciclastic and carbonate sediment possesses its own uniqueness. One of them is the interplay between two competing systems of clastic influx and carbonate factories in organizing a depositional environment (Mount, 1984; Zonneveld et al., 2012). Changes in sedimentation pattern and sequence architecture are sensitive to the complex interplay of various factors, such as climatic variations, tectonic activity, and sea-level fluctuations (Catuneanu, 2002, 2006; Jervey, 1988; Miall, 2010; Posamentier & Allen, 1999; Posamentier & Vail, 1988; Schlager, 2005). Yet, understanding the sequence architecture and geometry at a regional scale remains challenging. Limited datasets make geological interpretations difficult and highly uncertain. Moreover, the challenge of heterogeneity frequently encountered in typical mixed siliciclastic and carbonate systems increases the complexity of geological interpretation. Recent developments in mixed siliciclastic and carbonate system on applying stratigraphic forward modeling (SFM) provide a powerful tool for quantitative analysis in predicting sedimentary architecture and geometry, predict lateral and vertical variations of lithology and facies under high resolution of stratigraphic order (Baharudin et al., 2024; Borgomano et al., 2020; Hawie et al., 2017; Shabani et al., 2022; Zhang et al., 2019). Such research that integrates the multi-disciplinary and multi scale constrain to build the geological model and estimate the sediment source to sink was

studied in Levant margin with stratigraphic forward modeling approach to estimate the siliciclastic and carbonate infill in the Levant Basin (Hawie et al., 2017). The research explored and tested several scenarios for achieving best fit modeling in the basin such as single to multiple source scenario, quantification of siliciclastic source and insitu carbonate production and bring assumption from modern river as an analogue to the input parameters. Other studies also applied process based numerical modeling on mixed siliciclastic and carbonate of Albian Burgan – Kazhdumi succession to explore the lithology and facies distribution (Shabani et al., 2022). The research builds more precise regional sequence stratigraphy and stratigraphic architecture by integrating multi-disciplines and multi-scales of seismic and well data as data validation. The result helps guide the petroleum plays and stratigraphic potential in deltaic systems. Moreover, (Baharudin et al., 2024) applied numerical process based modeling to tested impact of sea level in greenhouse period and icehouse period to understand both characters in sedimentation and stratigraphic architecture as depicted in several simulated model scenarios.

The Toarcian Marrat Formation in Saudi Arabia is an ideal mixed siliciclastic and carbonate system due to its deposition during a transgressive-regressive depositional sequence, which led to the development of carbonate during the transgression phase (Murriss, 1980; Powers et al., 1966). An integrated approach utilizing sedimentology, seismic stratigraphy, and biostratigraphy was employed to investigate the stratigraphic evolution of the 3rd and 4th ordered sections in Marrat Formation, Saudi Arabia (Al-Hussaini et al., 2021; Al-Mojel et al., 2020). Although sedimentary environments and sequence stratigraphy architecture have been the primary focus of previous studies, there has been limited research on the quantification of these aspects through stratigraphic

forward modelling. Our study documents the best-fit reference model for the Marrat Formation using a stratigraphic forward modeling (SFM) approach. By testing multiple geological assumptions and plausible scenarios, we aim to construct a best fit reference geological model. Parameters tested include sediment sourcing scenarios, quantification of sediment supply and water discharge, quantification of carbonate production, sea level, subsidence, and wave energy. Following the proposed best-fit reference case model we also quantify the controlling parameters response to the sequence architecture and geometry based on sensitivity analysis. Through conducting numerous simulations and testing a range of parameters that influence each other, the sensitivity of the most influential parameters can be evaluated. The objectives of this research are to predict sequence architecture at the third stratigraphic order with limited datasets and to determine the outcomes of testing various geological assumptions or scenarios applied to the sedimentation processes of the Marrat Formation. The presented study also focuses on how main input parameters such as supply sediment, carbonate production, subsidence, sea level changes, wave energy, sediment transport coefficient response to the architecture and internal geometry of the model while achieving close match with observed data. Furthermore, the study provides insights into the variability of regional-scale geometries, considering lateral and vertical texture/facies heterogeneity. It also emphasizes the use of numerical process-based modeling to quantify the parameters that control sedimentation.

## **1.2 Problem Statement**

Understanding the sequence architecture and geometry at a regional scale remains challenging. Limited datasets make geological interpretations difficult and highly uncertain. Moreover, the challenge of heterogeneity frequently encountered in typical mixed siliciclastic and carbonate systems increases the complexity of geological interpretation. Considering several research findings, the research question related to this thesis can be outlined as follow:

- What controls the sedimentation processes and sequence architecture in the Marrat Formation (e.g., along strike variability)?
- How to improve our quantitative understanding on the development and evolution of the Marrat Formation with stratigraphic forward modeling?
- How to minimize uncertainty in 3D stratigraphic forward modelling?
- How 3D stratigraphic forward modelling can provide novel insights to petroleum prospectivity of the Marrat Formation?

## **1.3 Objective**

The main objectives of this proposed thesis are summarized as follow:

- To understand the interplay between siliciclastic and carbonate sedimentation in Marrat Formation.
- To test multiple scenarios that best-fit with the deposition in Marrat Formation with stratigraphic forward modelling.

- To understand the impact of different input parameters governing the sedimentation using sensitivity analysis with stratigraphic forward modelling.
- To build sequence architecture (lateral and vertical lithology/facies variations) that captured the distribution of reservoir/source rock potential with stratigraphic forward modelling.

## 1.4 Thesis Structure

This thesis is primarily presented as an alternate, journal-style, format which include four introductory and complimentary chapters: (i) **Chapter 1** as an introduction of the whole thesis; (ii) **Chapter 2** serves as literature review of the different topics covered in this thesis; and (iii) **Chapter 5** highlights and summarizes the main findings of this study and provides potential direction and recommendation for future study. Furthermore, the other two chapters (**Chapter 3, Chapter 4**) contain original contributions of this study which are intended to be self-contained with their own introduction, geological framework, research methodology, results, discussion and conclusion (summarized below). Throughout the thesis, some information may be repetitive, and this is unavoidable due to the nature of the thesis. The following section summarized the chapters that contain original contribution in this thesis:

### **CHAPTER 3 Testing Geologic Assumptions and Plausible Scenarios for Best Fit Reference Model in Marrat Formation using Stratigraphic Forward Modeling**

This chapter presents, for the first time, the discussion on the multiple scenarios and geologic assumptions to get the best fit reference model by using stratigraphic forward modeling approach in Marrat Formation. By exploring the role of eustasy, subsidence,

supply sediment, carbonate production and wave energy to generate sequence architecture. This study also demonstrated the best fit reference model calibrated with actual data (outcrop data). Furthermore, the study proposes insight into a variability of regional-scale geometries expected lateral and vertical lithology and facies variations.

#### **CHAPTER 4 Quantitative Controls on the Sequence Architecture and Geometries of the Marrat Formation using Stratigraphic Forward Modeling**

In this chapter, the complex sequence architecture and geometry are influenced by autogenic and allogenic processes. performed a process-based stratigraphic forward modeling approach to unravel the interplay between different allogenic and autogenic factors contributing to the formation of different sequence architectures in the Marrat Formation. The quantification of the controlling parameters response to the sequence architecture and geometry based on sensitivity analysis. Through conducting numerous simulations and testing a range of parameters that influence each other, the sensitivity of the most influential parameters can be evaluated. The presented study focuses on how main input parameters such as supply sediment, carbonate production, subsidence, sea level changes, wave energy, sediment transport coefficient response to the architecture and internal geometry of the model while achieving close match with observed outcrop data.

## **CHAPTER 2**

### **LITERATURE REVIEW**

#### **2.1 Study Area**

The research area focused in central area of Arabian platform. The platform was located on a passive margin setting. During Early Jurassic Period situated close to equator and deposited in broad epeiric platform spanning over 1000 km from a continental area to a shallow-marine environment within the tropical belt during the Early Jurassic (Murriss, 1980; Powers et al., 1966). The formation is characterized by a variety of depositional settings, consisting of non-marine to marine clastic, shallow marine clastic/carbonate platform, shallow marine carbonate platform and deep marine carbonate (Ziegler, 2001). The study encompassed a region of approximately 250,000 square kilometers, with dimensions of 600 kilometers by 500 kilometers (Figure 1).

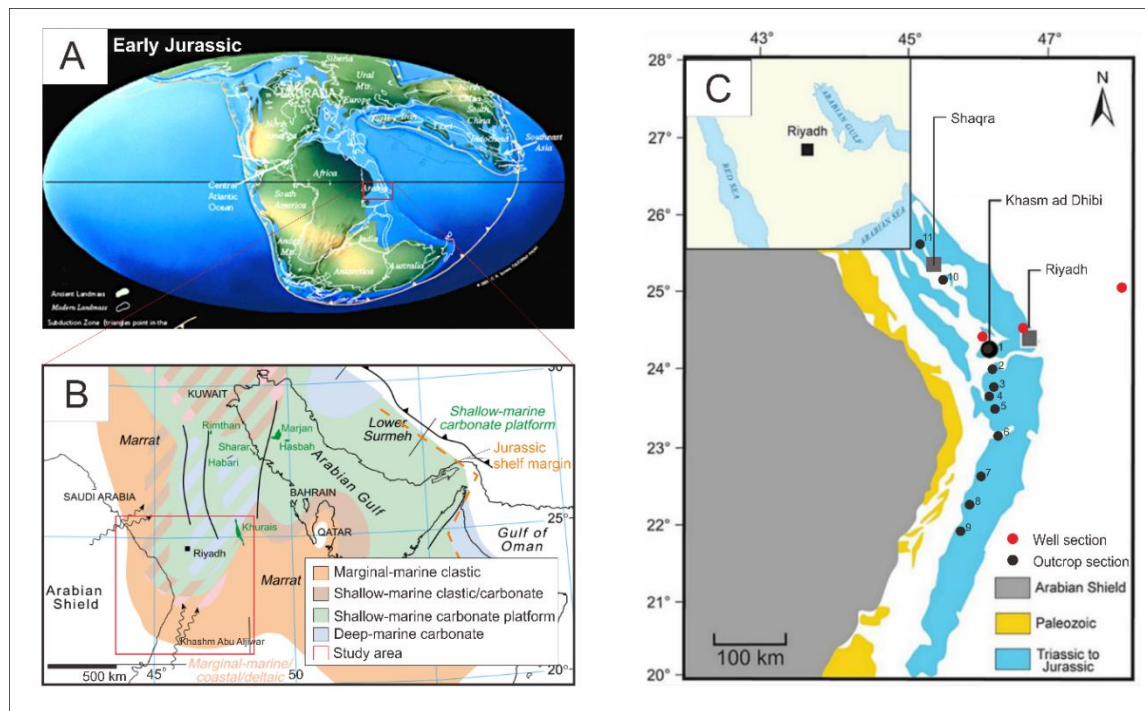


Figure 1. (A,B) Paleogeography map during the Early Jurassic period depicting the different depositional environments. The study area covers the exposed Arabian shield, non-marine to marine clastic, shallow marine clastic/carbonate, shallow marine carbonate platform, and deep marine carbonate. Modified after (Ziegler, 2001). (C) Geology map showing the measured section and well section done by (Al-Hussaini et al., 2021; Al-Mojel et al., 2020)

## 2.2 Geological Background

### 2.2.1 Paleogeographic and tectonic frameworks

The research area focused on the outcrop section in the central part of Arabian Platform. The platform was located on a passive margin. Deposited in a broad epeiric platform from a continental area to a shallow marine (Murriss, 1980; Powers et al., 1966) (Figure 1). The Arabian Plate was experienced by Zagros rifting during Late Permian to Middle Triassic

that has implication to thick carbonate deposition in the platform and intrashelf environments and continued until Early Jurassic. During late Triassic to Early Jurassic period was no deposition because of the collision of Iranian Plate with Eurasia through Zagros Suture called as Kimmeridgian orogeny and marked by Minjur unconformity (Beydoun, 1993; Sharland et al., 2001; Ziegler, 2001). The first major transgression occurred during the Late Triassic and Early Jurassic. Regional equivalents formation during this time including Mus Formation in Iraq, Marrat Formation in Kuwait, Saudi Arabia, United Arab Emirates, Qamchuqa Formation in Syria, and Nirim Formation in Levant. During this time, MFS J09 and MFS J10 to intra-J20 marked the maximum transgression period. There were two unconformities bounded the Saqra group, first was during the Early Jurassic occurred at the lowermost of Marrat Formation, marking the hiatus around 20 Ma, resulting the contact in form of paleosoil between Triassic and Toarcian sediments and the second was during Late Jurassic to Early Cretaceous. The base unconformity of Marrat Formation might be related to the uplift platform and erosion by Karoo rifting between Madagascar and East Africa and might be related with the separation of the Indian Plate with African-Arabian Plate (Delvaux & Weiss, 2001; Grabowski Jr & Norton, 1995; Khalifa, 2007). The top Marrat Formation also marked by a major unconformity, called Toarcian-Aalenian hiatus that considered as significant hiatus event across Arabian Platform. This unconformity marks the boundary between the Marrat and Dhurma Formations, with the latter representing the Middle Jurassic period. Thus, hiatus might be resulted from a combination of factors, including a major sea-level fall and large tectonic uplifts (Al-Husseini, 1997; Al-Mojel et al., 2022; Haq, 2018; Haq & Al-Qahtani, 2005; Le Nindre et al., 2003; Simmons et al., 2007; Simmons & Davies, 2018).

### **2.2.2 Paleoclimate**

During the Toarcian (Jurassic period), the Arabian Plate was located near or at the equator, resulting in warm and humid to semi-humid climates that later evolved to arid to semi-arid conditions. The deposition was controlled by global sea-level changes but also controlled by regional climate changes experienced in humid to warm climates during regression period and more arid during transgression period. The impact of humid to warm condition during regression affecting the high terrigenous input to the deposition of fluvial sandstone and shallow marine red shales deposition within bifrons Zone. There were short period of arid to semi-arid condition experienced during Toarcian provoked the forming of anhydrite deposit in Marrat Formation (Al-Aswad, 1995; Konert et al., 2001; Murriss, 1980; Sharland et al., 2001).

### **2.2.3 Stratigraphy and regional depositional history**

The distribution of Marrat Formation is extensive in the Khashm adh Dhibi region, reached maximum thickness around 111 and 142 meters (Powers, 1968; Powers et al., 1966). Marrat Formation characterized by its unconformable at base with the clastic Upper Triassic Minjur Formation and unconformable on top position with the Bajocian-Bathonian Dhruma Formation (Fischer et al., 2001; Manivit & Le Nindre, 1990). Marrat Formation exhibits a complex lithological composition, consisting of interbedded sandstones, mudstones (claystone), with limestone and anhydrites intercalated in lower part and upper part Formation (Al-Hussaini et al., 2021; Al-Mojel, 2020; Farouk et al., 2018; Le Nindre, 2022; Manivit et al., 1985; Jacques Manivit & Le Nindre, 1990; Powers et al., 1966; Powers, 1968; Vaslet et al., 1983) (Figure 2). The Marrat Formation has been subdivided into the lower member, middle member, and upper member.

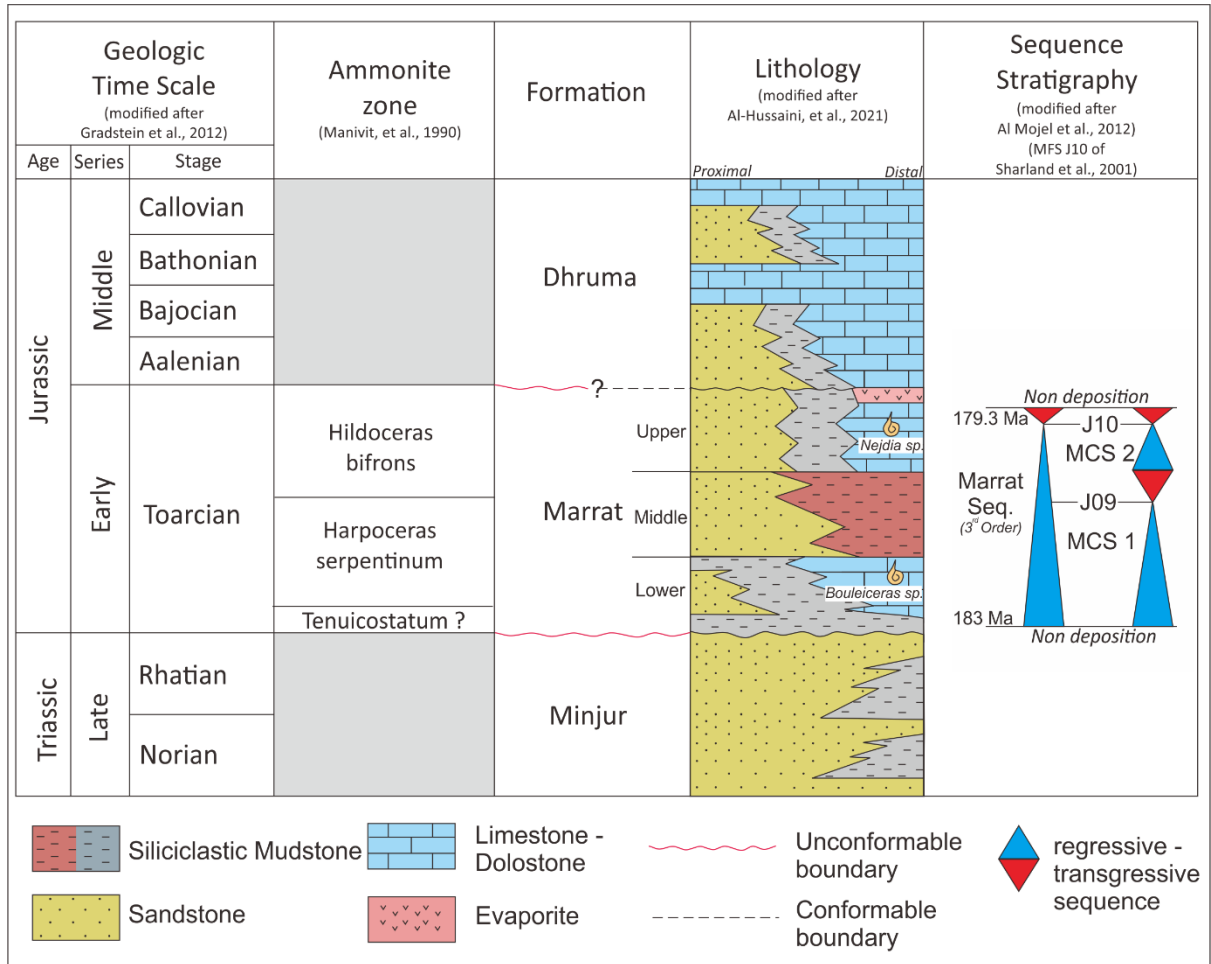


Figure 2. General stratigraphic chart showing stratigraphic position of Marrat Formation and its overlain and underlain Formation. The lithologies of the Minjur Formation, Marrat Formation and Dhurma Formations were obtained from (Al-Hussaini et al., 2019; Powers, 1968; Powers et al., 1966)

The lower member is characterized by an Early Jurassic unconformity, distinguished by a prominent iron-stained surface overlaying the Late Triassic Minjur Sandstone, with several sections displaying paleosols. This distinctive lower member may attain a thickness of up to 47 meters. Consisted of greenish – green colour, fine-grained to silt grain, succeeded by sandy marl and dolomitic limestone. Characterized by low abundance of faunal

assemblages in comparison to other members of the Marrat Formation. The deposition environments ranging from continental to intertidal-subtidal settings (Al-Husseini, 2009; Al-Mojel, 2020; El-Sorogy et al., 2017; Farouk et al., 2018; Le Nindre, 2022; Manivit et al., 1985; Jacques Manivit & Le Nindre, 1990; Powers et al., 1966; Vaslet et al., 1983). The dolomitic limestone is rich in fossils and characterized by bioturbation mainly in the initiation of middle member of Marrat Formation. This is followed by a succession of reddish mudstone and siltstone layers, which lack any distinguishable fossil remains. The uppermost section of this member is marked by calcareous shale, which contains a relatively low abundance of fauna. The thickness of this member ranges up to 40 meters, and it was formed in a depositional environment that ranges between subtidal and intertidal lagoon environment. The significance of middle Marrat member is established through the examination of ammonite fossils, with a focus on *Protogrammoceras sp.* and *Bouleiceras sp.* at the base of the member. It has been noted that there is a substantial reduction in the thickness of the middle member of Marrat Formation towards the southern areas. In this region, there are reddish mudstones replaced by sandstone-rich deposits (Powers, 1968; Powers et al., 1966). While, the upper part of Marrat Formation is a bioturbated limestone. It was deposited under a lagoonal environment. This member is overlain by a 7 meters thick layer of evaporite in form of anhydrite. This anhydrite layer has been identified by (Powers, 1968) which belongs to the Middle Jurassic period. In general, the Marrat Formation depicts a transgressive-regressive cycle, with the indication of Bouleiceras Horizon, located at the base of the Middle Marrat and identified as the maximum flooding surface (MFS J09) and maximum flooding surface (MFS J10) lying at the base of the Upper Marrat by the indication of Nejdia Horizon (Le Nindre, 2022).

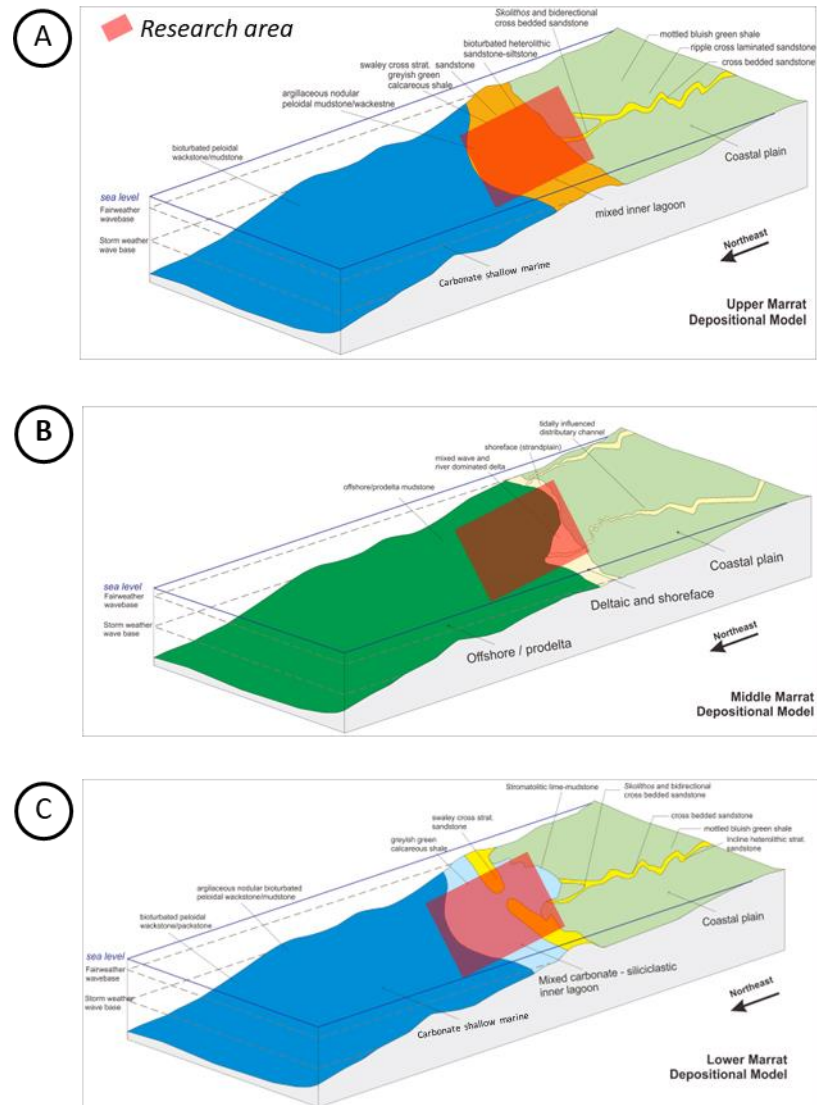


Figure 3. The schematic diagram shows the depositional environment of Marrat Formation. The facies were laid down in a broad and flat, inner platform depositional environment. The evolution of Marrat formation starting from lower Marrat (C), Middle Marrat (B), Upper Marrat (A). Lower Marrat and Middle Marrat modified from (Al-Mojel, 2020) and Middle Marrat data modified from (Al-Hussaini et al., 2021).

## 2.3 Previous Studies

Steineke in 1937 was initially introduced to the Marrat Formation, however, it was subsequently documented by Bramkamp and Steineke in 1952 (Arkell et al., 1952). Powers

and McClure, along with Manivit, extensively documented a more thoroughly of outcrop reference section in the Khashm Ad-Dhibi (24° 14' N), and later divided the Formation into three members, namely Lower Marrat , Middle Marrat, and also Upper Marrat Formation (Manivit & Le Nindre, 1990; Powers et al., 1966). Another work focused on the analysis of conceptual sequence stratigraphic model and high-resolution sequence-stratigraphic framework (Al-Hussaini et al., 2021; M. Al-Husseini, 2009; Al-Mojel et al., 2020; El-Sorogy et al., 2017; Farouk et al., 2018; Manivit et al., 1985; Manivit & Le Nindre, 1990; Le Nindre et al., 2022; Osman et al., 2020; Vaslet et al., 1983, 1988). Marrat Formation served as reservoir units located in the northeastern regions of Saudi Arabia and Kuwait (Al-Eidan et al., 2009; Al Sharhan & Nairn, 2003). Moreover, Marrat Formation also served as source rocks in Iraq and Kuwait (Abdullah & Connan, 2002; Aqrawi et al., 2010). Based on outcrop studies, it has been suggested that Toarcian Oceanic Anoxic Event (T-OAE) took place in shallow marine siliciclastic red beds within the middle Marrat Formation and bring an insight that there will be possibility source rock potential across the Arabian platform (Alnazghah et al., 2022).

The other study offers a more quantitative approach to evaluate the sedimentary deposition within the intrashelf basins situated along the Eastern Margin of the Arabian Plate, which includes the Toarcian Marrat basin and Hanifa basin. This approach utilizes computer simulation modeling techniques to provide a deeper understanding of the sedimentary processes involved in the basin's evolution (De Keyser & Kendall, 2014). The findings indicated that during the Lower to Middle Jurassic, the Arabian plate margin experienced two distinct phases of carbonate margin progradation and basinward infilling, as evidenced by onlapping sedimentation in Kuwait, Saudi Arabia, the UAE, and Oman. At the end of

the Middle Jurassic, there was an uplift and exposure of the Tuwaiq and Dhurma Formations, followed by erosion along the plate margin. The margin eventually collapsed, resulting in a drowning unconformity. Meanwhile, a base-level fall occurred outside the platform margin of the Arabian intrashelf basin, leading to accumulation of the Arab Formation and Hith evaporites.

In recent years, various stratigraphic forward modeling techniques have been extensively utilized to evaluate the general configuration and sedimentary architecture, as well as to predict the vertical and also horizontal changes with high-resolution stratigraphy (Borgomano et al., 2020). Using stratigraphic forward modeling can help to quantify the general concept of sequence stratigraphy by simulating sedimentary processes and deposition over time to test the carbonate sedimentary systems (CSSs), especially on shallow-water carbonate platforms (Borgomano et al., 2020). The results showed that stratigraphic forward modeling can be used to interpret sea-level changes and subsidence rates from carbonate sedimentary archives, and to estimate how much of the actual accommodation parameters are preserved in the sedimentary records. Additionally, a study conducted by (Hawie et al., 2017) utilized a variety of data sources including seismic data, well data, and outcrop data to quantify deposition process of mixed siliciclastic and carbonate system in the Middle to Upper Miocene along the northern Levant frontier region. The integration of data from geomorphological and hydrological databases , along with diffusion-based forward stratigraphic modeling, can aid in determining the ranges for sediment load, water discharge, and diffusion coefficients related to lithology (Syvitski et al., 2003; Syvitski & Milliman, 2007) with diffusion-based in forward stratigraphic

modelling help to assess the ranges for sediment load, water discharge and diffusion coefficients related to lithology (Borgomano et al., 2014; Burgess et al., 2006).

(Al-Wazzan et al., 2021) presented a study that involved simulating the integration of sedimentary and study ecological processes, including carbonate production in relation to depth, time, wave energy, and sediment transport, to illustrate the evolution of a Jurassic carbonate ramp system within at a 2nd to 3rd sequence stratigraphic order. Later work on Marrat Formation by (Hawie et al., 2021) conducted additional research on the Marrat Formation, with the aim of quantifying the impact of key controlling factors such as subsidence, eustacy, grain size, carbonate production rates, and wave energy on the development of Mesozoic carbonate systems in tropical settings. In addition, the study by (Hawie et al., 2021) integrated the simulated model with basin modeling to evaluate and reduce risk in reservoirs, cap rocks, charges, stratigraphic traps assessment in the Marrat Formation. (Shabani et al., 2022) utilized a stratigraphic forward modelling approach to predict the Burgan-Kazhdumi mixed siliciclastic-carbonate systems of the Albian and assess new exploration prospects. According to (Milliman & Syvitski, 1992) the analysis of modern rivers was used to estimate the source of sediment that has filled the Burgan-Kazhdumi basin with siliciclastic sediments from southern Arabia. The modeling results demonstrate that the distribution of fluvial sand sediment and carbonate is consistent with well data, with approximately 80% of the model calibrated to the observed data.

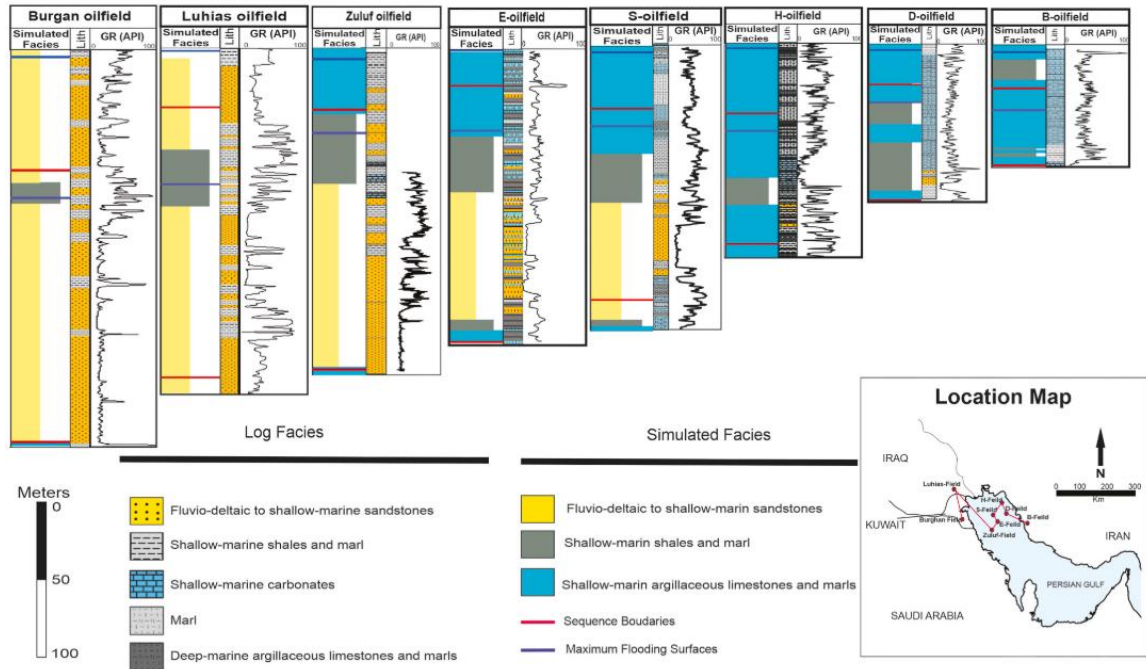


Figure 4. The Simulated facies generated by stratigraphic forward modelling of Burgan-Kazhdumi mixed siliciclastic-carbonate systems of the Albian. Comparison from simulated well data and actual wells along well section showing good consistency with approximately 80% (Shabani et al., 2022).

## 2.4 Stratigraphic Forward Modeling Principles

Stratigraphic forward modeling (SFM) is a numerical modeling technique that utilizes geological data from both surface and subsurface to simulate the sedimentary architecture in various systems, including carbonate, siliciclastic, or mixed siliciclastic and carbonate systems (Borgomano et al., 2014, 2020; Burgess et al., 2006; Granjeon, 2014). Numerous software allows simulation of stratigraphic forward modeling, some programs specialized either carbonate (Borgomano et al., 2014, 2020) or mixed siliciclastic – carbonate. One of three-dimensional stratigraphic modeling program developed by Beicip Franlab, DionisosFlow™, was employed to simulate the model. The software models sediment

transport by solving a diffusion equation, which correlates sediment flow with the depositional slope and a transport coefficient specific to the environment, also known as the diffusion coefficient. DionisosFlow is designed for the characterization of sedimentary basins at a regional scale (tens to hundreds of kilometres), and over geological time spans (tens of thousands to tens of millions of years) (Franlab, 2021). The model aims to simulate and quantify the interplay among various factors, such as subsidence, sediment flux or carbonate production, and eustatic variations, in a mixed siliciclastic and carbonate system (Borgomano et al., 2014, 2020; Burgess et al., 2006; Granjeon, 2014). The modern analogue studies such as modern delta or modern carbonate production help understanding the impact of the design on the modeling of sedimentary system and the application of numerical modeling by using DionisosFlow™ specially in applying sedimentary lithology and facies distribution along the modern analogue studies and describing numerical model by using time resolution (thousand to million years) and space resolution (tens to hundreds of kilometres) (Franlab, 2021). The idea of having modern observation is to build the stratigraphic forward model on a regional scale first order physical laws which simulate sedimentary process, basin deformation, sediment transport, sediment production along large area (simulated area greater than tens kilometers with cell size greater than hundreds of meters) and long period of time spans (simulated time interval greater than a few tens of thousands of years and time step longer than a few thousands of years) (Gvirtzman et al., 2014; Harris et al., 2016; Hawie et al., 2017).

Stratigraphic forward modeling aims to assess the key features of sedimentary basins, specifically focusing on determining the geometry, lithology and facies of sedimentary unit. The approach involves simulating the erosion, transportation, and deposition of

sediment caused by natural sedimentary processes across large spatial and temporal scales. These sediments, comprising natural materials moved by gravity and water flow, are characterized as large-scale sedimentation. The quantity of sediment within each numerical cell depends on erosion, production, transportation, and deposition mechanisms (Gvirtzman et al., 2014; Harris et al., 2016; Hawie et al., 2017). The stratigraphic model integrates two mechanisms: Linear slope-driven diffusion, known as hillslope creep, where transport is proportional to slope and Nonn-linear diffusion driven by water discharge and slope, termed water-discharge-driven transport. Empirical transport laws integrate gravity driven and water driven diffusion equations, incorporating both linear and non-linear slope-driven diffusion equations. These are collectively known as water driven transport equations and are expressed in equation (1) (Hawie et al., 2015; Tucker & Slingerland, 1994; Willgoose et al., 1991).

$$Q_s = \frac{K_{si}}{v_h - K_{wi}} Q_w^m S^n \quad (1)$$

The equation for sediment discharge,  $Q_s$  ( $\text{km}^2/\text{y}$ ), is dependent on several factors, including the diffusion coefficients of hill slope ( $K_s$ ) ( $\text{km}^2/\text{y}$ ) and  $K_w$  water diffusion coefficient, Water discharge ( $Q_w$ ) ( $\text{km}^2/\text{y}$ ), basin slope gradient ( $S$ ), elevation ( $h$ ), and the transported lithology ( $i$ ) (Granjeon, 2014). Additionally, the constants  $m$  and  $n$  are included in the equation, with values between 1 and 2. The diffusion coefficient parameters change based on particle type in both terrestrial and marine settings (Granjeon, 2014; Tucker & Slingerland, 1994).

Three primary environmental parameters are considered in stratigraphic forward modeling: Accommodation, sediment production (siliciclastic and insitu carbonate production) and

sediment transport. The Accommodation (responsible to subsidence and eustasy). Represents the overall available area for sediment deposition. Variations in accommodation are influenced by fluctuations in base level and tectonic processes such as subsidence, uplift, compaction, flexure and salt diapirism. Sedimentary supply encompasses both clastic sediment and in situ carbonate production. It is derived from the integration of structural depth and paleobathymetry maps and resulting in a calculation of subsidence or accommodation map.

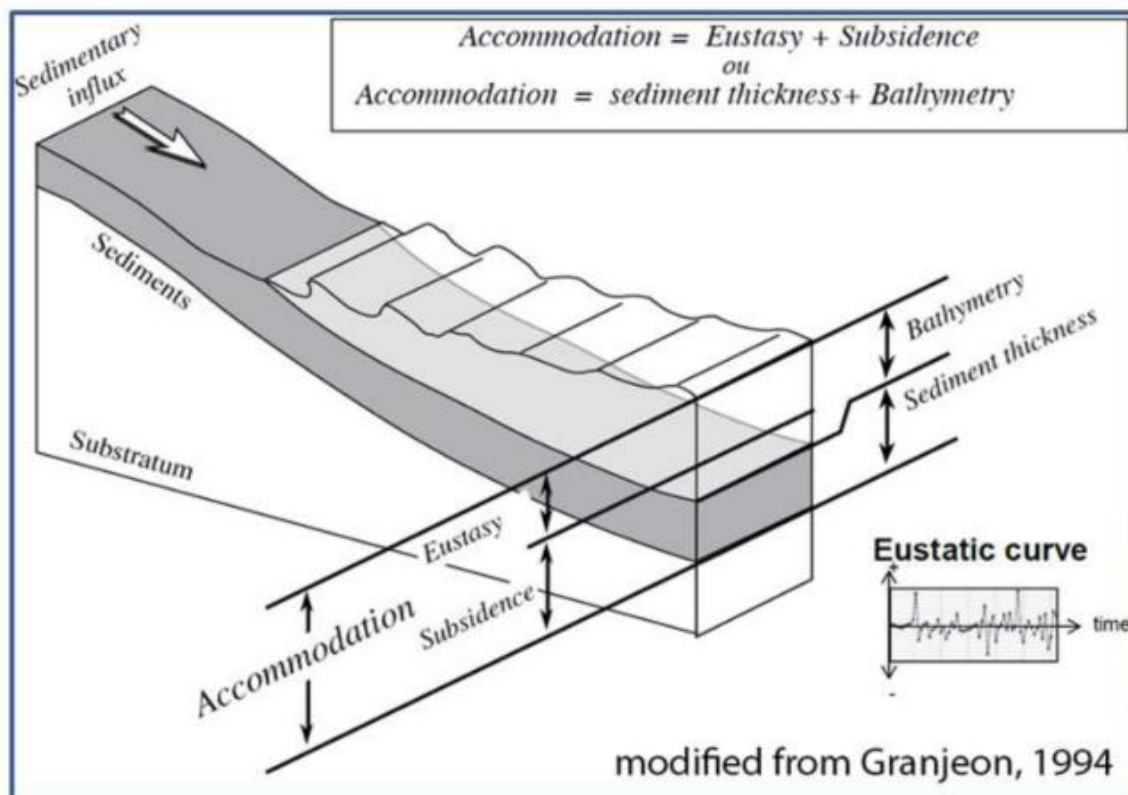


Figure 5. Schematic diagram of accommodation which refers to sum of eustasy and subsidence or sediment thickness and bathymetry.

Sediment in situ production refers to the creation of carbonate sediment directly within the model. This is achieved by incorporating laws governing carbonate production, which

consider various ecological factors such as water depth, wave energy, temperature, and surface illumination (as illustrated in Figure 5). Sediment transport delivered by water driven, slope driven or even via wave action. These actions apply macro-scale sediment transport laws as Lane's balance (1995), typically represented by diffusion equations (equation 1). These laws dictate how sediments are eroded, moved, and settled across the basin. Subsequently, calibration is conducted by adjusting all input parameters such as carbonate production, wave characteristics, and reworking parameters. The simulated result aims to accurately replicate the overall geometry and distribution of lithology and facies as identified through sequence stratigraphic framework (Granjeon & Joseph, 1999b).

## **CHAPTER 3**

### **Testing Geologic Assumptions and Plausible Scenarios for Best-Fit Reference Model in Marrat Formation using Stratigraphic Forward Modeling**

#### **Abstract**

A mixed siliciclastic and carbonate system in Marrat Formation, records significant changes in texture and sequence architecture. Their sedimentation governs by interplays between two competing systems clastic influx and carbonate factories in organizing a depositional system. Constructing a geological model that aligns with the stratigraphic framework and can be validated with real datasets remains a challenge. By employing a numerical process based stratigraphic forward modeling approach, we test geologic assumptions and plausible scenarios to provide the best fit simulated reference model. We investigate the influence of eustasy, subsidence, sediment supply, transport sediment, carbonate production, and wave energy on simulating the sequence architecture and geometry in Marrat Formation. The findings demonstrated the best fit reference model with double sediment supply sources scenario filling the basin. The simulated model observed aggradation–progradation geometries within the Marrat Formation in 3<sup>rd</sup> stratigraphic order. The simulated model shows good agreement with the outcrop and subsurface observations. Furthermore, the accurate quantification of multiple parameters enables a more precise spatial delineation of siliciclastic and carbonate distributions across the basin, particularly to capture along strike variability. These findings offer valuable insights for mixed systems in enhancing regional understanding on the spatio-temporal heterogeneity

of the Marrat Formation and aid in identifying potential petroleum reservoirs, subtle stratigraphic traps and informing exploration strategies by reducing the uncertainties.

Keywords: Marrat Formation, Mixed siliciclastic and carbonates, Stratigraphic Forward Modeling

### **3.1 INTRODUCTION**

Mixed siliciclastic and carbonate sediment possesses its own uniqueness. One of which is the interplay between two competing systems of clastic influx and carbonate factories in organizing a depositional environment. Changes in sedimentation pattern and sequence architecture are sensitive to the complex interplay of various factors, such as climatic variations, tectonic activity, and sea-level fluctuations. (Catuneanu, 2002, 2006; Jervey, 1988; Miall, 2010; Posamentier & Allen, 1999; Posamentier & Vail, 1988; Schlager, 2005a). Yet, understanding the sequence architecture and geometry at a regional scale remains challenging. Limited datasets make geological interpretations difficult and highly uncertain. Moreover, the challenge of heterogeneity frequently encountered in typical mixed siliciclastic and carbonate systems increases the complexity of geological interpretation.

The Toarcian Marrat Formation in Saudi Arabia is an ideal mixed siliciclastic and carbonate system due to its deposition during a transgressive-regressive depositional sequence, which led to the development of carbonate during the transgression phase. During the Toarcian (Early Jurassic period), Marrat Formation was deposited in a large epeiric tropical environment that covered the Arabian Platform. This transgression phase extended all the way up to the Triassic-Jurassic unconformity (Murris, 1980; Powers et al.,

1966). An integrated approach utilizing sedimentology, seismic stratigraphy, and biostratigraphy was employed to investigate the stratigraphic evolution of the 3rd and 4th ordered sections in Marrat Formation, Saudi Arabia (Al-Hussaini et al., 2021; Al-Mojel et al., 2020; Farouk et al., 2018; Manivit et al., 1985; Manivit & Le Nindre, 1990; Y. Le Nindre et al., 2022; Powers, 1968; Powers et al., 1966; Vaslet et al., 1983). Although sedimentary environments and sequence stratigraphy architecture have been the primary focus of previous studies, there has been limited research on the quantification of these aspects through stratigraphic forward modelling. Such research that integrates the multi-disciplinary and multi scale constrain to build the geological model and estimate the sediment source to sink was studied in Levant margin with stratigraphic forward modeling approach to estimate the siliciclastic and carbonate infill in the Levant Basin (Hawie, et al., 2017). The research explored and tested several scenarios for achieving best fit modeling in the basin such as single to multiple source scenario, quantification of siliciclastic source and insitu carbonate production and bring assumption from modern river as an analogue to the input parameters. Other studies also applied process based numerical modeling on mixed siliciclastic and carbonate of Albian Burgan – Kazhdumi succession to explore the lithology and facies distribution. The research builds more precise regional sequence stratigraphy and stratigraphic architecture by integrating multi-disciplines and multi-scales of seismic and well data as data validation. The result helps guide the petroleum plays and stratigraphic potential in deltaic systems (Shabani et al., 2022). Moreover, (Baharudin et al., 2024) applied numerical process based modeling to tested impact of sea level in greenhouse period and icehouse period to understand both characters in sedimentation and stratigraphic architecture as depicted in several simulated model scenarios.

Recent times, utilizing a process-based modeling approach, such as stratigraphic forward modeling, can assist in constructing geological models by testing various geological assumptions and scenarios aligned with the sequence stratigraphic framework. These models are calibrated with observed outcrop data and well data. Our study documents the best-fit reference model for the Marrat Formation using a stratigraphic forward modeling approach. By testing multiple geological assumptions and plausible scenarios, we aim to construct a best fit reference geological model. Parameters tested include sediment sourcing scenarios, quantification of sediment supply and water discharge, quantification of carbonate production, sea level, subsidence, and wave energy. The objectives of this research are to predict sequence architecture at the third stratigraphic order with limited datasets and to determine the outcomes of testing various geological assumptions or scenarios applied to the sedimentation processes of the Marrat Formation. Furthermore, the study proposes insight into a variability of regional-scale geometries as lateral and vertical texture/facies heterogeneity.

### **3.2 GEOLOGICAL SETTING**

The research area focused on the outcrop section in the central part of Arabian Platform. The platform was located on a passive margin. Deposited in a broad epeiric platform from a continental area to a shallow marine (Murriss, 1980; Powers et al., 1966) (Figure 6). The Arabian Plate was experienced by Zagros rifting during Late Permian to Middle Triassic that has implication to thick carbonate deposition in the platform and intrashelf environments and continued until Early Jurassic. During late Triassic to Early Jurassic period was no deposition because of the collision of Iranian Plate with Eurasia through Zagros Suture called as Kimmeridgian orogeny and marked by Minjur unconformity

(Beydoun, 1993; Sharland et al., 2001; Ziegler, 2001). The first major transgression occurred during the Late Triassic and Early Jurassic. Regional equivalents formation during this time including Mus Formation in Iraq, Marrat Formation in Kuwait, Saudi Arabia, United Arab Emirates, Qamchuqa Formation in Syria, and Nirim Formation in Levant. During this time, MFS J09 and MFS J10 to intra-J20 marked the maximum transgression period (Sharland et al., 2001).

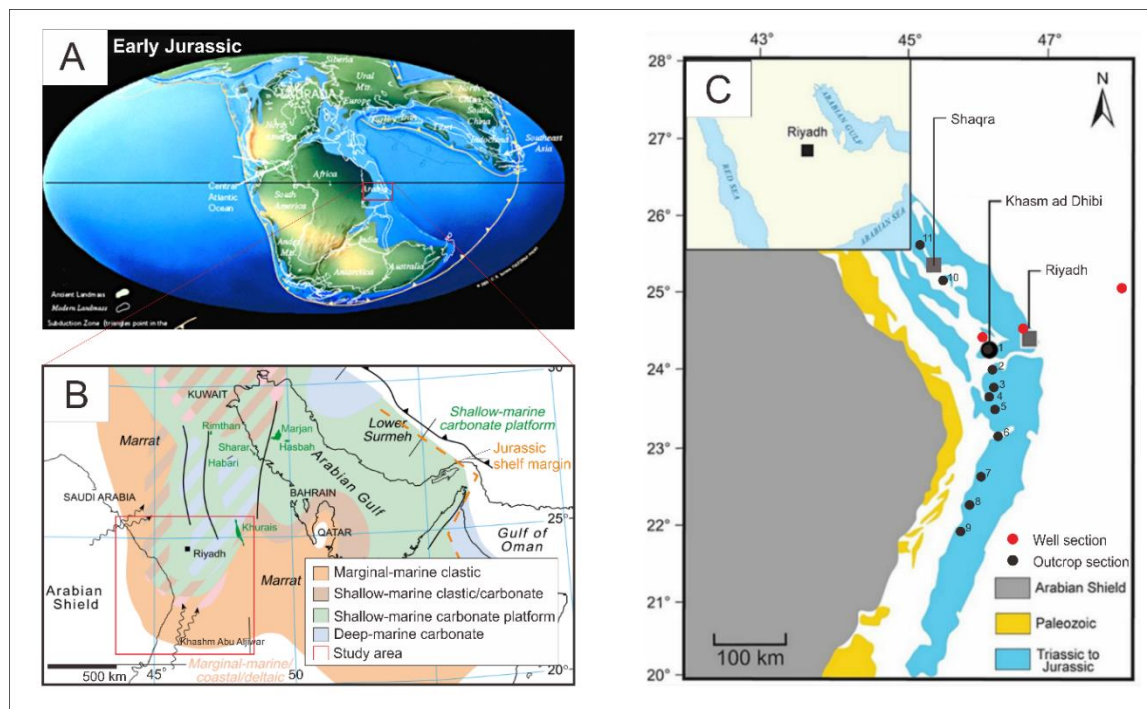


Figure 6. (A,B) Paleogeography map during the Early Jurassic period depicting the different depositional environments. The study area covers the exposed Arabian shield, non-marine to marine clastic, shallow marine clastic/carbonate, shallow marine carbonate platform, and deep marine carbonate. Modified after (Ziegler, 2001). (C) Geology map showing the measured section and well section done by (Al-Hussaini et al., 2021; Al-Mojel et al., 2020).

In Saudi Arabia, the distribution of Marrat Formation is extensive, especially in the Khashm adh Dhibi region, reached maximum thickness around 111 and 142 meters (Powers, 1968; Powers et al., 1966). Marrat Formation characterized by its unconformable at base with the clastic Upper Triassic Minjur Formation and unconformable on top position with the Bajocian-Bathonian Dhurma Formation (Fischer et al., 2001; Manivit & Le Nindre, 1990). Marrat Formation exhibits a complex lithological composition, consisting of interbedded sandstones, mudstones (claystone), with limestone and anhydrites intercalated in lower part and upper part Formation (Al-Hussaini et al., 2021; Al-Mojel, 2020; Farouk et al., 2018; Le Nindre, 2022; Manivit et al., 1985; Jacques Manivit & Le Nindre, 1990; Powers et al., 1966; Powers, 1968; Vaslet et al., 1983) (Figure 7). The Marrat Formation has been subdivided into the lower member, middle member, and upper member.

The lower member is characterized by an Early Jurassic unconformity, distinguished by a prominent iron-stained surface overlaying the Late Triassic Minjur Sandstone, with several sections displaying paleosols. This distinctive lower member may attain a thickness of up to 47 meters. Consisted of greenish – green colour, fine-grained to silt grain, succeeded by sandy marl and dolomitic limestone. Characterized by low abundance of faunal assemblages in comparison to other members of the Marrat Formation.

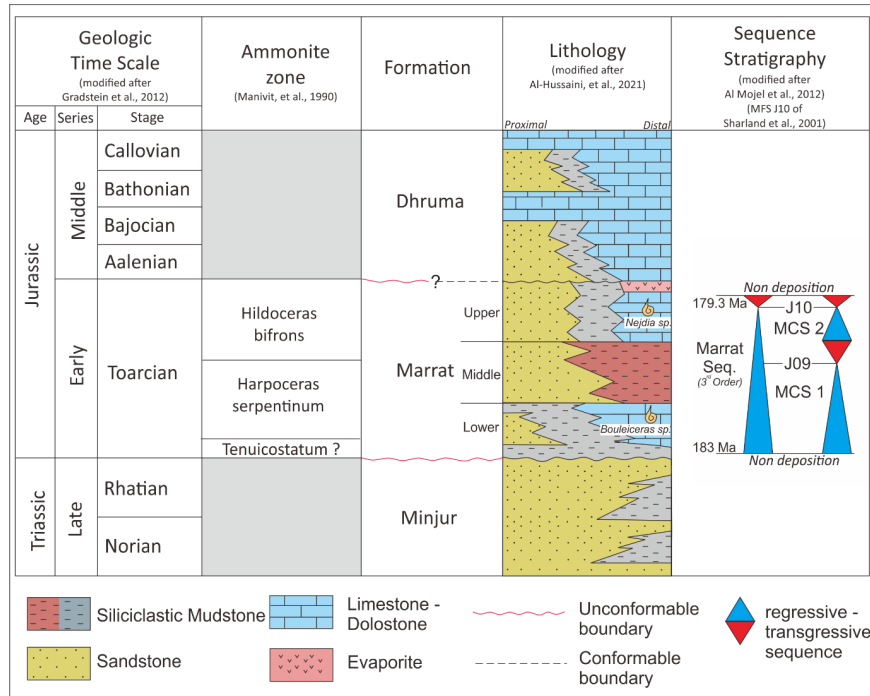


Figure 7. General stratigraphic chart showing stratigraphic position of Marrat Formation and its overlain and underlain Formation. The lithologies of the Minjur Formation, Marrat Formation and Dhruma Formations were obtained from (Al-Hussaini et al., 2019; Powers, 1968; Powers et al., 1966)

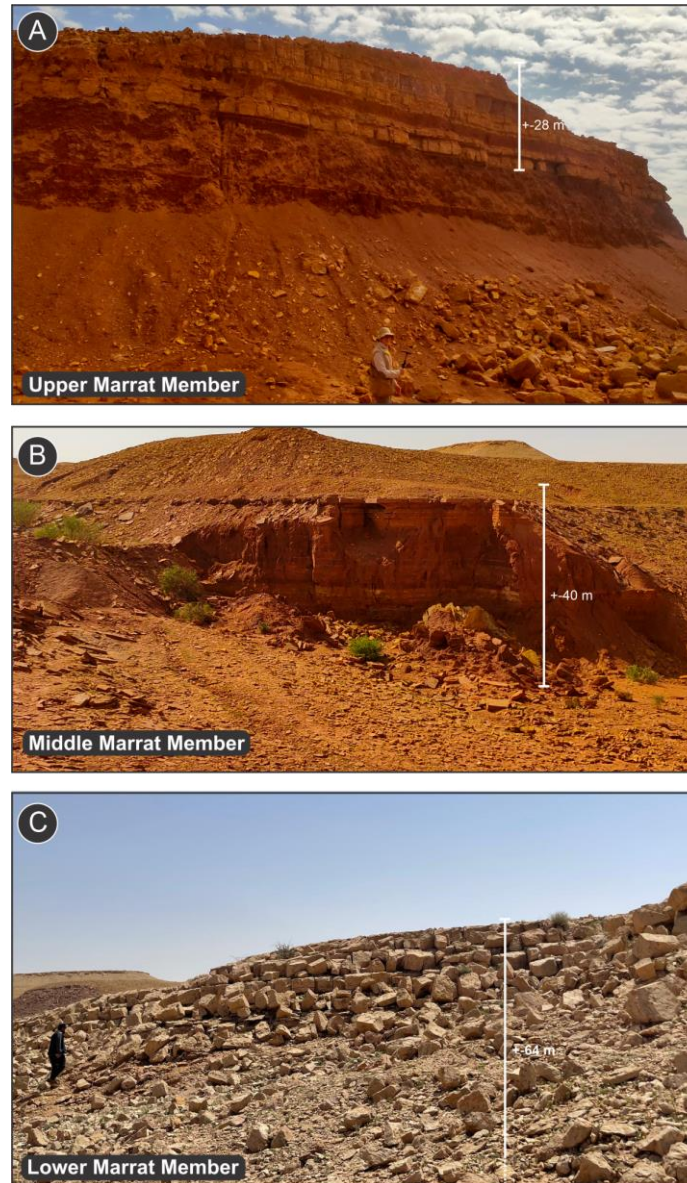


Figure 8. Outcrop photographs of Marrat Formation consist of upper Marrat member, middle Marrat member and lower Marrat member. The red beds found in middle Marrat member characterized by a succession of reddish mudstone and siltstone layers, which lack any distinguishable fossil remains.

The uppermost section of this member is marked by calcareous shale, which contains a relatively low abundance of fauna. The thickness of this member ranges up to 40 meters,

and it was formed in a depositional environment that ranges between subtidal and intertidal lagoon environment. The significance of middle Marrat member is established through the examination of ammonite fossils, with a focus on *Protogrammoceras sp.* and *Bouleiceras sp.* at the base of the member. The dolomitic limestone is rich in fossils and characterized by bioturbation mainly in the initiation of middle member of Marrat Formation. This is followed by a succession of reddish mudstone and siltstone layers, which lack any distinguishable fossil remains. It has been noted that there is a substantial reduction in the thickness of the middle member of Marrat Formation towards the southern areas. In this region, there are reddish mudstones replaced by sandstone-rich deposits (Powers, 1968; Powers et al., 1966). While, the upper part of Marrat Formation is a bioturbated limestone. It was deposited under a lagoonal environment. This member is overlain by a 7 meters thick layer of evaporite in form of anhydrite. This anhydrite layer has been identified by (Powers, 1968) which belongs to the Middle Jurassic period. In general, the Marrat Formation depicts a transgressive-regressive cycle, with the indication of Bouleiceras Horizon, located at the base of the Middle Marrat and identified as the maximum flooding surface (MFS J09) and maximum flooding surface (MFS J10) lying at the base of the Upper Marrat by the indication of Nejdia Horizon (Le Nindre, 2022).

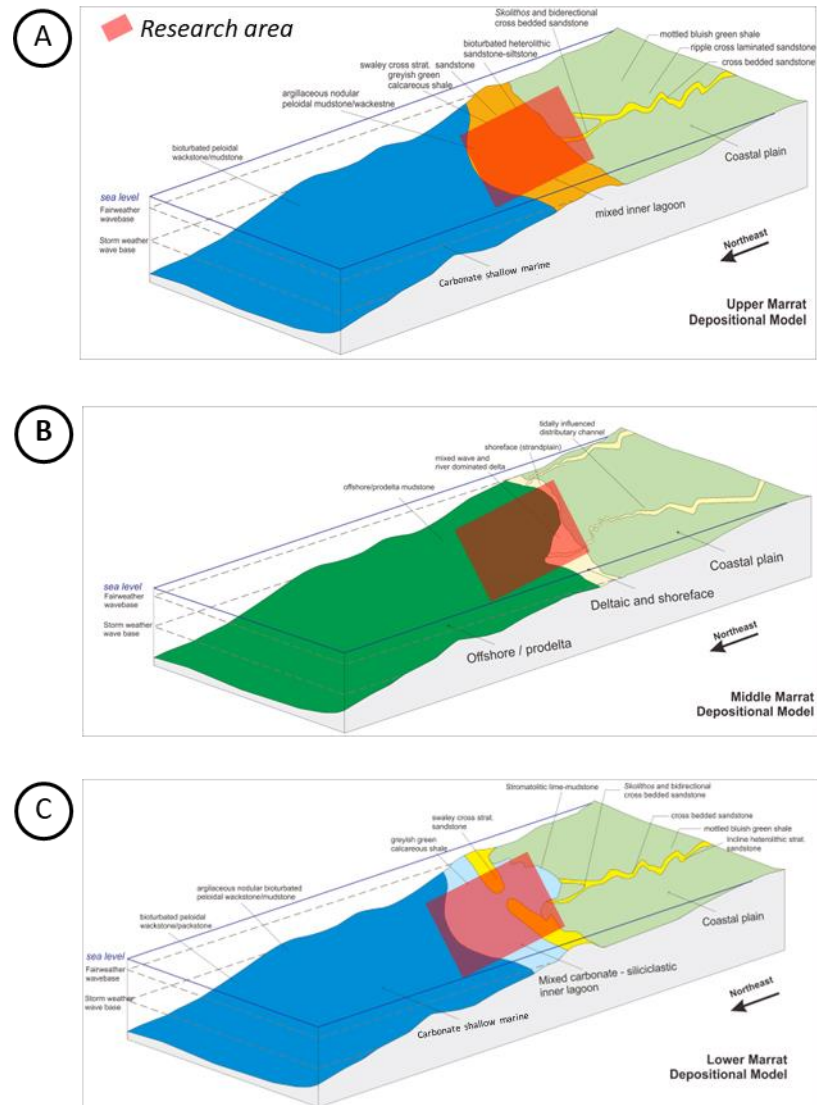


Figure 9. The conceptual model of the depositional environment of Marrat Formation. The facies were laid down in a broad and flat, inner platform depositional environment. The evolution of Marrat formation starting from lower Marrat (C), Middle Marrat (B), Upper Marrat (A). Upper Marrat member and Lower Marrat member modified from (Al-Mojel, 2020) and Middle Marrat member data modified from (Al-Hussaini et al., 2021).

### 3.3 RESEARCH METHOD

#### 3.3.1 Dataset

The Marrat Formation has been extensively studied with published datasets available from both outcrop and well data. One such dataset is the measured section of the Marrat Formation, which was taken along a north-south transect south of Riyadh in central Saudi Arabia (Figure 6) based on published data (Al-Hussaini et al., 2021; Al-Mojel, 2020) and 2 well data from Riyadh well and Khurais well (Al-Mojel, 2020). The data consist of lithostratigraphic, sequence stratigraphy, biostratigraphy (Manivit & Le Nindre, 1990). The data from the Marrat Formation, including information on facies, depositional environment, and depositional models, have been interpreted and are available for use. This data was obtained from both outcrop and well data, and a stratigraphic measured section was measured along a north-south transect south of Riyadh in central Saudi Arabia (Al-Hussaini et al., 2019; Al-Mojel, 2020) (Table 1).

**Table 1. Geological data are utilized for stratigraphic modeling and subsequently calibrated to improve the accuracy of the model**

| Whole data            | Data Type             | Data Location              | Coordinate             | Reference                |
|-----------------------|-----------------------|----------------------------|------------------------|--------------------------|
| 12 reference outcrops | Outcrop section logs  | Ushaiger section           | X: 515706 Y: 2805435   | Al-Hussaini et al., 2021 |
|                       |                       | Kumayt Qarayan section     | X: 804901 Y: 792485    | Al-Hussaini et al., 2021 |
|                       |                       | Khashm adh Dhibi_2 section | X: 612669.2 Y: 2691397 | Al-Hussaini et al., 2021 |
|                       | Sequence stratigraphy | Khashm adh Dhibi section   | X: 611557.8 Y: 2680675 | Al-Mojel et al., 2020    |
|                       |                       | Wadi Al Jufayr section     | X: 619815.4 Y: 2643481 | Al-Mojel et al., 2020    |
|                       | Facies                | Faridat Balum section      | X: 626053.3 Y: 2622822 | Al-Mojel et al., 2020    |

|                   |                       |                             |                        |                                   |
|-------------------|-----------------------|-----------------------------|------------------------|-----------------------------------|
|                   |                       | Khashm Al Khalta section    | X: 620236.8 Y: 2608828 | Al-Mojel et al., 2020             |
|                   |                       | Khashm Disman section       | X: 624905.7 Y: 2591588 | Al-Mojel et al., 2020             |
|                   |                       | Wadi Birk section           | X: 638986.1 Y: 2558650 | Al-Mojel et al., 2020             |
|                   |                       | Fara'id al Ahmar section    | X: 613436.4 Y: 2495312 | Al-Mojel et al., 2020             |
|                   |                       | Khashm Munayyifiyah section | X: 590802.2 Y: 2453209 | Al-Mojel et al., 2020             |
|                   |                       | Khashm Abu Al Jiwar section | X: 576089.3 Y: 2415667 | Al-Mojel et al., 2020             |
|                   | Biostratigraphy       | Khashm adh Dhibi section    |                        | Jacques Manivit & Le Nindre, 1990 |
| 2 reference wells | Well logs (GR log)    | Riyadh well                 | X: 635683 Y: 2735616   | Al-Mojel et al., 2020             |
|                   |                       | Khurais well                | X: 804902 Y: 2792485   | Al-Mojel et al., 2020             |
|                   | Sequence stratigraphy |                             |                        |                                   |

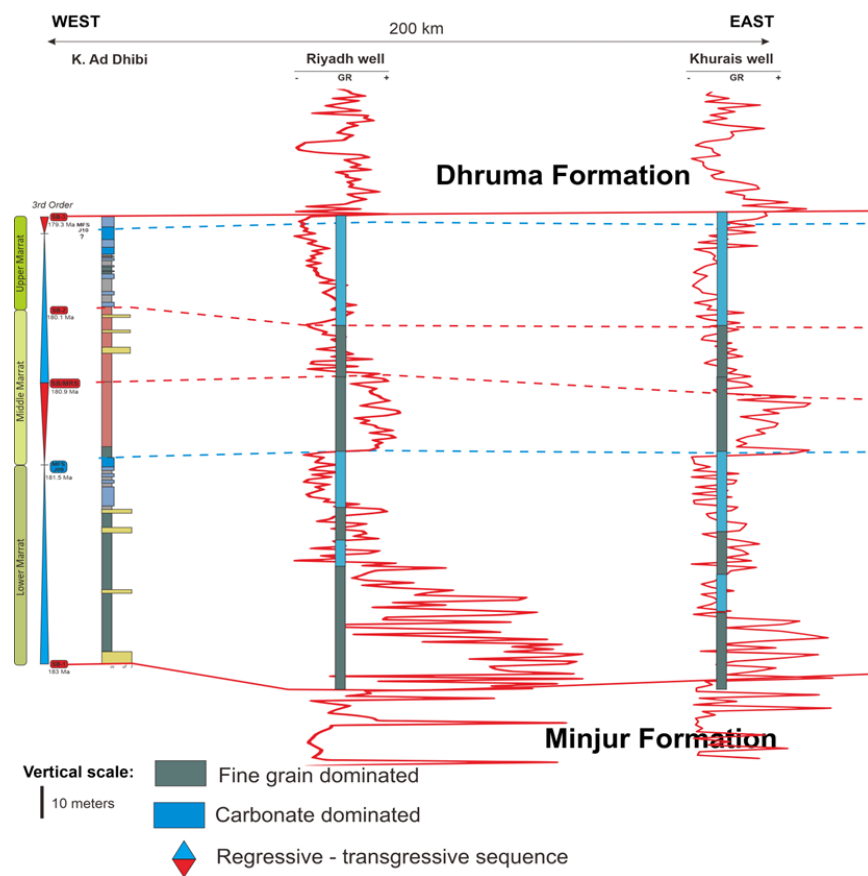


Figure 10. Correlating sequence stratigraphy from surface to subsurface by utilizing gamma-ray logs covering southwest to northeast trajectory (Khasm Ad Dhibi to Khurais area) (modified after Al-Mojel et al., 2020).

### **3.3.2 Methodology**

The aim of employing stratigraphic forward modeling is to generate simulations of various parameters in order to assess different assumptions and examine the influence of various contributing factors in controlling basin stratigraphy observed at present day. The model design or conceptual model of the depositional environment will be utilized to measure the geological processes by integrating all available data as a constraint for input parameters. The input parameters were categorized into two groups: basin conditions and sediment characteristics. A robust framework of quantified basin condition parameters was established based on a validated depositional model representative of the study area, to test and compare multiple scenarios. In this study, the general workflow and methodology are as follows: (i) comprehensive understanding and determination of various parameter values through reliable literature sources. (ii) Although running the simulation is a crucial step, many parameter values remain uncertain, making it difficult to explore the impact of each process individually through trial-and-error approaches. Therefore, an iterative process is required. (iii) The resulted prediction model will be calibrated with the available data such as outcrop data or well data. However, manual calibration through a trial-and-error approach can be very time-consuming in this context. The stratigraphic forward modelling will use Dionisos software as the primary platform to run the simulation. In addition, Petrel software will be utilized for data preparation, as well as the creation of 3D basemaps and bathymetry. The stratigraphic forward modeling process will consist of four primary

stages, starting with the preparation of data, followed by the analysis of input parameters and data processing. The third stage will involve stratigraphic forward modeling, and the final stage will be the calibration of the model (Figure 11).

### **3.3.3 Data Preparation**

The initial stage of data preparation involves selecting and gathering raw data. For this study, 12 outcrop measured sections were chosen based on previously published data (Al-Hussaini et al., 2021; Al-Mojel, 2020) and 2 well data from Riyadh well and Khurais well (Al-Mojel, 2020). The data consist of sedimentology and stratigraphy analysis, sequence stratigraphic framework, facies and deposition environment, biostratigraphy data and conceptual geological model. Sequence stratigraphic correlations were conducted throughout the studied sector using a third order framework based on sedimentological, biostratigraphic, and well log data. Biostratigraphic data provides important information for defining the age boundaries of the studied stratigraphic unit, as well as insights into the depositional bathymetry during the formation's deposition. A thorough understanding of the geological concepts of the study area will be crucial for the success of the forward stratigraphic modelling stage.

### **3.3.4 Input Parameter**

#### **3.3.4.1 Basin Condition (Domain or boundary definition)**

The model's parameters are specified within the confines of a boundary of 600 km × 500 km with cell sizes of 6 km × 5 km and simulated with time intervals of 100 kyrs to examine the broader third-order sequence of the sedimentary architecture. The Marrat Formation's chronostratigraphic framework relies on biozones (Ammonite zones) linked to Tethyan

time charts and sequence stratigraphic schemes. The Marrat Formation's total duration was approximately 3.7 million years (Al-Mojel, 2020; Jacques Manivit & Le Nindre, 1990). All input parameters are interpreted from ancient strata of Marrat Formation and selected within the natural range of equivalent parameters observed in the modern environment. The initial bathymetry of the Marrat Formation will be modeled based on the paleogeographic map represented by water depth, (Ziegler, 2001). Calculation of subsidence rate estimated from the ratio of apparent accommodation rate and sedimentation rate from stratigraphic record (outcrop and well log data) refer to (Borgomano et al., 2020) (Figure 11). The simulated model did not consider the sediment compaction and subsidence by sediment load because will intricate the modeling.

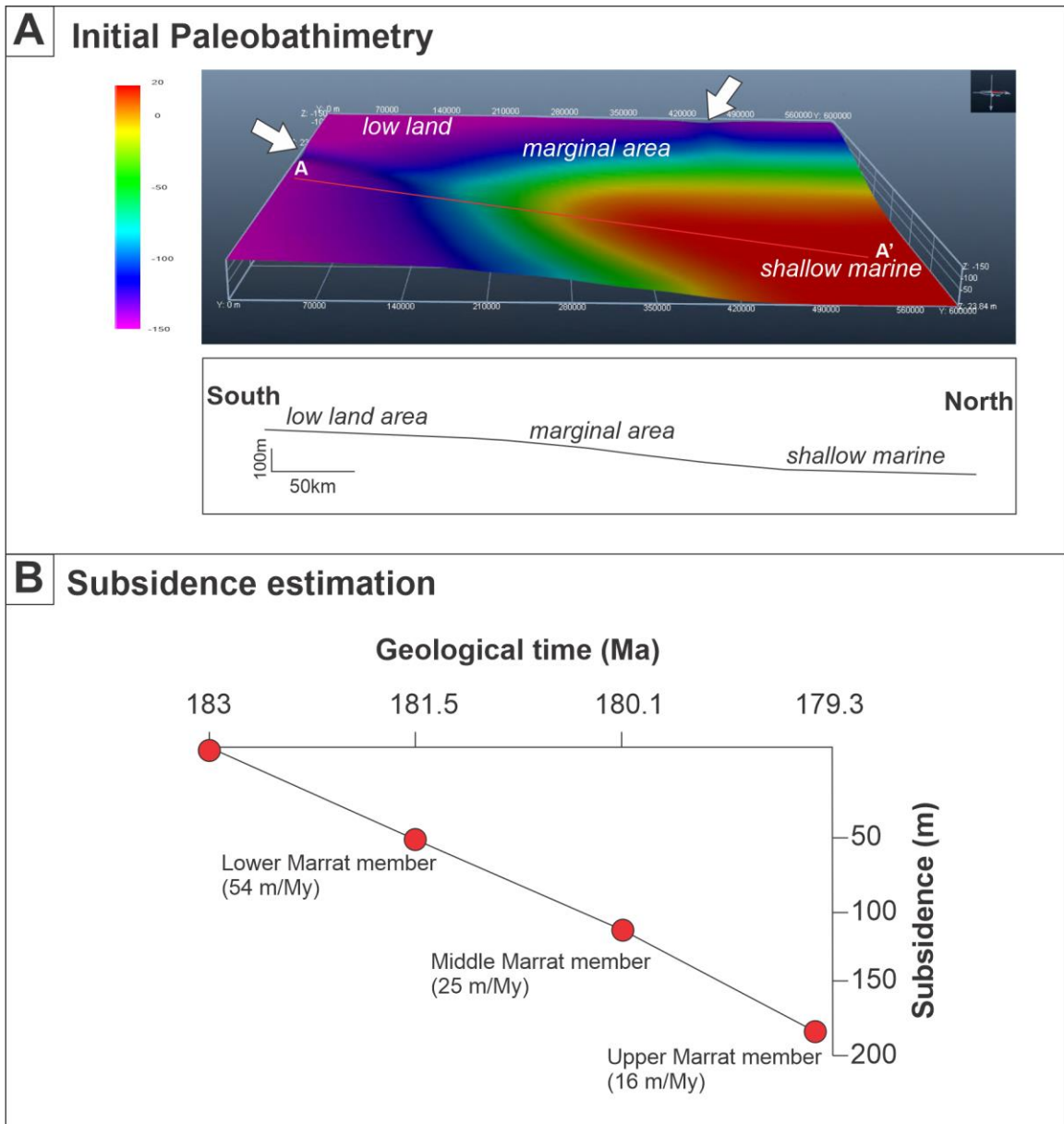


Figure 11. A. Initial bathymetry cover the area from low land area, marginal area to shallow marine area with water depth up to 20 meters water depth. The initial bathymetry of the Marrat Formation generated based on the paleogeographic map (Ziegler, 2001). B. Calculation of subsidence rate estimated from the ratio of apparent accommodation rate and sedimentation rate from stratigraphic record (outcrop and well log data) refer to

(Borgomano et al., 2020). Note: The subsidence value estimation is based on the average from the margins to the center of the basin.

### 3.3.4.2 Sea level

The eustatic sea level curve used in the study will be based on the relative and global sea level changes observed in the Arabian Plate (Haq, 2018) in 3<sup>rd</sup> sequence stratigraphic order (Figure 12).

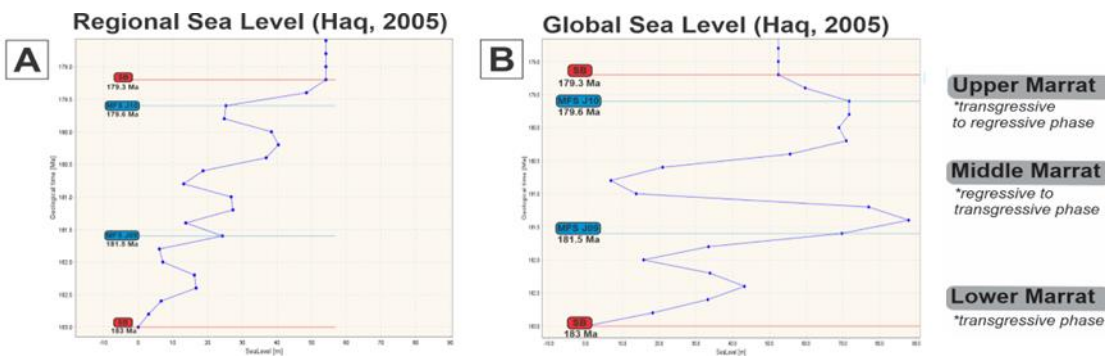


Figure 12. The eustatic sea level curve used in the study will be based on the (A) regional sea level and (B) global sea level changes observed in the Arabian Plate (Haq & Al-Qahtani, 2005) in 3<sup>rd</sup> sequence stratigraphic order. The Marrat Formation was deposited during a significant rise in sea level, whereas in the middle Marrat, there was initially a drop in sea level.

### 3.3.4.3 Ecological Restriction (Wave impact)

Wave energy distribution plays a dual role in the modelling: firstly, It influences sediment transport as one of the parameters in the diffusion equation and secondly, it is used to ecological limitations to specific simulated sediment types, like establishing distinct reef zones according to different levels of wave energy (Graus & Macintyre, 1989;

Montaggioni, 2005). This study determined wave parameters based on the paleogeographic location of Kuwait during the Early Jurassic period. It was determined that the primary wave direction originates from the northeast and extends towards the southwest, aligning with the direction of progradations (Al-Wazzan et al., 2021). The estimated range for the wave base values is 10–15 m as there was no direct connection to the open ocean during the Early Jurassic period. Range of wave energy in the simulation range from 30 - 110 kW/m<sup>2</sup> (Gerdes et al., 2010, Al-Wazzan et al., 2021).

#### **3.3.4.4 Sediment Characteristics**

Different methods of defining sediment classes exist based on the model's spatial and temporal resolution. When dealing with regional stratigraphic models featuring grid cells spanning several kilometers, a greater degree of simplification becomes necessary. In exploration scale and reservoir scale models, usually distinguish between sediment classes based on their grain size, assigning them with different diffusivity values, while keeping generalized production values constant (Al-Salmi et al., 2019; Hawie et al., 2015). The following parameters including to the sediment characteristics:

#### **3.2.4.5 Sediment class definition**

The transport and distribution of sediments are primarily influenced by properties such as grain size and density (Sangster et al., 2019). The grainsize categories used in this study include sand, silt and clay for siliciclastic sediments (Wentworth, 1922), and medium carbonate, and mud carbonate for carbonate sediments (Dunham, 1962) (Figure 13).

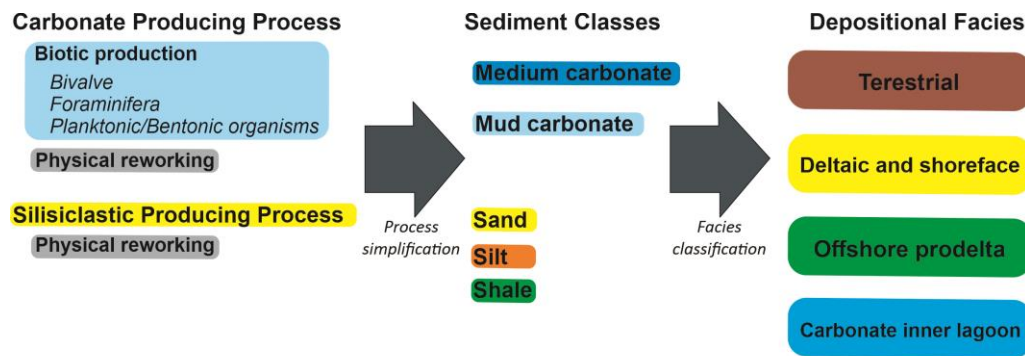


Figure 13. Sediment class definition in stratigraphic forward model consist of five sediment classes are medium carbonate , mud carbonate, sand, silt, shale based on siliciclastic and carbonate producing process. The sediment classes will classified to depositional facies model in the reference model (terrestrial, deltaic and shoreface, offshore prodelta and carbonate lagoon).

### 3.3.4.6 Carbonate production depth profiles and rates

The production laws for in-situ carbonate are dependent on multiple factors, such as depth, influx of siliciclastic sediments, wave energy, and climatic conditions. In tropical climates, the forming of carbonate is a result of the interplay of various factors (Schlager, 2005b). The production rates of carbonate tend to decrease as water depths increase, and this is generally observed in tropical climates controlled by interplay of various factors. The carbonate factory in Marrat Formation included as Tropical factory (T-factory) characterized by being light dependent and higher sediment production. The carbonate factory consists of sediments with a medium grain size that have a broader profile of production rates (1-0.9 (/), 50 -100 m/Ma) and occur in water depths ranging from shallow to slightly deeper (0-60 m). The deposition of carbonate mud is possible in both shallow marine/lagoonal settings and deeper slope to basinal environments with of production rates

(1-0.9 (/), 25-80 m/Ma), provided that the system remains unaffected by high wave energies (Hawie et al., 2015). Hence, carbonate mud values have remained consistent regardless of depth. With the production rates (0.9 (/), 80 m/Ma) (Figure 14). The carbonate production profile did not incorporate water salinity as a simulation parameter for simplifying the model.

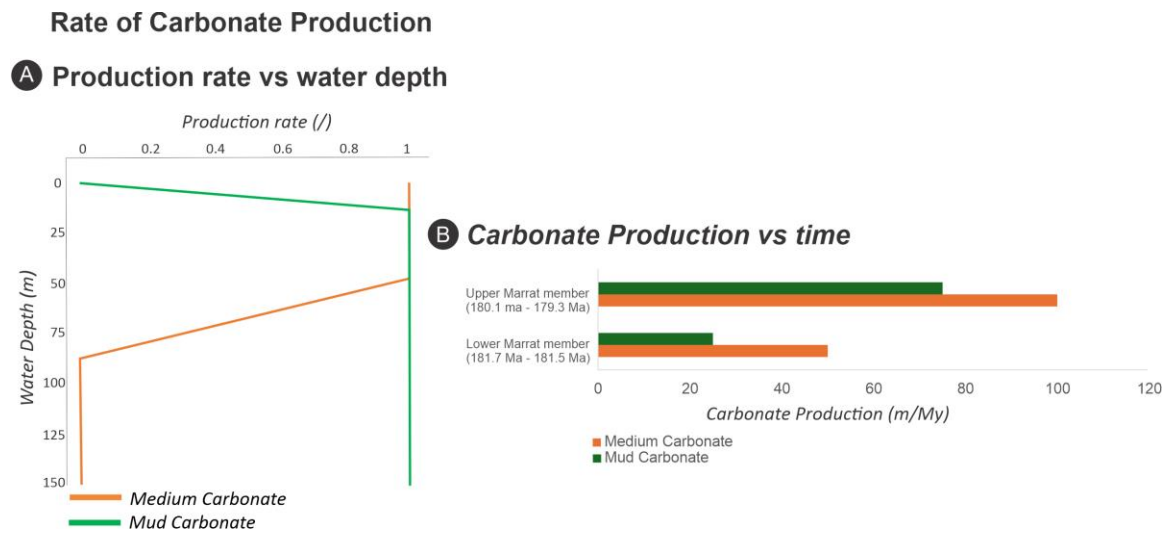


Figure 14. A. Carbonate production rate vs depth. The carbonate production represents a typical shallow water – lagoonal area where the usual trend is for carbonate production to decrease as water depth increases. B. Carbonate production rate varies from medium-grains carbonate about 50-100m/My and mud carbonate reach 25-80m/My.

### 3.3.4.7 Siliciclastics input

During the late Early Jurassic period, around the Toarcian age, the eastern Mediterranean region experienced backarc rifting, as noted by (Beydoun, 1993; Sharland et al., 2001; Ziegler, 2001). This was accompanied by a significant uplift in the central and southern regions of the Arabian plate (Sharland et al., 2001). Furthermore, according to (Ziegler, 2001) the sediment sources in the study area were mainly located in two directions, with

one source transporting sediments from west to east and the other from south to north. This sediment routing system was facilitated by a fluvial channel, which transferred the sediments to the basin. The source from southern Arabia tends to fill the basin. Estimating factors like catchment or drainage areas, sediment discharge or supply, water discharge is crucial for enhancing the precision of the outcomes achieved with stratigraphic forward modeling (SFM).

#### **3.3.4.8 Transport properties**

Empirical transport laws integrate gravity driven and water driven diffusion equations, incorporating both linear and non-linear slope-driven diffusion equations. These are collectively known as water driven transport equations and are expressed in equation (1) (Hawie et al., 2015; Tucker & Slingerland, 1994; Willgoose et al., 1991).

$$Q_s = \frac{K_{si}}{\nabla h - K_{wi}} Q_w^m S^n \quad (1)$$

The equation for sediment flux,  $Q_s$  ( $\text{km}^2/\text{y}$ ), is dependent on several factors, including the diffusion coefficients of hill slope ( $K_s$ ) ( $\text{km}^2/\text{y}$ ) and water discharge ( $K_w$ ) ( $\text{km}^2/\text{y}$ ), basin slope gradient ( $S$ ), elevation ( $h$ ), and the transported lithology ( $i$ ). Additionally, the constants  $m$  and  $n$  are included in the equation, with values between 1 and 2. The diffusion coefficient parameters change based on particle type in both terrestrial and marine settings (Granjeon & Joseph, 1999b; Hawie et al., 2013, 2015, 2016, 2018; Hawie, Callies, et al., 2017; Nagle et al., 2021).

#### **3.3.4.9 Water discharge and catchment area**

The empirical relationships established from the analysis of present-day global drainage systems have been utilized to estimate sediment transport in ancient systems by various

studies (Milliman & Syvitski, 1992b; Sømme et al., 2009; Syvitski et al., 2003; Syvitski & Milliman, 2007). According to the observation of 280 modern rivers by (Milliman & Syvitski, 1992b) water discharge volume ( $Q_w$ ) increases as the drainage area increases. Similarly, the volume of sediment supply or sediment load also increases as drainage area or catchment area and relief ( $R$ ) increases. Marrat Formation used modern river analogue with similar characteristics as wave to river dominated delta in Senegal Delta with sediment discharge =  $760 \text{ km}^3/\text{My}$  and water discharge =  $600 \text{ m}^3/\text{s}$ . The range estimation for Marrat river system range between  $750 \text{ km}^3/\text{My} - 5000 \text{ km}^3/\text{My}$  (sediment discharge) while  $500 \text{ m}^3/\text{s} - 5000 \text{ m}^3/\text{s}$  (water discharge) (Figure 15).

Modern Analogue of wave - river dominated delta Senegal Delta



Sediment discharge =  $760 \text{ km}^3/\text{My}$   
Water discharge =  $600 \text{ m}^3/\text{s}$

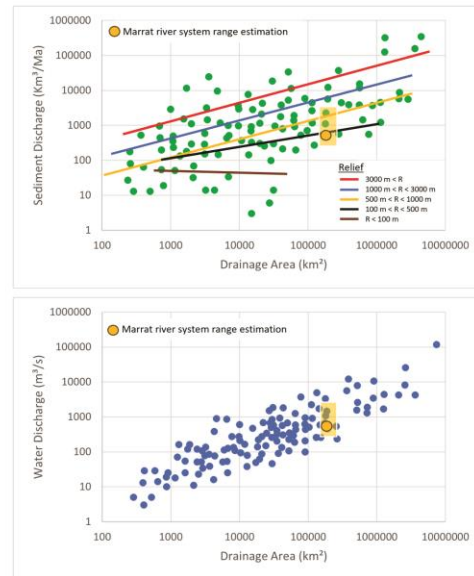


Figure 15. The global relationship between sediment discharge as a function of catchment area and relief ( $R$ ) and water discharge as a function of catchment area for rivers. The Marrat river system is denoted by a yellow circle (Milliman & Syvitski, 1992).

### Sediment Supply Estimation

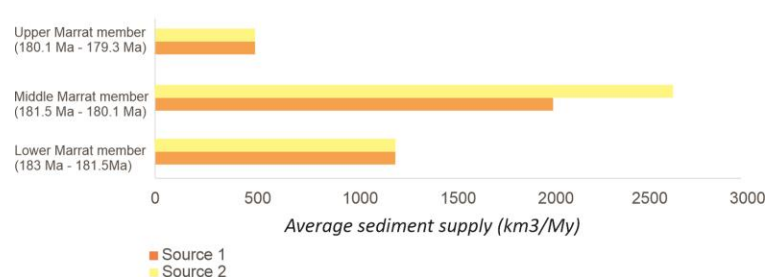


Figure 16. The assessment of sediment supply within the Marrat Formation across its various members indicates that the middle Marrat member demonstrates a notably higher supply compared to the other members.

**Table 2. Input parameters for initial deterministic scenario model.**

| Parameter                                     | Value                               | Reference                            |
|-----------------------------------------------|-------------------------------------|--------------------------------------|
| Domain length (x axis) (km)                   | 500                                 |                                      |
| Domain length (y axis) (km)                   | 600                                 |                                      |
| Grid spacing (km)                             | 5x5                                 |                                      |
| Run period (Ma)                               | 0.1                                 |                                      |
| Time Steps (My)                               | 3.7                                 |                                      |
| Gradient slope paleo bathymetry               | Less than 0.1                       |                                      |
| Sea level change                              | Relative sea level Arabian Platform | Haq & Alqahtani, 2005                |
| Subsidence                                    | Differential subsidence             | -                                    |
| <b>Sediment input setting (siliciclastic)</b> |                                     |                                      |
| source sediment                               | 2 source scenarios (west to east)   | Sharland et al., 2001; Ziegler, 2001 |
| Width (km)                                    | 25                                  |                                      |
| sediment discharge (km <sup>3</sup> /My)      | 750 - 5000                          | -                                    |

|                                                             |                                      |                           |
|-------------------------------------------------------------|--------------------------------------|---------------------------|
| water discharge (m <sup>3</sup> /s)                         | 500 - 5000                           | -                         |
| sediment grains (mm)                                        | 0.5 (sand)                           | (Wentworth, 1922)         |
|                                                             | 0.125 (silt)                         |                           |
|                                                             | 0.004 (clay)                         |                           |
|                                                             | 0.3 (medium carbonate)               | (Dunham, 1962)            |
|                                                             | 0.003 (carbonate muds)               |                           |
| sediment proportion (%)                                     | 10 (sand)                            |                           |
|                                                             | 25 (silt)                            |                           |
|                                                             | 65 (clay)                            |                           |
| <b>Transport Process Parameter for each sediment</b>        |                                      |                           |
| Gravity driven Diffusion Coefficient (km <sup>2</sup> /kyr) | 0.25 - 250 (continental sand)        | (Burgess et al., 2018)    |
|                                                             | 0.8 - 500 (continental silt)         | (Shabani et al., 2022a)   |
|                                                             | 1.7 - 750 (continental shale)        |                           |
|                                                             | 0.00 1 (continental f-carbonate)     |                           |
|                                                             | 0.001 (continental m-carbonate)      |                           |
|                                                             | 1 - 70 (marine sand)                 |                           |
|                                                             | 90 - 750 (marine silt)               | (Al-Wazzan et al., 2021a) |
|                                                             | 305 – 1500 (marine clay)             |                           |
|                                                             | 0.005 (marine medium-carb.)          |                           |
|                                                             | 0.005 (marine mud-carbonate)         |                           |
| Water driven Diffusion Coefficient (km <sup>2</sup> /kyr)   | 6.8 - 250 (continental sand)         | (Burgess et al., 2018)    |
|                                                             | 8 - 500 (continental silt)           | (Shabani et al., 2022a)   |
|                                                             | 750 - 15 (continental shale)         | (Al-Wazzan et al., 2021a) |
|                                                             | 0.005 (continental medium-carbonate) | (Shabani et al., 2022a)   |
|                                                             | 0.005 (continental mud-carbonate)    |                           |

|                                                   |                                                 |                                              |
|---------------------------------------------------|-------------------------------------------------|----------------------------------------------|
|                                                   | 1 - 600 (marine sand)                           | (Granjeon, 2019)                             |
|                                                   | 5 - 700 (marine silt)                           |                                              |
|                                                   | 10 – 2750 (marine clay)                         |                                              |
|                                                   | 0.5 (marine medium carbonate)                   |                                              |
|                                                   | 0.5 (marine mud carbonate)                      |                                              |
| Wave Diffusion Coefficient (km <sup>2</sup> /kyr) | 0.5 - 0.05 (continental sand, silt, shale)      | (Al-Wazzan et al., 2021a)                    |
|                                                   | 0.5 - 0.05 (continental medium - mud carbonate) | (Al-Salmi et al., 2019; Hawie et al., 2023). |
|                                                   | 0.5 - 0.05 (marine sand, silt, shale)           |                                              |
|                                                   | 0.5 - 0.05 (marine medium – mud carbonate)      |                                              |
| Wave Energy (kW/m)                                | 30 - 100                                        | (Al-Wazzan et al., 2021)                     |
| Wave base (m)                                     | 10 - 15                                         |                                              |
| Wave propagation azimuth (°)                      | 90 (east - west)                                |                                              |
| <b>Sediment input setting (carbonate)</b>         |                                                 |                                              |
| Carbonate production time                         | Medium carbonate (50 - 100 m/Ma)                |                                              |
|                                                   | Mud carbonate (20-80 m/Ma)                      |                                              |
| Carbonate production vs water depth               | Medium carbonate (10-60 m)                      |                                              |
|                                                   | Mud carbonate (0-to deeper)                     |                                              |

### 3.3.5 Model Calibration

The final stage of the process involves the quantification and evaluation of the model's performance in order to determine its accuracy. The calibration of the models is achieved through the use of detailed depth/thickness grids derived from three major outcrops data and one well data. To assess the validity of the model, virtual outcrops and wells generated

from the simulated stratigraphic forward model will be compared with actual outcrops and wells that were not used as input in the simulation database. The evaluation process depends on a conceptual model of the basin and calibration data acquired from outcrop observations, wells, or seismic data. Once the reference model has been constructed to align with the conceptual model in regard to its geometry and architecture, the next step involves adjusting the simulation parameters to align it with the observed real data. In this stage, the accuracy of the calibrated model is confirmed by contrasting the simulated model with real observed data (well data or outcrop data) at specific control points. This particular study utilizes outcrop data and well data to calibrate and validate the simulated lithologies and facies, by comparing them with lithology and facies logs. The thickness of the simulated model is validated by comparing them with the thickness observed in outcrops or well data, considering their estimated depositional age. The general methodology employed in the study area is illustrated in the figure below (Figure 17).

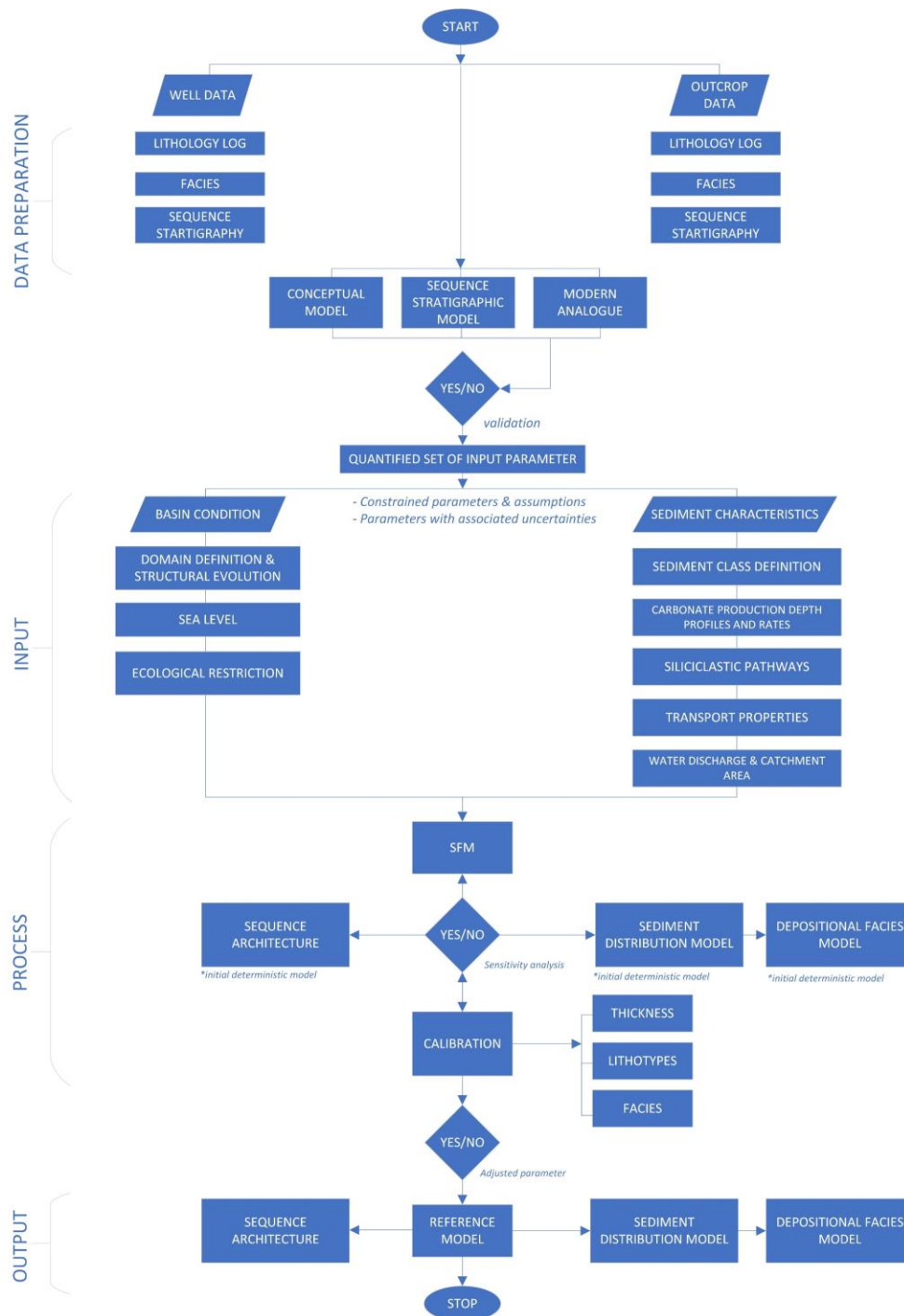


Figure 17. The general methodology employed in the study area. The methodology divided into four main stages: data preparation stage, input stage, process stage and output stage. In the data preparation stage, the data taken from published data (Al-Hussaini et al., 2021; Al-Mojel, et al., 2020).

## 3.4 RESULTS

### 3.4.1 Best Fit Scenario for Marrat Formation

The best fit scenario for Marrat Formation was achieved with multiple iteration and several geological assumptions testing several plausible scenarios that works with the geological process within Marrat Formation back at that time. The best fit reference model was built referring to several published data and applying modern analogue (recent river system and modern shallow water carbonate production). We calibrated the simulated stratigraphic model with observed outcrop log data and well log data covering north to south area of Marrat Formation from surface to subsurface. The calibration of reference model presented as cross sections across the model grid, as oblique strike direction (north - south direction) and dip direction (west east direction). The stratigraphic boundary corresponds to a sequence boundary and maximum flooding surface adapted from (Al-Mojel et al., 2020; Sharland et al., 2001) providing chronostratigraphic evolution within simulated model.

The model simulated between 183 Ma to 179.3 Ma. The simulated model is subdivided in three stages of sedimentary units or members which represent as: Lower Marrat member (183 Ma – 181.5 Ma), Middle Marrat member (181.5 Ma – 180.1 Ma), Upper Marrat Member (180.1 – 179.3 Ma). Those corresponding with the significant sea level rise. The model provides a comprehensive representation of sedimentary unit evolution on the development of mixed siliciclastic and carbonate on Marrat Formation.

*Phase 1: Drowning of Early Toarcian platform and development of carbonate inner ramp within aggradation – progradation sequence (Lower Marrat member 183 Ma – 181.5 Ma)*

The initial deposition unit was an epeiric platform covering continental area (marginal area) to a shallow marine (Murriss, 1980; Powers et al., 1966) marking the hiatus around 20 Ma, resulting the contact in form of paleosoil between Triassic and Toarcian sediments. This unconformity event modeled as an initial bathymetry in typical flat geometry. The first part represents a sea level rise with an amplitude up to 88 meters which coincided with the drowning of land and showing aggradation - progradation sequence and observed onlap termination to the basin margin (Figure 15A). The sedimentary unit was mainly composed of fine grain sediment dominated by shale 70%, silt 20% and sand 10% observed in Khasm Ad-dhibi outcrop while in Riyadh well and Khurais well dominated by shale up to 85% in the basinal. The thickness is about 55 meters, and it keeps constant from proximal to the basinal. On top of that unit, deposited carbonate adjacent with the vicinity of deltaic geometries with thickness around 20 meters. The carbonate distributed in the vicinity of marginal area and can be observed in Khasm Ad-dhibi outcrop which dominated by medium grain carbonate while in more basinal area observed in Riyadh well and Khurais well dominated by mud carbonate (Figure 12 & 15). The facies observed in this phase are located in deltaic to offshore prodelta facies and turn into inner ramp carbonate facies (Figure 16B). The bathymetry of both units ranges between 10-80 meters. The unit terminated by the MFS-J09 event will initiate the deposition of subsequent Middle Marrat member.

# **Best Fit Scenario Model at 181.5 Ma** **Lower Marrat Formation (Lithology Distribution)**

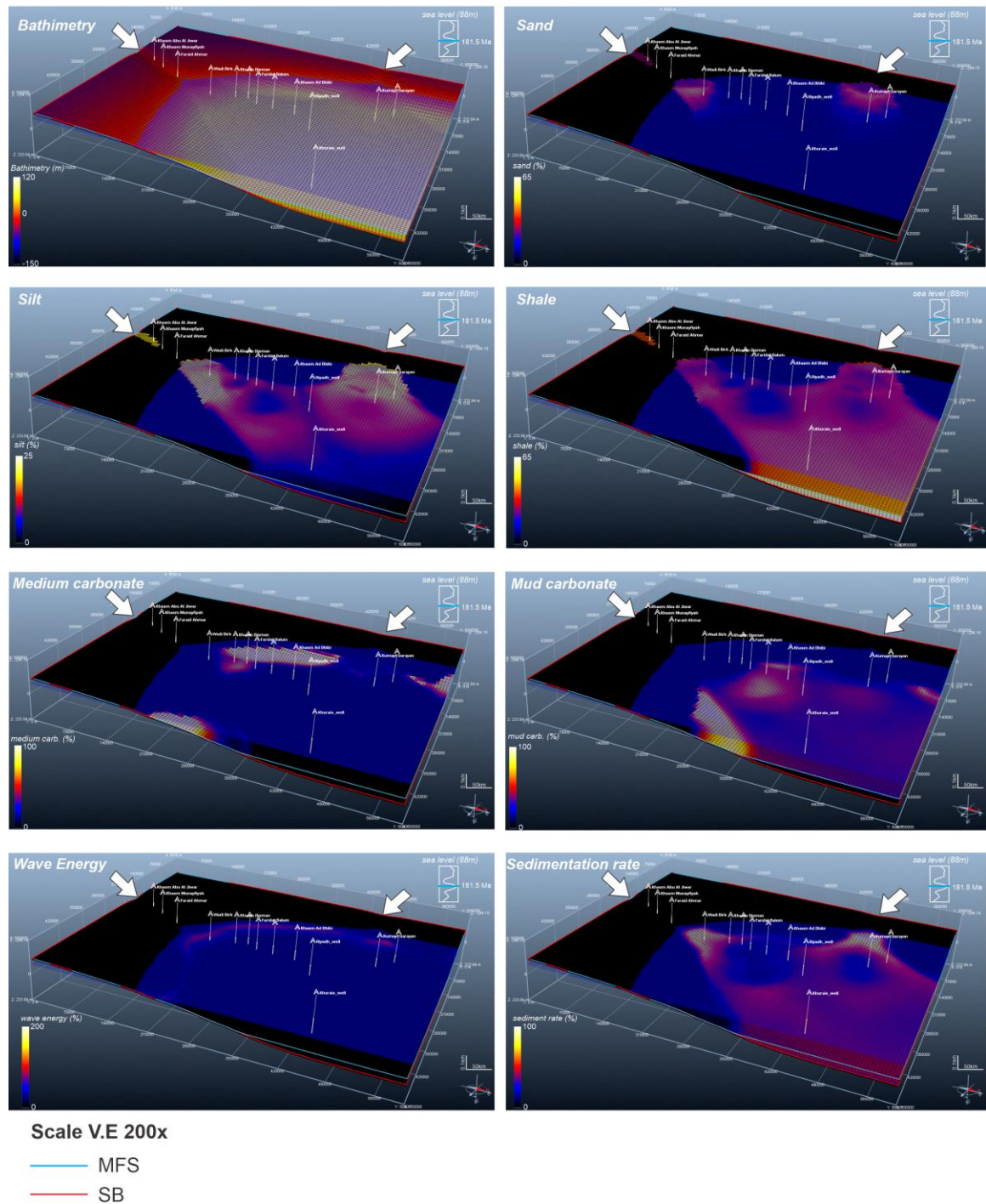


Figure 18. The simulated model in Lower Marrat member (183 Ma - 181.5 Ma). Highlight the sediment proportion in each lithologies (arrow direction is the source sediment supply).

*Phase 2: Development of siliciclastic deposition within progradation – retrogradation sequence (Middle Marrat member 181.5 Ma – 180.1 Ma)*

The unit developed during significant sea level drop and gradual sea level rise, characterized by an amplitude of sea level up to 10 meters. The unit exhibits slightly incline progradation to the basin area and turns to retrogradation before sequence boundary. The sedimentary unit was mainly composed of shale 60%, silt 20% and sand 10% observed in Khasm Ad-dhibi outcrop while in Riyadh well and Khurais well dominated by shale up to 85% in the basinal. The thickness is about 40-50 meters, and it keeps constant from proximal to the basinal (Figure 18). During sea level drop, nearly half of the area was exposed and eroded. Consequently, more than 50 % of the area is occupied by terrestrial facies and marine transition - deltaic and shoreface facies (Figure 22B). The bathymetry of these units ranges between 20-30 meters. The unit terminated by the sequence boundary event will initiate the deposition of subsequent Upper Marrat member.

**Best Fit Scenario Model at 180.7 Ma**  
*Middle Marrat Formation (Lithology Distribution)*

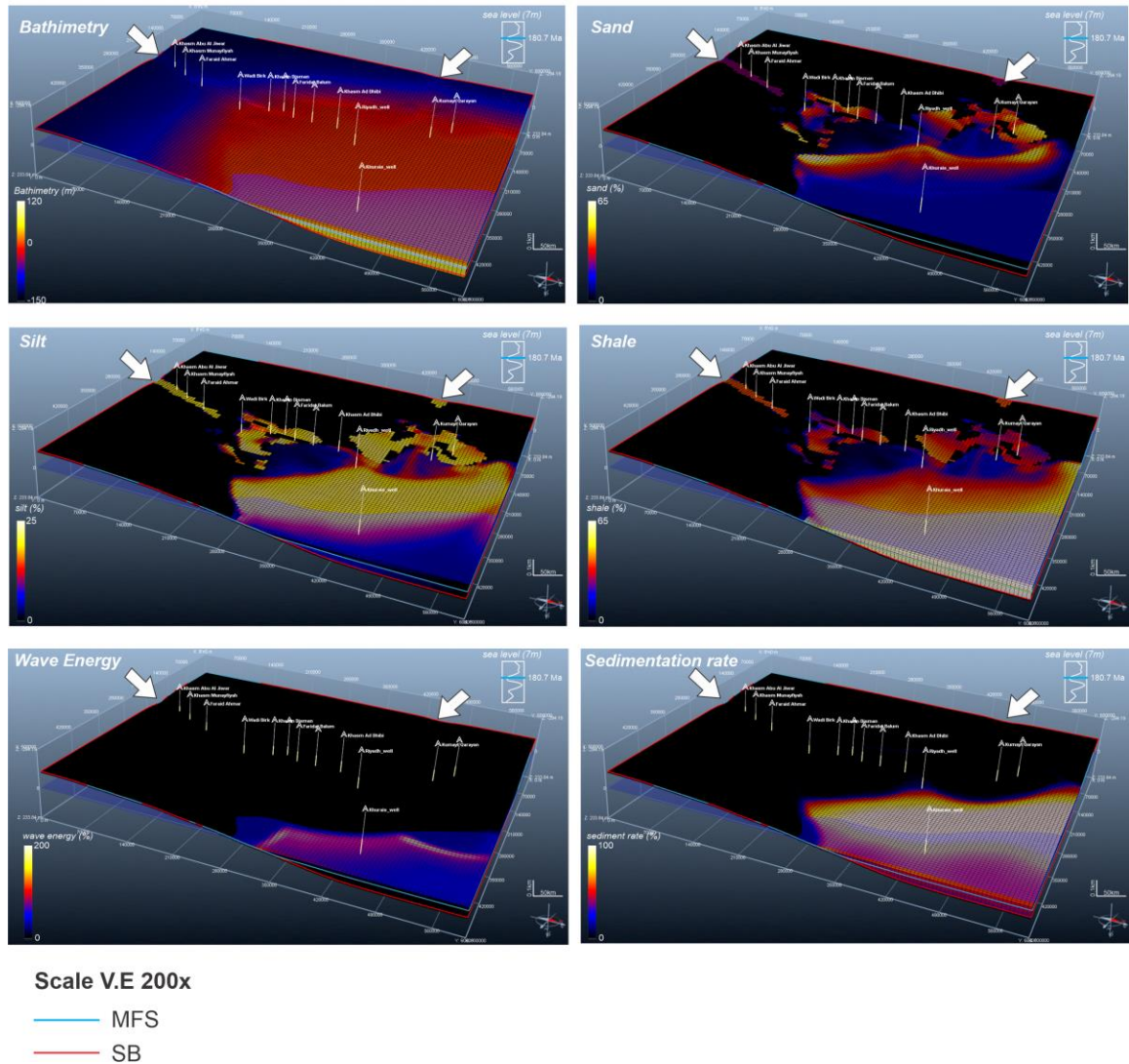


Figure 19. The simulated model in Middle Marrat member (181.5 Ma – 180.1 Ma). Highlight the geometry of delta deposited by sand up to 65% and silt up to 25% while shale dominated in the basinal area up to 65% (arrow direction is the source sediment supply).

*Phase 3: Development of carbonate within second aggradation - progradation sequence (Upper Marrat member 180.1 Ma – 179.3 Ma)*

Phase 3 represents a notable shift in the depositional system compared to the previous phase. Source sediment shift from siliciclastic to significant carbonate production impact the carbonate sediments deposited during this phase. The unit deposited during gradual sea level rise could promote enough accommodation space for the deposition of carbonate sediments. The carbonate sediments consisted of medium carbonate deposited in vicinity of Khasm Ad-dhibi outcrop to the south of Khasm Disman outcrop with carbonate proportion up to 100%. While mud carbonate deposited in the Khasm Ad-dhibi to the basin area, Riyadh well and Khurais well with sediment proportion up to 80% (Figure 21). Mostly medium carbonate growth in marginal areas with water depth range between 10-20 meters. While mud carbonate deposited deeper range between 20-60 meters. The simulated facies observed in this unit is located in carbonate inner lagoon (Figure 22B). The bathymetry of this units ranges between 60-80 meters. The unit terminated by the sequence boundary event as a remark for Aalenian unconformity and subsequent Dhurma Formation.

# **Best Fit Scenario Model at 179.3 Ma** *Upper Marrat Formation (Lithology Distribution)*

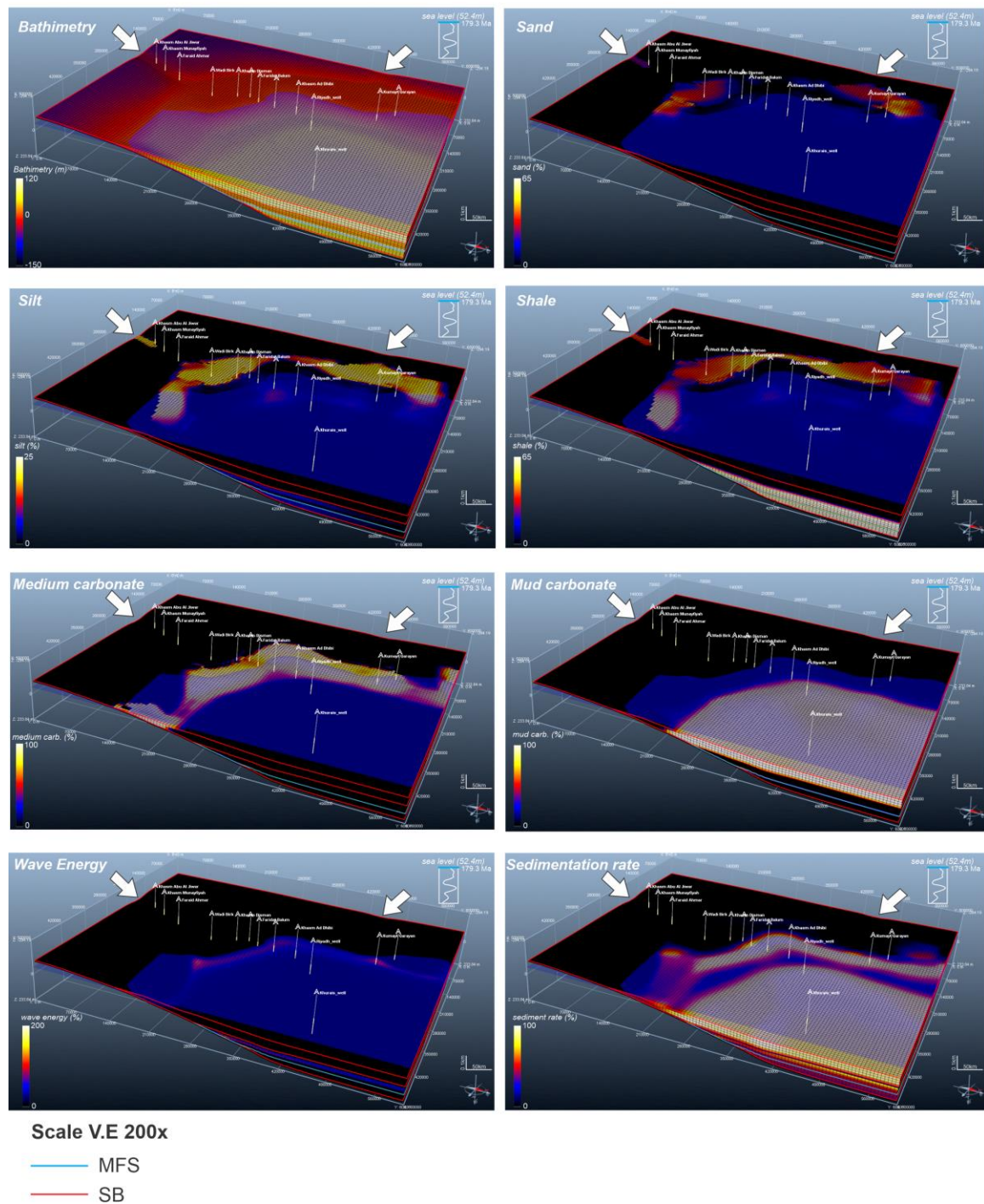


Figure 20. The simulated model in Upper Marrat member (180.1 Ma – 179.3 Ma). Highlight the geometry of delta and shoreface deposited by sand up to 30% and silt up to

20% while carbonate dominated in the marine transition area up to 100% and mud carbonate following to the basinal (arrow direction is the source sediment supply).

### **3.4.2 Sediment Proportion and Distribution**

The sediment proportion and distribution were observed through the map view generated by the simulated model in several well location point. In the southern part of the area, the proximal region displays fine-grained sediment proportions characterized by a silt lithology ranging between 45-65%, alongside minor occurrences of sand-shale lithology identified in specific locations such as Wadi Birk area, Khasm Disman area, Khasm Al Khalta area, and the Faridat Balum area. In contrast, the sediment source from the western part of the region is characterized by a prevalence of sand lithology, particularly notable in the Ushaiger and Kumayt Qarayan areas. The proportion ranging between 45-55% and the remaining is shale and carbonate proportion. As one moves towards the more basinal regions, the sediment composition is predominantly characterized by shale lithology, with proportions ranging between 50-60%. This pattern is notably observed in areas such as Wadi Al Jufyar, Khasm Ad-dhibi, as well as in the Riyadh and Khurais wells. The distribution of carbonate lithologies observed in widespread area, with carbonate proportion between 45–10%. Carbonate deposits are notably prominent in the western region, particularly in the Ushaiger and Kumayt Qarayan areas. In the southern part, carbonate presence is observed in locations such as Khasm Disman, Khasm Al Khalta, and Khasm Ad-dhibi, while in the central region, it is notable in the Riyadh and Khurais wells. Additionally, carbonate occurrences of less than 10% are observed in Khasm Disman.

### Marrat Formation (Sediment Proportion)

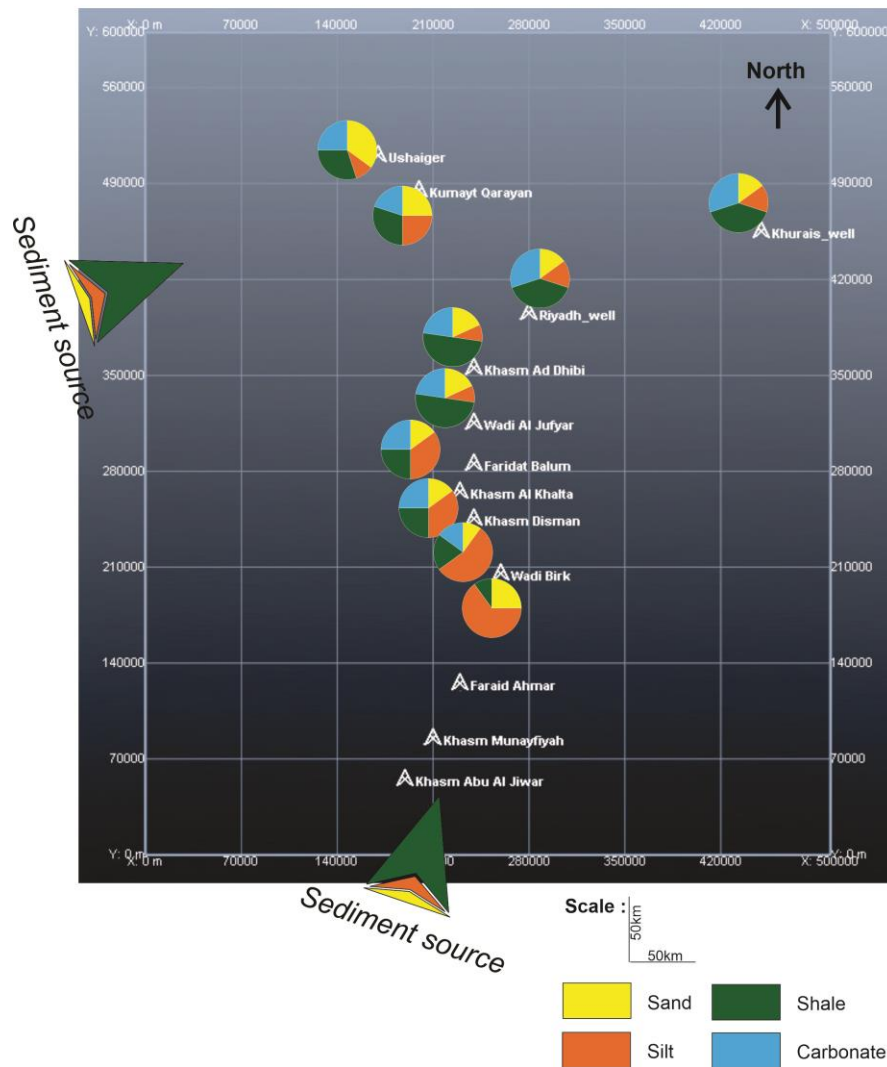


Figure 21. The map view of the simulated model displays the distribution of sediment proportions in a pie chart. This distribution notably emphasizes a high proportion of silt content in the proximal area, while carbonate sediments are also widespread across the region.

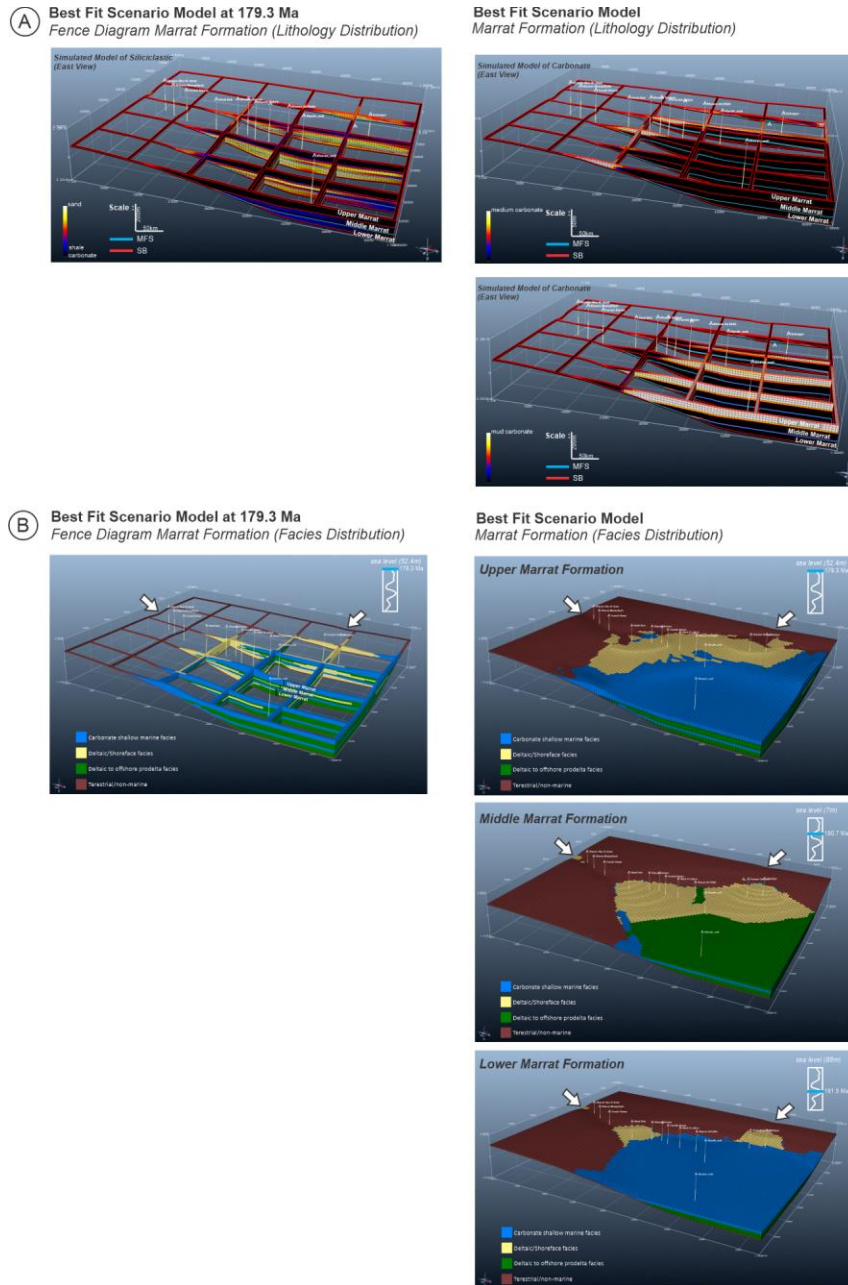


Figure 22. The map view of the best fit simulated model of lithology distribution and facies distribution. A. Showing the double sediment sources filling the basin, followed by the carbonate production developed in the the basin. B. Facies distribution in each member. Highlight significant facies changes from siliciclastic to mixed siliciclastic and carbonate facies.

### **3.4.3 Simulated Model Validation**

The simulated model effectively depicted the sequence architecture during the initial formation of the Marrat Formation which show the aggradation - progradation sequence geometries observed from strike section and dip section of Marrat Formation while the thickness of each sequence observed in simulated isopach map. The simulated model demonstrates good alignment in terms of thickness and lithology, enabling the reproduction of third-order sequence geometries and stratigraphic architectures within Marrat Formation based on the conceptual model outlined in the reference. The thickness and lithology calibration of the simulated model with observed data from outcrop data and well data in Saudi Arabia reached up to 90% accuracy for lithology prediction and up to 95% (Figure 24) for thickness prediction (Figure 25). Thickness error was observed to be approximately 10%, primarily occurring when the unit terminates at the sequence boundary and due to additional sediment input from exposed areas into the basin.

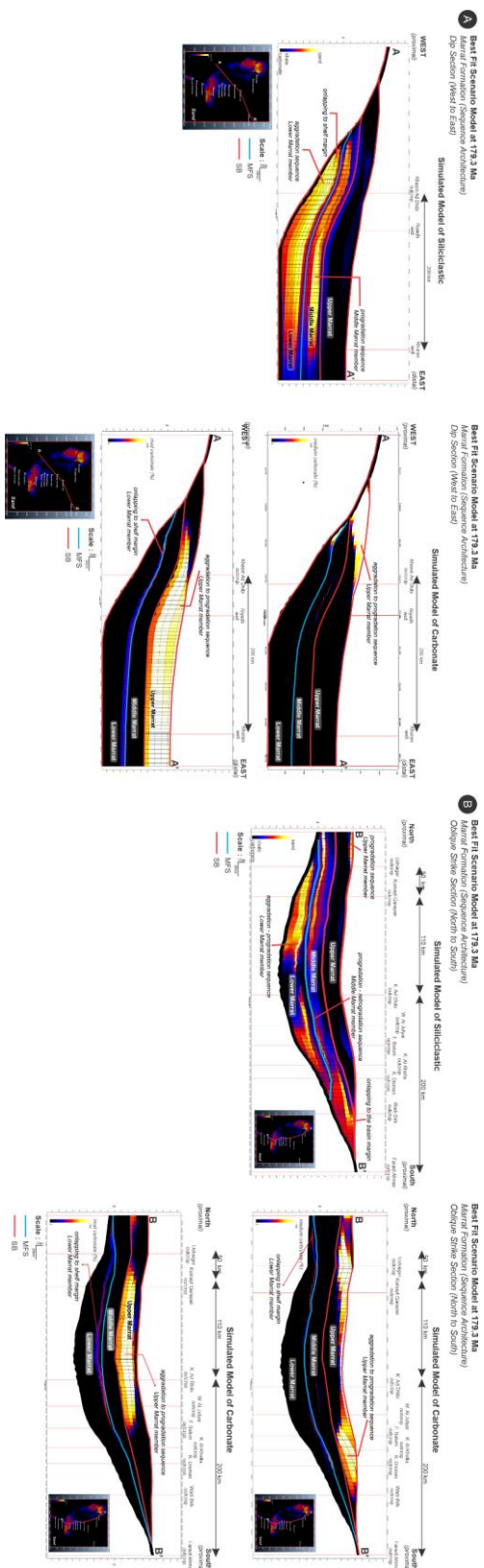


Figure 23. Simulated model observed in dip section covering west to east area and oblique strike covering north – south area. highlight the sequence variation from aggradation – progradation sequence to aggradation sequence and turning to progradation sequence in Upper Marat member.

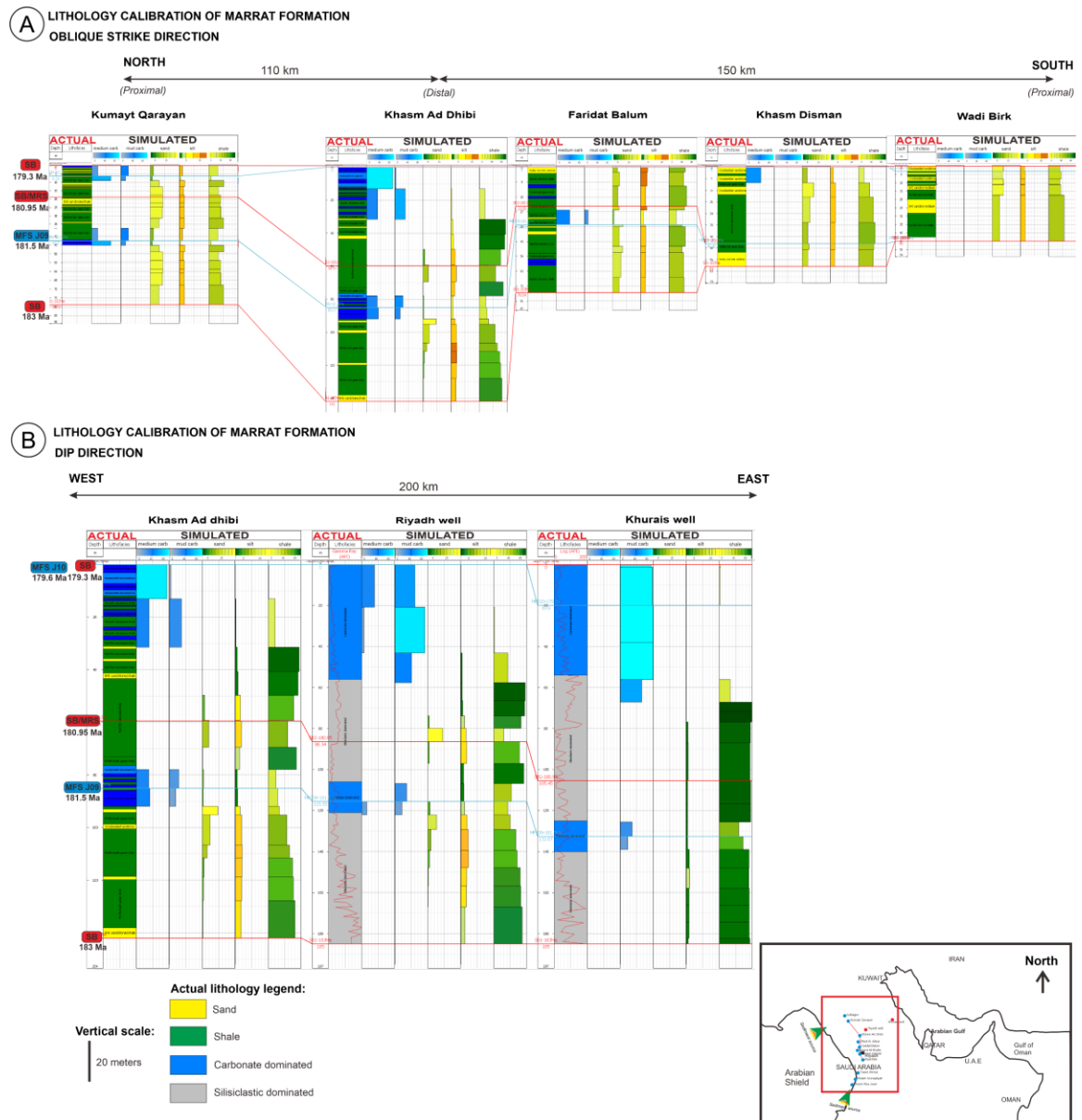


Figure 24. Observed lithology data observed in outcrop and well in Marrat Formation versus simulated model. The results show good calibration up to 95% for the thickness and 90% for the lithology.

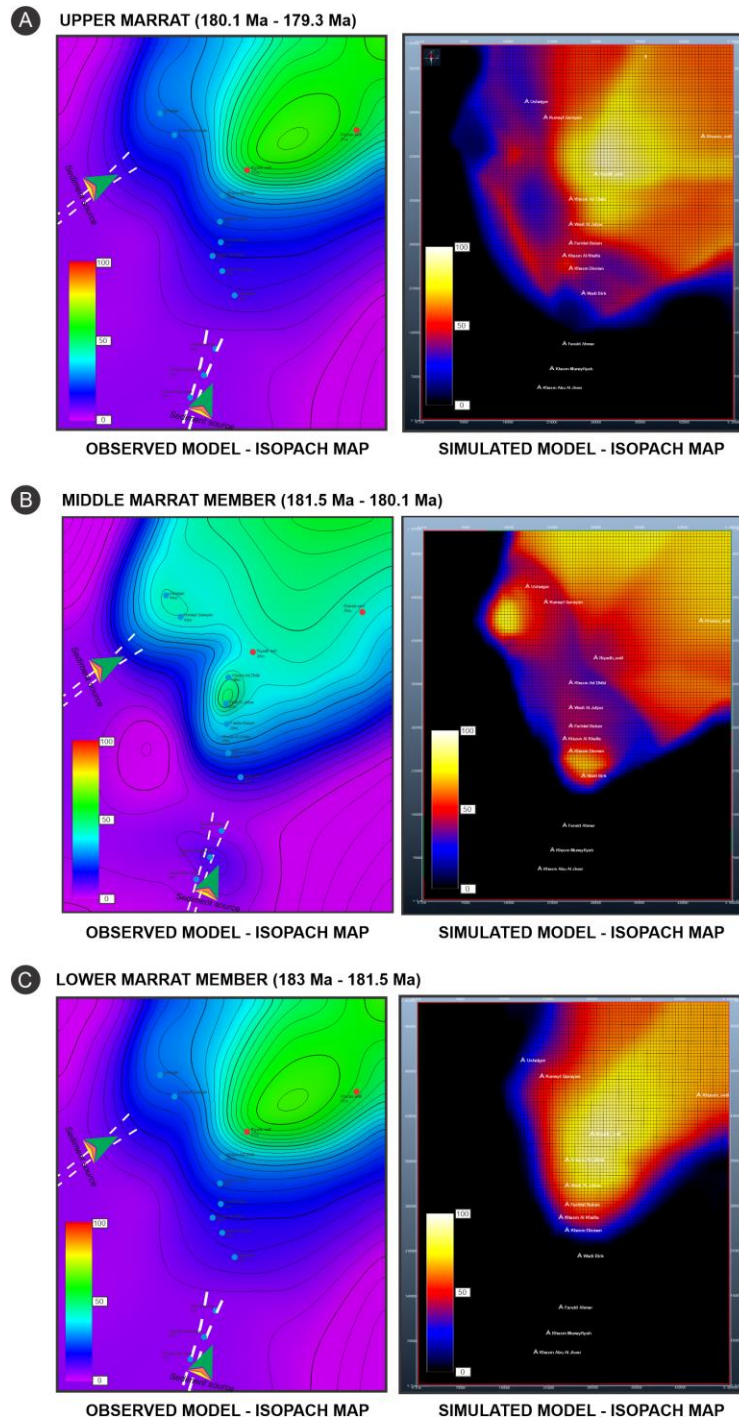


Figure 25. Observed isopach map generated from outcrop and well data in Marrat Formation versus isopach map from simulated model. The results show good calibration up to 95% for the thickness and 90% good thickness distribution.

## 3.5 DISCUSSION

### 3.5.1 Testing Plausible Scenario for Best Fit Model in Marrat Formation

#### *Multi source system and Carbonate Production*

Through the utilization of a stratigraphic forward modeling approach, we investigated several plausible scenarios and geological assumptions applied to Marrat Formation. The inherent constraints within available data introduce considerable uncertainties in assessing sediment volumes and lithological proportions within the basin. Nevertheless, through the improvement of the geological model and the application of modern analogues, we can effectively quantify the source system's influence on basin filling. Furthermore, (Hawie, et al., 2017) employed modern analogues to establish assumptions and quantify the sediment sources responsible for filling the basin in the Levant region. The result shows best fit plausible scenario quantifying multi source system from modern river analogue (Nile, Arabia, Latakia river system). Other studies also used similar approaches to estimate the simulated volume estimation in Burgan-Kazhdumi unit, northeast Kuwait with modern river analogue and yield good agreement with actual thickness (Shabani et al., 2022).

Notably, the modern river and wave deltaic settings was similar with the depositional characteristics observed within the Marrat Formation (Al-Hussaini et al., 2021). The typical character of deposition system in Marrat Formation was lowland covering marginal area to shallow marine to deep marine area (Sharland et al., 2001; Ziegler, 2001). The scenario is based on two sediment sources: Source 1 in the southern part and Source 2 in the western part (Ziegler, 2001), along with carbonate production. We set initial ranges for sediment supply and water discharge, using the Senegal Delta river system as a comparison, and looked at how carbonate production changes over time and depth. The

range value for the plausible scenario established from constant sediment supply ( $Q_s$ ) = 500 km<sup>3</sup>/My - 2000 km<sup>3</sup>/My – 5000 km<sup>3</sup>/My), constant water discharge ( $Q_w$ ) = 700 m<sup>3</sup>/s – 2000 m<sup>3</sup>/s – 5500 m<sup>3</sup>/s and constant carbonate production in specific time interval (range between: medium carbonate production = 50 – 100 m/My and mud carbonate production = 25 – 80 m/My). The quantification of river system guided by the relationship of sediment discharge and water discharge on several modern river (Milliman & Syvitski, 1992). The range between (sediment supply = 500 – 5000 km<sup>3</sup>/My and water discharge (500 – 5500 m<sup>3</sup>/s). The analogue from Senegal delta river system and its properties as a reference case (value of sediment supply = 760 km<sup>3</sup>/My & value of water discharge = 600 m<sup>3</sup>/s) (Figure 16).

However, the Senegal river system proved insufficient to fill the basin due to its low estimated sediment supply and sediment transported by water discharge (Figure 20). The most suitable model was found in Scenario No. 6, with sediment supply ranging between 1450 and 1800 km<sup>3</sup>/My and water discharge of 5500 m<sup>3</sup>/s. Significant sediment supply variations occurred during the middle Marrat deposition. The sediment supply ranged between 2700 km<sup>3</sup>/My from southern source sediment and 2000 km<sup>3</sup>/My in the western section. This corresponds to the sequence boundary event during the sea level drop at the middle Marrat member (181.5Ma - 180.1Ma). Carbonate production tends to decrease as siliciclastic sediment input interrupted carbonate production while filling the accommodation space, as illustrated in the mixed siliciclastic and carbonate system model in the greenhouse period (Baharudin et al., 2024). Additionally, the rates of carbonate production for mud carbonate were set at 25 – 80 m/My and medium carbonate at 50 – 100 m/My. The observed results showed better agreement with the actual thickness depicted in

(Figure 26). The values for sediment supply and water discharge within the typical range observed in modern river systems (Milliman & Syvitski, 1992). Moreover, the carbonate production rate has been adjusted to match the actual carbonate thickness, consistent with similar cases from the Jurassic and Cretaceous periods across the Arabian plate (Schlager, 1998).

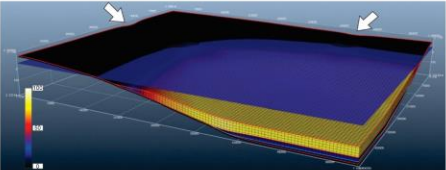
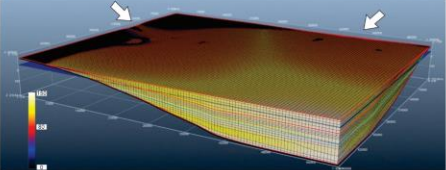
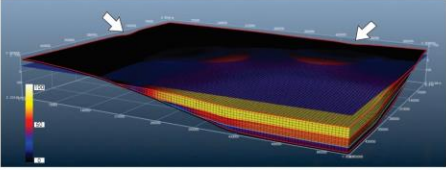
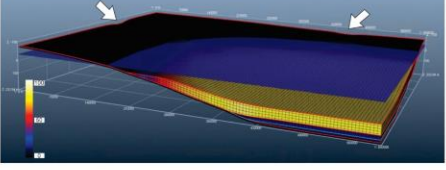
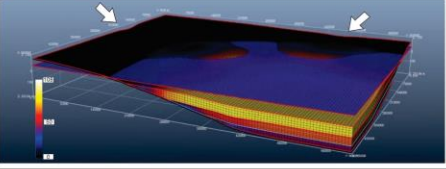
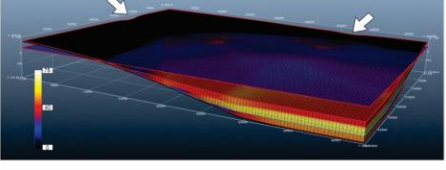
| Plausible Scenario Model at 179.3 Ma<br>Variable Qs and Qw |                                              |                                                                                      |                                                                                                                                                                                                                 |
|------------------------------------------------------------|----------------------------------------------|--------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                            | Parameters                                   | Simulated Model                                                                      | Result and Comment                                                                                                                                                                                              |
| Scenario 1                                                 | Qs1 = 500 Qs2= 500<br>Qw1 = 700 Qw2= 700     |    | Result cannot fit with the actual thickness<br>Low estimation for Qs<br>Low sediment transport to the basin                                                                                                     |
| Scenario 2                                                 | Qs1 = 5000 Qs2= 5000<br>Qw1 = 700 Qw2= 700   |   | Result cannot fit with the actual thickness<br>Over estimation of Qs<br>Basin infill over supply leads to very thick deposits (sediment production over sea level)                                              |
| Scenario 3                                                 | Qs1 = 2000 Qs2= 2000<br>Qw1 = 700 Qw2= 700   |  | Result more fit with the actual thickness<br>Value of Qs close to this range<br>Achieved good basin infill                                                                                                      |
|                                                            | Parameters                                   |                                                                                      |                                                                                                                                                                                                                 |
| Scenario 4                                                 | Qs1 = 500 Qs2= 500<br>Qw1 = 2000 Qw2= 2000   |  | Result cannot fit with the actual thickness<br>Low estimation for Qs<br>Not seen effect of increasing Qw with sediment transport and infill to the basin                                                        |
| Scenario 5                                                 | Qs1 = 2000 Qs2= 2000<br>Qw1 = 2000 Qw2= 2000 |  | Result more fit with the actual thickness<br>Value of Qs close to this range<br>Increase Qw not really affect the thickness<br>Not seen effect of increasing Qw with sediment transport and infill to the basin |
| Scenario 6                                                 | Qs1 = 1450 Qs2= 1800<br>Qw1 = 5500 Qw2= 5500 |  | Result more fit with the actual thickness<br>Value of Qs and Qw close to this range<br>Carbonate production already adjust and match with the range of global carbonate production during Jurassic time         |

Figure 26. The plausible scenario model tested to see how the sediment supply and water discharge filling the basin. Scenario No. 6 highlights the best plausible scenario to filling the basin.

### *Subsidence testing*

Alternative scenarios were tried for the subsidence parameter to see how the model responded to the subsidence that occurs during sedimentation. Several studies have discussed how differential subsidence impacts the Arabian platform margin, leading to lateral variations in energy levels that in turn influence the distribution of sedimentation (Alsharhan & Kendall, 1986) and also effect of sediment loading to the basin with total subsidence in the Marrat Formation (Toarcian - Aalenian) up to 200 meters (Le Nindre et al., 2003). The scenario without subsidence investigated in this study revealed that the model was unable to fill the accommodation to match the actual thickness (Figure 23A). The subsidence tested in this study following to the subsidence assessment as reported by (Hughes, 2006) involves a preliminary assessment of each formation within a similar Lower Jurassic section, utilizing the latest available absolute dating for each formation. Subsidence rates are reported for many Jurassic formations, including the Marrat Formation, which has rates ranging from 25.6 to 31 m/My.

The subsidence estimate was calculated within the average value in the Marrat Formation with subsidence rates of 20 m/My and 25 m/My, while the others divided the average value in each member with subsidence rates of 16 m/My in Upper Marrat, 25 m/My in Middle Marrat, and 54 m/My in Lower Marrat. The decreasing rate from the lower to upper Marrat suggests that during this period, the Marrat was influenced by thermo-tectonic subsidence.

The observed results demonstrate that the scenarios with averages of 20 and 25 m/My throughout the Marrat Formation fail to correspond with the actual thickness, however the third scenario does (Figure 25). The subsidence rate reported by Le Nindre et al. (2003) for the marginal to central trough was very low (0 to 3 m/My) (Le Nindre et al., 2003). This rate is too low to generate accommodation in the modeling when combined with global sea level changes and sediment influx. We believe that the best fit scenario model with actual thickness and a sequence architecture incorporating subsidence estimation is necessary. The subsidence rate shows how the subsidence rate decreases over time. These might have broader regional implications as accommodation changes caused by the interaction of differential subsidence, sea level changes, and sediment supply in each formation. Furthermore, the sequence architecture within the simulated model is consistent with regional studies from the Jurassic and Early Cretaceous periods (Droste & Van Steenwinkel, 2004; Pratt & Smewing, 1990).

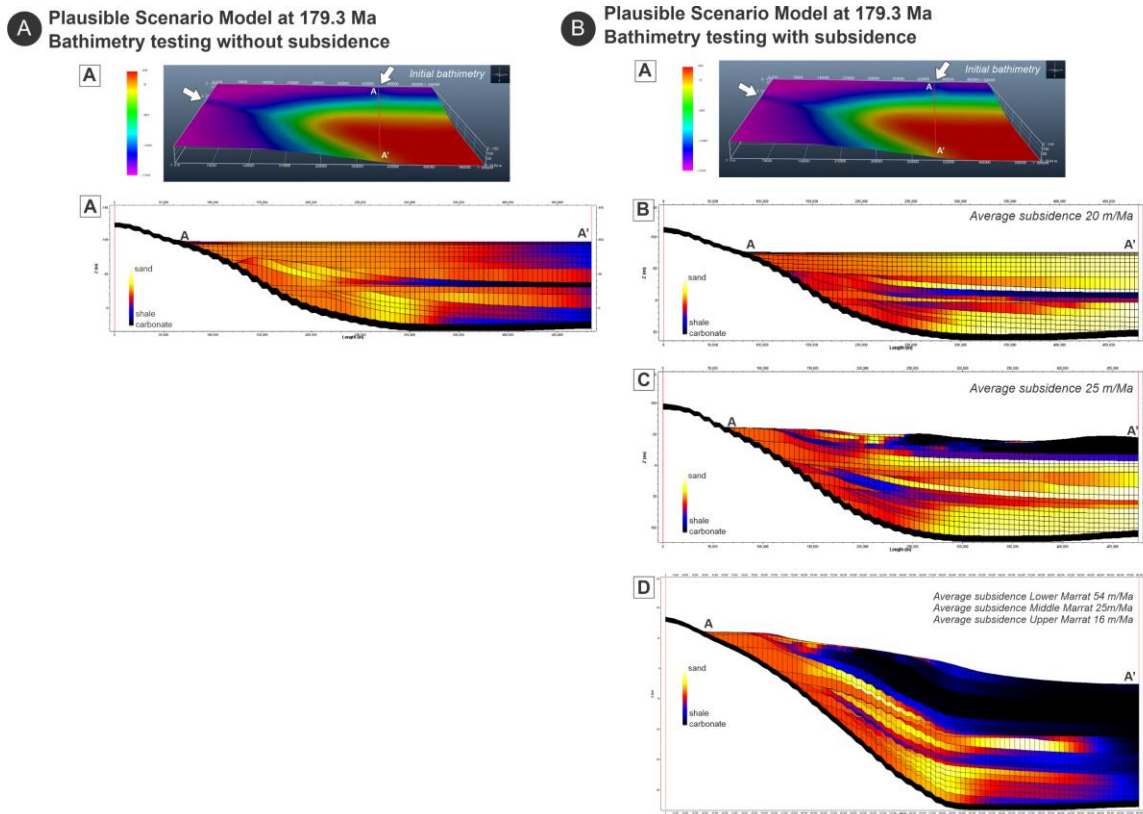


Figure 27. Scenario model incorporating subsidence testing (B) and without subsidence testing (A). B. Scenario model D using differential subsidence in each member, the subsidence rate shows increase over time. The best fit result with actual thickness shows in scenario model D.

### 3.5.2 Sequence Architecture and Lithology and Facies Distribution

The 3D forward stratigraphic model acquired the evolutionary processes of the Marrat Formation spans from 183 Ma – 179.3 Ma. The simulated model was consistent with the input of the data, whatever the range of input parameter it will consistently generate the simulated model constraint by its input value. The best fit simulated model successfully captures the heterogeneity of lithology variation across Marrat Formation. The simulated model also match with the observed on outcrop data measured stratigraphic section across

north – south direction (Al-Hussaini et al., 2021; Al-Mojel, et al., 2020). The simulated model observed in three stratigraphic sequence order shows distinct aggradation – progradation sequence on Lower Marrat member during sea level rise. The simulated sequence architecture also match with the simulated sequence observed in NW-SE Middle Marrat by (De Keyser & Kendall, 2014).

The model observed thick sediment about 50 meters in central area (Khasm Ad-dhibi) and thins out to the most northern section and southern section. This geometry also proved in measured stratigraphic section (Al-Hussaini et al., 2021; Al-Mojel, et al., 2020). The simulated facies observed in this unit was located in the deltaic – offshore prodelta the facies (marine environment to the center of the basin in the vicinity of Khasm Ad-dhibi and changing facies going up dip into northern Kumayt Qarayan and Ushaiger area) and southern section (observed in the Wadi Al-Jufyar, Faridat Balum, Khasm Khalta and Khasm Disman area) into deltaic and shoreface facies (Figure 22). This simulated model contradicts the interpretation provided by (Al-mojel et al., 2022) which suggested that the Lower Marrat formation was deposited in a non-marine region (fluvial-coastal plain), instead deposited in a marine environment (based on forward model testing). During late sea level rise deposited carbonate in the inner lagoon facies. And the carbonate pinch-out into silt - sand lithology in the southern area (Khasm Al-Khalta and Khasm Disman area). Middle Marrat member deposited during sea level drop observed significant progradation sequences deposited in the deltaic to offshore prodelta facies. The deltaic facies observed in the Wadi Al Jufyar to the southern part section while prodelta facies observed in the Khasm Ad-dhibi section. The thickness of the sequence slightly continuous from proximal to distal section. By this simulated model in Middle Marrat member also contradicts the

interpretation provided by (Al-mojel et al., 2022) which suggested that the Middle Marrat formation was deposited in a non-marine region (coastal plain), instead deposited in a marine environment (based on forward model testing). While Upper Marrat Formation suggested widely distributed of carbonate with aggrading to prograding sequence. The distribution continues in the southern section until Khasm Disman area and northern section to the Ushaiger area.

The heterogeneity of lithology and facies variation was successfully captured by this best-fit simulation. Adding the complexity of the mixed siliciclastic and carbonate system in the Marrat Formation. The actual geometry of Marrat Formation from the seismic scale in the northwest – southeast Kuwait (Al-Wazzan et al., 2021) showing continuity of aggradation – progradation – aggradation sequence also shows onlapping packages of Lower Marrat member and prograding Middle Marrat member and turning point to onlapping package on Upper Marrat member matched with the simulated model from SFM.

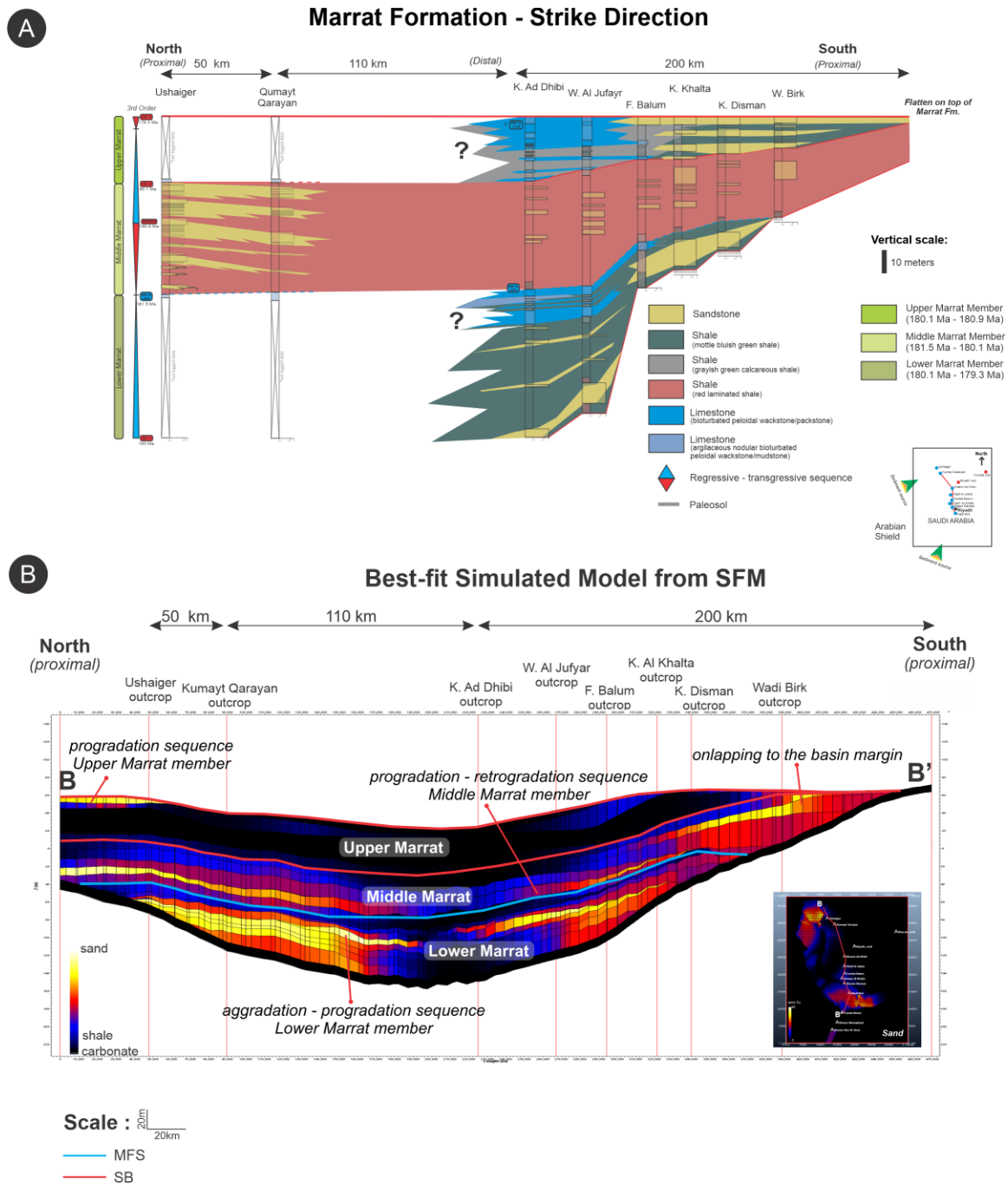


Figure 28. (A) Stratigraphic section from northern to southern area based on observed outcrop data (B) Simulated model from stratigraphic forward modeling shows continuous thickness and good agreement in sequence architecture.

### 3.5.3 General Implications of the Model

Stratigraphic forward modeling proves to be an exceptionally potential exploration tool as its ability to test multiple geological assumptions and plausible scenarios that can construct a best fit reference geological model. The presented first reference case stratigraphic model provided comprehensive quantitative geological process-based model to understand Marrat depositional systems, interplay between siliciclastic and carbonate system and its interaction with different controlling parameters response to stratigraphic architecture and geometries. Furthermore, the study successfully captured lateral and vertical texture/facies heterogeneity in regional-scale geometries under third sequence stratigraphic framework. Regarding energy exploration, the study helps simulated models exhibit an aggradation – progradation sequence including distinct lithology and facies variations, which can have important implications for facilitates comprehensive interpretation and construction of an optimized geological model, identifying and conceptualize the petroleum prospect area to more thoroughly.

Nevertheless, this research is facing substantial uncertainties arising from limitations in data, particularly within the lack of tectonic subsidence studies, global and regional eustasy, variable ecological constraints on carbonate production, etc. Future improvements to the simulation model are introducing complexity and generating higher resolution models (4th to 5th sequence order), which are essential for delineating and derisking petroleum systems. Several improvements need to be addressed including high-resolution sequence stratigraphy data, biostratigraphy analysis for build reliable paleobathymetry, cyclostratigraphy analysis for detailed sea-level proxies, calibrating and verifying models with seismic data, and uncertainty analysis assessment.

### **3.6 CONCLUSION**

The stratigraphic forward model accurately reproduces the geometries and stratigraphic architectures of the Toarcian Marrat Formation. This approach has proven powerful in testing and predicting scenarios to gain a quantitative understanding of regional studies regarding the sedimentation process, sequence architecture, texture, and facies distribution by integrating data and established conceptual models. The findings demonstrated the best fit reference model with double sediment supply sources scenario filling the basin. The simulated model observed aggradation–progradation geometries within the Marrat Formation in third stratigraphic order. The simulated model shows good agreement with the outcrop and subsurface observations. Furthermore, the accurate quantification of multiple parameters enables a more precise spatial delineation of siliciclastic and carbonate distributions across the basin, particularly to capture along strike heterogeneity. These findings offer valuable insights for mixed systems in enhancing regional understanding on the spatio-temporal heterogeneity of the Marrat Formation and aid in identifying potential petroleum reservoirs, subtle stratigraphic traps and informing exploration strategies by reducing the uncertainties.

### **3.7 ACKNOWLEDGEMENT**

The authors wish to thank IFP-Beicip for providing Dionisos with academic license software to support this study. Deeply grateful to the College of Petroleum Engineering & Geosciences (CPG) of King Fahd University of Petroleum and Minerals (KFUPM). Thanks to Predict Research Group for their unwavering discussions and support during the

development of this manuscript. Reviewers are acknowledged for providing constructive feedback that led to the improvement of the manuscript.

## **CHAPTER 4**

# **Quantitative Controls on the Sequence Architecture and Geometries of the Marrat Formation using Stratigraphic Forward Modeling**

### **Abstract**

A mixed siliciclastic and carbonates system provides a unique opportunity to study the interaction of two competing systems, clastic influx and carbonate factories, in organizing a depositional system. The Toarcian Marrat Formation represents an ideal mixed carbonate-siliciclastic system developed under transgressive–regressive sequence. Despite extensive outcrop-based studies, understanding and quantifying the controlling processes behind the development of evolution of this mixed carbonate-clastic system is still a great challenge. Here, we performed a process-based stratigraphic forward modeling approach to unravel the interplay between different allogenic and autogenic factors contributing in the formation of different sequence architectures in the Marrat Formation. From the best-fit scenario, a more realistic reference model was developed, and calibrated. A wide range of plausible scenarios impact the sequence architecture and geometry also quantified such as eustasy, subsidence, sediment supply, transport sediment, carbonate production, and wave energy. The sensitivity analysis shows that sediment supply and carbonate production are the most controlling parameters compared to sea level changes on dictating the sedimentary architecture and dynamics. These findings offer valuable insights into understanding more precise regional sequence stratigraphic and the main characteristics of

sedimentary basin with multiple parameter contributions on the basin filling and sequence architecture variation.

Keywords: Marrat Formation, Mixed siliciclastic and carbonates, Stratigraphic Forward Modeling

## **4.1 INTRODUCTION**

Sedimentation patterns and sequence architecture are influenced by several variables, including climate changes, tectonic activity, and sea level oscillations (Catuneanu, 2002, 2006b; Jervey, 1988; Koeshidayatullah et al., 2016; Miall, 2010; Posamentier & Allen, 1999; Posamentier & Vail, 1988; Schlager, 2005a). Mixed siliciclastic-carbonate deposits are sedimentary formations that contain both siliciclastic and carbonate components. Mixing patterns occur at many scales, including bed/core plug, lithofacies, well-log, and stratigraphic/seismic, leading to considerable vertical and lateral fluctuations. Mixing can occur as both compositional fluctuations and variations within individual layers (Borer & Harris, 1991; Budd & Harris, 1990; Chiarella et al., 2012, 2017; Doyle & Roberts, 1983; Zuffa, 1980). As a result, mixing between the two heterolithic components can occur in a variety of patterns and sizes, depending on relative sea-level fluctuations and the climate during both greenhouse and icehouse times. Sediment patterns are heavily influenced by sea level variations. They can even control the development of large shelf incisions and inhibit the progradation of deltas by developing incised valleys and channeling sediment away from the delta front (Haq, 1991; Jervey, 1988; Talling, 1998). The sedimentation patterns seen during both greenhouse periods demonstrate a remarkable amount of

complexity and variety, which can be correlated to the many geological processes that were controlling at the time (Algeo et al., 2014; Burgess, 2018; Burgess et al., 2022; Harris et al., 2020; Sømme et al., 2009).

The Marrat Formation in Saudi Arabia is an ideal mixed siliciclastic and carbonate system due to its deposition during a transgressive-regressive depositional sequence, which led to the development of carbonate during the transgression phase. It contains evidence of greenhouse deposits deposited during the Toarcian Early Jurassic (Murriss, 1980; Powers et al., 1966). Marrat Formation is characterized by multiple reservoir units in northeastern region of Saudi Arabia and Kuwait. Furthermore, Marrat Formation has source rock potential that found in Kuwait (Abdullah & Connan, 2002; Al-Eidan et al., 2010; Al Sharhan & Nairn, 2003; Aqrawi et al., 2010; Huc, 2016). In recent times, most studies on Marrat Formation concentrated on the sedimentary process, depositional environments and sequence stratigraphy architecture and characteristics based on outcrop data (Al-Hussaini et al., 2021; Al-Mojel et al., 2020; El-Sorogy et al., 2017; Farouk et al., 2018; Le-Nindre et al., 1990, 2022; Manivit et al., 1985; Powers, 1968; Powers et al., 1966; Vaslet et al., 1983). Recent developments in mixed siliciclastic and carbonate system on applying stratigraphic forward modeling (SFM) provide a powerful tool for quantitative analysis in predicting sedimentary architecture and geometry, predict lateral and vertical variations of lithology and facies under high resolution of stratigraphic order (Baharudin et al., 2024; Borgomano et al., 2020; Hawie et al., 2017; Shabani et al., 2022; Zhang et al., 2019).

Recent research has employed numerical stratigraphic forward modeling to examine plausible scenarios and develop an optimal best-fit reference model that validated with actual data for the Marrat Formation. This study integrates multi-scale and multi-constraint

datasets to derive the interpretation and build the best-fit model from diverse parameters utilizing a numerical stratigraphic forward modeling approach (Baharudin et al., in prep.). Yet, there has not been a significant focus on numerical modelling investigating the role of controlling parameters on the response of sequence architectures and geometry. Following the proposed best-fit reference case model we aimed to quantify the controlling parameters response to the sequence architecture and geometry based on sensitivity analysis. Through conducting numerous simulations and testing a range of parameters that influence each other, the sensitivity of the most influential parameters can be evaluated. The presented study focuses on how main input parameters such as supply sediment, carbonate production, subsidence, sea level changes, wave energy, sediment transport coefficient response to the architecture and internal geometry of the model while achieving close match with observed outcrop data. However, this study highlights the numerical process-based modeling on quantifying the controlling parameters in sedimentation. Understanding Marrat Formation is the focus of our investigation, and integrating with these processes is crucial for understanding stratigraphic succession in the mixed siliciclastic and carbonate system.

## **4.2 GEOLOGICAL FRAMEWORK**

The research area focused on the outcrop section in the central part of Arabian Platform. The platform was located on a passive margin. Deposited in a broad epeiric platform from a continental area to a shallow marine (Murriss, 1980; Powers et al., 1966) (Figure 30). Marrat Formation characterized by its unconformable at base with the clastic Upper Triassic Minjur Formation and unconformable on top position with the Bajocian-Bathonian Dhurma Formation (Fischer et al., 2001; Manivit & Le Nindre, 1990). Marrat Formation

exhibits a complex lithological composition, consisting of interbedded sandstones, mudstones (claystone), with limestone and anhydrites intercalated in lower part and upper part Formation (Al-Hussaini et al., 2021; Al-Mojel, 2020; Farouk et al., 2018; Le Nindre, 2022; Manivit et al., 1985; Jacques Manivit & Le Nindre, 1990; Powers et al., 1966; Powers, 1968; Vaslet et al., 1983) (Figure 31). The Marrat Formation has been subdivided into the lower member, middle member, and upper member. The deposition environment of the study area covers from shallow marine clastic/carbonate to shallow marine carbonate platform (Ziegler, 2001).

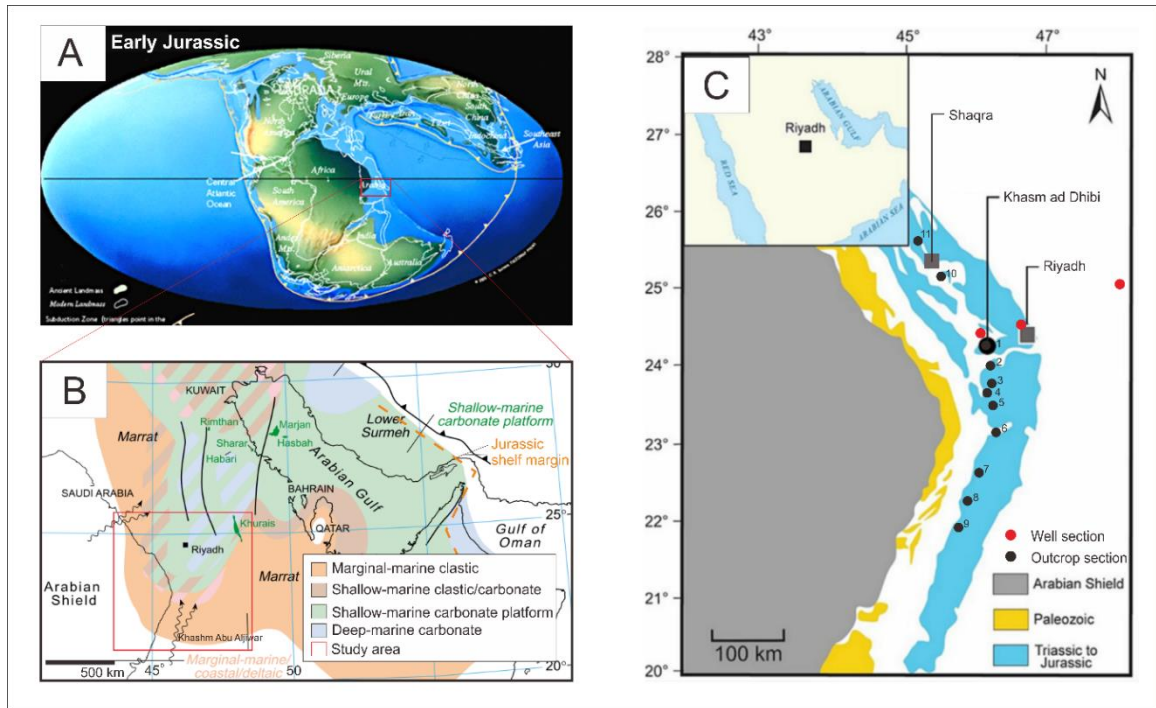


Figure 29. (A,B) Paleogeography map during the Early Jurassic period depicting the different depositional environments. The study area covers the exposed Arabian shield, non-marine to marine clastic, shallow marine clastic/carbonate, shallow marine carbonate platform, and deep marine carbonate (modified after, Ziegler, 2001). (C) Geology map

showing the measured section and well section done by (Al-Hussaini et al., 2021; Al-mojel et al., 2022).

### **4.3 RESEARCH METHOD**

The proposed reference model on Marrat Formation by (Baharudin et al., in prep.) will be tested by sensitivity analysis approach. The method used sensitivity analysis to determine the most influence parameter in the modeling simulation (Agrawal et al., 2015; Hawie et al., 2015). The number of input parameters are necessary to build basin models in terms of stratigraphic architecture and its geometry (e.g. sediment supply, carbonate production, sea level changes, transport parameter, wave actions and others). Sensitivity analysis was performed through arranging the minimum and maximum value of several parameters to see their complex interactions in the process controlling basin filling. This quantification then helps to determine the most influential parameters for the modeling.

The sensitivity of stratigraphic models generated using Cougar Flow<sup>TM</sup>. Response Surface Modeling (RSM) involves running multiple models where uncertain parameters are adjusted. These adjustments generate a response surface, depicting how the models respond to these variations (Box & Draper, 2007; Box & Wilson, 1951). The objective of RSM is to estimate the relationship between uncertain parameters and simulation outcomes. This research utilizes Latin hypercube sampling RSM, which involves conducting simulations with randomly sampling values for the uncertain parameters within predetermined maximum and minimum range of value. This allows for predicting the model's response to various values of the uncertain parameters (Delaplace et al., 2013). To validate the accuracy of the generated RSM, a limited number of confirmation runs are conducted, and their outcomes are compared with the RSM developed by (Lacroix, S., & Albadi, 2012).

### 4.3.1 Input sensitivity parameter

#### *Define uncertainty parameter*

Several parameters will be tested in sensitivity analysis. These parameters are sea level changes, sediment supply, carbonate production, sediment transport, wave action.

**Table 3. Uncertain range for the input parameters**

| Input Parameters                      |                                           | Initial value                    | Minimum Value | Maximum Value |
|---------------------------------------|-------------------------------------------|----------------------------------|---------------|---------------|
| <b>Sea Level</b>                      | Sea level period 3.7 My                   | Global Sea level Haq curve, 2005 | -25% min      | 25% max       |
| <b>Sediment Supply</b>                | Source-1 southern area                    | 2000                             | 1500          | 3000          |
|                                       | Source-2 western area                     | 2800                             | 2000          | 3600          |
| <b>Carbonate Production</b>           | Carbonate prod vs time (medium carbonate) | 100                              | 70            | 150           |
|                                       | Carbonate prod vs time (mud carbonate)    | 50                               | 0             | 100           |
| <b>Sediment transport coefficient</b> | Sand cont. gravity coef.                  | 250                              | 125           | 500           |
|                                       | Shale cont. gravity coef.                 | 750                              | 400           | 1500          |
|                                       | Carbonate cont. gravity coef.             | 0.005                            | 0.01          | 0.001         |
| <b>Wave action</b>                    |                                           | 30                               | 0             | 100           |

#### *Experimental Design*

This design will explore the whole range of the uncertain parameter's definition, taking into account its distribution law by using Latin hypercube to conduct multi-realization (20 simulation). The Experimental Design approach is employed in stratigraphic simulations to create a range of plausible parameter combinations from a multidimensional distribution. Latin hypercube design offers random sampling of each design variable with each similar

weight, ensuring uniform distribution across the designated design domain space without correlations between variables. This method enables sampling of the entire uncertain domain, with the sampling size typically limited by computational resources and time constraints (Agrawal et al., 2015; Hawie et al., 2015).

#### *Quantification of Controlling factors*

After the initial multi-realization loop, a subset of the environmental parameters that exert the most significant influence on thickness calibration is chosen as uncertain in the subsequent automated sensitivity loop. The global sensitivity analysis shows the total and primary effect and the main interactions on the variation of the response. The primary effect is the effect on the variation of the response (the extracted maps) when the parameter is the only one varying. The total effect is the effect of the variation of the parameter on the response when all parameters are varying. This process also generated simulated models in each simulation of experimental design.

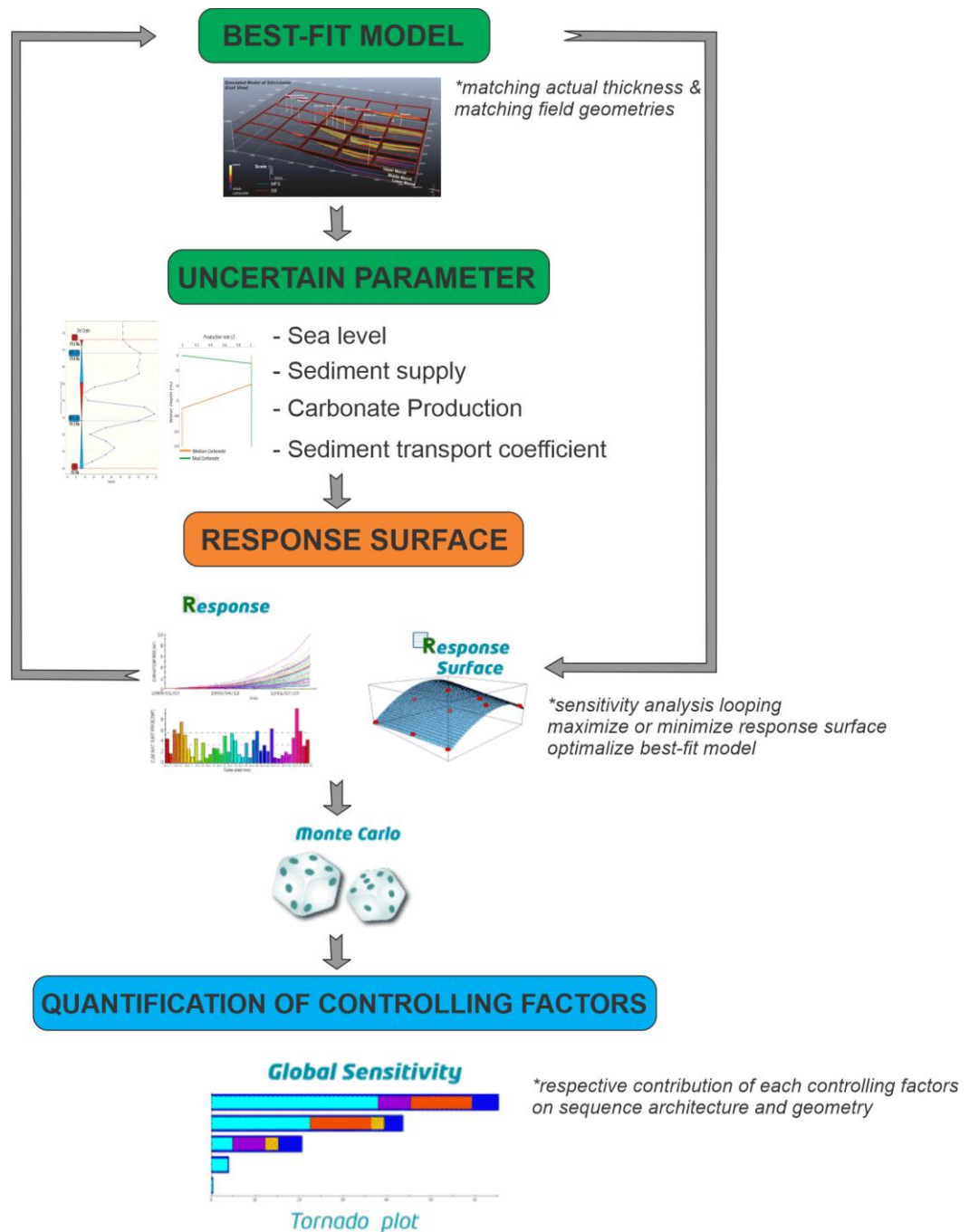


Figure 30. The general methodology employed in the study area. The methodology is divided into four main stages: Input of best fit model, define uncertain parameter, process sensitivity looping by response surface and controlling factors result in global sensitivity analysis plot (modified after Franlab, 2021).

## **4.4 RESULTS**

### **4.4.1 Reference Model: Geometry and Lithology and Facies Distribution**

The reference model was compared with observed outcrop data and well data along Marrat Formation covering Riyadh area to the Khurais area. The lithology and facies model presented as good match with geometry and sequence architecture compared with high-resolution sequence-stratigraphic cross section of the Marrat Formation along the outcrop data (Figure 29). Initially, within the lower Marrat Formation, the model noted a transition from basinward aggradation to progradation, characterized by the presence of deltaic facies that gradually shift into prodelta facies. However, the influx of sediment from western sources leading to additional progradation complicates the basin-filling process, particularly inhibiting the development of adjacent prodelta facies. However, as sea level rise, the sediment supply get push landward and developed continuous inner carbonate lagoon as marked by MFS-J09. Middle Marrat Formation mark the significant drop of sea level which lead the high sediment supply influx the basin coming from both southern and western sources highlight the progradation – retrogradation sequence with changing in deltaic to offshore prodelta facies. While in the Upper Marrat the deposition happens during sea level stand leading carbonate aggradation – progradation (Figure 36 B).

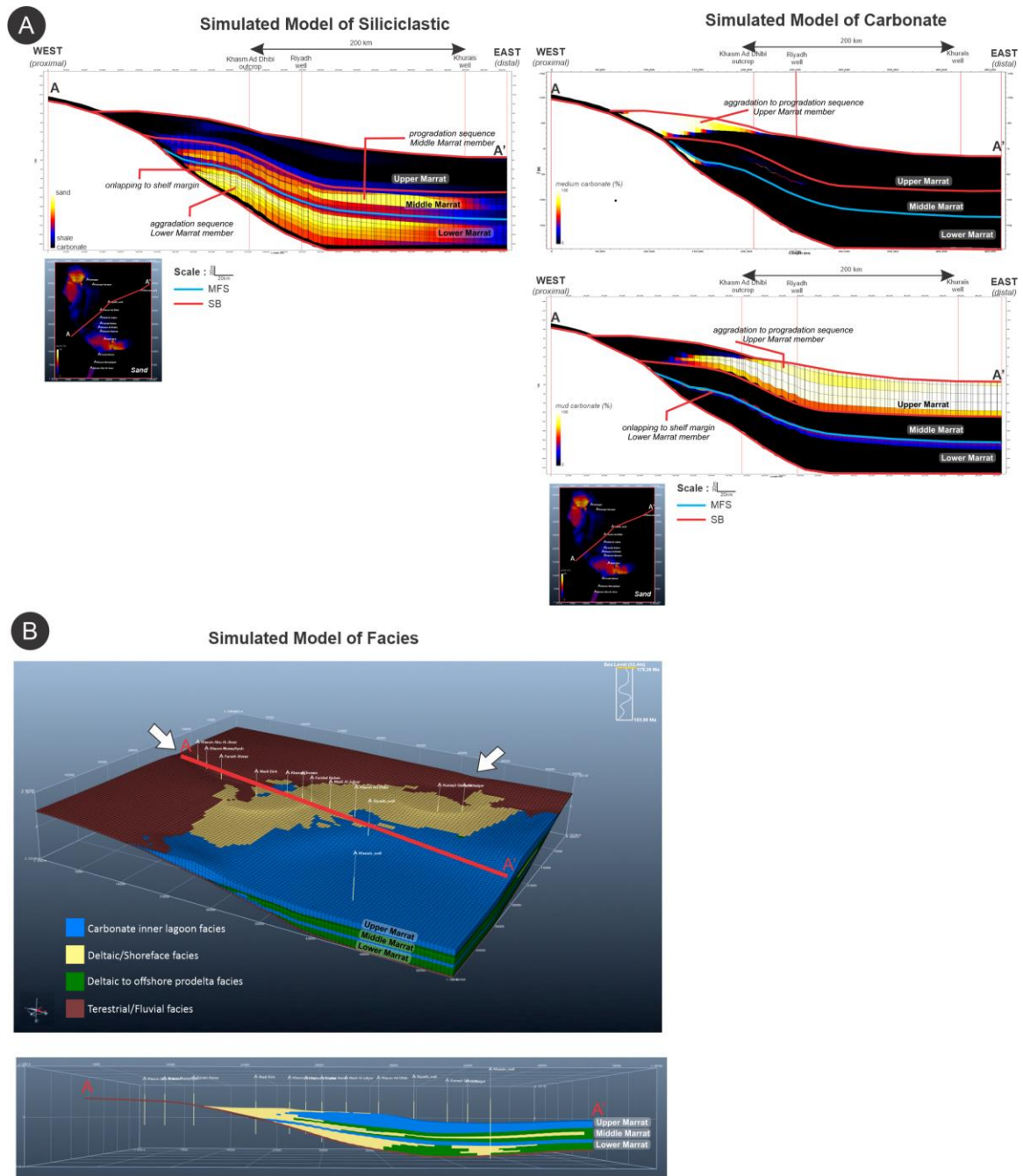


Figure 31. The reference model of Marrat Formation. Showing geometry of lithology and facies distribution along aggradation – progradation sequence. Reference model having good match with geometry and architecture under third sequence stratigraphic framework.

#### 4.4.2 Global Sensitivity Analysis

In this study, generated 20 simulations to test the reference model following the Latin hypercube sampling method. The simulation also generated 20 simulation models. The statistical analysis from each simulated model response to thickness showing good response with mean value is 174 meters while the mean  $\pm$  standard deviation value between 170 – 178 meters.

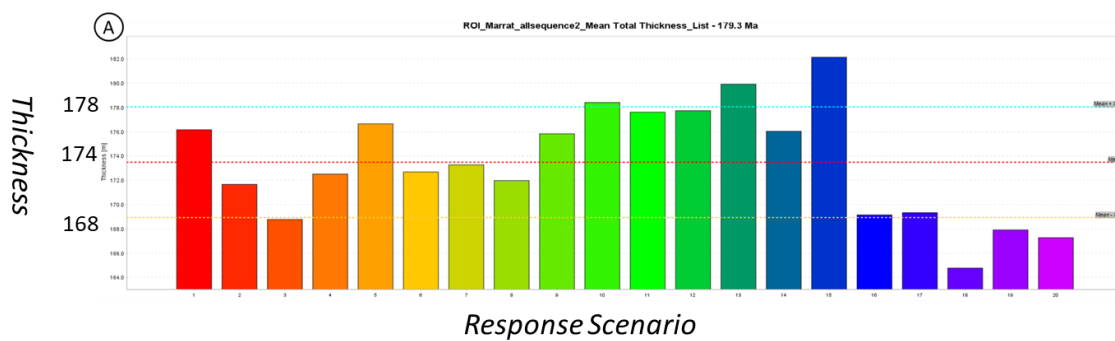


Figure 32. Results of the global sensitivity analysis in the study area. (A) Bar plot showing thickness variations for 20 models. (B) Good confidence interval plot for 20 models.

In terms of global sensitivity analysis, the most influential parameters from the simulated model observed in different periods are represented by color (red as Upper Murrat 179.3 Ma-180.4 Ma, green as Middle Murrat 180.4 Ma - 181.6 Ma, and blue as Lower Murrat 181.6 Ma - 183 Ma) (Figure 31). The most important controlling factors are sediment supply and carbonate production, particularly mud carbonate production. Carbonate production was the most important characteristic in the Upper Murrat member. In the middle and lower Murrat members, sediment supply will be the most influential parameter. This finding notably observed that sea level changes don't have significant parameters response to the modeling.

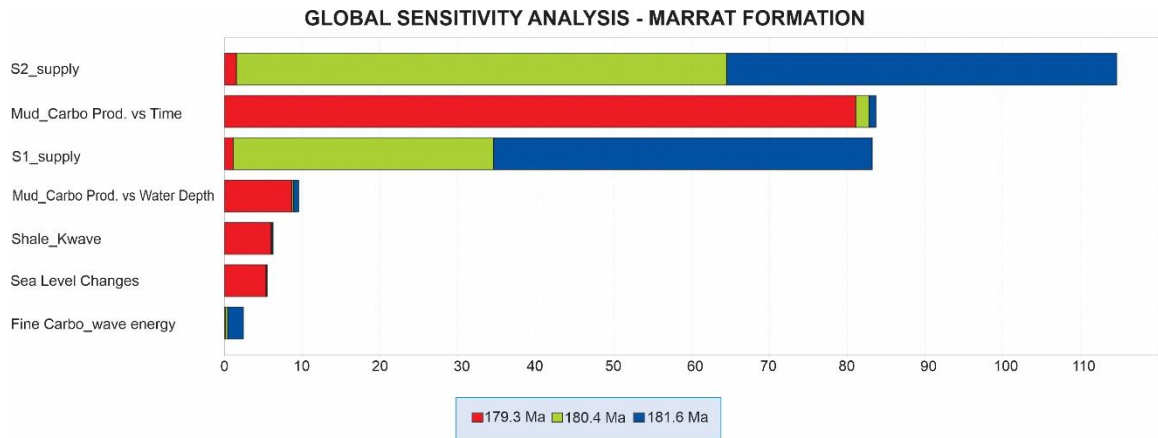


Figure 33. Global sensitivity analysis showing the most influential parameters in different periods represented by its color (red color for 179.3 Ma-180.4 Ma, green color for 180.4 Ma - 181.6 Ma, blue color for 181.6 Ma – 183 Ma). The bar plot highlights that supply sediment (S2) is the most influential parameter.

## 4.5 DISCUSSION

### 4.5.1 Controls on Stratigraphic Architecture in The Marrat Formation

The sensitivity testing indicates that the carbonate production and sediment supply parameters have the most effect on the modeling. This indicates that the simulated model will provide more successful results when both parameters are adjusted more accurately compared compared to real data. When comparing our simulation results to high resolution sequence stratigraphy analysis from measured outcrop sections along Jabal Tuwaiq outcrops, we found good match sequence architecture under the third sequence stratigraphic framework (Al-Mojel et al., 2020). The model observed aggradation – progradation sequence along with varying the sediment supply and carbonate production over the time period. While sea level variation influences the facies migration from terrestrial - deltaic – offshore prodelta and carbonate inner lagoon facies. The sediment input variation differs in each period of time that will response to the accommodation

space. Better adjusting the rate of the input both sediment supply and carbonate production with the rate of accommodation space (sea level and subsidence) resulting good match with the sequence architecture (Catuneanu, 2002; Curray, 1964; Posamentier & Allen, 1999).

The simulated model identified an aggradation-progradation sequence in the Lower Marrat member coinciding with a rise in sea level. On the basin margin, onlapping geometries were also observed. Our quantification involved balancing the rate of sediment supply with the rates of sea level rise and subsidence, resulting in a good response in terms of stratigraphic architecture. This aligns with previous reports indicating that differential subsidence of the Arabian Platform contributes to onlapping geometries over the underlying Minjur unconformity (Stewart et al., 2016; Yousif & Nouman, 1997). Subsequently, a notable discovery in the middle Marrat member was the clear observation of progradation from delta to offshore delta plain. This was notably attributed to a high sediment supply originating from both the southern and western sediment source areas. Possibly triggered by significant CO<sub>2</sub> emissions resulting from the Karoo-Ferrar volcanic activity, this severe disruption is also thought to have led to a shift in humid climate belts towards mid and high-latitudes, as well as global increases in weathering rates (Dera et al., 2009, 2015). These time intervals coincided with the Toarcian Oceanic Anoxic Event (T-OAE), suggesting a period of marine anoxia occurring alongside the deposition of Marrat red beds (Alnazghah et al., 2022). These beds, interpreted as shallow marine deposits as we argue and tested with the simulated stratigraphic forward model. Moreover, within the Upper Marrat member, there existed a carbonate inner lagoon. The deposition rate of carbonate, matching the accommodation space (sea level and subsidence) during that period, resulted in carbonate aggradation. Subsequently, as the sea level gradually declined,

the carbonate began to prograde into the basin. In general, the sequence architecture observed in the simulated model aligns with findings from regional studies conducted during the Jurassic and Early Cretaceous periods (Droste & Van Steenwinkel, 2004; Pratt & Smewing, 1990).

#### **4.5.2 Influence of Global and Regional Eustatic Sea Level (Accommodation space variations)**

Referring to sea level changes in the Arabian Platform as outlined by (Haq & Al-Qahtani, 2005), we investigated how these changes affected our model's sequence architecture and geometry. We found that the differences between regional and global sea levels were minor, as there wasn't much variation in the sequence architecture and thickness. Interestingly, sea level changes alone didn't cause big shifts in the sequence architecture. However, we did notice that when sea levels significantly dropped, our model tended to prograde more towards the basin. This trend was especially clear in the Upper Marrat carbonate, which showed a noticeable carbonate progradation towards the basin (Figure 38). Our results suggest that the Marrat Formation's development is mostly influenced by changes in regional sea levels, instead of global sea level that have significant sea level drop. As reported by (Hallam, 2001) that absence of any significant erosion and incision during this extended hiatus indicates that there was no significant drop in sea level during this period. This hiatus, widespread across the Tethyan region, may instead be linked to thermal doming in the North Sea.

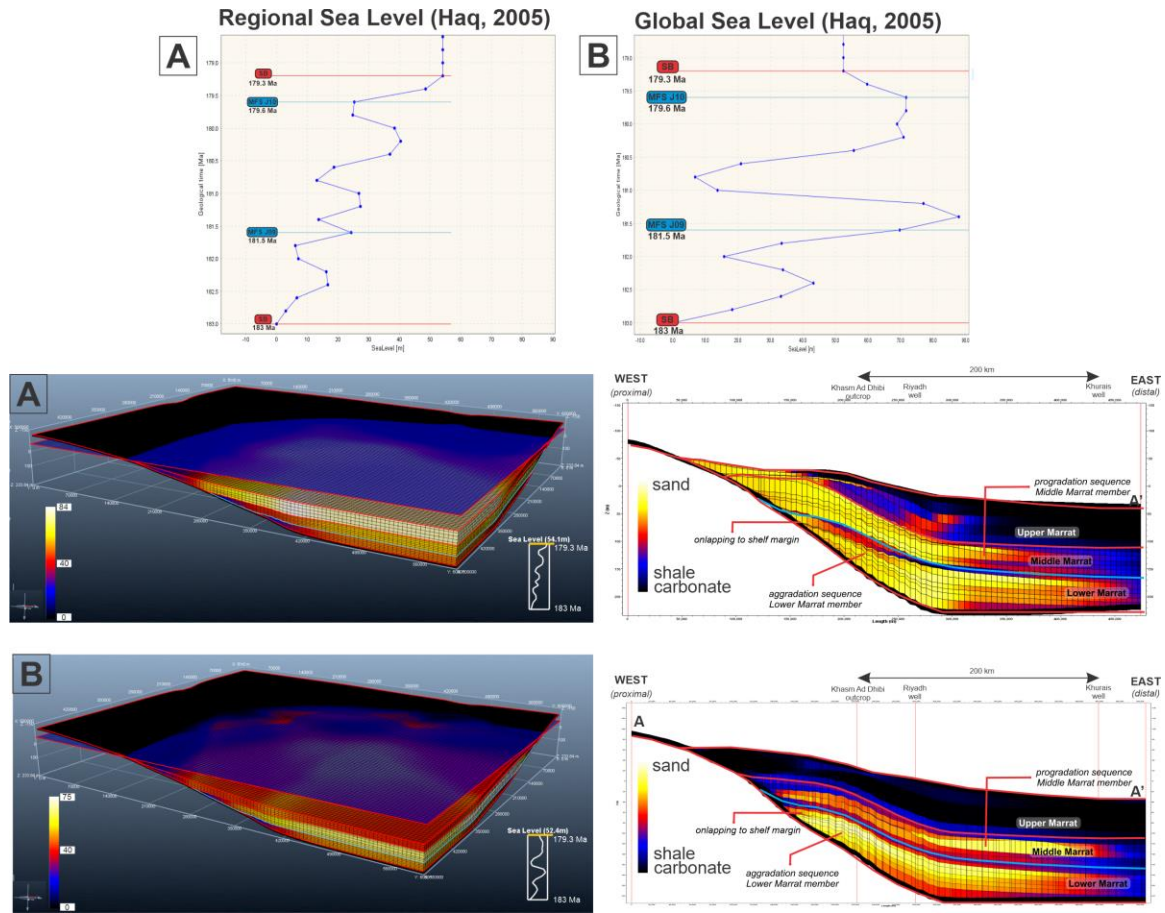


Figure 34. Regional sea level vs Global Sea level. Both models show similar sequence architecture and thickness, meaning that sea level alone couldn't impact the sequence architecture. (A) Upper Marrat member showing carbonate progradation while (B) Showing significant difference in progradation sequence in Middle Marrat member.

#### 4.5.3. Influence of Coefficient Transport to the Sequence Geometries

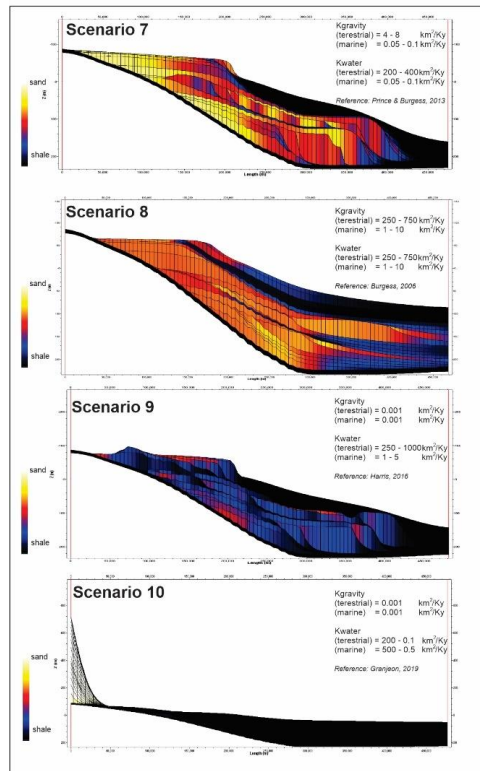
The quantification of sediment load and water discharge needed to fill the basin by transporting sufficient sediment. Employing numerical stratigraphic forward modeling methods incorporates diffusion processes that depend on various factors such as the diffusion coefficient, water flow, and slope (Granjeon, 2014; Granjeon & Joseph, 1999; Gvirtzman et al., 2014). The concept of diffusion laws combines the diffusion coefficient

value in transporting sediment through alluvial, river, floodplains mountains foreland basin (Slingerland & Smith, 2004). However, estimating the diffusion coefficient is challenging as it calculated from the relationship of grain, shape, size, accommodation space (Gvirtzman et al., 2014).

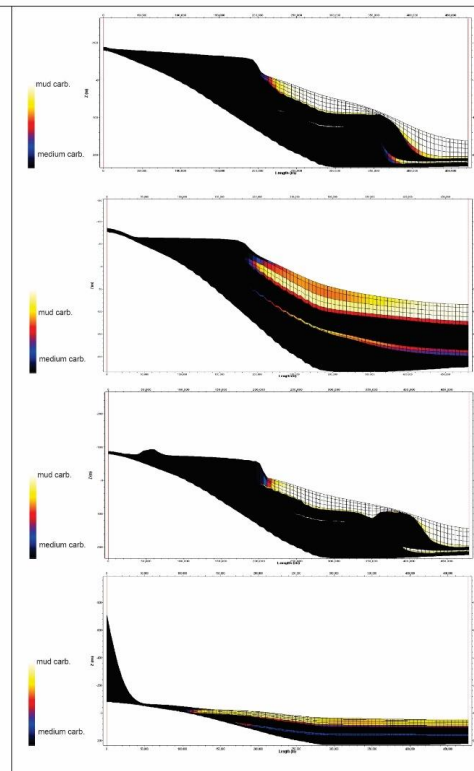
The proposed scenario investigates the role of diffusion transport in shaping sequence architecture and geometry. The diffusion coefficient across scenarios 7 to 14 was adopted from reference models in various studies to determine the most appropriate value for this study (Burgess et al., 2006; Granjeon, 2019; Harris et al., 2016; Prince & Burgess, 2013; Shabani et al., 2022; Zhang et al., 2019). Most scenarios resulted in a progradation sequence and fail to match to the actual thickness calibration. However, scenarios with low terrestrial Kgravity values (ranging from 0.001 to 80) failed to produce the best-fit sequence architecture and geometry (Scenarios 7, 8, 9, 11, 12). In Scenario 10, where terrestrial Kgravity was very low (0.001), sediment tended to accumulate in the source area rather than being transported to the basin. Conversely, marine Kgravity had minimal impact on sequence architecture and geometry. Nonetheless, we observed that high terrestrial Kgravity values (ranging from 500 to 1500) and high terrestrial Kwater values (ranging from 250 to 750) had a greater influence on sequence architecture and geometry. This corresponds well with sediment input estimated at 2700 km<sup>3</sup>/My and water discharge ranging from 5000 m<sup>3</sup>/s. It is estimated that the drainage area in the Marrat Formation during the Toarcian periods was from low to moderate land, ranging from 100 meters to 500 meters. As observed in Scenario 14, this model emerged as the best-fit reference model. The diffusion coefficient, similar to the model proposed by (Burgess et al., 2006), was applied across deltaic to deep marine settings. However, applying the diffusion

coefficient in similar settings sometimes necessitates adjusting the range of values to better align with observed actual data. In summary, maintaining a constant diffusion coefficient can lead to achieving the actual thickness, sequence architecture, and geometry, provided that the sediment transport values remain realistic within the range observed in modern river sediment and water discharge, as outlined by (Milliman & Syvitski, 1992), without overestimating, particularly under extreme water discharge conditions.

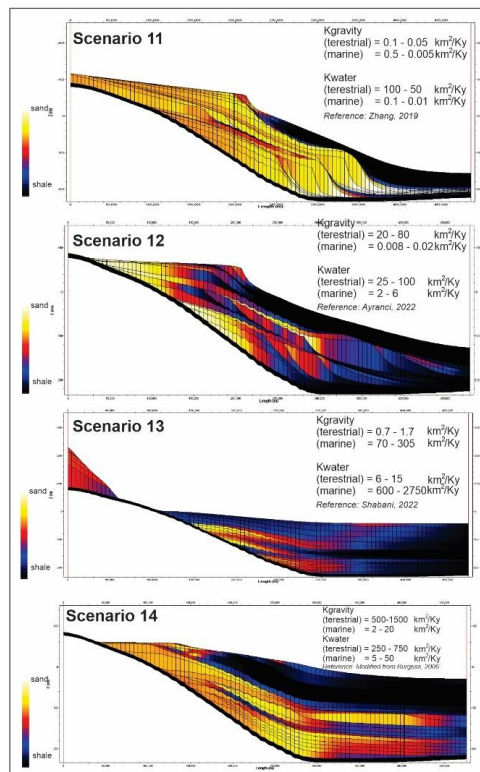
### Simulated Model Siliciclastic



### Simulated Model Carbonate



### Simulated Model Siliciclastic



### Simulated Model Carbonate

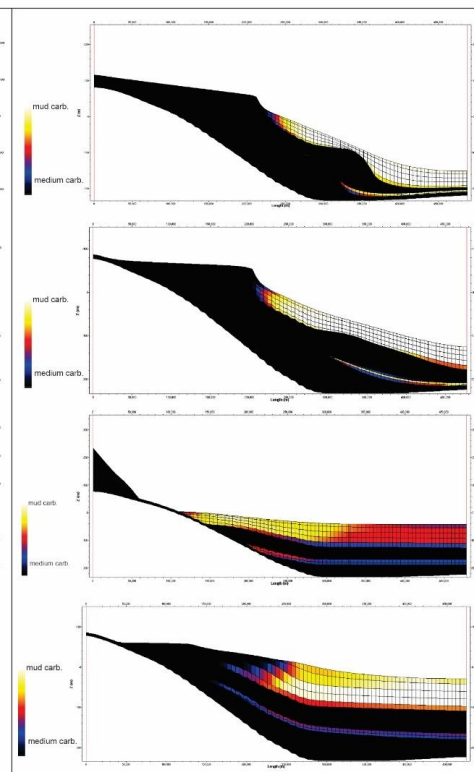


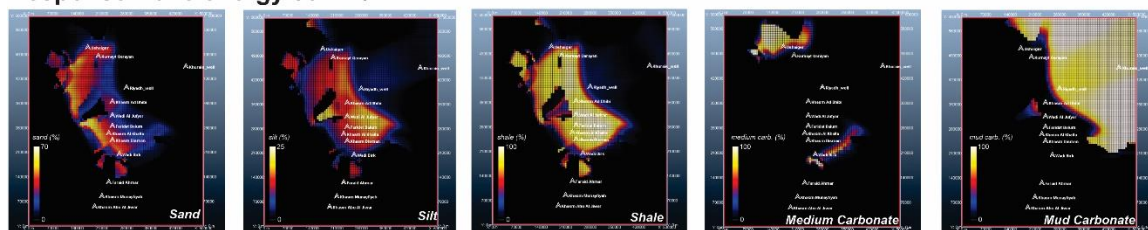
Figure 35. Summary of modeling result at 179.3 Ma. The scenario model applied several diffusion coefficients to reach the best fit with actual thickness data and good agreement with sequence architecture and geometry.

#### **4.5.4 Effect of Carbonate Production and Wave Action**

Incorporating in situ carbonate production, wave transport, gravity transport, and water influx (Hawie et al., 2015) plays a crucial role. The estimation of carbonate production involves assessing the carbonate accumulation ratio per time or employing a reference case model with a similar geological setting. A study conducted by Al Wazzan (2021) in Kuwait indicates that Early Jurassic carbonate production ranged from 120 to 200 m/My, aligning with the reference case of the Jurassic and Cretaceous periods across the Arabian plate (Schalger et al., 1998). According to our findings, carbonate production of medium-grained carbonate, ranging from 50 to 100 m/My, occurs across a wide of water depths, from shallow to slightly deeper (0-60 meters), with production rates ranging from 1 to 0.9 (/). Consequently, carbonate mud values have remained consistent regardless of depth, with production rates ranging between 0.9 (/) and a rate of 25 to 80 m/My. This rate of carbonate production aligns well with our best-fit model, which corresponds to a conceptual reference model. Our estimation takes into account ecological factors, particularly the impact of wave energy on carbonate production, which exhibits lateral distribution based on energy levels along the shelf. When applying a low wave energy of 30 kW/m, lithology distribution does not match the actual data adequately. However, employing a moderate wave energy value of 110 kW/m yields a more varied distribution of sediments and appears to better correspond with the actual data. We argue, in agreement with (Hawie et al., 2015) that the Marrat system remains unaffected by high wave energies.

**Plausible Scenario Model at 179.3 Ma**  
**Response from wave parameters**  
*(transport parameter 0.05)*

**Response wave energy 30 Kw/m**



**Response wave energy 110 Kw/m**

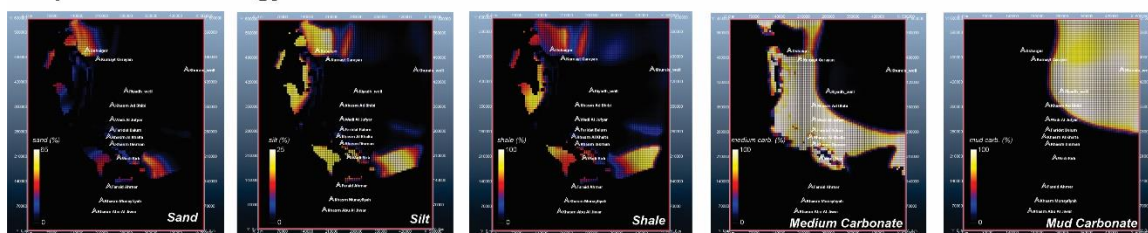


Figure 36. The simulated model shows the response of different wave action in distributing the lithology.

#### 4.5.5 Potential and limitations of the modeling

Stratigraphic forward modeling proves to be an exceptionally potential exploration tool as its ability to test multiple geological assumptions and plausible scenarios that can construct a best fit reference geological model. The presented first reference case stratigraphic model provided comprehensive quantitative geological process-based model to understand Marrat depositional systems, interplay between siliciclastic and carbonate system and its interaction with different controlling parameters response to stratigraphic architecture and geometries. Furthermore, the study successfully captured lateral and vertical texture/facies heterogeneity in regional-scale geometries under third sequence stratigraphic framework. Regarding energy exploration, the study helps simulated models exhibit an aggradation – progradation sequence including distinct lithology and facies variations, which can have important implications for facilitates comprehensive interpretation and construction of an

optimized geological model, identifying and conceptualize the petroleum prospect area to more thoroughly.

The availability of comprehensive data significantly facilitates the interpretation and construction of an optimized geological model. Nevertheless, this research is facing substantial uncertainties arising from limitations in data, particularly within the lack of tectonic subsidence studies, uncertainty of global and regional eustasy, variable ecological constraints on carbonate production, and the absence of distributed well data point, seismic data, etc. However, the proposed model in this study provides a reference case model for quantitatively comprehending the evolution of the Marrat Formation through geological time by testing several scenarios that best fit with the reference conceptual model. Furthermore, the model offers insights into the interplay between siliciclastic and carbonate system during the development of the basin, as its responses to various parameters such as eustatic sea level, subsidence, supply sediment, in situ production, ecological constraints, etc. Future improvements to the simulation model are introducing complexity and generating higher resolution models (4th to 5th sequence order), which are essential for delineating and derisking petroleum systems. Several improvements need to be addressed including high-resolution sequence stratigraphy data, biostratigraphy analysis for build reliable paleobathymetry, cyclostratigraphy analysis for detailed sea-level proxies, calibrating and verifying models with seismic data, and uncertainty analysis assessment.

## **4.6 CONCLUSION**

The stratigraphic forward model accurately reproduces the geometries and stratigraphic architectures of the Toarcian Marrat Formation. This approach has proven powerful in

testing and predicting scenarios to gain a quantitative understanding of regional studies regarding the sedimentation process, sequence architecture, texture, and facies distribution by integrating data and established conceptual models. The simulated model observed aggradation–progradation geometries within the Marrat Formation in third stratigraphic order. The simulated model shows good agreement with the outcrop and subsurface observations. From the best-fit scenario, a more realistic reference model was developed, and calibrated. A wide range of plausible scenarios impact the sequence architecture and geometry also quantified such as eustasy, subsidence, sediment supply, transport sediment, carbonate production, and wave energy. The sensitivity analysis shows that sediment supply and carbonate production are the most controlling parameters compared to sea level changes on dictating the sedimentary architecture and dynamics. These findings offer valuable insights into understanding more precise regional sequence stratigraphic and the main characteristics of sedimentary basin with multiple parameter contributions on the basin filling and sequence architecture variation. However, this study Understanding Marrat Formation is the focus of our investigation, and integrating with these processes is crucial for understanding stratigraphic succession in the mixed siliciclastic and carbonate system. These findings highlight the numerical process-based modeling on quantifying the controlling parameters in sedimentation. Also adding valuable insights for mixed systems in enhancing regional understanding on the spatio-temporal heterogeneity of the Marrat Formation and aid in identifying potential petroleum reservoirs, subtle stratigraphic traps and informing exploration strategies by reducing the uncertainties.

## **4.7 ACKNOWLEDGEMENT**

The authors wish to thank IFP-Beicip for providing Dionisos with academic license software to support this studie. Deeply grateful to the College of Petroleum Engineering & Geosciences (CPG) of King Fahd University of Petroleum and Minerals (KFUPM). Thanks to Predict Research Group for their unwavering discussions and support during the development of this manuscript. Reviewers are acknowledged for providing constructive feedback that led to the improvement of the manuscript.

## **CHAPTER 5**

### **CONCLUSIONS AND FUTURE DIRECTIONS**

The stratigraphic forward model accurately reproduces the geometries and stratigraphic architectures of the Toarcian Marrat Formation. This approach has proven powerful in testing and predicting scenarios to gain a quantitative understanding of regional studies regarding the sedimentation process, sequence architecture, texture, and facies distribution by integrating data and established conceptual models. The simulated model observed aggradation–progradation geometries within the Marrat Formation in third stratigraphic order. The simulated model shows good agreement with the outcrop and subsurface observations. From the best-fit scenario, a more realistic reference model was developed, and calibrated. The findings demonstrated the best fit reference model with double sediment supply sources scenario filling the basin. Furthermore, the accurate quantification of multiple parameters enables a more precise spatial delineation of siliciclastic and carbonate distributions across the basin, particularly to capture along strike variability. A wide range of plausible scenarios impact the sequence architecture and geometry also quantified such as eustasy, subsidence, sediment supply, transport sediment, carbonate production, and wave energy. The sensitivity analysis shows that sediment supply and carbonate production are the most controlling parameters compared to sea level changes on dictating the sedimentary architecture and dynamics. These findings offer valuable insights into understanding more precise regional sequence stratigraphic and the main characteristics of sedimentary basin with multiple parameter contributions on the basin filling and sequence architecture variation. Yet, the importance of numerical process-based

modeling in quantifying the controlling parameters in sedimentation. In addition, the studies adding valuable insights for mixed systems in enhancing regional understanding on the spatio-temporal heterogeneity of the Marrat Formation and aid in identifying potential petroleum reservoirs, subtle stratigraphic traps and informing exploration strategies by reducing the uncertainties.

## REFERENCES

- Abdullah, F. H., & Connan, J. (2002). Geochemical study of some Cretaceous rocks from Kuwait: comparison with oils from Cretaceous and Jurassic reservoirs. *Organic Geochemistry*, 33(2), 125–148.
- Agrawal, D., Dwivedi, S., Barrois, A., Koeck, C.H., El Wazir, Z., Al Madani, N., Aillud, G. (2015). Impact of Environmental Parameters on Forwards Stratigraphic Modelling from Uncertainty Analysis; Lower Cretaceous, Abu Dhabi. *Paper SPE-175683-MS*.
- Al-Aswad, A. A. (1995). Middle Jurassic non-marine siliciclastic facies in southern central Saudi Arabia. *Journal of African Earth Sciences*, 20(3–4), 253–262.
- Al-Eidan, A. J., Narahari, S. R., Al-Awadi, M., Al-Ajmi, N. H., Pattnaik, C., Al-Ateeqi, K., Al-Houli, M. M., Kidambi, V. K., & De Keyser, T. (2010). Jurassic tight carbonate gas fields of North Kuwait: Exploration to early development. *Deep Gas Conference and Exhibition 2010, DGAS 2010, Fig 4*, 260–265. <https://doi.org/10.2118/130914-ms>
- Al-Eidan, A. J., Neog, N., Narhari, S. R., Al-darmi, A., Al-mayyas, R. H., Keyser, T. L. De, & Perrin, C. (2009). Carbonate Facies and Depositional Environments of the Marrat Formation ( Lower Jurassic ), North Kuwait. *AAPG Annual Convention and Exhibition, Search and Discovery Article #50223*, 50223.
- Al-Hussaini, A., Alnazghah, M., Al-Ramadan, K., Fallatah, M., & Polo, C. (2021a). Asymmetrical wave-dominated siliciclastic shorelines with evidence of along-strike variability of sedimentary processes: A revised interpretation for the Toarcian Marrat

- red beds, central Arabia. *Marine and Petroleum Geology*, 126. <https://doi.org/10.1016/j.marpetgeo.2021.104915>
- Al-Hussaini, A., Alnazghah, M., Al-Ramadan, K., Fallatah, M., & Polo, C. (2021b). Asymmetrical wave-dominated siliciclastic shorelines with evidence of along-strike variability of sedimentary processes: A revised interpretation for the Toarcian Marrat red beds, central Arabia. *Marine and Petroleum Geology*, 126, 104915. <https://doi.org/10.1016/J.MARPETGEO.2021.104915>
- Al-Hussaini, A., Steel, R. J., Melvin, J., Olariu, C., Ertug, K., & Hooker, N. (2019a). New evidence of regressing and transgressing Jurassic siliciclastic coastlines within the Dhurma Formation in Northern Central Arabia, Saudi Arabia. *Sedimentary Geology*, 379, 114–137. <https://doi.org/10.1016/j.sedgeo.2018.11.006>
- Al-Hussaini, A., Steel, R. J., Melvin, J., Olariu, C., Ertug, K., & Hooker, N. (2019b). New evidence of regressing and transgressing Jurassic siliciclastic coastlines within the Dhurma Formation in Northern Central Arabia, Saudi Arabia. *Sedimentary Geology*, 379, 114–137. <https://doi.org/10.1016/J.SEDGEO.2018.11.006>
- Al-Husseini, M. (2009). Update to Late Triassic - Jurassic stratigraphy of Saudi Arabia for the Middle East Geologic Time Scale. *GeoArabia*, 14(2), 145–186. <https://doi.org/10.2113/geoarabia1402145>
- Al-Husseini, M. I. (1997). Jurassic Sequence Stratigraphy of the Western and Southern Arabian Gulf. *GeoArabia*, 2(4), 361–382. <https://doi.org/10.2113/geoarabia0204361>
- Al-Mojel, A., Razin, P., Al-Eidan, A. J., Narahari, S. R., Al-Awadi, M., Al-Ajmi, N. H.,

- Pattnaik, C., Al-Ateeqi, K., Al-Houli, M. M., Kidambi, V. K., De Keyser, T., Al-Hussaini, A., Steel, R. J., Melvin, J., Olariu, C., Ertug, K., Hooker, N., Aldaajani, T., Furlong, K. P., ... Al-Ramadan, K. (2022). Asymmetrical wave-dominated siliciclastic shorelines with evidence of along-strike variability of sedimentary processes: A revised interpretation for the Toarcian Marrat red beds, central Arabia. *Marine and Petroleum Geology*, 9(June), 260–265. <https://doi.org/10.2118/130914-ms>
- 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. *Journal of African Earth Sciences*, 165, 103803. <https://doi.org/10.1016/J.JAFREARSCI.2020.103803>
- Al-mojel, A., Razin, P., Dera, G., Al-mojel, A., Razin, P., & High-resolution, G. D. (2022). *High-resolution sedimentology and sequence stratigraphy of the Oxfordian-Kimmeridgian , Hanifa , Jubaila and Arab outcrops along Jabal Tuwaiq , Central Saudi Arabia To cite this version : HAL Id : hal-03489971.*
- Al-Mojel, A., Razin, P., Le Nindre, Y.-M., & Dera, G. (2020a). Shallow-marine depositional sequences in a transgressive mixed siliciclastic-carbonate system: The Early Jurassic Marrat Formation from central Saudi Arabia. *Journal of African Earth Sciences*, 167, 103429. <https://doi.org/https://doi.org/10.1016/j.jafrearsci.2019.02.011>
- Al-Mojel, A., Razin, P., Le Nindre, Y.-M., & Dera, G. (2020b). Shallow-marine depositional sequences in a transgressive mixed siliciclastic-carbonate system: The

- Early Jurassic Marrat Formation from central Saudi Arabia. *Journal of African Earth Sciences*, 167. <https://doi.org/10.1016/j.jafrearsci.2019.02.011>
- Al-Salmi, M., John, C. M., & Hawie, N. (2019). Quantitative controls on the regional geometries and heterogeneities of the Rayda to Shu'aiba formations (Northern Oman) using forward stratigraphic modelling. *Marine and Petroleum Geology*, 99(September 2018), 45–60. <https://doi.org/10.1016/j.marpetgeo.2018.09.030>
- Al-Wazzan, H. A., Hawie, N., Al-Haggan, H., Al-Mershed, M. K., Al-Sahlan, G., & Al-Wadi, M. (2021a). 3D forward stratigraphic modelling of the Lower Jurassic carbonate systems of Kuwait. *Marine and Petroleum Geology*, 123(August 2020), 104699. <https://doi.org/10.1016/j.marpetgeo.2020.104699>
- Al-Wazzan, H. A., Hawie, N., Al-Haggan, H., Al-Mershed, M. K., Al-Sahlan, G., & Al-Wadi, M. (2021b). Sedimentary evolution of overlapped sand bodies in terrestrial faulted lacustrine basin: Insights from 3D stratigraphic forward modeling. *Marine and Petroleum Geology*, 123, 104699. <https://doi.org/10.1016/j.marpetgeo.2020.104699>
- Al Sharhan, A. S., & Nairn, A. E. M. (2003). the Latest Part of the Zuni and Tejas Cycles in the Middle East: the Cenozoic. *Sedimentary Basins and Petroleum Geology of the Middle East*, 393–465. <https://doi.org/10.1016/b978-044482465-3/50010-3>
- Algeo, T. J., Meyers, P. A., Robinson, R. S., Rowe, H., & Jiang, G. Q. (2014). Icehouse – greenhouse variations in marine denitrification. 1273–1295. <https://doi.org/10.5194/bg-11-1273-2014>
- Alnazghah, M., Koeshidayatullah, A., Al-Hussaini, A., Amao, A., Song, H., & Al-

- Ramadan, K. (2022). Evidence for the early Toarcian Carbon Isotope Excursion (T-CIE) from the shallow marine siliciclastic red beds of Arabia. *Scientific Reports*, 12(1), 1–11. <https://doi.org/10.1038/s41598-022-21716-0>
- Alnazghah, M., Koeshidayatullah, A., Alhussaini, A., Amao, A., & Al-Ramadan, K. (2022). *Expanding our understanding of the Toarcian Oceanic Anoxic Event in the Tethys Ocean: New insights from the Arabian Plate*. June. <https://doi.org/10.21203/rs.3.rs-1658904/v1>
- Aqrabi, A. A. M., Mahdi, T. A., Sherwani, G. H., & Horbury, A. D. (2010). Characterisation of the Mid-Cretaceous Mishrif reservoir of the southern Mesopotamian Basin, Iraq. *American Association of Petroleum Geologists Conference and Exhibition*, 7, 7–10.
- Arkell, W. J., Bramkamp, R. A., & Steineke, M. (1952). Jurassic ammonites from Jebel Tuwaiq, central Arabia with stratigraphical introduction. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 236(633), 241–314.
- Baharudin, F., Herlambang, A., & Koeshidayatullah, A. (2024). 3D stratigraphic forward modeling of mixed carbonate-siliciclastic systems: Insights to energy prospectivity. *Geoenergy Science and Engineering*, 235(January), 212699. <https://doi.org/10.1016/j.geoen.2024.212699>
- Beydoun, Z. R. (1993). Evolution of the northeastern Arabian plate margin and shelf: Hydrocarbon habitat and conceptual future potential. *Revue de l'Institut Français Du Pétrole*, 48(4), 311–345.

- Borer, J. M., & Harris, P. M. (1991). Depositional facies and model for mixed siliciclastics and carbonates of the Yates formation, Permian basin. *SEPM Core Workshop (Society of Economic Paleontologists and Mineralogists)*, 15, 1–133. <https://doi.org/10.2110/cor.91.01.0001>
- Borgomano, J., Lanteaume, C., Léonide, P., Fournier, F., Montaggioni, L. F., & Masse, J. P. (2020). Quantitative carbonate sequence stratigraphy: Insights from stratigraphic forward models. *AAPG Bulletin*, 104(5), 1115–1142. <https://doi.org/10.1306/11111917396>
- Borgomano, J., Lanteaume, C., Ridet, O., Rousseau, M., & Vilasi, N. (2014a). *3D Stratigraphic Forward Modelling for the Prediction of Carbonate Platform Architectures : Evaluation of Stratigraphic Trap Potential in Middle East Mesozoic Carbonate Sequences \**. 41328.
- Borgomano, J., Lanteaume, C., Ridet, O., Rousseau, M., & Vilasi, N. (2014b). *3D Stratigraphic Forward Modelling for the Prediction of Carbonate Platform Architectures : Evaluation of Stratigraphic Trap Potential in Middle East Mesozoic Carbonate Sequences \**. 41328.
- Box, G. E. P., & Draper, N. R. (2007). *Response Surfaces, Mixtures, and Ridge Analyses*. Wiley. <https://books.google.com.sa/books?id=pTb9PgbQAvYC>
- Box, G. E. P., & Wilson, K. B. (1951). On the Experimental Attainment of Optimum Conditions. *Journal of the Royal Statistical Society: Series B (Methodological)*, 13(1), 1–38. <https://doi.org/10.1111/j.2517-6161.1951.tb00067.x>

- Budd, D. A., & Harris, P. M. (1990). *Carbonate-siliciclastic Mixtures: Selected Papers*  
*Reprinted from Journal of Sedimentary Petrology, Geology, AAPG Bulletin,*  
*Sedimentary Geology, GSA Bulletin, the Persian Gulf* (Issue 14). Sepm Society for  
 Sedimentary.
- Burgess, P., & Burgess, P. M. (2018). *Impact of eustatic amplitude variations on shelf  
 morphology , sediment dispersal , and sequence stratigraphic interpretation :  
 Icehouse versus greenhouse systems : COMMENT Impact of eustatic amplitude  
 variations on shelf morphology , sediment dispersal , . May 2010.*  
<https://doi.org/10.1130/G30693C.1>
- Burgess, P. M., Lammers, H., van Oosterhout, C., & Granjeon, D. (2006). Multivariate  
 sequence stratigraphy: Tackling complexity and uncertainty with stratigraphic  
 forward modeling, multiple scenarios, and conditional frequency maps. *American  
 Association of Petroleum Geologists Bulletin*, 90(12), 1883–1901.  
<https://doi.org/10.1306/06260605081>
- Burgess, P. M., Zhang, J., & Steel, R. (2022). Narrow is normal: Exploring the extent and  
 significance of flooded marine shelves in icehouse, transitional, and greenhouse  
 climate settings. *Geology*, 50(4), 496–499. <https://doi.org/10.1130/G49468.1>
- Catuneanu, O. (2002). Sequence stratigraphy of clastic systems: concepts, merits, and  
 pitfalls. *Journal of African Earth Sciences*, 35(1), 1–43.
- Catuneanu, O. (2006a). *Principles of Sequence Stratigraphy*.
- Catuneanu, O. (2006b). *PRINCIPLES OF SEQUENCE STRATIGRAPHY*. Elsevier

Radarweg 29, PO Box 211, 1000 AE Amsterdam, The Netherlands.

- Chiarella, D., Longhitano, S. G., Sabato, L., & Tropeano, M. (2012). Sedimentology and hydrodynamics of mixed (siliciclastic-bioclastic) shallow-marine deposits of Agerenza (Pliocene, Southern Apennines, Italy). *Italian Journal of Geosciences*, 131(1), 136–151. <https://doi.org/10.3301/IJG.2011.36>
- Chiarella, D., Longhitano, S. G., & Tropeano, M. (2017). Types of mixing and heterogeneities in siliciclastic-carbonate sediments. *Marine and Petroleum Geology*, 88, 617–627. <https://doi.org/10.1016/j.marpetgeo.2017.09.010>
- Curry, J. . (1964). transgressions and regressions, in Miller, RL,. *Papers in Marine Geology*, New York, The Macmillan Company, 175-203.
- De Keyser, T. L., & Kendall, C. G. (2014). Jurassic and Cretaceous sedimentary fill of Intraself basins of the eastern margin the Arabian Plate. *Annual Convention and Exhibition*, 30322, A30322.
- Delaplace, P., Renard, G., Delamaide, E., Euzen, T., Roggero, F., & Kopecký, P. (2013). Reservoir Simulations of a Polymer Flood Pilot in the Pelican Lake Heavy Oil Field (Canada): a Step Forward. In *SPE Reservoir Characterization and Simulation Conference and Exhibition* (p. SPE-166028-MS). <https://doi.org/10.2118/166028-MS>
- Delvaux, D., & Weiss, R. H. (2001). Karoo rifting in western Tanzania: precursor of Gondwana break-up. *Contributions to Geology and Paleontology of Gondwana in Honor of Helmut Wopfner: Cologne, Geological Institute, University of Cologne*, 111–125.

- Dera, G., Pellenard, P., Neige, P., Deconinck, J.-F., Puc  at, E., & Dommergues, J.-L. (2009). Distribution of clay minerals in Early Jurassic Peritethyan seas: Palaeoclimatic significance inferred from multiproxy comparisons. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 271(1), 39–51. <https://doi.org/https://doi.org/10.1016/j.palaeo.2008.09.010>
- Dera, G., Prunier, J., Smith, P. L., Haggart, J. W., Popov, E., Guzhov, A., Rogov, M., Delsate, D., Thies, D., Cuny, G., Puc  at, E., Charbonnier, G., & Bayon, G. (2015). Nd isotope constraints on ocean circulation, paleoclimate, and continental drainage during the Jurassic breakup of Pangea. *Gondwana Research*, 27(4), 1599–1615. <https://doi.org/https://doi.org/10.1016/j.gr.2014.02.006>
- Doyle, L., & Roberts, H. H. (1983). AAPG/SEPM carbonate to clastic facies change I. *Bull. Amer. Ass. Petrol. Geol.*, 67.
- Droste, H., & Van Steenwinkel, M. (2004). *Stratal geometries and patterns of platform carbonates: the Cretaceous of Oman*.
- Dunham, R. J. (1962). *Classification of carbonate rocks according to depositional textures*.
- El-Sorogy, A. S., Gameil, M., Youssef, M., & Al-Kahtany, K. M. (2017a). Stratigraphy and macrofauna of the Lower Jurassic (Toarcian) Marrat Formation, central Saudi Arabia. *Journal of African Earth Sciences*, 134, 476–492. <https://doi.org/10.1016/j.jafrearsci.2017.07.001>
- El-Sorogy, A. S., Gameil, M., Youssef, M., & Al-Kahtany, K. M. (2017b). Stratigraphy and macrofauna of the Lower Jurassic (Toarcian) Marrat Formation, central Saudi

- Arabia. *Journal of African Earth Sciences*, 134, 476–492.  
<https://doi.org/10.1016/j.jafrearsci.2017.07.001>
- 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. *Marine and Petroleum Geology*, 98, 369–383.  
<https://doi.org/10.1016/j.marpetgeo.2018.08.030>
- Fischer, J.-C., Le Nindre, Y.-M., Manivit, J., & Vaslet, D. (2001). Jurassic Gastropod Faunas of Central Saudi Arabia. *GeoArabia*, 6(1), 63–100.  
<https://doi.org/10.2113/geoarabia060163>
- Franlab, B. (2021). *DionisosFlow*.
- Gerdes, K. D., Winefield, P., Simmons, M. D., & Van Oosterhout, C. (2010). The influence of basin architecture and eustacy on the evolution of Tethyan Mesozoic and Cenozoic carbonate sequences. *Geological Society, London, Special Publications*, 329(1), 9–41.
- Grabowski Jr, G. J., & Norton, I. O. (1995). *Tectonic controls on the stratigraphic architecture and hydrocarbons systems of the Arabian Plate*.
- Granjeon, D. (2014). 3D forward modelling of the impact of sediment transport and base level cycles on continental margins and incised valleys. *From Depositional Systems to Sedimentary Successions on the Norwegian Continental Margin*, 9781118920, 453–472. <https://doi.org/10.1002/9781118920435.ch16>
- Granjeon, D. (2019). Use of high-performance stratigraphic forward modelling to improve

siliciclastic and carbonate reservoir depositional architecture description \* . *Journal of the Japanese Association for Petroleum Technology*, 84(1), 59–70.  
<https://doi.org/10.3720/japt.84.59>

Granjeon, D., & Joseph, P. (1999a). Concepts and Applications of A 3-D Multiple Lithology, Diffusive Model in Stratigraphic Modeling. In J. W. Harbaugh, W. L. Watney, E. C. Rankey, R. Slingerland, R. H. Goldstein, & E. K. Franseen (Eds.), *Numerical Experiments in Stratigraphy: Recent Advances in Stratigraphic and Sedimentologic Computer Simulations* (Vol. 62, p. 0). SEPM Society for Sedimentary Geology. <https://doi.org/10.2110/pec.99.62.0197>

Granjeon, D., & Joseph, P. (1999b). Concepts and Applications of A 3-D Multiple Lithology, Diffusive Model in Stratigraphic Modeling. In J. W. Harbaugh, W. L. Watney, E. C. Rankey, R. Slingerland, R. H. Goldstein, & E. K. Franseen (Eds.), *Numerical Experiments in Stratigraphy: Recent Advances in Stratigraphic and Sedimentologic Computer Simulations* (Vol. 62, p. 0). SEPM Society for Sedimentary Geology. <https://doi.org/10.2110/pec.99.62.0197>

Graus, R. R., & Macintyre, I. G. (1989). The zonation patterns of Caribbean coral reefs as controlled by wave and light energy input, bathymetric setting and reef morphology: computer simulation experiments. *Coral Reefs*, 8(1), 9–18.  
<https://doi.org/10.1007/BF00304687>

Gvirtzman, Z., Csato, I., & Granjeon, D. (2014). Constraining sediment transport to deep marine basins through submarine channels: The Levant margin in the Late Cenozoic. *Marine Geology*, 347, 12–26. <https://doi.org/10.1016/j.margeo.2013.10.010>

- Hallam, A. (2001). A review of the broad pattern of Jurassic sea-level changes and their possible causes in the light of current knowledge. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 167(1), 23–37. [https://doi.org/https://doi.org/10.1016/S0031-0182\(00\)00229-7](https://doi.org/https://doi.org/10.1016/S0031-0182(00)00229-7)
- Haq, B. U. (1991). Sequence stratigraphy, sea-level change, and significance for the deep sea. *Sedimentation, Tectonics and Eustasy: Sea-Level Changes at Active Margins*, 1–39.
- Haq, B. U. (2018). Jurassic sea-level variations: A reappraisal. *GSA Today*, 28(1), 4–10. <https://doi.org/10.1130/GSATG359A.1>
- Haq, B. U., & Al-Qahtani, A. M. (2005). Phanerozoic cycles of sea-level change on the Arabian platform. *GeoArabia*, 10(2), 127–160. <https://doi.org/10.2113/geoarabia1002127>
- Harris, A. D., Covault, J. A., Baumgardner, S., Sun, T., & Granjeon, D. (2020). Numerical modeling of icehouse and greenhouse sea-level changes on a continental margin: Sea-level modulation of deltaic avulsion processes. *Marine and Petroleum Geology*, 111(September 2019), 807–814. <https://doi.org/10.1016/j.marpetgeo.2019.08.055>
- Harris, A. D., Covault, J. A., Madof, A. S., Tao, S. U. N., Sylvester, Z., & Granjeon, D. (2016). Three-dimensional numerical modeling of eustatic control on continental-margin sand distribution. *Journal of Sedimentary Research*, 86(12), 1434–1443. <https://doi.org/10.2110/jsr.2016.85>
- Hawie, N., Aillud, G., Barrois, A., Marfisi, E., Murat, B., Hall, J., Madani, N. Al, & El-

- wazir, Z. (2016). *Improving Carbonate Heterogeneity Prediction along the Arabian Plate using Innovative Forward Stratigraphic Modelling and Response Surface Approaches*. 90254.
- Hawie, N., Al-Wazzan, H. A., Al Mershed, M., Al Awadhi, M., Prakash, A., & Al-Adwani, T. (2023). Improving off-structure carbonate reservoir characterization using integrated shared earth approach and forward stratigraphic modelling: The marrat Fm of southern Kuwait. *Marine and Petroleum Geology*, 106129. <https://doi.org/10.1016/j.marpetgeo.2023.106129>
- Hawie, N., Al-Wazzan, H., Al-Ali, S., & Al-Sahlan, G. (2021). De-risking hydrocarbon exploration in lower Jurassic carbonate systems of Kuwait through forward stratigraphic models. *Marine and Petroleum Geology*, 123. <https://doi.org/10.1016/j.marpetgeo.2020.104700>
- Hawie, N., Barrois, A., Marfisi, E., Murat, B., Hall, J., El-Wazir, Z., Al-Madani, N., & Aillud, G. (2015). Forward stratigraphic modelling, deterministic approach to improve carbonate heterogeneity prediction; Lower cretaceous, Abu Dhabi. *Society of Petroleum Engineers - Abu Dhabi International Petroleum Exhibition and Conference, ADIPEC 2015, November*. <https://doi.org/10.2118/177519-ms>
- Hawie, N., Callies, M., & Marfisi, E. (2017). Integrated multi-disciplinary forward stratigraphic modelling workflow in petroleum systems assessment. *SPE Middle East Oil and Gas Show and Conference, MEOS, Proceedings, 2017-March*, 1405–1412. <https://doi.org/10.2118/183835-ms>
- Hawie, N., Covault, J. A., Dunlap, D., & Sylvester, Z. (2018). Slope-fan depositional

- architecture from high-resolution forward stratigraphic models. *Marine and Petroleum Geology*, 91(July 2017), 576–585.  
<https://doi.org/10.1016/j.marpetgeo.2017.12.033>
- Hawie, N., Deschamps, R., Granjeon, D., Nader, F. H., Gorini, C., M€uller, C., Montadert, L., & Baudin, F. (2017). Multi-scale constraints of sediment source to sink systems in frontier basins: a forwardstratigraphic modelling case studyof the Levant region. *Basin Research*, 29, 418–445. <https://doi.org/10.1111/bre.12156>
- Hawie, N., Gorini, C., Deschamps, R., Nader, F. H., Montadert, L., Granjeon, D., & Baudin, F. (2013). Tectono-stratigraphic evolution of the northern Levant Basin (offshore Lebanon). *Marine and Petroleum Geology*, 48, 392–410.  
<https://doi.org/10.1016/j.marpetgeo.2013.08.004>
- Huc, A.-Y. (2016). Source Rocks : Global and regional control on organic matter accumulation ; Middle East Examples ( Keynote ). *AAPG Geosciences Technology Workshop*, “Source Rocks of the Middle East,” Abu Dhabi, UAE, January 25-26, 2016, #30456(June).
- Jervey, M. T. (1988). *Quantitative geological modeling of siliciclastic rock sequences and their seismic expression*.
- Khalifa, M. A. (2007). TRIASSIC-JURASSIC BOUNDARY ON THE SOUTHERN MARGIN OF TETHYS: IMPLICATIONS OFFACIES, TECTONICSAND VOLCANISM. *The Global Triassic: Bulletin 41*, 41, 110.
- Koeshidayatullah, A., Al-Ramadan, K., Collier, R., & Hughes, G. W. (2016). Variations in

- architecture and cyclicity in fault-bounded carbonate platforms: Early Miocene Red Sea Rift, NW Saudi Arabia. *Marine and Petroleum Geology*, 70, 77–92. <https://doi.org/10.1016/J.MARPETGEO.2015.10.017>
- 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. <https://doi.org/10.2113/geoarabia0603407>
- Lacroix, S., & Albadi, B. S. (2012). Improving the Uncertainty Understanding for the Optimal Development of an Abu Dhabi Offshore Green Field. *Abu Dhabi International Petroleum Conference and Exhibition*.
- Le Nindre, Y.-M., Vaslet, D., Énay, R., Manivit, J., & Al-Husseini, M. I. (2022). *Sequence architecture of the Toarcian Marrat Formation, Saudi Arabia: The Khashm adh Dhibi reference section*. May.
- Le Nindre, Y. M., Vaslet, D., Le Métour, J., Bertrand, J., & Halawani, M. (2003). Subsidence modeling of the Arabian Platform from Permian to Paleogene outcrops. *Sedimentary Geology*, 156(1–4), 263–285. [https://doi.org/10.1016/S0037-0738\(02\)00291-9](https://doi.org/10.1016/S0037-0738(02)00291-9)
- 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.
- Manivit, J., & Le Nindre, Y.-M. (1990). *Le jurassique d'Arabie centrale* (Vol. 194). Editions du BRGM.

- 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)*.
- Miall, A. D. (2010). *The geology of stratigraphic sequences*. Springer Science & Business Media.
- Milliman, J. D., & Syvitski, J. P. M. (1992a). Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *Journal of Geology*, 100(5), 525–544. <https://doi.org/10.1086/629606>
- Milliman, J. D., & Syvitski, J. P. M. (1992b). Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *The Journal of Geology*, 100(5), 525–544.
- Montaggioni, L. F. (2005). History of Indo-Pacific coral reef systems since the last glaciation: Development patterns and controlling factors. *Earth-Science Reviews*, 71(1–2), 1–75. <https://doi.org/10.1016/j.earscirev.2005.01.002>
- Mount, J. F. (1984). Mixing of siliciclastic and carbonate sediments in shallow shelf environments. *Geology*, 12(7), 432–435.
- Murris, R. J. (1980). Middle East: stratigraphic evolution and oil habitat. *AAPG Bulletin*, 64(5), 597–618.
- Nagle, J., Marfisi, E., Piper, D. J. W., Pe-Piper, G., & Saint-Ange, F. (2021). How is stratigraphic modeling of frontier basins dependent on data: A case study of the Shelburne sub-basin, offshore SE Canada. *Marine and Petroleum Geology*, 132(July),

105227. <https://doi.org/10.1016/j.marpetgeo.2021.105227>

Nindre, Y. Le, Vaslet, D., Énay, R., & Manivit, J. (2022). *Sequence architecture of the Toarcian Marrat Formation , Saudi Arabia : The Khashm adh Dhibi reference section*  
*Sequence architecture of the Toarcian Marrat Formation , Saudi Arabia : The Khashm adh Dhibi reference section.* May.

Osman, M., Abdullatif, O., & Arabia, S. (2020). *Digital Outcrop Modeling of the Lower Silurian Qusaiba Shale Member ; Implications for Reservoir Quality and Architecture , Central Saudi Arabia.* 11322. <https://doi.org/10.1306/11322Osman2020>

Posamentier, H. W., & Allen, G. P. (1999). Siliciclastic sequence stratigraphy. *Concepts and Applications: SEPM, Concepts in Sedimentology and Paleontology*, 7, 210.

Posamentier, H. W., & Vail, P. R. (1988). *Eustatic controls on clastic deposition II—sequence and systems tract models.*

Powers, R. W. (1968). *Saudi Arabia (excluding Arabian Shield).* Centre national de la recherche scientifique.

Powers, R. W., Ramirez, L. F., Redmond, C. D., & Elberg, E. L. J. (1966). Geology of the Arabian Peninsula Sedimentary Geology of Saudi Arabia. *U.S. Geological Survey Professional Paper*, 560-D, 154.

Pratt, B. R., & Smewing, J. D. (1990). Jurassic and Early Cretaceous platform margin configuration and evolution, central Oman Mountains. *Geological Society Special Publication*, 49, 69–88. <https://doi.org/10.1144/GSL.SP.1992.049.01.06>

Prince, G. D., & Burgess, P. M. (2013). Numerical modeling of falling-stage topset

- aggradation: Implications for distinguishing between forced and unforced regressions in the geological record. *Journal of Sedimentary Research*, 83(9), 767–781.  
<https://doi.org/10.2110/jsr.2013.62>
- Sangster, C., Piper, D. J. W., Hawie, N., Pe-Piper, G., & Saint-Ange, F. (2019). Forward stratigraphic modelling of sediment pathways and depocentres in salt-influenced passive-margin basins: Lower Cretaceous, central Scotian Basin. *Basin Research*, 31(4), 728–753.
- Schlager, W. (1998). Sedimentation rates, observation span, and the problem of spurious correlation. *Mathematical Geology*, 30(5), 547–556.  
<https://doi.org/10.1023/A:1021742228242>
- Schlager, W. (2005a). Carbonate Sedimentology and Sequence Stratigraphy. In *Carbonate Sedimentology and Sequence Stratigraphy*. <https://doi.org/10.2110/csp.05.08>
- Schlager, W. (2005b). Carbonate Sedimentology and Sequence Stratigraphy. In *Carbonate Sedimentology and Sequence Stratigraphy* (Issue 8).  
<https://doi.org/10.2110/csp.05.08>
- Shabani, F., Amini, A., Tavakoli, V., Honarmand, J., & Gong, C. (2022a). 3D forward stratigraphic modeling of the Albian succession in a part of the northeastern margin of the Arabian Plate and its implications for exploration of subtle traps. *Marine and Petroleum Geology*, 145(August), 105880.  
<https://doi.org/10.1016/j.marpetgeo.2022.105880>
- Shabani, F., Amini, A., Tavakoli, V., Honarmand, J., & Gong, C. (2022b). 3D forward

- stratigraphic modeling of the Albian succession in a part of the northeastern margin of the Arabian Plate and its implications for exploration of subtle traps. *Marine and Petroleum Geology*, 145(June), 105880.  
<https://doi.org/10.1016/j.marpetgeo.2022.105880>
- Sharland, P. R., Archer, R., Casey, D. M., DAVIES, R. B. H., SH, H., & AP, H. (2001). Arabian plate sequence stratigraphy. *GeoArabia Special Publication*, 2, 371.
- Simmons, M. D., & Davies, R. B. (2018). Triassic to Middle Jurassic stratigraphy of the Arabian Plate: an introduction. *Lower Triassic to Middle Jurassic Sequence of the Arabian Plate, Houten, Netherlands, EAGE*, 9–32.
- Simmons, M. D., Sharland, P. R., Casey, D. M., Davies, R. B., & Sutcliffe, O. E. (2007). Arabian plate sequence stratigraphy: Potential implications for global chronostratigraphy. *GeoArabia*, 12(4), 101–130.  
<https://doi.org/10.2113/geoarabia1204101>
- Slingerland, R., & Smith, N. D. (2004). River avulsions and their deposits. *Annu. Rev. Earth Planet. Sci.*, 32, 257–285.
- Sømme, T. O., Helland-hansen, W., & Granjeon, D. (2009). *Impact of eustatic amplitude variations on shelf morphology , sediment dispersal , and sequence stratigraphic interpretation : Icehouse versus greenhouse systems.* 7, 587–590.  
<https://doi.org/10.1130/G25511A.1>
- 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*

*Bulletin*, 100(5), 819–841.

- Syvitski, J. P. M., & Milliman, J. D. (2007). Geology, geography, and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean. *Journal of Geology*, 115(1), 1–19. <https://doi.org/10.1086/509246>
- Syvitski, J. P. M., Peckham, S. D., Hilberman, R., & Mulder, T. (2003). Predicting the terrestrial flux of sediment to the global ocean: A planetary perspective. *Sedimentary Geology*, 162(1–2), 5–24. [https://doi.org/10.1016/S0037-0738\(03\)00232-X](https://doi.org/10.1016/S0037-0738(03)00232-X)
- Talling, P. J. (1998). How and where do incised valleys form if sea level remains above the shelf edge? *Geology*, 26(1), 87–90.
- Tucker, G. E., & Slingerland, R. L. (1994). Erosional dynamics, flexural isostasy, and long-lived escarpments: A numerical modeling study. *Journal of Geophysical Research: Solid Earth*, 99(B6), 12229–12243.
- Vaslet, D., Brosse, J. M., Breton, J. P., Manivit, J., Le Strat, P., Fourniguet, J., & Shorbaji, H. (1988). Geologic map of the Shaqra'quadrangle, sheet 25H, Kingdom of Saudi Arabia. *Saudi Arabian Directorate General of Mineral Resources Geoscience Map GM-120*, 29.
- Vaslet, D., Manivit, J., Le Nindre, Y. M., Brosse, J. M., Fourniguet, J., & Delfour, J. (1983). Explanatory notes to the geologic map of the Wadi Ar Rayn Quadrangle, Kingdom of Saudi Arabia. *Geoscience Map GM-63C, Scale, 1(250,000)*.
- Wentworth, C. K. (1922). A scale of grade and class terms for clastic sediments. *The Journal of Geology*, 30(5), 377–392.

- Willgoose, G., Bras, R. L., & Rodriguez-Iturbe, I. (1991). A coupled channel network growth and hillslope evolution model: 2. Nondimensionalization and applications. *Water Resources Research*, 27(7), 1685 – 1696. <https://doi.org/10.1029/91WR00936>
- Yousif, S., & Nouman, G. (1997). Jurassic Geology of Kuwait. *GeoArabia*, 2(1), 91–110. <https://doi.org/10.2113/geoarabia020191>
- Zhang, J., Burgess, P. M., Granjeon, D., & Steel, R. (2019). Can sediment supply variations create sequences? Insights from stratigraphic forward modelling. *Basin Research*, 31(2), 274–289. <https://doi.org/10.1111/bre.12320>
- Ziegler, M. A. (2001). Late Permian to Holocene paleofacies evolution of the Arabian countries and their hydrocarbon occurrences. *Petroleum Play Assessment*, 6(3), 445–504.
- Zonneveld, J.-P., Gingras, M. K., Beatty, T. W., Bottjer, D. J., Chaplin, J. R., Greene, S. E., Martindale, R. C., Mata, S. A., McHugh, L. P., & Pemberton, S. G. (2012). Mixed siliciclastic/carbonate systems. In *Developments in Sedimentology* (Vol. 64, pp. 807–833). Elsevier.
- Zuffa, G. G. (1980). Hybrid arenites: their composition and classification. *Journal of Sedimentary Petrology*, 50(1), 21–29. <https://www.scopus.com/inward/record.uri?eid=2-s2.0-0018916679&partnerID=40&md5=161c15df12e252f1933b947e045597cf>

## VITAE

Name : Baharudin Fahmi

Nationality : Indonesia

Date of Birth : March, 16<sup>th</sup> 1996

Email : fahmibahaar@gmial.com

Address : Pahlawan Street 5 No 34 Tanjung, Purwokerto Selatan,  
Banyumas Jawa Tengah Indonesia Postal Code 53143

Research Interest : Sedimentology & stratigraphy analysis, sequence  
stratigraphy analysis, reservoir characterization and  
stratigraphic forward modeling.

Academic Background : Masters in Geology, 2021 – 2024. Geoscience Department,  
King Fahd University of Petroleum & Minerals, Saudi  
Arabia.

Bachelor in Geology, 2014 - 2018. Geological Engineering  
Department, Universitas Pembangunan Nasional Veteran  
Yogyakarta, Indonesia.

Published article : Journal of Geoenergy Science and Engineering (Volume 235, April 2024, 2126992024)

Title: 3D stratigraphic forward modeling of mixed carbonate-siliciclastic systems: Insights to energy prospectivity

**(On manuscript preparation)** Title: Testing Geologic Assumptions and Plausible Scenarios for Best-Fit Reference Model in Marrat Formation using Stratigraphic Forward Modeling

**(On manuscript preparation)** Title: Quantitative Controls on the Sequence Architecture and Geometries of the Marrat Formation using Stratigraphic Forward Modeling

**(On manuscript preparation)** Title: Quantitative Stratigraphy of The Middle to Upper Jurassic Carbonate System In The Arabian Intrashelf Basin Using 3D Stratigraphic Forward Modeling

Conference article : IPTC Conference, Al Khobar (12-14 February 2024)

Title: Quantitative Stratigraphy of The Middle to Upper Jurassic Carbonate System In The Arabian Intrashelf Basin Using 3D Stratigraphic Forward Modeling

AAPG-Process based Modeling Conference, Abu Dhabi (27  
– 29 May 2024)

Title: Quantifying the Dynamics Of Mixed Siliciclastic And  
Carbonate System Of The Toarcian Marrat Formation, Saudi  
Arabia: Insights From 3d Stratigraphic Forward Modeling