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NEW INSIGHT INTO THE DEPOSITIONAL AND TECTONIC CONSTRAINTS OVER THE PALEOGENE AND NEOGENE EVOLUTION WITHIN THE ARABIAN PENINSULA

Aimen Hussein Amer

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ABSTRACT

Geological studies over the Arabian Peninsula were initiated in the 1930s, and 30 years later an area equivalent to 3.5 million km2 was covered, laying the groundwork for the stratigraphic nomenclature of the Arabian Peninsula. Since then, not much has changed in terms of formation ages and formation naming, where subsequent authors largely took the results of the earlier work for granted. This thesis will evaluate the sedimentological and depositional facies of exposed rock units in the countries of Kuwait and Bahrain with the objective of developing a depositional facies model that can explain the complex facies architecture. During this study, it was revealed that the exposed rock units in Kuwait at the Jal Az-Zor escarpment all belong to the Lower Fars Formation (also known as Kuwait Formation), whereas previous interpretations assigned these rocks to Ghar, Lower Fars, and Dibdibba formations. This study further revealed that the depositional environment of the Lower Fars Formation is dominated by marginal marine deposits manifested by a riverine to tidally influenced estuary setting, which is contrasting to the fluvio-deltaic setting within previous interpretations. The origin of the NE-SW trending Jal Az-Zor escarpment has been disputed in Kuwait, where it has been proposed either a surface erosion expression, or an underlying unspecified basement fault. Detailed 2D seismic processing and interpretation revealed unprecedented structural features such as detachment, tight concentric and recumbent folds, thrust faults, and fault propagation folds. Tectonic deformation of the Kuwait Formation within the subsurface at the Jal Az-Zor escarpment reflects the initial stage of fault propagation folding resulting from the Kuwait Arch plunge towards the south of the Jal Az-Zor area. Kinematic analysis suggests that the Jal Az-Zor escarpment is a surface expression of a principal displacement zone that is dominated by dextral strike-slip motion and is found to play a major role in the rotation of the Arabian Plate since the early Pleistocene (Calabrian). Throughout this study, it has been observed that detachment could have occurred along the Dammam and Rus formations. Subsequent analysis of the composition of these two formations indicates that the Rus Formation exhibits a greater potential for generating detachment surfaces. The Rus Formation was earlier thought to be dominated by evaporites which favours detachment and was considered a regional seal covering the majority of the Arabian Peninsula. However, detailed sedimentological field work at the Horse-Racing Club outcrop in Bahrain and subsequent published borehole data suggest that the Rus Formation in Bahrain is predominantly composed of dolomites. These changes in understanding facies types and spatial distribution open the door for an in-depth evaluation of the whole Arabian Peninsula facies distribution. The complexity of the Arabian Peninsula's sedimentology and structural development was highlighted in this thesis, demonstrating the need for a re-evaluation of the region's facies nomenclature and tectonic history in light of current geological knowledge and newly available data.

KEYWORDS: Barrier island, Bioturbation, Hydrocarbon seal, Jal Az-Zor escarpment, Complex duplex folding, Microbialites, Regressive staking pattern, Restricted lagoon, Storm beds

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ABSTRAKTI

Arabian niemimaan geologiset tutkimukset alkoivat 1930-luvulla. 30 vuotta myöhemmin tutkimukset kattoivat koko 3.5 miljoonan neliökilometrin suuruisen alueen sekä olivat luoneet pohjan Arabian niemimaan stratigrafiselle terminologialle. Sen jälkeen monetkaan asiat muodostumien iän ja nimeämisen suhteen eivät ole muuttuneet, koska uudempien tutkimustulosten julkaisijat ovat pitäneet aiempien töiden tuloksia pitkälti itsestäänselvyytenä. Tässä opinnäytetyössä esitetään ja läpikäydään Kuwaitin ja Bahrainin alueella paljastuneiden kivilajiyksiköiden sedimentologisia ominaispiirteitä, ja työn tavoitteena on laatia näiden yksiköiden perusteella kerrostumismalli, niin kutsuttu fasiesmalli, joka selittää niiden monimutkaisen ilmenemisen nykypäivänä. Tutkimuksessa havaittiin, että Kuwaitin Jal Az-Zorin kivilajiyksiköt kuuluvat kaikki Alempaan Farsin Muodostumaan (tunnetaan myös nimellä Kuwaitin Muodostuma; Fm), kun taas aikaisempien tulkintojen mukaan yksiköt kuuluvat muodostumiin Ghar Fm, Alempi Fars Fm ja Dibdibba Fm. Tutkimuksessa havaittiin lisäksi, että Alemman Farsin Muodostuman kerrostumisympäristöä hallitsee matalan meren kerrostumisympäristö, jota luonnehtii mm. joki- ja vuorovesivaikutteisen suisto-alueen sedimentaatio. Tämän tyyppinen kerrostumisympäristö on ristiriidassa aiempien tulkintojen mukaisen joki-delta ympäristön kanssa. Kuwaitissa sijanitsevan, Koillis-lounas -suuntaisen Jal Az-Zorin jyrkänteen alkuperä on kiistelty, ja sen synty on liitetty joko maankamaran eroosioon tai jyrkänteen alapuolella olevan, muuten tuntemattoman siirroksen olemassaoloon. Seismisten aineistojen yksityiskohtaisen 2D-prosessoinnin ja tulkinnan perusteella kohteesta tunnistettiin mm. aiemmin tuntemattomia ylityöntösiirroksia sekä näihin liittyviä poimuja. Niiden perusteella Kuwaitin Muodostuman tektoninen deformaatio Jal Az-Zorin jyrkänteen alapuolisessa kallioperässä heijastaa siirroksen etenemiseen liittyvän poimutuksen varhaisia vaiheita, jotka voidaan edelleen yhdistää Kuwaitin kaaren kohti etelää suuntautuneeseen kohoamiseen. Nyt tuotettu kinemaattinen analyysi viittaa siihen, että Jal Az-Zorin jyrkänne on ilmentymä syvemmällä olevasta siirrosvyöhykkeestä, jota luonnehtii oikeakätinen vaakasuuntainen siirtymä, ja jolla oli merkittävä myötävaikutus Arabian laatan kiertymisessä myötäpäivään varhaisen Pleistoseeniepookin (Calabrian) aikana. Kauttaaltaan tässä tutkimuksessa on havaittu, että Dammam ja Rus Muodostumissa voi esiintyä rakenteellisia irtautumisvyöhykkeitä. Näiden kahden muodostuman koostumuksen tarkempi analyysi osoitti, että irtautumisvyöhykkeet esiintyvät todennäköisemmin Rus Muodostumassa. Aiemmissa töissä Rus Muodostuman arveltiin koostuvan vallitsevasti evaporiiteista, joka suosii teoriaa irtautumisvyöhykkeiden syntymisestä. Samalla muodostumaa pidettiin hydraulisesti johtamattomana sulkupintana (seal), joka peittää suurimman osan Arabian niemimaasta. Yksityiskohtaiset sedimentologiset kenttätyöt Horse-Racing Clubin paljastumalla Bahrainissa, ja myöhemmin julkaistut kairaustiedot viittaavat kuitenkin siihen, että Bahrainin puolella oleva Rus Muodostuma koostuu pääasiassa dolomiiteista. Nämä muutokset alueen fasiestyyppeihin ja niiden alueellisen jakautumiseen auttavat ymmärtämään koko Arabian niemimaan kallioperän litofasieksia aivan uudella tavalla ja avaavat uusia näkökulmia niiden syvälliseen tarkasteluun. Tässä opinnäytetyössä korostettiin Arabian niemimaan sedimentologian ja rakenteellisen kehityksen monimutkaisuutta. Tutkimus osoittaa, että alueen fasieksiin liittyvää terminologiaa ja tektonista historiaa on arvioitava uudelleen nykyisen geologisen tiedon ja uusien aineistojen valossa.

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Abbreviations

2D	2 Dimensional
3D	3 Dimensional
AGS	Automatic Gain Control
BOPD	Barrels of Oil Per Day
CRE	The Middle East Center for Reliability and Efficiency
Fm	Formation
GTW	Geoscience Technology Workshop
HRC	Horse-Racing Club
Km	kilometres
KOC	Kuwait Oil Company
Ma	Million years
PDZ	Principal Displacement Zone
SDCR	SLB Dhahran Carbonate Research Center
SNR	Signal-to-Noise Ratio
TDR	Time Depth Relation
USGS	US Geological Survey
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

List of Original Publications

This thesis is based on the subsequent original publications, referenced within the text using Roman numerals:

I Amer, A., Al-Hajeri, M., Najem, A., Al-Qattan, F. (2019). Facies architecture of lower Fars formation at Jal Az-Zor escarpment, Kuwait. *Springer, Arabian Journal of Geosciences*, 12(16), 1–22.

II Amer, A., Al-Hajeri, M. (2020). The Jal Az-Zor escarpment as a product of complex duplex folding and strike-slip tectonics; A new study in Kuwait, northeastern Arabian Peninsula. Elsevier*, Journal of Structural Geology*, 135, 104024.

III Amer, A., Skyttä, P., Ojala, A., Heilimo, E (2023). New insights into the depositional facies of the Early Eocene Rus Formation, Bahrain. Elsevier, *Marine and Petroleum Geology*, 2023, 106338, ISSN 0264-8172.

The original publications have been reproduced with the authorization of the copyright holders. The main contribution of A. Amer to the original papers was as follows:

Paper I: Performing the outcrop description field work on the Jal Az-Zor escarpment; developing the facies and facies associations; writing the manuscript; and act as the corresponding author.

Paper II: Perform the seismic post-stake inversion; interpret the seismic lines for horizons and fault systems in Petrel software; perform structural restoration using Dynel 2D software; synthesizing; write the manuscript; and act as corresponding author.

Paper III: Field description in Bahrain, including collecting rock samples and sending them to two separate labs for processing; facies and facies association interpretation; regional mapping of the Rus Formation over the Arabian Peninsula; synthesizing; and writing most of the manuscript.

1 Introduction

Positioned to the southwest of Asia and the northeast of Africa, the Arabian Peninsula is situated between the Red Sea in the western direction and the Arabian Gulf to the east. Its southern boundary is distinctly characterized by the presence of the Gulf of Aden in the southwestern region, alongside the Gulf of Oman and the Arabian Sea in the southeastern area. (**Fig. 1**). Encompassing a total area of 3.2 million km^2, the northern region of the peninsula falls within the subtropical climate zone, while the southern part experiences a tropical climate. The Arabian Peninsula belongs to the Arabian Plate, which is formerly part of the African Plate throughout most of the Paleozoic and Cenozoic eras. During the Eocene epoch, the Red Sea rifting led to the separation of Africa and Arabia in the Oligocene epoch (Golonka, 2004). Since then, the Arabian Plate has been gradually moving towards the Eurasia resulting in the development of the Zagros Thrust Zone (Goff et al., 1995; Sharland et al., 2001; Ziegler, 2001). The Arabian Peninsula is a region responsible for producing 25.8 million barrels of oil per day (BOPD), representing 33% of the world's production (IEA, 2022). Despite the high production figures, the facies architecture and distribution of many Paleogene and Neogene periods succession are widely unknown at several localities (**Fig. 2**). Furthermore, the tectonic evolution of some major structural elements of the Arabian Peninsula is found to be equivocal interpretations and contain several hypotheses, leading to significant uncertainties in the regional structural interpretation.

For decades, a persistent debate has revolved around the depositional facies of the rock-forming units exposed at the Jal Az-Zor escarpment in Kuwait and the central Bahrain exposures, leaving no definite answers. Moreover, the origin and tectonic history of the Jal Az-Zor escarpment are being largely unknown, which adds to the complexities surrounding the area's structural evolution.

As such, there is a clear need to improve our knowledge of these sedimentary formations in the Arabian Gulf's eastern and northern regions. For the first time, the current investigation will attempt to identify the intricacies of facies and depositional environments. Building realistic facies models for the Rus Formation in Bahrain and the Lower Fars Formation exposure at the Jal Az-Zor escarpment in Kuwait is the main goal of this thesis. Furthermore, this study explores the structural mechanisms

that led to the creation of the Jal Az-Zor escarpment and associated features, such the Al-Batin Fault, and establishes connections to the kinematics of the Arabian Plate.

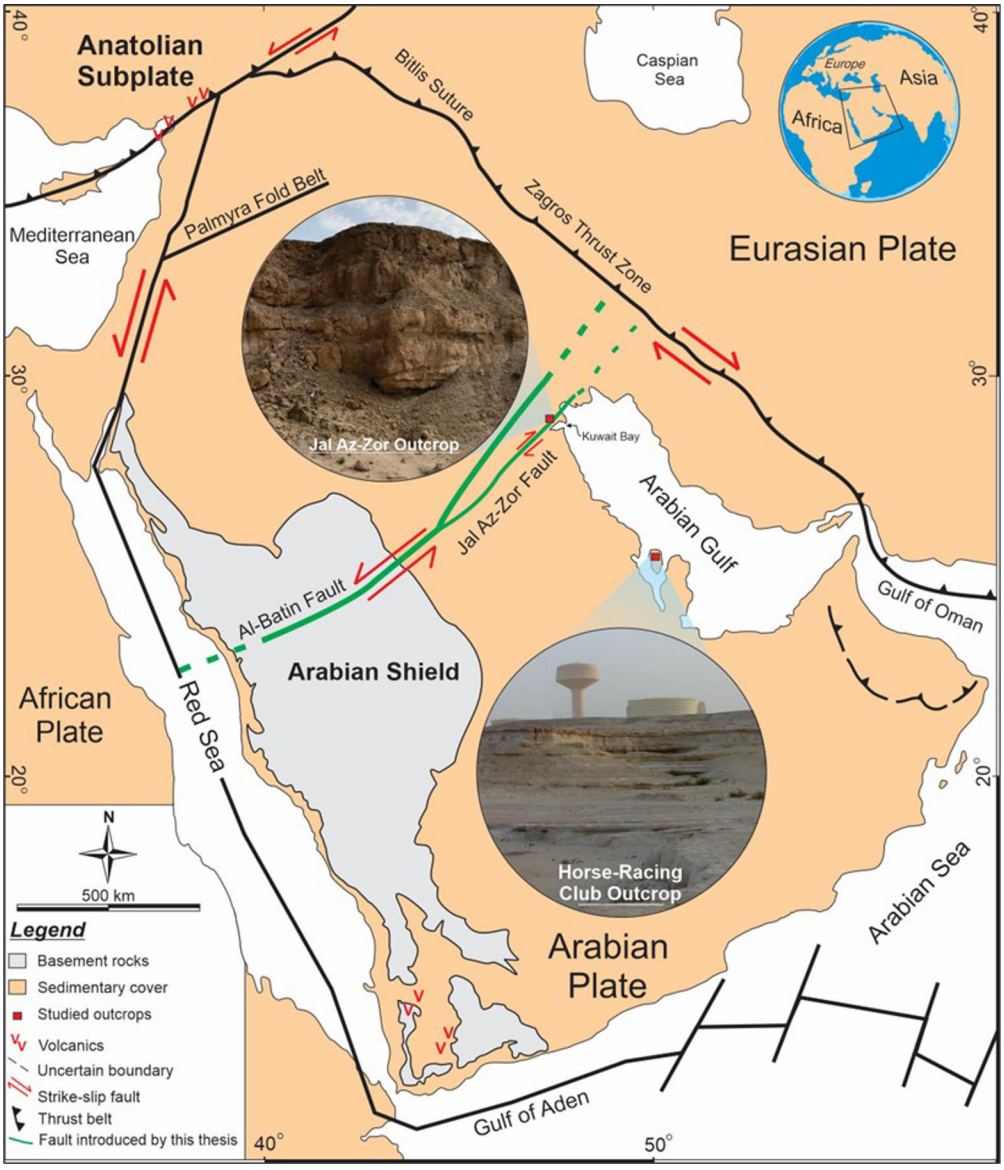

Figure 1. Location map showing the Jal Az-Zor outcrop in Kuwait and the Horse-Racing Club outcrop in Bahrain. (Modified after Amer and Al-Hajeri, 2020).

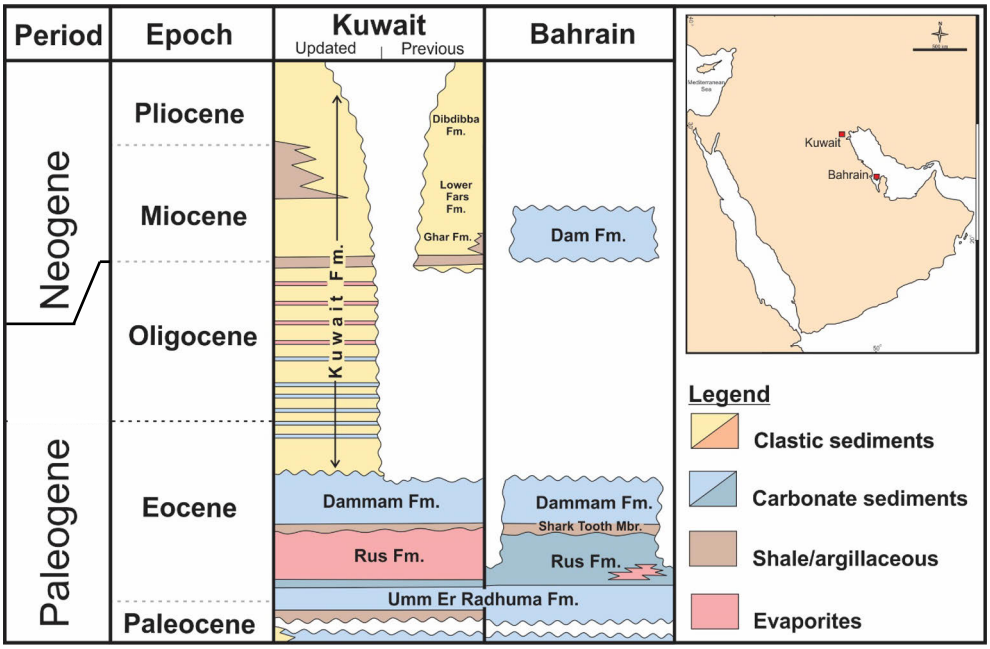

Figure 2. Chronostratigraphic chart of the studied areas, Kuwait and Bahrain. (Modified after Abahussain, 2015; Al-Juboury and McCann, 2008; Alkhaldi et al., 2021; Al-Saad and Ibrahim, 2002; Amer and Al-Hajeri, 2019; Hussain and Al-Ramadan, 2009; Jassim and Goff, 2006; Sharland et al., 2001).

In the early description, the rock-forming units at the Jal Az-Zor escarpment in Kuwait were classified through a three-party division of the Kuwait Group, encompassing the Dibdibba, Lower Fars, and Ghar formations (Al-Awadi et al., 1997; Milton, 1967; Owen and Nasr, 1958; Fig. 2). However, other researchers, like Salman, (1979), proposed an alternative subdivision, recognizing the Mutla and Jal Az-Zor formations. The average 328 m thickness of the Kuwait Group, as revealed by oil well reports in the Jal Az-Zor escarpment vicinity, raised doubts about whether all formations could be accommodated within the limited 9.1 m high cliff exposure. Furthermore, the facies exposed at this site have been subject to varying interpretations, where some researchers, such as Owen and Nasr, (1958), attributed the rock-forming units to carbonate-dominated facies, while others, like Ahmed et al., (2015), interpreted them as fluvio-deltaic facies. A study by Amer and Al-Hajeri, (2019) conducted radiometric ($^{87}Sr/^{86}Sr$) dating on the exposed rock-forming units and on well samples around the Jal Az-Zor exposure, providing age range from 24.39 Ma to 30.32 Ma, reflecting an Oligocene age, leading to renaming the Kuwait Group succession as the Kuwait Formation. This research eliminated the undifferentiated Dibdibba, Lower Fars, and Ghar formations division inherited from neighboring countries.

The origin of the Jal Az-Zor escarpment was investigated by Salman, (1979) and Al Sarawi, (1982). Both authors postulated that the escarpment is associated with a large fault plane located in the offshore area within the Kuwait Bay during the Neogene period, eroding over time to its present location. Carman, (1996) followed the previous authors and placed the Jal Az-Zor fault line across the Kuwait Bay, adopting the earlier work. By contrast, Bou-Rabee and Kleinkopf, (1994) interpreted the Jal Az-Zor fault line utilizing free air Bouguer gravity anomaly survey and suggested that the escarpment represents a surface manifestation of a basement strike-slip fault, accommodating small crustal plate movements. Furthermore, interpretation of an old NW-SE 2D-seismic section acquired during the 1960s, crossing the escarpment, revealed a chains of blind wrench faults with no major throw within the proximity of the Jal Az-Zor area (Al-Anzi, 1995).

Before the present study, there have been limited geological studies on the Rus Formation exposures in Bahrain, and only few studies were published over the last century. In 1956, the US Geological Survey (USGS) released Bahrain's first geological map, describing the exposed Rus Formation consisting of chalky dolomitic limestones (Willis, 1967). The USGS conducted this study primarily for oil exploration and the drilling of several wells in central area of the Awali structure in Bahrain's (Willis, 1967). Penetrating the Rus Formation was marked by drilling-mud losses that have been mostly attributed to the downward displacement of layers above dissolved anhydrite beds (Willis, 1967). This interpretation contributed to the notion of evaporites being prevalent in the Rus Formation in Bahrain. Powers et al., (1966) portrayed the Rus Formation exposed at the Dammam Dome in Saudi Arabia's Eastern Province as a typical soft chalky limestone, dominated by evaporites with only a few porous beds. In contrast, Alkhalifa and Kurison, (2023) presented a different view. They described an evaporitic layer of merely 2.5 cm thickness within the 56 m thick Rus Formation at the Dammam Dome, questioning the prior discoveries made by Powers et al., (1966).

2 Objectives

This thesis aims to identify the facies and depositional settings of the Jal Az-Zor exposure in Kuwait, resolve its tectonic origin, and investigate the facies composition of the Jal Az-Zor detachment plane by evaluating the Rus Formation exposures in Bahrain.

The first aim was to identify the facies, facies associations, facies architecture, and depositional settings of the Jal Az-Zor escarpment (Paper I). This outcropping cliff spans nearly 60 km across Kuwait, and despite its size, neither the exposed formation naming, nor the depositional facies are well defined. In general, identifying facies over these outcrops is a fundamental aspect of geological research, which contributes to our understanding of the nature of the geological processes. It allows the reconstruction of ancient depositional environments, correlation of geological formations, and make informed decisions in various applications, such as mining of metals and minerals or hydrocarbon exploration and field development in nearby fields.

The second aim addressed in this thesis was to resolve the tectonic origin of the Jal Az-Zor escarpment (Paper II). Prior to this work, there were two competing scenarios: the first suggested that the Jal Az-Zor escarpment is associated with a main fault plane located offshore within the Kuwait Bay during the Neogene period through weathering to its existing location (Al Sarawi, 1982; Salman, 1979). According to the second scenario (Bou-Rabee and Kleinkopf, 1994), the escarpment is the surface expression of a subsurface fault plane.

The third aim was to characterize the facies composition of the Rus Formation, with specific insights into the Jal Az-Zor detachment plane that was identified in the subsurface and to investigate the nature of the reginal seal of the Rus Formation exposures in Bahrain. The Rus Formation has been considered by several authors as a major hydrocarbon seal in the Arabian Peninsula (Pierce, 1993; Sharland et al., 2004). Following a field excursion in 2022 to the Rus Formation exposures in Bahrain, it was evident that the outcrops lacked the presence of evaporites. Consequently, a detailed sedimentological and stratigraphic evaluation was required (Paper III).

The outcomes of Papers I and II provides a deeper understanding of the tectonostratigraphic evolution of the Jal Az-Zor escarpment in Kuwait, where the facies distribution and tectonic evolution has been revealed. An important aspect that arose from Paper II was to address the knowledge gap related to the association of the detachment plane to the Rus Formation, which contributed to the development of complex duplex folding discover in Kuwait (Paper II). Therefore, the second field mapping campaign associated with Paper III was strategically planned to assess the facies of the Rus Formation in Bahrain, due to the lack of Rus Formation exposures in Kuwait.

3 An Overview of the Applied Methods

The interconnected studies of geological facies, seismic data, and specific techniques such as ichnology and structural restoration are essential components in the field of geology and geophysics because they provide valuable insights into conducting fieldwork, understanding surface, and subsurface geology. Additionally, such studies can unravel the past depositional and tectonic history along with enabling resource exploration and development. This review section provides a brief introduction into the principals, concepts, and methods of this study, inducing facies analysis, seismic analysis, and structural restoration.

3.1 Facies Analysis

Geological facies are unique rock units characterized by specific sedimentary attributes, resulting from the interplay of sedimentary processes within a given depositional setting. (Middleton, 1978). The study of geological facies plays a crucial role in understanding past depositional environments, the interpretation of sedimentary sequences, and reconstructing paleogeography (Walker and James, 1992).

The understanding of facies and the significance of Walther's Law were effectively adopted by many geologists and applied in Europe in the 19th century. However, their widespread application on a global scale did not arise until the 1930s. Walther's Law, as postulated, asserts that vertical facies progression arises from the sequential arrangement of depositional environments that are laterally adjacent to one another. The term “facies” is believed to be established by Gressly, (1838) based on the review article publication of Teichert, (1958). Geologists classify facies based on various attributes, including and not limited to lithology, color, grain size, sedimentary structures, fossil content, and chemical composition (Miall, 1999; Tucker, 2011). Common facies types include fluvial, marine, lacustrine, aeolian, glacial, deltaic, and shallow marine, each representing a specific depositional environment (Amer and Alexander, 2005; Fleming et al., 1998; Muniz and Bosence, 2015; Polo et al., 2020; Ryer and Anderson, 2004). Facies analysis aims to identify

characteristic associations of the sedimentary features, resulting in distinct lithofacies, or even ichnofacies. The specific attributes of these facies types offer significant insights into the depositional processes, environment of deposition, and sometimes post-depositional phenomena's as described by Paper I and Paper II.

3.2 Seismic Structural Analysis

The seismic techniques deployed in this thesis, in particular Paper II, are divided into two parts. The first deals with the seismic data processing and the second with seismic interpretation of faults and horizons. In general, the fundamental goal of seismic data processing in geophysical exploration is to enhance the quality and interpretability of the subsurface seismic data that has been gathered. (Hatton et al., 1986). It involves a series of sophisticated algorithms and techniques designed to remove noise, correct for acquisition-related artifacts, and transform raw seismic data into accurate subsurface images (Davogustto, 2011; Mafakheri et al., 2022).

Seismic data processing includes a wide range of data processing methods including pre-stack and post-stack processing that are usually implemented in time and depth domains (Shakir et al., 2022). From experience, geophysicists tend to prefer processing the data in time, whereas geologists prefer the depth domain. However, the availability of a representative and good quality time depth relation (TDR) is critical for the ability to shift between the two domains (Bourges et al., 2012). The technique implements in this thesis focused on the post-stack processing, that is applied on the pre-migrated seismic data with the objective of enhancing the signal-to-noise ratio (SNR) (MacBeth and Izadian, 2023; McLeman et al., 2023). The SNR is a critical indicator used to assess the quality of a signal compared to the level of background noise present in a given dataset.

In the context of seismic data processing, SNR evaluation is crucial as it directly impacts the interpretability and reliability of subsurface images and the identification of geological features (Chopra and Marfurt, 2007; Yilmaz, 2008), hence its utilization in this study.

3.3 Structural Restoration and Balancing

Structural restoration and balancing are comprehensive techniques in the field of structural geology and tectonics (Ramsay, 1986). This involves the reconstruction of deformed geological structures to their initial pre-deformational states, providing insights into the tectonic evolution of the studied structures and uncertainties within the interpretations (Amer et al., 2013).

The field of structural restoration dates back to the 20th century, when geologists realized how crucial it was to reconstruct the deformational history of rocks. (Price,

1966). The advent of computational methods, such as graphical techniques, analog models, and finite element methods (Dunbar and Cook, 2003), allowed geologists to perform more sophisticated structural restoration models. With today's available technologies such as Dynel 2D and Dynel 3D software's, structural restoration can be performed in the two-dimensional domain, as well as in the third dimensions (Abuhabbial et al., 2017; Amer et al., 2014).

Furthermore, utilizing such software capabilities the stain and stress along the deformed sections can be calculated and captured providing insights into the potential natural fracture and fault systems distribution across the studied area. This technique is also used in quality checking regional correlations of structural interpreted horizons on regional seismic lines (Wilkerson and Dicken, 2001), basin modeling (Hantschel and Kauerauf, 2009), and subseismic fault modeling (Maerten and Maerten, 2006).

4 Original Publications

4.1 Paper I

The motivation for writing this article came from the lack of depositional facies studies over the Jal Az-Zor outcrops and a two-decade hiatus in related publications on these exposures. Additionally, following an American Association of Petroleum Geologists (AAPG) Geoscience Technology Workshop (GTW) field trip to these outcrops in 2015, I noticed a misinterpretation of some lithofacies and depositional settings. Bioturbations such as Ophiomorpha, Thalassinoides, and Skolithos burrows were falsely thought to represent Rhizoliths. Consequently, a separate section with outcrop examples in Paper I was dedicated to explain these ichnofacies and how they are differentiated from Rhizoliths.

Paper I focused on producing a descriptive stratigraphic section of the Jal Az-Zor exposed rock units by identifying facies cyclicity along with the facies architecture (**Fig. 1**). We achieved this by characterizing the sedimentological facies and facies associations.

The methods included outcrop field work, a detailed sedimentological description, and X-ray diffraction (XRD) and X-ray fluorescence (XRF) analyses of 20 rock samples. The sedimentological work focused on identifying the lithology, grain sizes, minerology, fossil content, sedimentary structures, and ichnofabric.

The results of this research article demonstrate that understanding the principal building blocks of the Jal Az-Zor exposed sequences is critical in understand its facies architecture (**Fig. 3**). Over the study area in Kuwait, sixteen genetically related facies were identified based on lithological and sedimentological attributes, and further grouped into six facies associations detailed in **Table 1**.

Paper I concluded that the Jal Az-Zor escarpment comprises fluvial, shoreface, barrier island, back-barrier, tidal channel estuarine complexes. These depositional facies are characterized by parasequence sets that generally reflect a regressive stacking pattern. Paleocurrent analysis performed on the observed channel scours, lateral accretion surfaces, and trough cross beddings indicate a NE terrestrial river flow direction and a NW-SW paleoshoreline trend. Our work developed a detailed depositional facies model that was able, for the first time, in the Jal Az-Zor escarpment, to explain the vertical and lateral facies relationships (**Fig. 3**).

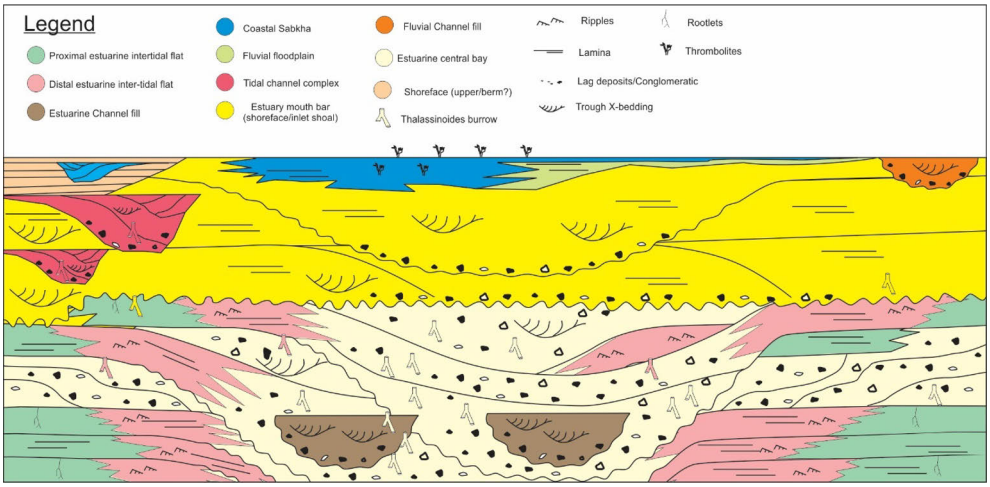

Figure 3. An overview of the facies architecture developed of the Jal Az-Zor outcrop in Kuwait (Modified after Amer et al., 2019).

Table 1. Paper I facies and facies associations summary table (Amer, et al. 2019).

Facies association		No#	Facies	Abbreviation	Depositional environment
FA-1	Estuarine	1	Bioturbated cross-bedded	(F1)	Estuarine central bay (channel bar)
		2	Cross-bedded conglomeratic	(F2)	Estuarine channel fill
		3	Red claystone	(F3a)	Distal estuarine intertidal flat
		4	Reddish-green claystone	(F3b)	Proximal estuarine intertidal flat
		5	Calcareous sandstone	(F4)	Estuary mouth bar (shoreface/inlet shoal)
FA-2	Tidal channel	6	Cross-bedded sandstone	(F5a)	Tidal channel fill
		7	Lateral accretion red sandstone	(F5b)	Tidal channel point bar
		8	Bedded red muddy sandstone	(F5c)	Tidal channel overbank
FA-3	Shoreface	9	Fine-grained-bedded sandstone	(F6b)	Foreshore
		10	Microbialites	(F6c)	Intertidal to supratidal
FA-4	Terrestrial	11	Yellowish-green siltstone	(F8)	Fluvial overbank
		12	Trough cross-bedded sandstone	(F7)	Fluvial channel fill
FA-5	Barrier island	13	Coarsening-upward calcareous sandstone	(F9)	Barrier island
		14	Fossiliferous sandstone	(F6a)	Fossiliferous shoal
		15	Microbialites	(F6c)	Intertidal to supratidal
FA-6	Back-barrier	16	Unconsolidated silty-sand	(F6d)	Backshore/berm
		17	Calcareous sandstone lenses	(F10)	Shoal inlet
		18	Yellowish-green siltstone	(F8)	Back-barrier lagoon
		19	Microbialites	(F6c)	Intertidal to supratidal

4.2 Paper II

The motivation to write this paper was following a review of a few seismic lines conducted during the first study (Paper I) and the paper by Carman, (1996) that proposed the presence of the Jal Az-Zor fault plane in the Kuwait Bay area. As I was reviewing the seismic data, I did not find the large fault plane under the Kuwait Bay; on the other hand, a deep-seated, wrench fault system underlaying the Jal Az-Zor escarpment was evidenced during my initial assessment (**Fig. 1**).

The aim of this article was to reprocess recently acquired shallow seismic data along the Jal Az-Zor escarpment and the Kuwait Bay area and further interpret the structural elements that led to the formation of this pronounced structure. This interpretation involved the picking of horizons, faults, and 2D structural restoration and balancing. The main challenge of using such data is selecting a method that can enhance the signal-to-noise ratio in the post-stack time domain. Furthermore, because of the low signal-to-noise ratio, the shallow portion of the seismic data has been overlooked, hence the structural complexities have not been revealed, leading to the general assumption of a simple tectonic history of the escarpment.

The methodology adopted in this paper was based on developing a relationship between surface and subsurface structures with a focus on the shallow geological section using Petrel software. Post-stack time automatic gain control (AGC) processing was performed on seismic data designed to image deeper reservoirs, and the aim was to enhance formation reflectors and attenuate noise. This is followed by the horizon and fault interpretation on 2D seismic lines that cross the Jal Az-Zor escarpment at three localities. The new interpretation was compared to a previous interpretation performed on older seismic line previously acquired over the same grid line by Al-Anzi, (1995). Lastly, 2D structural restoration and balancing was performed on a representative seismic line that crosses the escarpment using Dynel 2D software. The seismic interpretation revealed several structures which have not been identified previously in Kuwait over the studied area and concluded that the fault described by Carman, (1996) does not excise. This paper also concludes that a basement fault system underlies the Jal Az-Zor escarpment and is found to be responsible for its topography. The Jal Az-Zor fault system comprises recumbent and detachment folds, thrust faults, and fault propagation folds, forming what can be described as a complex folded duplex system. In this work we postulated that these structures formed as a result of a principal displacement zone (PDZ) system that connected to the larger Batin Fault system to the northeast and collectively acted as a pivot for current counterclockwise rotation of the Arabian Plate. 2D restoration suggested a total of 6.25 km of shortening, and Calabrian timing for the event leading to the formation of the escarpment. Furthermore, a new E-W fault system was identified and interpreted for the first time in Kuwait, where it has been found on seismic and

surface topography. We named this dextral strike-slip fault system the Majeelis-Al liyah Fault after the two villages it passes through (**Fig. 4**). This work underlined the importance of evaluating the near-surface structures in conjunction with surface topography to unravel the final stages of tectonic evolution.

In conclusion, the surface relief of the Jal Az-Zor escarpment has been discovered to be caused by fault propagation folding along the Jal Az-Zor basement fault and increased friction along the basal detachment plan due to increased dip of beds near the Kuwait Arch to the south of the line. Based on 2D structural restoration and balancing, the timing of the development of the recumbent folds was during the early Pleistocene epoch, whereas the formation of the propagation fold that led to the final emergence of the Jal Az-Zor escarpment was during the Holocene epoch.

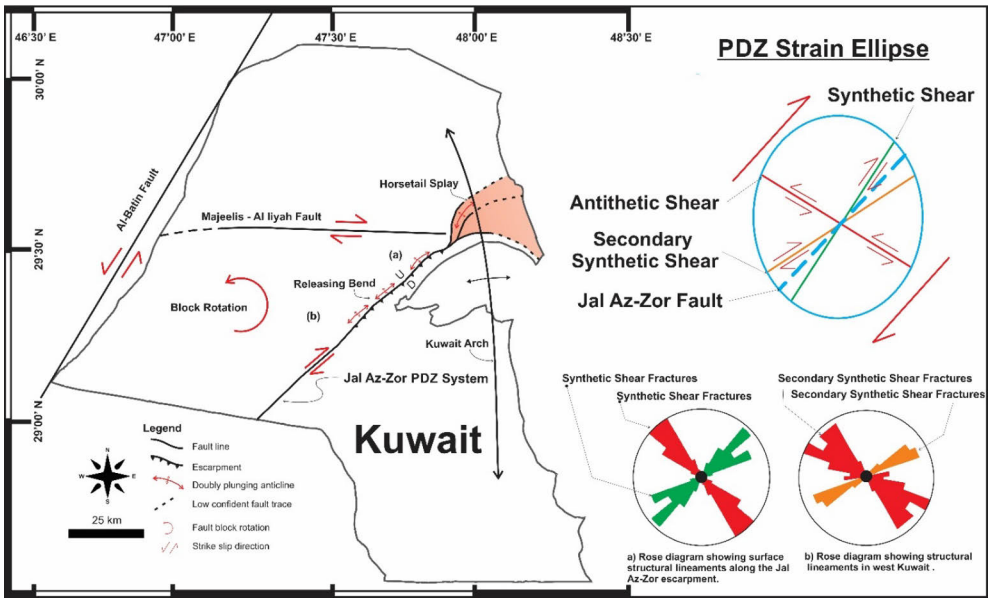

Figure 4. The Jal Az-Zor principal displacement zone along with its stain ellipse. Rose diagram (a) and (b) modified after (Chitaransh, 2014) to show the strain ellipse components that confirm the introduced PDZ concept in this region (Modified after Amer and Al-Hajeri, 2020).

4.3 Paper III

The impetus to write this article originated from knowledge gap related to the facies composition of the detachment plane discovered at the Jal Az-Zor duplex fold complexes at the Rus Formation level, and a visit to the early Eocene Rus Formation outcrops in Bahrain, where I was expecting to see a succession of evaporites as

indicated by several regional sources (Pierce, 1993; Powers et al., 1966; Sharland et al., 2004, 2001; Ziegler, 2001). Instead, I found a section dominated by carbonates interbedded with clay and negligible amounts of evaporite deposits.

The objective of this article was to perform a detailed sedimentological and stratigraphic analyses of the Horse-Racing Club (HRC) outcrop in Bahrain (**Fig. 1**), to develop a stratigraphic section and identify the depositional environment of the Rus Formation in Bahrain (**Fig. 2**).

Detailed sedimentological analyses of the early Eocene Rus Formation Horse Racing Club exposure in Bahrain reveal that the exposed rock units are dominated by dolomites, which are interbedded with minor clay and marl units. Thirteen facies were identified in the Rus Formation that are grouped into five facies associations. The recognized facies are chalky dolostone (F1), lithoclastic chalky dolostone (F2), peloidal dolostone (F3), foraminiferal dolostone (F4), claystone (F5), evaporite (F6), argillaceous dolostone (F7), dolomitic marl (F8), bioturbated chalky dolostone (F9), cross bedded dolostone (F10), microbial dolostone (F11), bedded dolostone (F12), and clinoformal dolostone facies (F13). Furthermore, the facies associations are described as; barrier island and washover complexes, peritidal channel complexes, sabkha complexes, transgressive lag, and lagoonal complexes (**Fig. 5**).

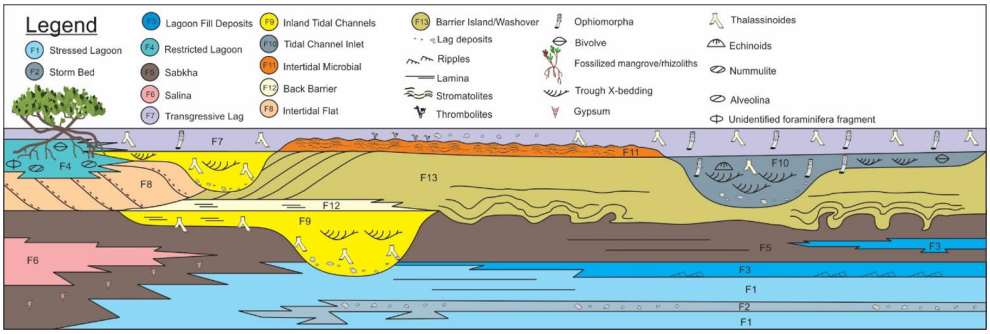

Figure 5. An overview of the facies architecture of the HRC outcrop in Bahrain.

We demonstrate that the Rus Formation in Bahrain is dominated by porous dolomites with porosities reaching up to 17%, marking this formation as a potential hydrocarbon reservoir or water aquifer. Furthermore, the regional evaluation revealed that the early Eocene Rus Formation is considered a source rock in North Oman (Al Hajari and Khaled, 1994) and a water aquifer in Bahrain (Zubari, 1999) and Qatar (Baalousha, 2016), contrasting the previous considerations. However, in Kuwait (Abdullah et al., 1997) the Rus Formation is dominated by evaporites, which facilitated the detachment and the formation of the duplex fold complexes discovered in Paper II. This work highlights the uncertainty associated with the efficiency and

presence of the early Eocene Rus Formation evaporitic unit over the region which demands a petroleum systems reassessment of the area. Our work demonstrated for the first time that the Rus Formation composition varies widely and evaporites are a minority facies in Bahrain, making the Rus Formation a potential reservoir, and not as seal, contrary to previous believes.

5 Discussion

The Paleogene and Neogene periods succession and its exposures across the Arabian Peninsula are not yet understood and up to date only limited geological studies have been performed to resolve their complexities. In this thesis, the challenge was divided into two categories, one focused on the sedimentological and stratigraphic aspect of the outcrops, whereas the second one concentrated on the structural development of some of the major structures in northern Arabia, in particular the Jal Az-Zor escarpment. My thesis focused on two main regions within the Arabian Peninsula, which are the state of Kuwait and the Kingdom of Bahrain. Additionally, I highlighted the role the Jal Az-Zor escarpment played in the overall Arabian Plate rotational matrix. Out of the three detailed studies, represented by Papers I to III, new insights were revealed in terms of the depositional facies of the Lower Fars Formation exposure at the Jal Az-Zor escarpment, the structural evolution of the Jal Az-Zor escarpment, and the depositional facies of the Rus Formation in Bahrain.

In particular, the rock-forming units of the Jal Az-Zor escarpment were previously thought to be represented by three formations, which are Ghar, Lower Fars, and Dibdibba (Alsharhan and Nairn, 1995; Duane et al., 2015; Mukhopadhyay et al., 1996; Owen and Nasr, 1958). It has been demonstrated in Paper I that the exposed unit cannot accommodate the three formations, and based on the presented field sedimentological analysis, the Lower Fars Formation nomenclature was adopted because of the absence of biostratigraphic markers and radiometric age dating. To address this challenge, a follow-up article was later published, which determined through strontium isotopes radiometric dating the ages of the exposed units and proposed a change in the Neogene and Paleogene nomenclature of Kuwait (for more details see Amer and Al-Hajeri, 2019).

Before publishing Paper II, there was an equivocal debate regarding the origin of the largest escarpment in the northeastern region of Arabia, where the origin was assumed to be a result of erosion (Al Sarawi, 1982; Salman, 1979), while others suggested the escarpment was a result of basement faulting (Bou-Rabee and Kleinkopf, 1994). The detailed seismic interpretation and structural restoration confirmed the latter suggestion and demonstrated that the escarpment uplift occurred during the early Pleistocene epoch. Furthermore, this work revealed the regional role

that the Jal Az-Zor fault plane is playing in the counterclockwise rotation of the Arabian Plate and the impact of the basal detachment over the Rus Formation in generating the Jal Az-Zor escarpment surface expression.

Over the Arabian Peninsula, it was widely thought that the Rus Formation is a regional hydrocarbon seal composed predominantly of evaporitic deposits (Pierce, 1993; Sharland et al., 2004, 2001; Ziegler, 2001). Conducting a thorough literature review in Paper III, I determined that the cause of this misconception is most likely a result of the early work of Powers et al., (1966) and Willis, (1967). These authors attributed the soft sediment deformation and drilling losses to being caused by anhydrite dissolution. Furthermore, despite the dominance of carbonates in the Rus Formation reference section (26° 19' 04"-50° 07' 51") in the Eastern Province of Saudi Arabia, they still described the formation as being dominated by evaporites with few porous beds. Some authors (Sharland et al., 2001; Ziegler, 2001) used this knowledge in developing the regional petroleum system and correlations, that led to at least partially inaccurate evaporitic dominance of the Rus Formation. My work evaluated the Rus Formation exposures in Bahrain, revealing that the Rus Formation is represented by dolostones that are associated with claystone, and marls. The evaporitic deposits are found to represent a minority facies in Bahrain, on the contrary of Kuwait where the formation is dominated by anhydrites and were found to be responsible for the detachment and the formation of duplex fold complexes of the Jal Az-Zor escarpment (**Fig. 6**).

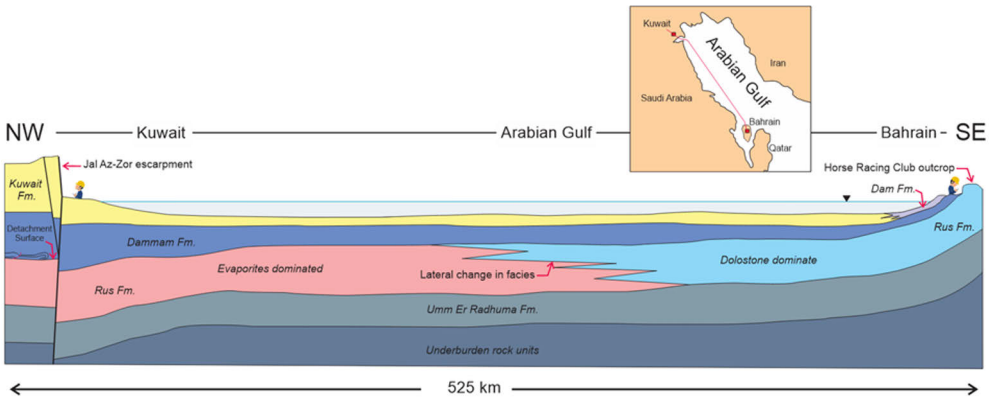

Figure 6. Schematic diagram illustrating the relationship between the Jal Az-Zor escarpment in Kuwait and the exposed Rus Formation units in Bahrain.

This works highlights the heterogeneous nature of the Rus Formation facies across the region, underpinning the change from evaporites to dolomite dominated facies, and its impact on the hydrocarbon seal capacity (**Fig. 2**). The evaporitic facies

of the Rus Formation encompass the entire area of Kuwait including the offshore region (Al-Fares et al., 1998) and exhibits a total thickness that ranges from 100 to 192 m (Abdullah et al., 1997). Such criteria are considered adequate to act as a local hydrocarbon seal. This understanding is confirmed by the hydrocarbon accumulations found in the Wafra Field onshore Kuwait (Meddaugh et al., 2013, 2007) where the Rus Formation provides a wide catchment area canopy for petroleum. In contrast, the Rus Formation is considered more of a reservoir or aquifer in Bahrain, due to the limited occurrence of the evaporitic facies and the wide spread of porous dolomites.

The most important implications of this thesis resulted in a nomenclature change in Kuwait's Neogene and Paleogene successions, highlighted the role of the Jal Az-Zor escarpment in the overall Arabian Plate rotation, and emphasised that the Rus Formation in Bahrain is considered a reservoir and not a seal.

6 Conclusions

The work performed in this thesis revealed new sedimentological and structural insights over the Arabian Peninsula. This thesis concluded with the following points:

- The lithological units exposed over the Jal Az-Zor escarpment can't be represented by the tripartite subdivision of the Kuwait Group; hence, the exposed facies belong to the Lower Fars Formation.

- Sixteen facies with genetic connections and six facies associations have been detailed and identified over the Jal Az-Zor exposure in Kuwait.

- Paleocurrent analysis of the facies exposed at the Jal Az-Zor rock-units suggests a NW-SE paleoshoreline and a NE fluvial paleoflow direction.

- The reprocessed seismic data over the Jal Az-Zor area allowed the interpretation of unprecedented structures in Kuwait, such as recumbent and detachment folds, thrust faults, and fault propagation folds, forming a complex folded duplex system.

- The seismic interpretation over Kuwait also revealed a new fault system that had an extensive influence on Kuwait's geomorphology, which was identified as the Majeelis-Al liyah fault line.

- The Jal Az-Zor fault plane has been interpreted as a dextral strike-slip fault that represents a PDZ that is connected to the Al-Batin Fault system and is found to act as a critical component in the Arabian Plate counterclockwise rotation kinematics.

- The 2D structural analysis and restoration of a key 2D line intersecting the Jal Az-Zor escarpment suggest a total shortening of approximately 6.25 km. When accounting for the velocities and directions of the Arabian Plate, the

estimated time required for this deformation to transpire is approximately 1 Ma from present.

- Over the Rus Formation exposed in Bahrain, thirteen genetically related facies have been identified over the HRC outcrop that are grouped into five facies associations.

- The Rus Formation facies model suggests that the evaporitic deposits over Bahrain are restricted to saline areas and that the area was impacted by periodic storm events.

- This work showed a paradigm shift in the Rus Formation capability to act as a seal, whereas in Bahrain it is considered a reservoir with porosities reaching up to 17 %.

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Aimen Amer

12 November 2023

Aimen Hussien Amer

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