

**3D Subsurface Geological Modeling of a Structurally Complex
Area: A Case Study from Al-Hassa Oasis, Eastern Saudi
Arabia**

Abid Khogali

GEOLOGY

May, 2024

3D Subsurface Geological Modeling of a Structurally Complex Area: A Case Study from Al-Hassa Oasis, Eastern Saudi Arabia

BY

Abid Khogali

A Dissertation 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

DOCTOR OF PHILOSOPHY

In
GEOLOGY

May, 2024

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

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


Dr. John D. Humphrey
Department Chairman


Prof. Suliman Saleh Al-Homidan
Dean of Graduate Studies

Date




Prof. Panteleimon Soupios
(Advisor)


Dr. Israa Abu-Mahfouz
(Co-Advisor)


Dr. Bassam Tawabini
(Member)


Dr. Sherif Hanafy
(Member)


Dr. Abdulaziz M. Al-Shaibani
(Member)

© Abid Khogali

2024

To my parents and brothers

To my wife and my son Basil

To the Sudanese community at King Fahd University of Petroleum and minerals

ACKNOWLEDGMENTS

I am immensely grateful to the Department of Geosciences and the College of Petroleum Engineering and Geosciences at King Fahd University of Petroleum and Minerals for providing me with the opportunity to pursue my PhD. The facilities and assistance afforded to me have been crucial in my research.

Special thanks to my supervisor, Prof. Panteleimon Soupios, for his invaluable guidance, assistance, and unwavering support throughout my PhD. I also wish to express my gratitude to my co-advisor, Israa Abu-Mahfouz, and committee members Dr. Bassam Tawabini, Dr. Sherif Hanafy, and Dr. Abdulaziz Al-Shaibani for their expert advice and helpful insights.

My sincere thanks go to Dr. John Humphery, the chairman of the Geosciences Department, for his support and encouragement during this research.

I am deeply appreciative of the unwavering support, prayers, and patience of my family—my wife, my son, my parents, and my brothers. Their constant encouragement has been a cornerstone of my strength and perseverance.

Lastly, I am thankful to my colleagues and friends at the Geosciences Department and KFUPM for their camaraderie and the collaborative environment they provided, which has been instrumental in my academic and personal growth.

This journey would not have been possible without the collective support and encouragement of each individual mentioned and many others who have contributed in various ways to my studies and this research.

TABLE OF CONTENTS

ACKNOWLEDGMENTS	V
TABLE OF CONTENTS	VI
LIST OF TABLES	IX
LIST OF FIGURES	X
LIST OF ABBREVIATIONS	XVII
ABSTRACT	XVIII
ملخص الرسالة	XXI
CHAPTER 1 INTRODUCTION	1
1.1 Introduction	1
1.2 Problem statement and research gap	3
1.3 Objectives of the thesis	4
1.4 Study area	5
1.5 Literature review	5
1.5.1 Tectonics	6
1.5.2 Stratigraphic framework	7
1.5.3 Hydrogeology	13
1.6 Data and Methodology	15
1.6.1 Geological, Hydrogeological, and Geophysical Field Investigations:	15
1.6.2 Groundwater Sampling:	17
1.6.3 Laboratory analysis	18

CHAPTER 2 STRUCTURAL ANALYSIS OF NEOGENE SANDSTONE SEQUENCE THROUGH INTEGRATED DIGITAL OUTCROP MODELING AND FIELD INVESTIGATIONS	20
2.1 Introduction	20
2.2 Study area, geological and tectonic settings.....	22
2.3 Methodology	25
2.4 Results	27
 CHAPTER 3 SUBSURFACE CHARACTERIZATION OF THE AL-HASSA NATIONAL PARK, EASTERN SAUDI ARABIA, USING MULTI-GEOPHYSICAL METHODS	31
3.1 Introduction.....	31
3.2 Study area, Geology and Tectonic Regime	34
3.3 Geophysical Survey Methods and Data Acquisition	37
3.3.1 Magnetic Data	40
3.3.2 Gravity Data	41
3.3.3 Magnetotelluric Data	44
3.3.4 Transient Electromagnetic Data.....	45
3.4 Geophysical Data Results	47
3.4.1 Magnetic	47
3.4.2 Gravity.....	47
3.4.3 MT and TEM	51
 CHAPTER 4 RECONSTRUCTION OF THE SUBSURFACE OF AL-HASSA OASIS USING GRAVITY GEOPHYSICAL DATA	55
4.1 Introduction.....	55
4.2 Study area - Geological and Tectonic settings	59
4.3 Gravity survey	63
4.3.1 Gravity data processing	65

4.4	Results	68
 CHAPTER 5 SUBSURFACE COMPLEXITY CONTROLS THE AQUIFER HETEROGENEITY: A CASE STUDY FROM THE AL-HASSA OASIS, EASTERN SAUDI ARABIA.....		
		74
5.1	Introduction.....	74
5.2	The study area	75
5.3	Geological, hydrological, and tectonic setting	77
5.4	Methodology	80
5.5	Results	85
5.5.1	Hydrochemical investigations.....	85
5.5.2	Gravity Survey	96
 CHAPTER 6 DISCUSSION		99
6.1	Structural analysis of Neogene sandstone sequence through integrated digital outcrop modeling and field investigations	99
6.1.1	Fracture characteristics	99
6.1.2	Implications for hydrocarbon exploration	103
6.2	Subsurface characterization of the Al-Hassa national park, eastern Saudi Arabia, using multi- geophysical methods	104
6.3	Reconstruction of the subsurface of Al-Hassa Oasis using gravity geophysical data	111
6.4	Subsurface complexity controls the aquifer heterogeneity: a case study from the Al-Hassa oasis, eastern Saudi Arabia	115
 CHAPTER 7 CONCLUSION.....		122
 REFERENCES.....		124
 VITAE.....		148

LIST OF TABLES

Table 1: 3D inversion settings	45
Table 2: Summary of descriptive statistics for hydrochemical parameters, comparison with international and local drinking water standards, and proportion of parameters surpassing permissible thresholds.	86
Table 3: Correlation matrix of chemical parameters of the groundwater in the study area. The strong correlation between different parameters is highlighted in bold.	89
Table 4: Oxygen and hydrogen isotopic ratios of 11 selected samples along with the total well depths and TDS.	91

LIST OF FIGURES

Figure 1: Google map showing the study area in Al-Hassa, the locations of the major hot and cold springs (after personal communication with Dr. M. Alfarhan), and approximate zones of hot and cold water with respect to the sampled wells in the Al-Hassa area.	2
Figure 2: Explanation of temperature variations in different springs (Nabulsi, 1987).	3
Figure 3: Nearly vertical fracture sets in the Hofuf Formation at Jabel Al-Bariqa. A) NW set B) NE set.	7
Figure 4: Stratigraphic column and aquifers system of the Cretaceous and Tertiary periods in Saudi Arabia (Dirks et al 2018).	9
Figure 5: Geological map of the Gulf of eastern Saudi Arabia modified from Al-Sayari and Zötl (1978).	11
Figure 6: Lithological column of the Hofuf and Dam formations (Saner et al, 2005).	13
Figure 7: Geological and hydrological characteristics of the study area (Al Tokhais and Rausch, 2008)	14
Figure 8: a) Structural and Tectonic map of Arabian Plate showing the location of the study area (from Ziegler (2001)). b) Geological map of the study area (modified from Al-Mahmoud, (1987)).	23
Figure 9: Generalized stratigraphic column of eastern Saudi Arabia and the lithostratigraphic sequence of the Hofuf Formation (modified after Dirks et al. (2018); Powers et al. (1966); Saner et al. (2005))	24
Figure 10: Digital Outcrop Model (DOM) of the Hofuf Formation in the Al-Hassa area.	26

Figure 11: a) Structural data acquisition using traditional fieldwork. b) Structural data acquisition GeoAnalysisTools extension. C) An example of the fractures observed in the calcareous sandstone unit of the Hofuf Formation.....	26
Figure 12: DOM structural data a) Orientation of open fractures or joints within the Hofuf Formation. b) Histogram depicting the dip angles of fractures.	28
Figure 13: Traditional fieldwork structural data a) Orientation of open fractures or joints within the Hofuf Formation. b) Histogram depicting the dip angles of fractures.	28
Figure 14: DOM fracture length analysis a) Distribution of open fracture. b) Log-log plot of fracture lengths distribution.....	29
Figure 15: DOM fracture aperture analysis a) Distribution of open fracture aperture. b) Log-log plot of fracture aperture distribution.	30
Figure 16: (a) The coverage of Saudi Arabia by geological maps released by the Saudi Geological Survey is presented by the colored rectangles. A thick black square depicts the location of the study area. (b) Geological map of the wider area (modified from (Al-Mahmoud, 1987)). A black rectangle shows the study area of the National Park. (c) The study area with all the acquired geophysical (AMT, MT, TEM, gravity, and magnetic) measurements.....	35
Figure 17: (a) W-E section showing the geologic formations, the groundwater flow (black and red arrows), and the subsurface deformation due to basement uplift beneath the study area (Al Tokhais and Rausch, 2008). (b) Fault zone pattern (Hussain et al., 2006) and (c) Fault zone field photo showing the major ENE-WSW and NNW-SSE directions observed at an outcrop within the study area.	37

Figure 18: The magnetic response along the measured profile is indicated with the black line and the recorded magnetic field (color scale). (a) The data before noise filtering and spike removal. The three high-amplitude responses, marked with yellow circles, correspond to cultural noise sources. (b) The results after the data processing.....	48
Figure 19: The results of the gravity data processing. The white dots correspond to the measured gravity stations. (a) The complete Bouguer anomaly map. (b) The residual gravity field map.	49
Figure 20: Enhancement filters on the gravity data. (a) The tilt derivative and the interpreted lineaments (black lines) correspond to structural edges. (b) The terracing map is overlaid by the results of the tilt-depth method and shown as colorful dots (the depth in the color bar is positive down).	50
Figure 21: The 3D model of the Al-Hassa National Park survey area shows the negative density contrast bodies. (a) Top view of the model. The residual gravity field map overlays the anomaly sources, and the locations of the acquired gravity stations are shown as black points. (b) Side view of the model, in which the depth of the interpreted bodies can be studied. The directions of the geotectonic elements and their relative positions are also shown.	50
Figure 22: The 3D inversion results of MT data collected in the Al-Hassa National Park. The 3D resistivity model is presented as xy-sections for different depth ranges. The triangle symbols show the MT station locations. Depth increases from left to right and top to bottom.....	51

Figure 23: The 3D inversion results of MT data along three MT profiles. Each section line's location is shown on the plan view of the survey area given on the right side of the related 2D section.....	52
Figure 24: Quasi-3D TEM modeling. The depth slices for the depths of (a) 0-100 m, (b) 100-200 m, and (c) 200-300 m. (d) The depth slice for the depth of 170-220 m below the ground surface from the 3D MT data inversion.	54
Figure 25: a) The coverage of Saudi Arabia by geological maps released by the Saudi Geological Survey is presented by the colored rectangles. A thick black square depicts the location of the study area. (b) Geological map of the wider area (modified from Al-Mahmoud (Al-Mahmoud, 1987)). A red rectangle shows the location of the caves map on Figure 1d. (c) The study area with all the acquired gravity geophysical measurements is presented. The camera icon shows the location of the photo shown in Figure 1f (d) The fault zone pattern described by Hussain et al. (Hussain et al., 2006) is depicted. (e) W-E section shows the geologic formations, the groundwater flow (blue and red arrows), and the subsurface deformation due to basement uplift beneath the study area (modified from Al Tokhais and Rausch (Al Tokhais and Rausch, 2008)), and (f) Fault zone field photo showing the major ENE-WSW and NNW-SSE directions observed at an outcrop within the study area.....	61
Figure 26: The complete Bouguer anomaly map of the Al-Hassa study area. The white points correspond to the locations of the gravity stations.....	69

Figure 27: The residual gravity field map with the locations of the gravity stations (white points). The black rectangle indicates the boundaries of the 3D modeling area.	70
Figure 28: a) The tilt derivative and the interpreted lineaments (black lines), which correspond to structural edges (tectonic lineaments and/or rock contacts) are presented. b) Rose diagram of the interpreted lineaments (insert into the Figure with the tilt derivative and the lineaments).	71
Figure 29: The terracing map overlaid by the results of the tilt-depth method (shown as colorful dots). The depth in the depth color bar is positive down.	72
Figure 30: a) The top view of the 3D model of the Al-Hassa oasis area shows the positive (pink bodies) and negative (blue bodies) density contrast anomalies. b) 3D model of the study area, showing the negative density bodies, that correspond to subsurface basins.	73
Figure 31: a) Location of the study area within the Arabian Peninsula. b) Sample locations and geophysical measurement stations. C) Geological map of the study area. d) Potentiometric surface in the eastern section of the study area.	77
Figure 32: a) Stratigraphic column of the study area (modified after Al Tokhais and Rausch, 2008; Dirks et al., 2018; Powers et al., 1966). b) West-east geological section crossing central Saudi Arabia to the Arabian Gulf showing major aquifers and the recharge and discharge zones. The extent of this cross-section is shown in Figure1a (modified from Al Tokhais and Rausch, 2008).	80
Figure 33: Hydrochemical facies classification of the groundwater of Al-Hassa oasis using Piper diagram.	88

Figure 34: a) Dendrogram clustering based on the chemical parameters of 113 groundwater samples in the study area. b) The relationship between the clustered groups based on the chemical characteristics of the sampled groundwater.	90
Figure 35: a) The relation between the TDS and well depths of 11 selected groundwater samples. b) Plot of $\delta^2\text{H}$ vs $\delta^{18}\text{O}$ of the selected samples.	91
Figure 36: Spatial distribution maps of a) TDS b) EC c) Ca^{2+} d) Cl^- e) HCO_3^- f) K^+ g) Mg^{2+} h) Na^+ i) NO_3^- j) SO_4^{2-}	93
Figure 37: Gibbs diagrams illustrating the mechanisms controlling hydrochemical evolution of the analyzed groundwater based on a) Na^+ to Ca^{2+} and b) Cl^- to HCO_3^- ratios.	94
Figure 38: Scatter plots displaying the relationship between the saturation indices of calcite, dolomite, anhydrite, halite, and gypsum in the present study.....	94
Figure 39: Scatter plots of the relationship between a) HCO_3^- + SO_4^{2-} and Ca^{2+} + Mg^{2+} , b) Na^+ and Cl^- , c) Ca^{2+} and HCO_3^- , d) Ca^{2+} and SO_4^{2-}	95
Figure 40: Residual Bouguer anomaly map of the study area based on 571 gravity stations, as depicted by green squares.	97
Figure 41: Total horizontal derivative (THDR) and terracing map.	98
Figure 42: Fracture aperture size vs length measured from the DOM. Fissure: open fracture with an aperture size > 1 cm. Joint: open fracture with an aperture size <1 cm.	102
Figure 43: A comparison between the 2D MT and gravity models along the W-E direction. (a) The 2D MT cross-section of the 3D resistivity model (Figure 8b). (b) root mean square (rms) interpretation as the discrepancy between the observed and	

calculated values of the gravity measurements, and (c) the 2D model is based on the inversion of gravity data.	108
Figure 44: The 3D resistivity model for the study area of the Al-Hassa National Park is presented.	111
Figure 45: Spatial distribution of TDS and water temperature and their relation to density variations in the subsurface.....	121

LIST OF ABBREVIATIONS

AMT	:	Audio Magnetotelluric
CBA	:	Complete Bouguer anomaly
DEM	:	Digital Elevation Model
DGPS	:	Differential Global Positioning System
EM	:	Electromagnetic
MASL	:	Meters above sea level
MCM	:	Million cubic meters
MT	:	Magnetotelluric
SRTM	:	Shuttle Radar Topography Mapping
TDS	:	Total dissolved solids
TEM	:	Transient electromagnetic
THDR	:	Total horizontal derivative

|

ABSTRACT

Full Name : [Abid Gasmalbari Ahmed Khogali]
Thesis Title : [3D Subsurface Geological Modeling of a Structurally Complex Area:
A Case Study from Al-Hassa Oasis, Eastern Saudi Arabia]
Major Field : [Geology]
Date of Degree : [May 2024]

The Al-Hassa area is well-known for its geological and hydrogeological importance since it has historically boasted over 280 natural springs, which were used to irrigate the largest oasis in the world. Al-Hassa is located near the renowned Ghawar oil field, the largest conventional oil field globally. This study utilizes geophysical surveys and geological and hydrogeological investigations to understand and reconstruct the subsurface heterogeneity in the Al-Hassa Oasis area. The covered area in this study is more than 350 km². Therefore, we divided the area into two parts based on the acquired data set to better understand the subsurface. The first part is about 40 km² and is located in the Al-Hassa National Park area in the northeast of the Al-Hassa Oasis. Five geophysical methods were used in this part: 210 gravity stations, a 3.6 km magnetic profile, forty-six magnetotelluric, six audio-magnetotelluric, and 35 transient electromagnetic stations to reconstruct a 3D subsurface model for the Al-Hassa National Park with the highest accuracy. The second part consists of the whole Al-Hassa oasis and is covered with 571 gravity stations and 113 groundwater well hydrochemical data. This study also utilized ground photogrammetry data and regular structural field data acquired from a well-exposed outcrop in the Al-Hassa capturing the Upper Miocene to Lower Pliocene Hofuf Formation. In the Al-Hassa National Park, all electromagnetic soundings were processed and combined to achieve maximum resolution

from the surface to maximum depth of investigation. Gravity and electromagnetic data were combined to create the 3D model. Magnetic data was unimportant, so no interpretation was made. The 3D geophysical subsurface modeling of the study area showed a complex underground structure. Integrating geophysical datasets revealed lateral resistivity discontinuities, a possible salt dome structure, and fracture zones that facilitate or impede groundwater flow. In the whole Al-Hassa part, the resulting 3D geophysical subsurface modeling unveiled an intricate subterranean configuration. It revealed lateral variations in density, indicating the presence of a potential salt dome structure, as well as fracture zones that serve as conduits or obstacles to the flow of the subsurface fluids. The combined hydrochemical and geophysical results show a good agreement between groundwater quality and density (gravity anomalies) distribution within the study area. The southeastern part of the study area exhibits distinctive positive gravity anomalies, indicating denser rock formations alongside high total dissolved solids (TDS) in groundwater, reflecting poor water quality. Conversely, the southwest displays significant negative gravity anomalies, suggesting loose sediments or basins and low TDS values, signifying good water quality. Additionally, the study reveals a pattern in groundwater temperature distribution, with cooler waters in the areas characterized by negative gravity anomalies (basins), and hotter waters emerging from areas with positive gravity anomalies. These findings suggest that groundwater quality differences may stem from varying sub-basins and interactions with distinct geological substrates. Temperature variations may also be attributed to differing subsurface flow pathways. The structural investigations revealed a dominant fracture system trending WNW-ESE, and a series of secondary fracture systems on NW-SE and NE-SW orientations. This suggests that a complex interplay of tectonic

stresses has shaped the area over the geological timescale. Overall, this thesis tries to explain the controlling factors for the subsurface heterogeneity in the Al-Hassa oasis area, emphasizing the role of geological, tectonic, and hydrogeological elements in shaping this oasis's subsurface pattern. |

ملخص الرسالة

الاسم الكامل: عابد قسم الباري احمد خوجلي

عنوان الرسالة: نمذجة ثلاثية الابعاد تحت سطحية لمنطقة ذات تركيب معقد. مثال من واحة الاحساء، شرق المملكة العربية السعودية

التخصص: جيولوجيا

تاريخ الدرجة العلمية: مايو 2024

تُعد منطقة الأحساء معروفة بأهميتها الجيولوجية والهيدروجيولوجية، حيث كانت تضم أكثر من 280 نبعاً طبيعياً استُخدمت تاريخياً لري أكبر واحة في العالم. تقع الأحساء بالقرب من حقل الغوار النفطي، أكبر حقول النفط التقليدية على مستوى العالم. يستخدم هذا البحث المسوحات الجيوفيزيائية والدراسات الجيولوجية والهيدروجيولوجية لفهم وإعادة تصور التنوع الجوفي في منطقة واحة الأحساء. تغطي المنطقة المدروسة أكثر من 350 كم²، ولذلك قسمنا المنطقة إلى جزئين استناداً إلى البيانات المتوفرة لفهم الباطن بشكل أفضل. الجزء الأول يبلغ حوالي 40 كم² ويقع في منطقة منتزه الأحساء الوطنية شمال شرق واحة الأحساء. تم استخدام خمس طرق جيوفيزيائية في هذا الجزء: 210 محطات جاذبية، وخط مغناطيسي بطول 3.6 كم، وستة وأربعون محطة كهرومغناطيسية، وست محطات كهرومغناطيسية سمعية، وخمس وثلاثون محطة كهرومغناطيسية وقتية لبناء نموذج ثلاثي الأبعاد للباطن في حديقة الأحساء الوطنية بأعلى دقة ممكنة. الجزء الثاني يشمل كامل واحة الأحساء ويغطي بـ 571 محطة جاذبية وبيانات هيدروكيميائية لـ 113 بئر مياه جوفية. كما استخدمت الدراسة بيانات الفوتوغرامميتري الأرضية ودراسة الخصائص التركيبية التي تم الحصول عليها من متكشف صخري في الأحساء يغطي تكوين الهفوف من العصر الميوسيني الأعلى إلى البليوسيني الأدنى. في حديقة الأحساء الوطنية، تم معالجة جميع القياسات الكهرومغناطيسية ودمجها لتحقيق أقصى دقة من السطح إلى أقصى عمق للتحقيق. تم دمج البيانات الجاذبية

والكهرومغناطيسية لإنشاء النموذج ثلاثي الأبعاد. لم تكن البيانات المغناطيسية مهمة، لذا لم يتم إجراء تفسير. أظهر نمذجة الباطن الجيوفيزيائي ثلاثية الأبعاد لمنطقة الدراسة بنية تحتية معقدة. كشف دمج مجموعات البيانات الجيوفيزيائية عن انقطاعات في المقاومة الجانبية، وبنية قبة ملحية محتملة، ومناطق كسور وفوالق أرضية تسهل أو تعيق تدفق المياه الجوفية. في الجزء الكامل من الأحساء، كشفت نمذجة الباطن الجيوفيزيائي ثلاثية الأبعاد عن تكوين تحتي معقد وكشفت عن تغيرات جانبية في الكثافة، مما يدل على وجود بنية قبة ملحية محتملة، بالإضافة إلى مناطق الكسر التي تعمل كممرات أو عقبات لتدفق السوائل تحت السطح. أظهرت النتائج الهيدروكيميائية والجيوفيزيائية المدمجة توافقاً جيداً بين جودة المياه الجوفية وتوزيع الكثافة (التشوهات الجاذبية) داخل منطقة الدراسة. يعرض الجزء الجنوبي الشرقي من منطقة الدراسة تشوهات جاذبية إيجابية مميزة، مما يشير إلى تكوينات صخرية أكثر كثافة إلى جانب مواد صلبة ذائبة عالية (TDS) في المياه الجوفية، مما يعكس جودة المياه الرديئة. على النقيض من ذلك، يعرض الجنوب الغربي تشوهات جاذبية سلبية كبيرة، مما يشير إلى رواسب فضفاضة أو أحواض رسوبية وقيم TDS منخفضة، مما يدل على جودة مياه جيدة. بالإضافة إلى ذلك، كشفت الدراسة عن نمط في توزيع درجة حرارة المياه الجوفية، حيث تظهر المياه الباردة في المناطق التي تتميز بتشوهات جاذبية سلبية (الأحواض)، وتظهر المياه الأكثر دفئاً من المناطق التي تتميز بتشوهات جاذبية إيجابية. تشير هذه النتائج إلى أن اختلافات جودة المياه الجوفية قد تنشأ من تفاعلات متفاوتة مع الرواسب الجيولوجية المتميزة. قد تُعزى التغيرات في درجات الحرارة أيضاً إلى مسارات تدفق تحت السطح المختلفة. كشفت الاستقصاءات الهيكلية عن نظام كسر سائد يميل من الغرب الشمالي الغربي إلى الشرق الجنوبي الشرقي، وسلسلة من أنظمة الكسر الثانوية على التوجهات الشمالية الغربية-الجنوبية الشرقية والشمالية الشرقية-الجنوبية الغربية. يوحي ذلك بأن تفاعلاً معقداً من الضغوط التكتونية قد شكل المنطقة عبر الأزمنة الجيولوجية. بوجه عام، تحاول هذه الأطروحة شرح العوامل المسيطرة على التباين تحت السطحي في منطقة واحة

الأحساء، مع التأكيد على دور العناصر الجيولوجية والتكتونية والهيدروجيولوجية في تشكيل نمط الواحة تحت السطحي. |

CHAPTER 1

INTRODUCTION

1.1 Introduction

Al-Hassa region features Saudi Arabia's largest oasis and one of the world's largest naturally irrigated oasis (Figure 1)(Abderrahman and Ukayli, 1984). In the past, date palms were cultivated in an area of around 120 km². Natural artesian pressure has led to a massive amount of groundwater discharging from the underlying aquifers, which allowed for a great area of agricultural land (Al Tokhais and Rausch, 2008).

The irrigation water in this oasis is derived from 280 natural springs. The overall spring discharge was around 315 MCM/a (10 m³/s) in the mid-twenties century (Abderrahman and Ukayli, 1984). The discharge varied greatly, with some springs producing more than 1 m³/s. Even though locals owned several minor springs, many of them, including the major ones, were connected to a public irrigation system (Al-Dakheel et al., 2010). The old irrigation method was clever and effective: with the help of gravity, water was moved and reused across the oasis at varying elevations. The spring's discharge was around 10 m³/s at the turn of the century, but they aren't flowing anymore. Groundwater levels have dropped substantially because of the overexploitation of groundwater resources (Al Tokhais and Rausch, 2008).

Generally, the water in these springs used to be warm, with temperatures ranging from 27 °C to 32 °C (Al-haqel and Bahlah springs); nevertheless, some of them are called hot springs, with temperatures exceeding 32 °C (Al-harra, Al-jawharia, Al-khadoud, Um-saba'a, Najim). The presence of such variability in spring water temperature within this limited area raises a question about the source/s of this groundwater (Figure 1). In 1987, Nabulsi tried to explain this temperature variation as a function of the water flow pathways from the source aquifer to the ground (Figure 2). Hotter springs flow via shorter paths through geological fissures. In contrast, cooler springs groundwater rises through longer paths pecculating within subordinate higher aquifers and flowing sub-horizontally before being able to seep towards the Earth's surface.

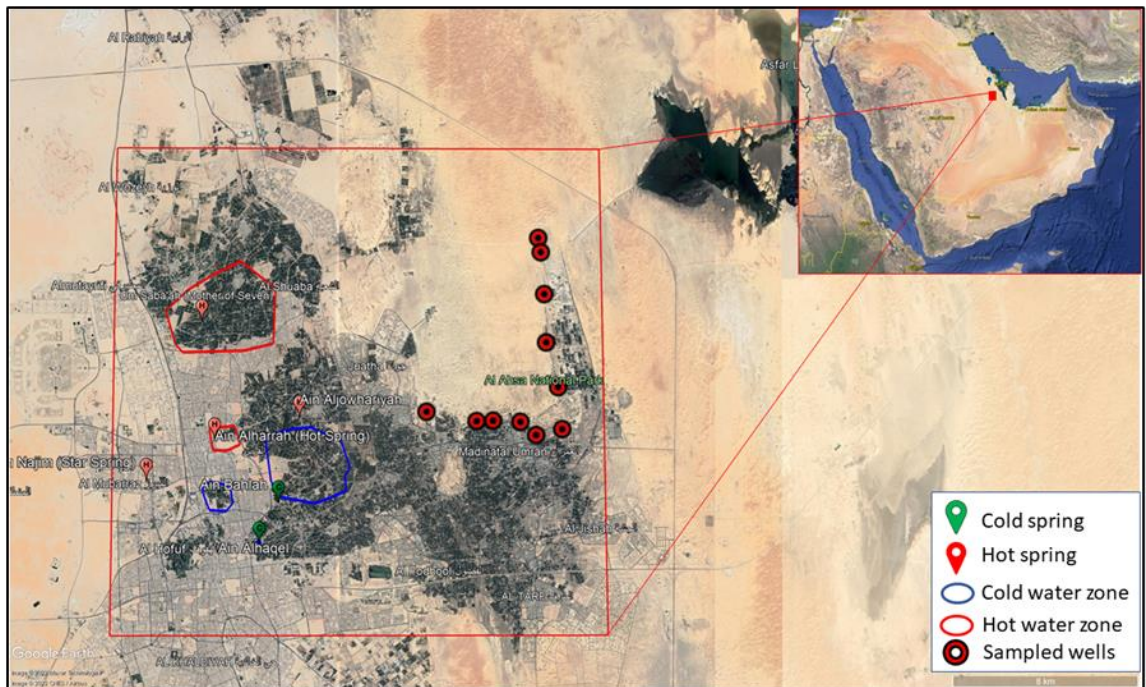


Figure 1: Google map showing the study area in Al-Hassa, the locations of the major hot and cold springs (after personal communication with Dr. M. Alfarhan), and approximate zones of hot and cold water with respect to the sampled wells in the Al-Hassa area.

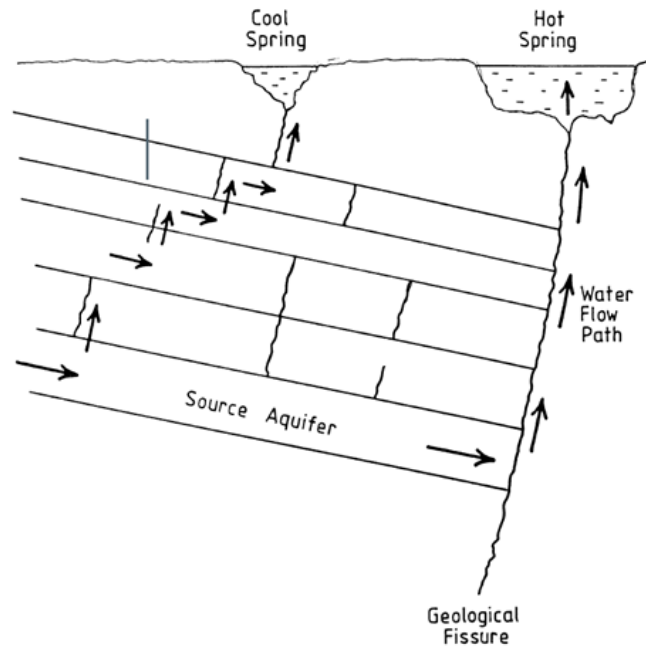


Figure 2: Explanation of temperature variations in different springs (Nabulsi, 1987).

1.2 Problem statement and research gap

Al-Hassa represents one of the important geological areas in Saudi Arabia. The study area comprises the largest oasis in the world. Due to the area's proximity to the giant Ghawar oil field, the oil industry has conducted several geological, tectonic, and geophysical surveys in the past. However, this data remains confidential.

The developed fracture system has led to the formation of one of the most complex aquifers in the Arabian Peninsula. This groundwater system used to discharge a total of 315 MCM/y (million cubic meters/year) from its natural springs (Vidal, 1951), but with the increased overexploitation of groundwater, the drawdown reached 150 m in the last 30 years and numerous wells fell dry (Al Tokhais and Rausch, 2008). In response to this, the Ministry of Environment, Water, and Agriculture has gradually supplied the agricultural area with treated wastewater until it eventually stops depending on groundwater. Several

hydrological and geological studies (Abderrahman and Ukayli, 1984; Alabdula'aly et al., 2010; Al-Dakheel et al., 2010; Al-Naeem, 2011; Al-Omran et al., 2018; Al-Zarah, 2011; Bakiewicz et al., 1982; Chapman, 1974, 1971; Dirks et al., 2018; Hussain, 2006; Kalbus et al., 2011; Nabulsi, 1987; Saner et al., 2005; Sharaf, 2001; Tleel, 1973) have been conducted on Al-Hassa due to its agricultural and historical importance. However, due to its complex nature, these studies did not fully characterize the subsurface geology and the aquifer system. Therefore, there is an urgent need for comprehensive research to investigate such a complex area for its geology, structures, aquifers, and the processes that have shaped all these elements throughout its long history. Additional studies are required utilizing integrated techniques including hydrogeology, tectonic, and geophysical tools to characterize the subsurface geology and aquifer properties and construct a 3D subsurface geological model in the area. |

1.3 Objectives of the thesis

The main aim of this thesis is to develop a comprehensive methodology for characterizing the subsurface geological and structural features of a complex area, specifically the Al-Hassa Oasis, and construct a 3D subsurface geological model. The Al-Hofuf area has been extensively studied by numerous researchers and the oil and gas industry over the years, yet a convincing integrated 3D subsurface model has not been produced to provide a thorough understanding of the subsurface geology.

The primary objectives of this research are listed as follows:

1. To collect and analyze relevant geophysical, geological, and hydrogeological data to understand the complex subsurface geology of the Al-Hassa Oasis.

2. To model and interpret the collected data, generating subsurface models using all available data as inputs.

Ultimately, the goal is to integrate and construct a 3D subsurface geological model that incorporates all available surface and subsurface data from the study area.

1.4 Study area

The Al-Hassa Oasis is located about 60 kilometers west of the Arabian Gulf (Figure 1), between 25° 20' 02" and 25° 32' 30" N Latitudes and 49° 46' 40" and 49° 34' 30" E Longitudes and occupies an area of around 600 km². The region has an elevation that varies between 130 and 160 meters above sea level.

The phrase "Al-Hassa," which derives from Arabic, describes a terrain characterized by piled sand and an impenetrable layer underneath it. When rain falls on such a terrain, the water seeps through the sand (which also shields it from evaporation) and is held by the impermeable base layer, ultimately forming an aquifer. In 2018, the oasis was included on the UNESCO World Heritage Sites list. Additionally, since December 2015, it has been a participant in the UNESCO Creative Cities Network. The most significant oases in the Arabian Peninsula are Al-Hassa Oasis in Saudi Arabia and Al Ain Oasis in the United Arab Emirates near the border with Oman.

1.5 Literature review

The Arabian Plate is often regarded as one of the most significant geological zones on Earth. In the Arabian Shield to the west, it is composed of volcanic rocks, while in the east, it is composed of sedimentary rocks. A complex multi-aquifer system is formed from the

Late Cretaceous and Tertiary formations in Saudi Arabia (Bakiewicz et al., 1982; BRGM, 1976; GTZ/DCO, 2006).

In the subsequent sections, the tectonics, geology, and hydrogeology of the study area are briefly summarized.

1.5.1 Tectonics

The Al-Hassa oasis is located to the east of the Ghawar oil field. It extends from the Ghawar hills to the Al Jafurah sand desert. In this area, naturally flowing springs are the source of the oasis's water and vegetation. This oasis is situated at an elevation of around 130–160 m above sea level, with the Shedgum Plateau reaching a height of 290 meters.

The joint systems that trend either northwest or north-northwest in Jabal Al Qarah have originated by marine waves. These caverns were subsequently changed by fluvial weathering (Al-Sayari and Zötl, 1978). More than one and a half kilometers long, Ghar An Nasab may be found on the eastern slope of Jabal Al-Qarah. It was formed within large and regularly shaped interconnected joints that have various forks. Hussain et al. (2001) investigated the geology of the area around the Jabal Al-Qarah caves. The horizontally bedded Hofuf formation was eroded to develop several geomorphological features in the region. In contrast, the heart of the flat-lying Shedgum plateau is devoid of well-defined stream courses. The fact that there are several big sinkholes that are just a few feet deep and that the rocks underneath them are permeable is evidence that infiltration is a far more important factor in the change of the landscape than runoff erosion.

Saner et al. (2005) noted that the fracture orientations in the outcrops of the Hofuf Formation are randomly distributed and there is no clear fracture pattern. However, during

our reconnaissance field trip, we noticed two clear vertical fracture sets in the outcrop in the NW and NE directions (Figure 3). This may highlight the necessity for a more detailed tectonic investigation of the Hofuf Formation.



Figure 3: Nearly vertical fracture sets in the Hofuf Formation at Jabel Al-Bariqa. A) NW set B) NE set.

1.5.2 Stratigraphic framework

The studied stratigraphic interval comprises (from older to younger), the Cretaceous Wasia and Aruma Groups, the Paleocene Umm Er Radhuma Formation, the early Eocene Rus Formation, and the Eocene Dammam Formation. The Neogene section consists of Hadrukh, Dam, and Hofuf formations. The geological map and stratigraphic column of the study area are shown in Figures 4 and 5.

The Cretaceous Aruma Formation

Powers et al. (1966) provided a comprehensive overview of the Aruma Formation, which had previously been characterized by Steineke et al. (1958). After a further study by El Asa'ad (1984, 1983a, 1983b), the Aruma Formation was found to be composed of three units: the Khanasir member, the Hajajah member, and the Lina member. The Aruma Formation was elevated to the status of a Group and consequently elevated its units to the status of formations by Alsharhan and Nairn in 1990. The Khanasir Formation is made up of limestone with abundant fauna (Vaslet et al., 1991), and it was dated using ammonites as the primary dating method (Le Nindre et al., 2008). The Hajajah Formation comprises limestone with mudstone and shale intercalated throughout it (Philip et al., 2002). The Lina Formation is mostly composed of shales but contains some dolomitic limestone alterations (Philip et al., 2002).

Age	Formation	Lithology	Thickness (m)	Aquifer	
				North	South
Quaternary	surface deposits				
NEOGENE	Plio.			Neogene	
	Hofuf				
	Dam				
	Hadruk				
PALEOGENE	Eocene	Dammam	140-500	Dammam	
		Rus	120-450		
	Paleocene	Umm Er Radhuma	100-270	Umm Er Radhuma	
			405-800		
CRETACEOUS	Aruma		200-250	Aruma	
	Wasia		300-500	Wasia - Biyadh	
	Shu'aiba		<60		
	Biyadh		300-500		
	Buwaib		10-200	Lower Cretaceous	
	Yamama				
	Sulaiy		<200		

Figure 4: Stratigraphic column and aquifers system of the Cretaceous and Tertiary periods in Saudi Arabia (Dirks et al 2018).

The Paleocene Umm Er Radhuma Formation

The reference section of the Paleocene Umm Er Radhuma Formation is approximately 243 m thick and contains a very fine to medium-grained yellowish gray dolomite and includes quartz geodes and chert nodules (Powers et al., 1966). These rocks are believed to be

dolomized later from shallow marine limestone (Tleel, 1973). It contains fragments of pelecypods, echinoid spines, and undefined Foraminifera (Al-Sayari and Zötl, 1978).

The Early Eocene Rus Formation

The type-section of the Early Eocene Rus Formation is at Jabal Umm Ar Russ, consisting of three units (Powers et al., 1966; Steineke et al., 1958). The bottom unit is about 21 m thick and consists of gray color dolomitic limestone with chert nodules and quartz geodes (Tleel, 1973). The middle unit is about 10 m in thickness and comprises limestone with mud balls and calcite geodes. The top unit consists of 25 m of dolomitic limestone with some gypsum in the upper part. Rus Formation is interpreted as deposited in a shallow marine environment (Al-Sayari and Zötl, 1978; Tleel, 1973).

The Eocene Dammam Formation

The typical section of the Dammam Formation is exposed in the Dammam area where it conformably overlies the Rus Formation. It consists of five members: Midra member; Saila member; Alveolina member; Khobar member, and Alat member (Powers et al., 1966). The Midra member is about 3m and comprises laminated shale with unclean limestone, gypsum lenses, and shark teeth. The Saila Shale member consists of impure gray limestone and fissile shale (Tleel, 1973). The Alveolina member comprises microcrystalline dolomitic limestone of about 1 m thickness and includes common *Alveolina elliptica* (Tleel, 1973). The Khobar member is about 10m and consists of dolomitic marl in the lower part and

limestone in the upper part. The Alat member is about 15m and contains dolomitic marl and dolomitic limestone (Al-Sayari and Zötl, 1978).

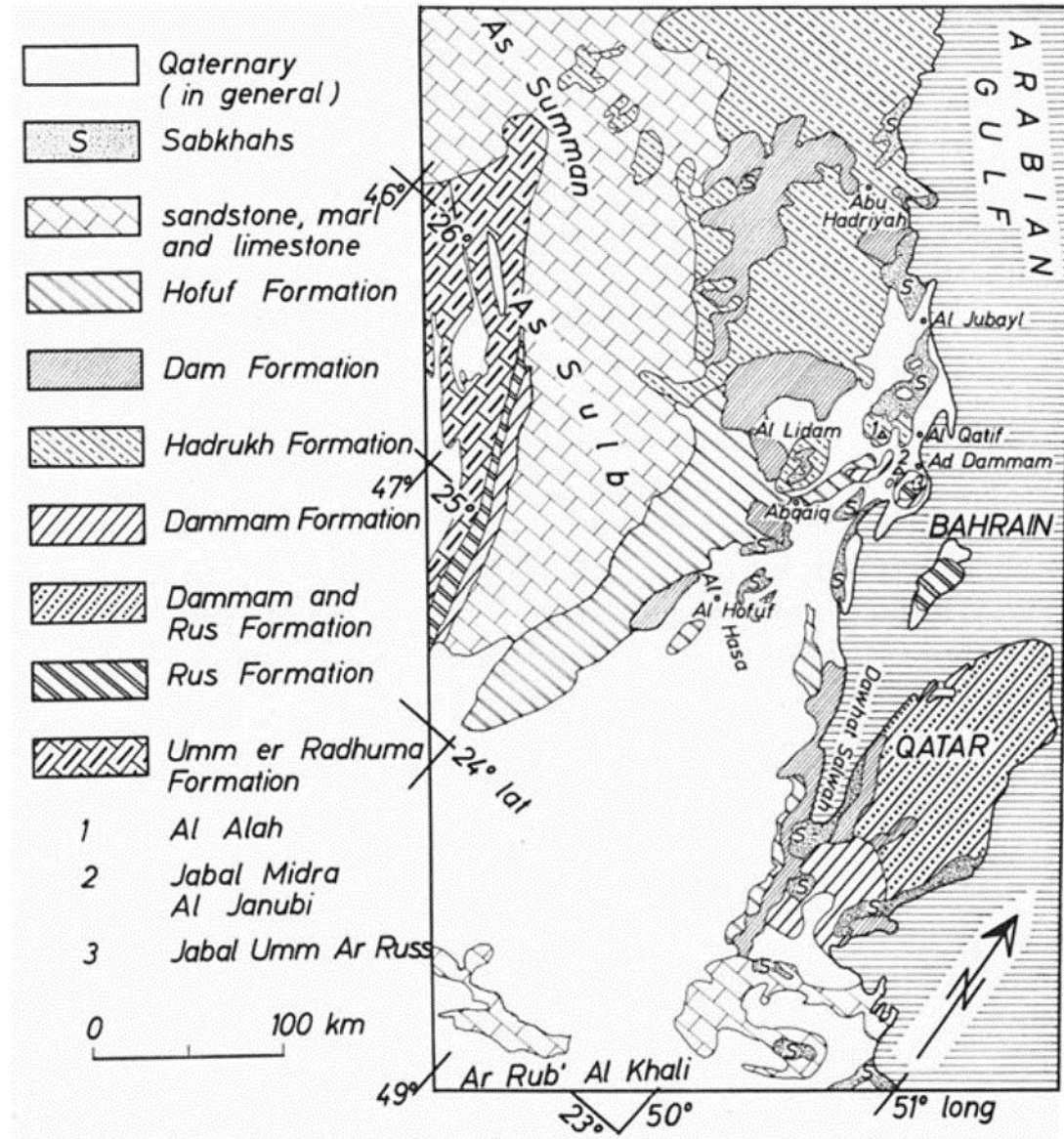


Figure 5: Geological map of the Gulf of eastern Saudi Arabia modified from Al-Sayari and Zötl (1978).

The Miocene Hadrukh Formation

The Hadrukh Formation ranges from 20 m to 120 m in thickness and consists of sandstone, marl, limestone, and claystone, with some gypsum and common chert. The color is predominantly greenish gray, along with other colors like pink, brown, red, and white (Al-Sayari and Zötl, 1978; Powers et al., 1966).

The Miocene Dam Formation

Dam Formation was first studied by Steinke. M and T.W in 1935 where it was considered as a phase (Figure 6). Later, it was upgraded to a formation of the Miocene age and formally published by (Steineke et al., 1958). Its type-section is Jebel Al Lidam, which is about 90 m thick although only the lower part of the Dam Formation crops out in this area (Powers et al., 1966). The Dam Formation unconformably tops Rus and Dammam Formations at the Dammam dome area. It is composed of reddish marl interbedded with greenish clay, packstone, grainstone, sandstone, and limestone (Al-Sayari and Zötl, 1978).

The Miocene Hofuf Formation

The type locality of the Hofuf Formation is at Hofuf City in eastern Saudi Arabia where it covers huge areas. The Hofuf Formation varies in lithology and thickness in different locations. At Hofuf city it is about 93 m thick. The bottom part is about 17 m and consists of a white and brown conglomerate. Then, an 18 m thick impure calcareous sandstone. On top of that, about 49 m of red mudstone and sandstone. The upper part is about 9m of limestone (Al-Sayari and Zötl, 1978).

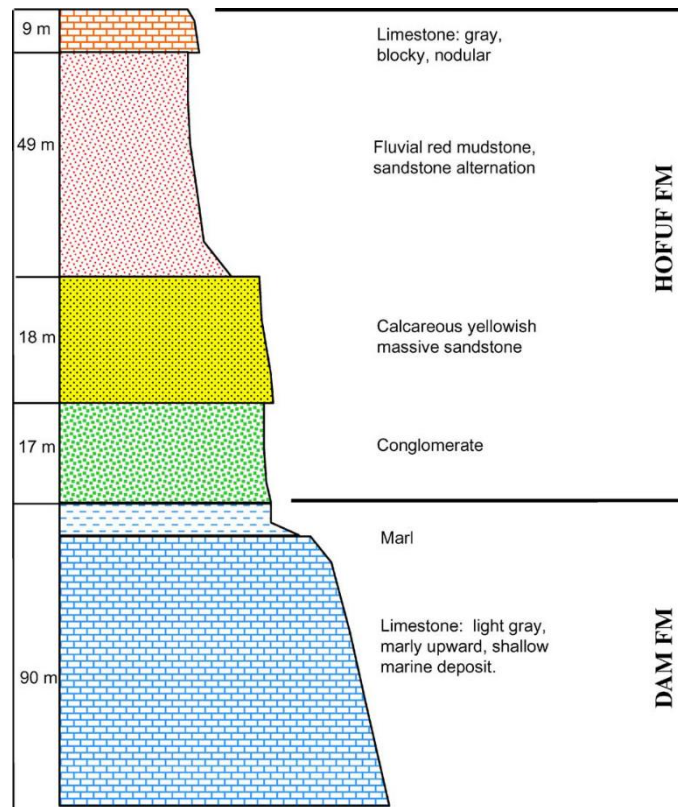


Figure 6: Lithological column of the Hofuf and Dam formations (Saner et al, 2005).

1.5.3 Hydrogeology

The complex multi-aquifer system in the study area contains four partially connected karstified fractured aquifers (Figure 7). Aruma aquifer at the bottom, Dammam aquifer, Umm Er Radhuma aquifer, and Neogene aquifers at the top. The Rus Formation which consists of evaporites, marls, and limestones, performs as an aquitard disconnecting the Umm Er Radhuma from the Dammam aquifers in some parts. It also interconnects the two aquifers in other areas where secondary permeabilities are created by fissures and the dissolution of evaporite layers. The bottom portion of the Aruma Formation, which is composed of clay and shale, serves as an aquitard, dividing these aquifers from the Wasia aquifer underneath it. The natural springs have been formed because of the preferential

flow routes that have emerged along the Ghawar anticline because of intense fracturing. They interconnect the multiple aquifers and direct groundwater to surface discharge.

Based on previous hydrochemical and hydrological studies in the area, the spring water is concluded to be derived from the lower Umm Er Radhuma aquifer (Bakiewicz et al., 1982; BRGM, 1976). The Wasia groundwater has isotope characteristics distinct from those of the Umm Er Radhuma aquifer (Shampine et al., 1979).

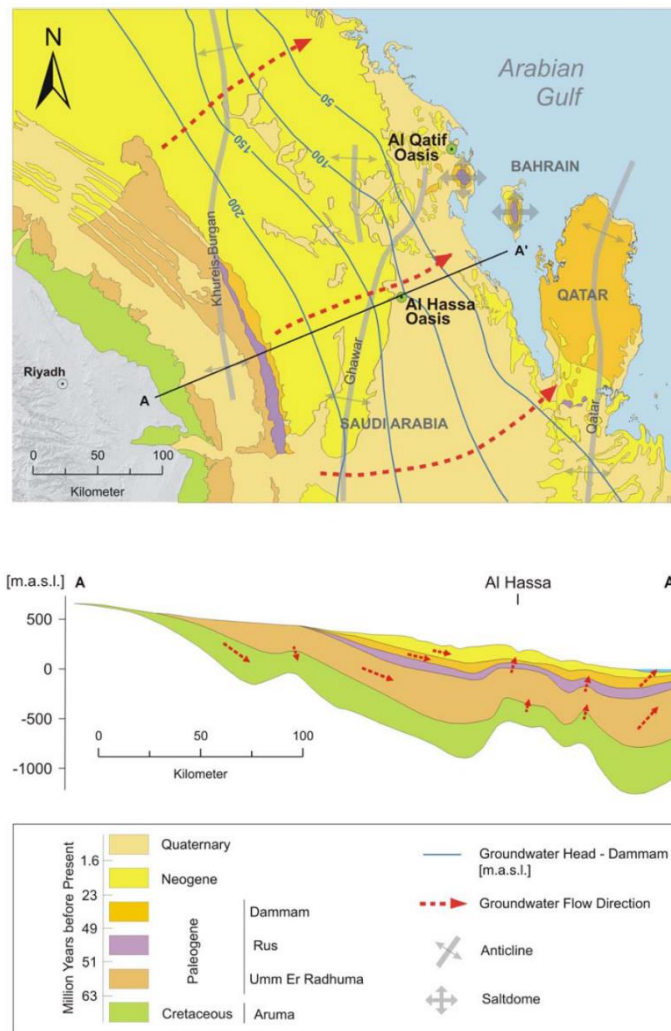


Figure 7: Geological and hydrological characteristics of the study area (Al Tokhais and Rausch, 2008)

The aquifer system's major groundwater flow is directed westward into the Arabian Gulf from outcrop areas. Groundwater migration occurs predominantly through secondary openings within the aquifer system, like fractures, joints, and beddings, which are usually developed by dissolution. At the outcrop areas and for some distance eastward, the multiple aquifers are unconfined until the groundwater table overlaps with the aquitards' confining layers. The groundwater in the study area is dated as 20000 years based on isotopes. This is because of the deep aquifers, the long distance, and the slow percolation time (Al-Sayari and Zötl, 1978; Bakiewicz et al., 1982). Significant recharge and discharge occur because of the downward and upward flow of groundwater from the multiple interconnected aquifers. The groundwater salinity ranges between 1,000 and 2,000 mg/l in the study area (Al Tokhais and Rausch, 2008).

1.6 Data and Methodology

The current study has three phases: data acquisition, data processing and interpretation, and modeling and data integration. An overview of the various methods and procedures is illustrated and discussed in greater detail in the paragraphs that follow:

1.6.1 Geological, Hydrogeological, and Geophysical Field Investigations:

1.6.1.a Geology:

The geological investigation in this study focuses on tectonic features and structural trends in the nearby outcrops using remote sensing and outcrop inspections.

1.6.1.b Hydrogeology:

Water wells were selected for groundwater sampling based on previous studies along with current field investigations. Selection was based on well location and depth, well status, and well use. Focusing on current or daily operating wells ensured getting representative samples from the targeted aquifer. Water level measurements and field parameter measurements (Total dissolved solids (TDS), Temperature, Electrical Conductivity (EC), pH) were carried out using multiparameter meters. Global Positioning System (GPS) was used for determining well locations and elevations.

1.6.1.c Geophysical:

Electromagnetic:

The Audio-Magnetotelluric (AMT) technique is a passive electromagnetic approach that measures changes in magnetic and electric fields at the same time (Cagniard, 1953; Tikhonov, 1950). The resistivity matrix is given from transfer functions between magnetic and electric fields, and it represents an upright profile of the subsurface's electrical characteristics. The frequency range of the AMT is 10^5 to 1 Hz (Farzamian et al., 2019). AMT method provides high resolution for the upper 1.5km.

An alternating current serves as the source for the TEM method, which is implemented by injecting it into an inductively coupled transmitter loop. After the current has been shut off for a period, it will disperse into the subsurface by moving downward and outward. To record the transient decay of the induced voltage, a receiver coil or wire loop that detects the fading of the induced current is used (Farzamian et al., 2019). The TEM method provides high-resolution 1D models of the conductivity variation with depth for the upper 500m.

The magnetotelluric (MT) approach investigates the electrical resistivity system of the subsurface at depths up to tens of kilometers by utilizing the Earth's natural electromagnetic fields (Agyemang, 2020). Because the electric and magnetic responses are sensitive to vertical and horizontal fluctuations in resistivity, the magnetotelluric approach is ideally suited for studying complex geological settings. The investigation depth ranges from 0.3 km when using higher frequencies to 10's km when using lower frequencies for long-period soundings.

The different passive (MT and AMT) and active (TEM) EM methods applied, were integrated to provide the highest-accuracy models from the top to the max depth of a few km below the measured stations. Gravity measurements were used to constrain and complementary support the final resulting quasi-3D EM model for the study area.

Gravity:

Two Calibrated CG-5 instruments were used in the acquisition. Three cycles per 1-minute measurement were recorded at each station to make sure that we have good data for the processing. For the Q/C, Max tilt X/Y of +/- 4.2 units.

The OASIS MONTAJ will be used for the processing part for the corrections and filtering.

1.6.2 Groundwater Sampling:

Sampling groundwater for analysis was carried out using polyethylene bottles (PE) depending on the required analysis in terms of groundwater sample amount and preservation type.

The PE bottles underwent a triple pre-rinsing process using deionized water to prevent any cross-contamination. The wells were subjected to an approximately one-hour purging period before sampling to obtain water samples that accurately represented the subsurface quality conditions.

For general hydrochemical analysis, one 200-ml sample was taken from each well. The sample was preserved in a cooling box under 4° C and then taken to the laboratory to be analyzed as soon as possible.

For minor and trace elements analysis, one 200-ml sample was collected and preserved by adding nitric acid (HNO₃).

For Oxygen and Hydrogen isotopes, a 200-ml sample was taken.

1.6.3 Laboratory analysis

Ionic concentrations and isotopic analyses were carried out at King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia. Major ion concentrations within the milligrams per liter (mg/L) range were determined using the Dionex ICS-6000 Ion Chromatograph (IC) following the EPA 9056A standard method (US-EPA, 2007). Bicarbonate levels were determined using titration. Oxygen and hydrogen stable isotopes were analyzed using PICARRO cavity ringdown spectrometer L2130-I isotopic H₂O. This included quantitative analysis of the following ions: Calcium (Ca²⁺), magnesium (Mg²⁺), sodium (Na⁺), potassium (K⁺), bromide (Br⁻), ammonium (NH₄⁺), chloride (Cl⁻), sulfate (SO₄²⁻), bicarbonate (HCO₃⁻), nitrate (NO₃⁻), nitrite (NO₂⁻), fluoride (F⁻), phosphate (PO₄³⁻) and total dissolved solids (TDS).

For minor and trace elements, the analysis was carried out using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). The following elements are expected: Aluminum (Al), arsenic (As), boron (B), lithium (Li), silver (Ag), cadmium (Cd), iron (Fe), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), lithium (Li), manganese (Mn), molybdenum (Mo), nickel (Ni), vanadium (V) and zinc (Zn).

Oxygen (^{16}O & ^{18}O) and hydrogen isotopes (H & D) analysis were carried out using a Picarro L2130-i Cavity Ringdown Spectrometer CRDS analyzer.

CHAPTER 2

Structural analysis of Neogene sandstone sequence through integrated digital outcrop modeling and field investigations

Khogali, A.; Abu-Mahfouz, I.; Arrofi, D.; AlGhamdi, M.; Soupios, P. Structural analysis of Neogene sandstone sequence through integrated digital outcrop modeling and field investigations. Submitted to the Journal of Structural Geology 2024, Under Review.

2.1 Introduction

The Al-Hassa area hosts Saudi Arabia's largest oasis and one of the world's most expansive naturally irrigated lands (Al Tokhais and Rausch, 2008). Historically, over 280 natural springs, some yielding warm water, were utilized for oasis irrigation (Al-Zarah, 2011). The water quality and temperature diversity observed across the area (Sen and Al-Dakheel, 1987; Al-Omran et al., 2008) hint at a complex subsurface geological framework that requires thorough characterization. Given the acknowledged challenges in characterizing subsurface fractures (Laubach et al., 2019), in this study, we integrated traditional fieldwork and digital outcrop modeling (DOM) to elucidate the subsurface geological complexities within the study area.

A considerable amount of work on automated outcrop fracture analysis has been published (e.g., Zeeb et al., 2013a, 2013b; Prabhakaran et al., 2019). DOM is a globally utilized method in geological research (e.g., Buckley et al., 2006; Alfarhan et al., 2020; Villarreal et al., 2020; Thomas et al., 2021; Uzbeda et al., 2022; Eltom et al., 2023; and Panara et al., 2023), and its applications are gaining popularity. Various studies demonstrate that digital

photogrammetry can yield high-quality datasets (e.g., Buckley et al., 2006), allowing for accurate spatial measurement extraction.

High-resolution DOMs have proven to be incredibly valuable in the field of geology, providing a wealth of diverse geological data (Villarreal et al., 2020). The applications of DOMs span across multiple areas of geoscience, including structural geology (e.g., Uzbeda et al., 2022), geothermal exploration (e.g., Thomas et al., 2021), geohazard assessment (e.g., Valkaniotis et al., 2018), stratigraphy (e.g., Nesbit et al., 2018), reservoir outcrop analogue studies (e.g., Eltom et al., 2023; Thomas et al., 2021) and sedimentology (e.g., Bilmes et al., 2019). Numerous studies have demonstrated the effectiveness of DOMs in these domains, showcasing their wide-ranging capabilities.

In structural geology, DOMs hold substantial significance by providing continuous spatial observations of rock units, lithological contacts, and the geometry of geological structures. Despite the wide range of research on ground photogrammetry in structural geology worldwide, there has been limited application of ground photogrammetry in structural geology studies in Saudi Arabia, as evidenced by the lack of relevant publications.

Moreover, the Hofuf Formation has been the subject of limited geological investigations in Saudi Arabia, primarily focusing on its broader geological context in regional studies (e.g., Powers et al., 1966; Hussain et al., 2006; Kumar, 2013). The present study mainly aims to map fractures and examine the structural characteristics of the Hofuf Formation using DOM, and then validate the results using traditional methods. It presents, for the first time, a comprehensive structural analysis of the Hofuf Formation and examines the implications on reservoir quality. Through this study, we demonstrate the utility and

effectiveness of DOM techniques, particularly ground photogrammetry, in unraveling complex fracture networks and understanding the structural evolution within the Hofuf Formation. Furthermore, our study provides valuable insights and new perspectives into the tectonic history of the Al-Hassa region in Saudi Arabia.

2.2 Study area, geological and tectonic settings

The study area comprises a series of well-exposed outcrops in Jebel Al-Shubah in the Al-Hassa area, which is located around 60 kilometers west of the Arabian Gulf (Figure 8). The area mainly lies between 25° 20' 02" and 25° 32' 30" N Latitudes and 49° 46' 40" and 49° 34' 30" E Longitudes and occupies an area of around 600 km². The region has an elevation that varies between 120 and 220 meters above sea level.

The type locality of the Upper Miocene to Lower Pliocene Hofuf Formation is at the Hofuf city in eastern Saudi Arabia (Figure 8). The formation was observed in Qatar along with the Dam Formation (Figure 9) as outliers. The Hofuf Formation represents the youngest Neogene deposits in the study area (Figure 9). The term "Hofuf" was initially introduced by Thralls and Hasson, in 1956 (Al-Saad et al., 2002).

The Hofuf Formation comprises randomly distributed hills and is composed of brittle rocks ranging in color from brown to light yellow and from grey to pale white, exhibiting fining upward cycles. This formation is situated unconformably above the calcareous Middle Miocene argillaceous Dam Formation. The upper part of the Hofuf Formation is either eroded or concealed beneath recent deposits (Powers et al., 1966). In its type section, the Hofuf Formation reaches a thickness of approximately 95 meters and is divided into four distinct units. These are a basal conglomerate unit, with a thickness of 17 meters, composed

of pebbles and boulders, an 18-meter-thick unit of calcareous sandstone, a 49-meter-thick unit of argillaceous sandstone of red mudstone-sandstone interval, and a blocky/nodular

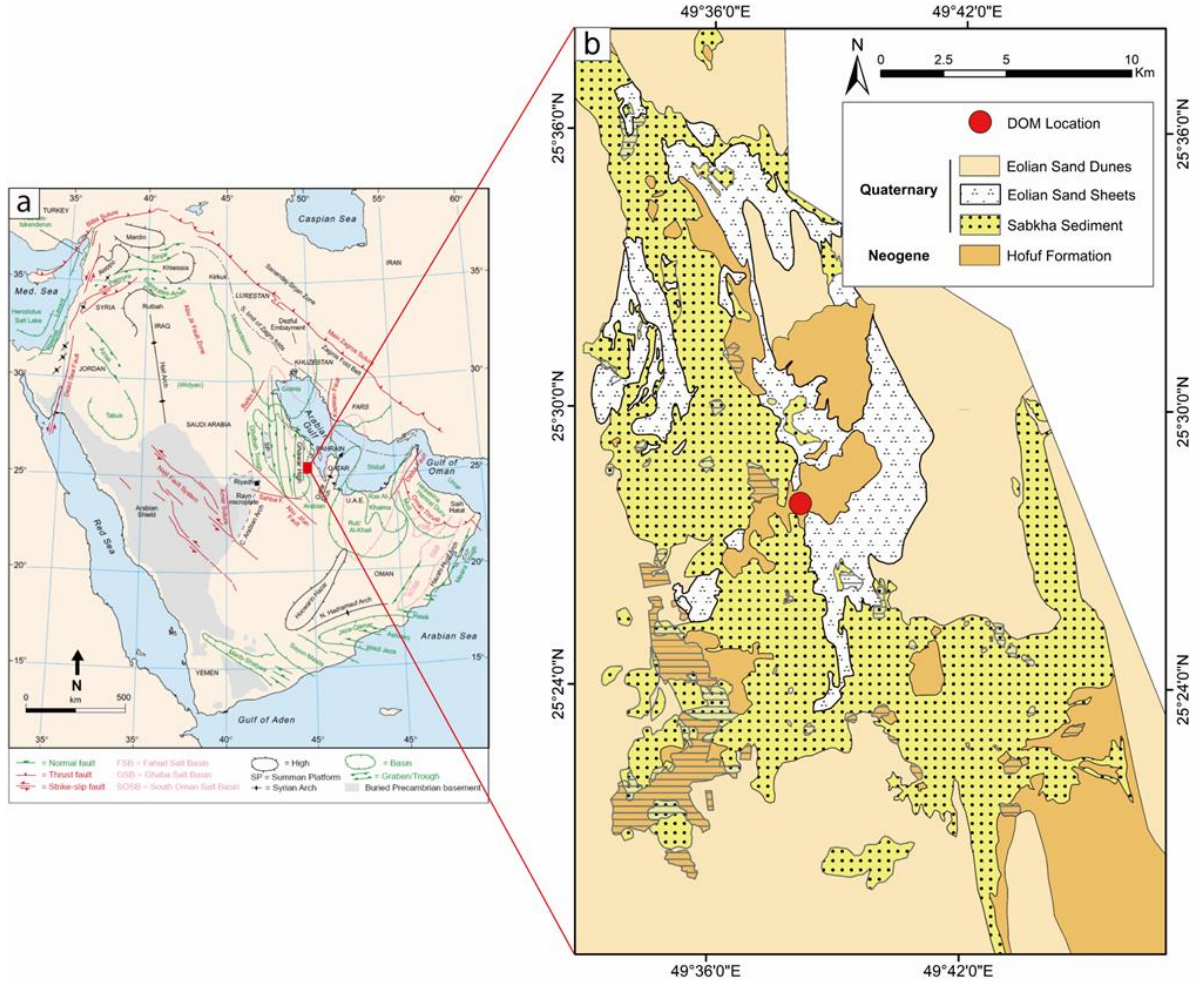


Figure 8: a) Structural and Tectonic map of Arabian Plate showing the location of the study area (from Ziegler (2001)). b) Geological map of the study area (modified from Al-Mahmoud, (1987)).

limestone unit, with a thickness of 9 meters (Figure 9) (Al-Sayari and Zötl, 1978; Al-Saad et al., 2002).

The Neogene sedimentary sequence in the Arabian Gulf region is characterized by an elongated NW-SE asymmetrical basin called the Zagros Syncline in the East Arabian Block (Powers et al., 1966; Murris, 1980). This area underwent changes attributed to global

Mid-Oligocene emergence and regional uplift from the Oligocene to the Miocene (Weijermars, 1998). The development of the Hofuf Formation is linked to the Neogene evolution of the East Arabian Block, supported by evidence such as grabens, strike-slip faults, and transpressive folds (Hancock and Kadhi, 1978; Vaslet et al., 1991; Weijermars, 1998). Late Cretaceous-Eocene marked the initiation of doming in the Arabian-African Shield, and Late Eocene-Oligocene witnessed rift development and separation of Africa from Arabia. The tectonic activity of the Late Miocene-Pliocene has led to the Red Sea floor spreading, causing drainage from the uplifted Arabian Shield and the deposition of significant quartzose clastic sediments, forming the Miocene Hudruk and Mio-Pliocene Hofuf formations (Al-Saad et al., 2002). The regional topography, sloping eastward, facilitated the west-to-east sediments transport of the basement erosion.

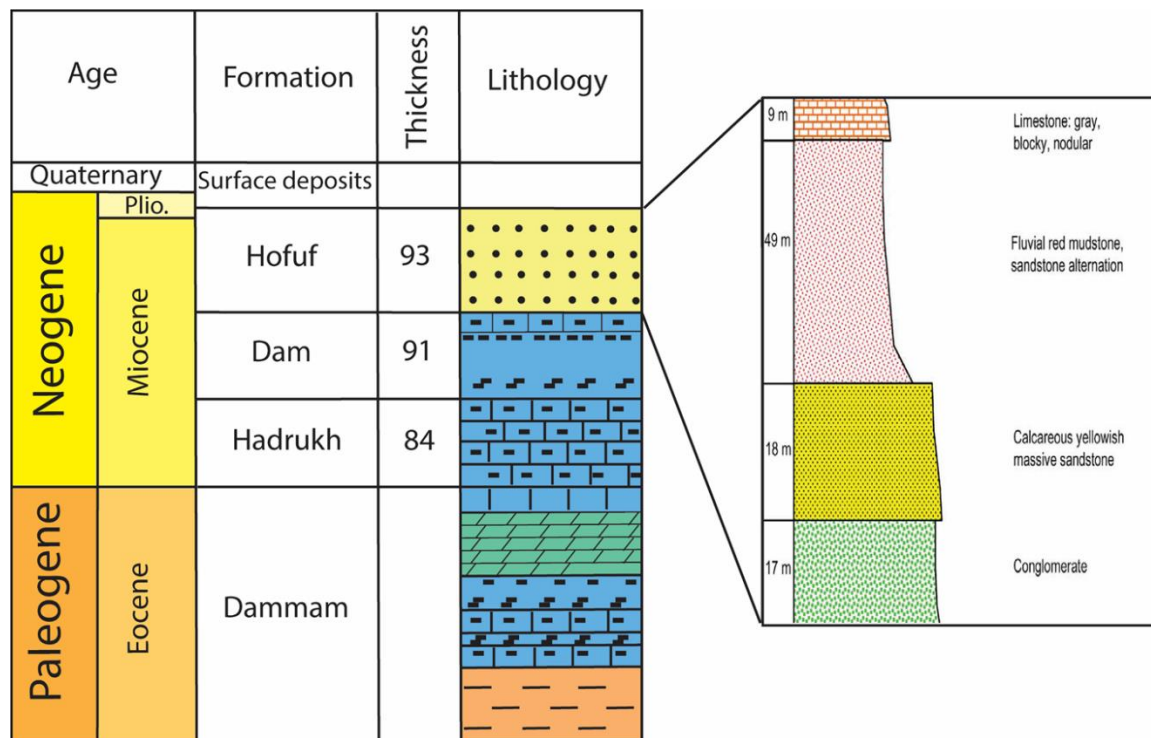


Figure 9: Generalized stratigraphic column of eastern Saudi Arabia and the lithostratigraphic sequence of the Hofuf Formation (modified after Dirks et al. (2018); Powers et al. (1966); Saner et al. (2005)).

2.3 Methodology

Two different techniques were used to collect data from the studied outcrop: digital photogrammetry (Figures 10, and 11b) and traditional geological field methods (Figures 11a and 11c). Digital methodologies offer many advantages compared to conventional fieldwork; nevertheless, they also come with certain disadvantages. The strengths primarily lie in the faster data acquisition and processing and the easiness of transferring the data into meaningful figures and maps. On the other hand, it is worth mentioning that there are certain limitations associated with electronics in general, such as calibration, battery lifespan, and susceptibility of electronics to field conditions.

In the Al-Hassa area, hundreds of digital georeferenced photographs have been captured around a small outcrop of the red mudstone and sandstone unit of the Hofuf Formation (Figure 11). Applying the photogrammetry method outlined by Alfarhan et al. (2020), a 3D model was created from the collected georeferenced photographs. The creation of this model involved several steps, such as identifying the photo's location, constructing a TIN mesh, simplifying it, applying texture to the mesh, and finally transporting the model from the photogrammetry software to the ArcGIS platform for further processing.

In ArcGIS, the GeoAnalysisTools software extension was used to pick georeferenced surfaces of different fractures from the 3D photogrammetry outcrop model. The strike and dip of those surfaces/fractures were detected and mapped automatically by the software during the processing (Figure 11b). The utilization of a 3D fracture mapping technique facilitated the effective visualization of various sets of fractures, enabling a reliable



Figure 10: Digital Outcrop Model (DOM) of the Hofuf Formation in the Al-Hassa area.

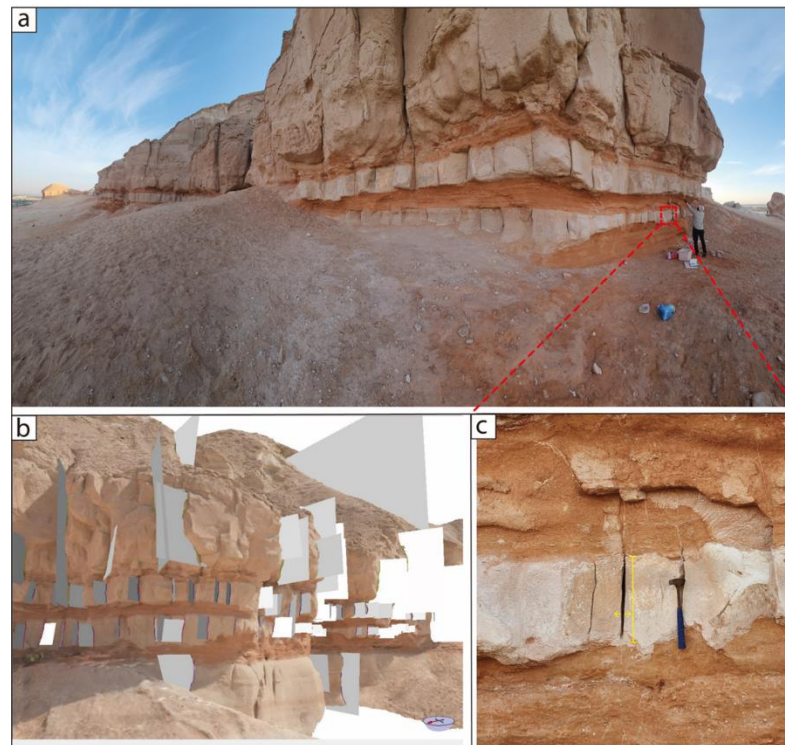


Figure 11: a) Structural data acquisition using traditional fieldwork. b) Structural data acquisition GeoAnalysisTools extension. C) An example of the fractures in calcareous sandstone unit the Hofuf Formation.

measurement of fracture density and the identification of fracture sets across the entire outcrop sections.

In the conventional fieldwork investigation, fracture measurements were acquired to compare and cross-validate the structural elements and characteristics obtained from the digital outcrop modeling technique (Figure 11a, 11c). The primary method for documenting fractures in this fieldwork involved systematically measuring fracture attributes along linear transects. Fracture orientation, dip angle, aperture, and height were recorded for each identified fracture set within the examined beds. To measure the heights of fractures, we used a standard tape measure. Aperture widths were measured with the aid of a hand lens and a specialized comparator (Ortega et al., 2006), which facilitated the measurement of displacement sizes down to an approximate accuracy of 0.05 mm.

2.4 Results

A total of 210 fractures were traced from the DOM. Most of the fractures observed on the DOM are open fractures (joints and fissures) with a WNW-ESE primary orientation. However, secondary orientations were also observed, including NE-SW and NW-SE (Figure 12a). Most of the joints have an almost vertical dip angle, as observed also from the field (Figure 12b). The histogram statistics in Figure (12b) show a negative skewness value of -1.56 and a kurtosis value of 3.07, indicating a pronounced skewness towards vertical fractures and the presence of heavy tails in the distribution.

A total of 45 main fractures were traced using traditional field techniques. As shown in Figure (13a), the dominant fracture orientation was E-W, followed by WNW-ESE orientations (100, 120, and 130 degrees, with 110 degrees also observed). Figure (13b)

indicates that 36 out of the 45 fractures were nearly vertical, with dip angles ranging from 87 to 90 degrees. Additionally, 5 fractures had dip angles between 82 and 86 degrees, while 3 fractures exhibited dip angles between 70 and 82 degrees. One fracture had a dip angle of approximately 50 degrees. The statistical analysis of the dip angles in Figure (13b) yielded a skewness value of -3.74 and a kurtosis value of 16.04, indicating a highly skewed distribution with heavy tails. The range of dip angles spanned 40 degrees, with a standard deviation of 6.85 and a mean dip angle of 86.69 degrees.

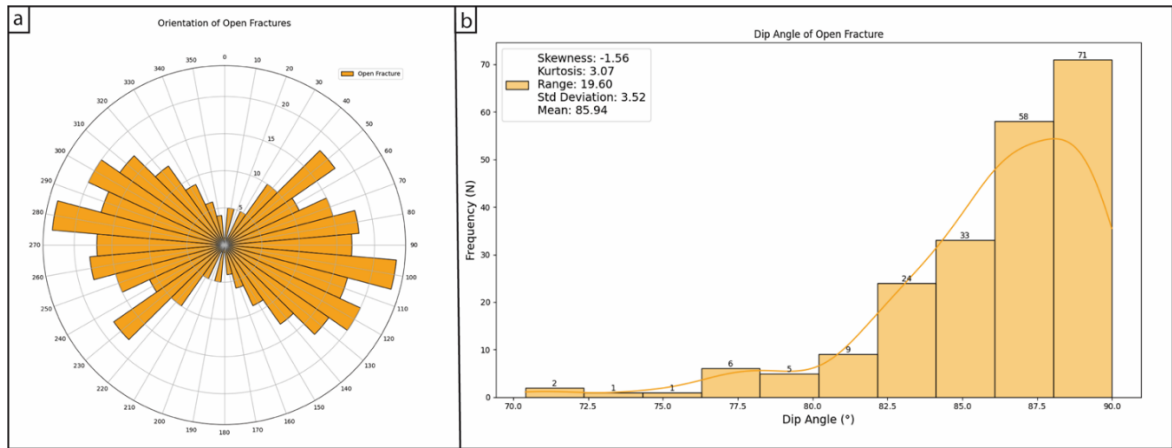


Figure 12: DOM structural data a) Orientation of open fractures or joints within the Hofuf Formation. b) Histogram depicting the dip angles of fractures.

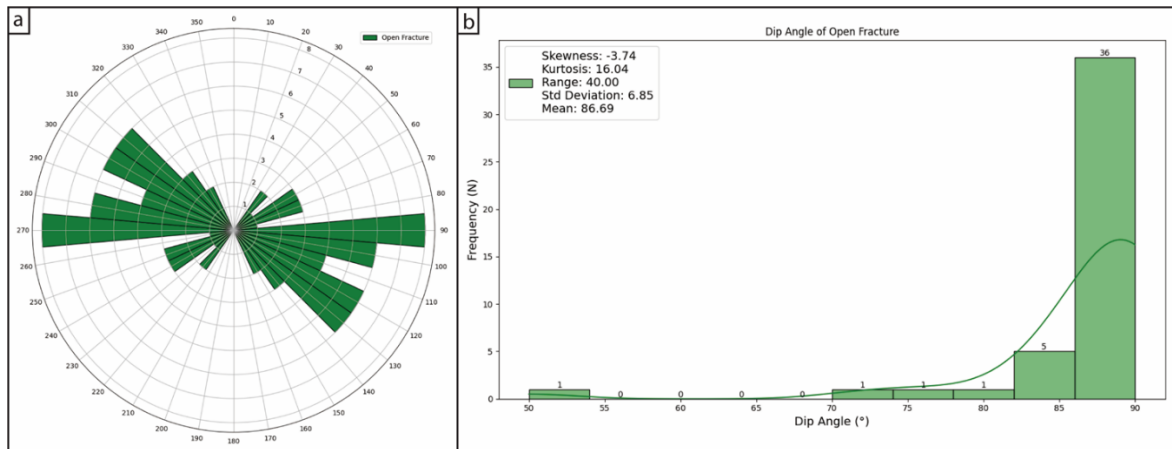


Figure 13: Traditional fieldwork structural data a) Orientation of open fractures or joints within the Hofuf Formation. b) Histogram depicting the dip angles of fractures.

The results of fracture height analysis from the DOM method show that the fractures within the Hofuf formation are dominated by short fractures of less than 100 cm, mainly confined to their host beds (Figure 14a). Specifically, most of the fractures are bounded within the calcareous sandstone layer; only very few small fractures are observed cutting to the mudstone layer. The data is characterized by a positive skewness of 3.79, indicative of a right-skewed distribution, and a kurtosis value of 18.72, suggesting heavy-tailed data. The dataset exhibits a standard deviation of 109.53, reflecting notable data dispersion and a mean of 60.88 as its central tendency.

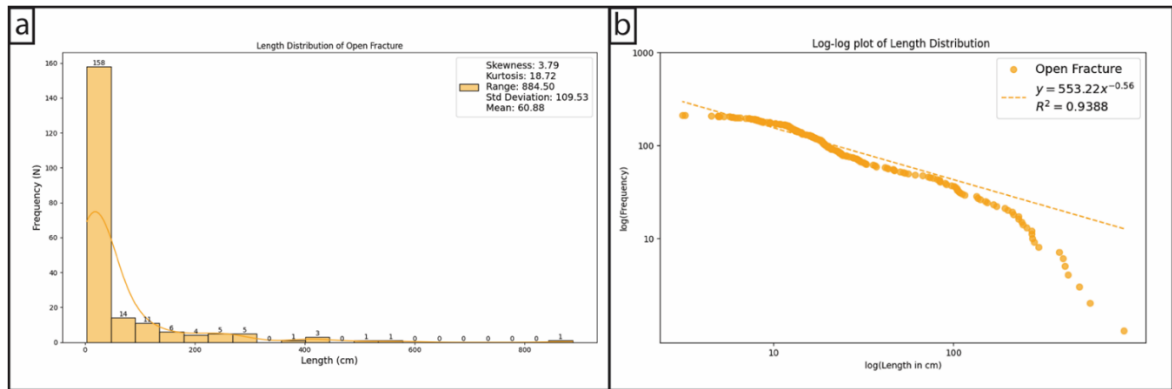


Figure 14: DOM fracture length analysis a) Distribution of open fracture. b) Log-log plot of fracture lengths distribution. DOM fracture height distribution following power law distribution (Figure 14b). This suggests that all the data is scale-independent, indicating a similarity in the structural geometry across various scales and showing a significant variation in the measured quantity (Seebeck et al., 2014). Therefore, fractures can be easily upscaled, aiding the correction and interpretation of seismic imaging (Menegoni et al., 2022).

The dataset of fractures aperture reveals a positively skewed distribution with a skewness value of 2.87 (Figure 15a). The kurtosis value is 10.42, indicating a leptokurtic distribution. The range of aperture values spans from 0 to 22.7 cm, with a standard deviation of 3.56 cm

and a mean aperture of 3.46 cm. Notably, most fractures exhibit relatively smaller apertures, with 64 fractures having apertures less than 1 cm, while only 4 fractures have apertures between 13 to 18 cm and 2 fractures around 22 cm. Fracture aperture distribution following power law distribution (Figure 15b). This suggests that all the data is scale-independent, indicating a similarity in the structural geometry across various scales and showing a significant variation in the measured quantity.

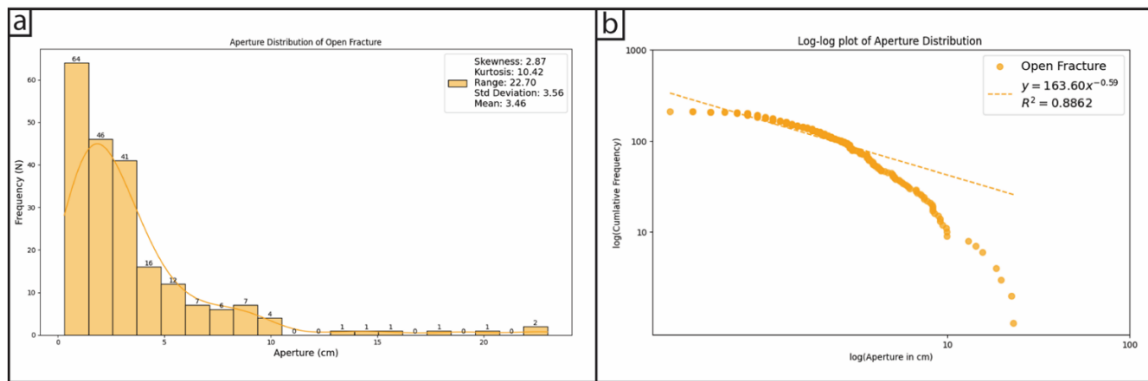


Figure 15: DOM fracture aperture analysis a) Distribution of open fracture aperture. b) Log-log plot of fracture aperture distribution.

CHAPTER 3

Subsurface characterization of the Al-Hassa National Park, Eastern Saudi Arabia, using multi-geophysical methods

***Khogali, A;** Chavanidis, K; Kirmizakis, P; Stampolidis, A; Ashadi, A. L.; Hanstein, T; Candansayar, E; Soupios, P; 2024, Subsurface characterization of the Al-Hassa National Park, Saudi Arabia, using multi-geophysical methods, submitted to Arabian Journal for Sciences and Engineering, Springer, Under review.*

3.1 Introduction

The Al-Hassa region in eastern Saudi Arabia is renowned for hosting the world's largest oasis and the most expansive naturally irrigated lands globally (Al Tokhais and Rausch, 2008). Al-Hassa is adjacent to Ghawar, the world's largest conventional oil field. With a historical reliance on over 280 natural springs, some yielding warm water for agricultural irrigation (Al-Zarah, 2011), the area's varied water quality suggests the presence of complex subsurface geological structures warranting meticulous examination.

Previous studies on the hydrochemistry and hydrogeology of the Al-Hassa area offer a comprehensive understanding of the subsurface complexity in the study area. Bakiewicz et al. (Bakiewicz et al., 1982) studied the hydrogeology of the Umm Er Radhuma aquifer. This early work was followed by evaluating hydrochemical facies within the same aquifer (Sen and Al-Dakheel, 1986). Sharaf (Sharaf, 2001) highlighted groundwater's hydrogeological and hydrochemical aspects, pointing out seawater intrusion risks. Al Tokhais and Rausch (Al Tokhais and Rausch, 2008) addressed the hydrogeology of the Al-Hassa springs, forecasting a grim future for water availability and quality if current

extraction rates persist. Al-Dakheel (Al-Dakheel, 2009) presented spatial modeling for groundwater salinity, marking shifts over time. Al-Naeem (Al-Naeem, 2011) and Al-Zarah (Al-Zarah, 2011) furthered this by evaluating groundwater for irrigation and studying elemental compositions. Al-Omran et al. (Al-Omran et al., 2018) characterized groundwater quality, while Dirks et al. (Dirks et al., 2018) expanded on the hydrogeology of the Umm Er Radhuma aquifer. Most recently, Abba et al. (Abba et al., 2024b, 2024a) employed advanced techniques like machine learning and spatial mapping to investigate trace element pollution and nitrate concentrations, offering cutting-edge insights into groundwater vulnerability and pollution in Al-Hassa.

Geophysical investigations are indirect and non-invasive methods used to analyze and describe the properties of materials in the subsurface. Thorough knowledge of the underlying formations and their structures is crucial for preserving natural resources through exploration and exploitation. Seismic and non-seismic geophysical methods are available for characterizing and monitoring the subsurface. However, it is insufficient to depend solely on one geophysical method; to attain the most favorable outcome, it is advisable to employ various methodologies and combine their findings to the greatest extent.

Recent advancements in geophysical methods, including magnetotelluric (MT) and transient electromagnetic (TEM) methods, offer promising avenues for non-invasive and cost-effective subsurface imaging. The TEM method, known for its high resolution in shallow- and medium-depth imaging, has been extensively utilized in hydrogeophysical studies (Massoud et al., 2009), groundwater exploration (Costabel et al., 2017; Siemon et al., 2009), investigations of seawater intrusion (Demirci et al., 2020; Yang et al., 1999) and

soil salinization (Al-Garni and El-Kaliouby, 2011). Combining TEM with supplementary geophysical methods enhances the resolution of the subsurface features (Farzamian et al., 2019).

Additionally, broadband MT data, including AMT frequencies, provide shallow and deeper insights than TEM surveys, particularly regarding greater depth penetration (Árnason et al., 2010; Patro, 2017). M.T. has been widely applied in studying geothermal resources, exploring aquifer boundaries, and imaging saltwater/freshwater interfaces (Ashadi et al., 2024; Erdoğan and Candansayar, 2017; Nenna et al., 2013; Ueda et al., 2014). The joint use of MT/AMT and TEM methods has been recognized for mapping medium-depth and deep structures (Bai et al., 2001; Farzamian et al., 2019; Mohamed et al., 2002; Zhang et al., 1995).

Moreover, potential field (gravity and magnetic) methods offer broader-scale information on subsurface depressions, basins, and fractures (Chavanidis et al., 2022).

Despite its geological significance, the Al-Hassa area in Saudi Arabia has received limited attention in geological and geophysical investigations (Al Tokhais and Rausch, 2008; Al-Dakheel et al., 2008; Mahmoudi et al., 2011). This study aims to fill this research gap by mapping and characterizing the subsurface using various geophysical methods.

The primary purpose of this survey is to demonstrate the utility and effectiveness of multi-geophysical techniques, particularly electromagnetic (TEM, AMT, and MT) methods and potential field (gravity and magnetic) methods, in unraveling complex fracture networks and understanding the structural evolution and the tectonic history of the Al-Hassa region in Saudi Arabia. A 3D resistivity model of the study area was obtained using three-

dimensional (3D) AMT/MT data inversion. We also obtained a pseudo-two-dimensional resistivity model using laterally constrained TEM data inversion. Afterward, a density model from gravity data inversion constrained by a 3D resistivity model was obtained. All geophysical models and available surface and borehole information were combined to reconstruct the complex 3D subsurface structure of the Al-Hasa oasis.

3.2 Study area, Geology and Tectonic Regime

The study area is situated within the eastern province of Saudi Arabia, notable for its predominant geological feature, a vast expanse covered by a layer of sand (Figure 16a). Thus, no geological map with lithological information for the area under investigation has been published. Beyond the confines of the park area, outcrops are evident, with the notable presence of Hofuf formation outcrops depicted in Figure 1b of the geological map. These outcrops likely extend to other locations within the eastern province. The Al-Hassa region lies approximately 60 kilometers west of the Arabian Gulf (Figure 16b), positioned between latitudes 25° 20' 02" N and 25° 32' 30" N and longitudes 49° 46' 40" E and 49° 34' 30" E, covering an expanse of approximately 600 km². Elevations within the area range from 120 to 220 meters above sea level. The study area is within the Al-Hassa National Park, a natural oasis in Umran's neighborhood near Qarah Mountain. The park was established in 1962 in an area of about 45 km² (5.3 km wide "W-E" and 7.36 km length "S-N") to act as a barrier for the dunes' migration into the Al-Hassa urban and oasis area. The place is designed in an L-shape (Figure 16c), with the first half extending along the southern border of the dunes and the other part extending along the eastern area. This windbreak is roughly 20 km long and 250 - 750 meters wide, creating a solid barrier between the sandy desert and residential and farming areas in the region.

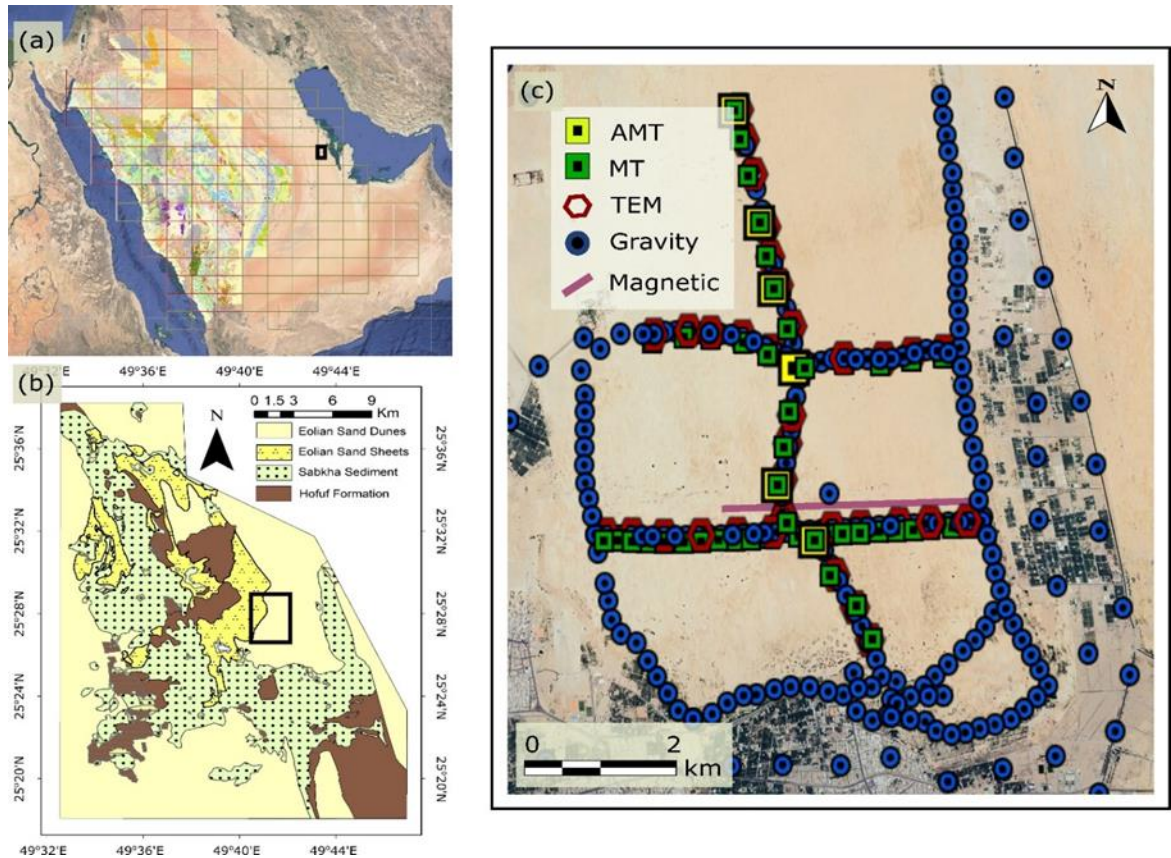


Figure 16: (a) The coverage of Saudi Arabia by geological maps released by the Saudi Geological Survey is presented by the colored rectangles. A thick black square depicts the location of the study area. (b) Geological map of the wider area (modified from (Al-Mahmoud, 1987)). A black rectangle shows the study area of the National Park. (c) The study area with all the acquired geophysical (AMT, MT, TEM, gravity, and magnetic) measurements.

The area predominantly comprises sand dunes/sheets and Quaternary deposits, with only sporadic outcrops revealing the Upper Miocene to Lower Pliocene Hofuf Formation (Figure 16b). Overall, the area has few published geological research due to the proximity of the study area to the Ghawar oilfield, and the groundwater wells have no lithological information. The Hofuf Formation is characterized by conglomerates, calcareous sandstones interbedded with reddish mudstones, and limestones (Al-Saad et al., 2002a). Situated beneath the Hofuf Formation are the limestones and reddish marls of the Dam Formation, succeeded by the sandstones, limestones, and marls of the Hadrukh Formation (Powers et al., 1966). Subsequently, the sequence includes the dolomitic and limestone

formations of the Eocene Dammam Formation. Further, underlying formations consist of the early Eocene Rus Formation, comprising dolomitic limestone and gypsum, and the Paleocene Umm Er Radhuma Formation, which includes limestone and dolomite featuring quartz geodes and chert nodules (Al-Sayari and Zötl, 1978; Powers et al., 1966).

The Neogene sedimentary sequence in the Arabian Gulf area is characterized by a stretched NW-SE asymmetrical basin known as the Zagros Syncline, situated within the East Arabian Block (Murris, 1980; Powers et al., 1966). Tectonic movements in this region are attributed to global emergence during the Mid-Oligocene and subsequent uplift from the Oligocene to the Miocene (Weijermars, 1999). The formation of the Hofuf Formation is related to the Neogene development of the East Arabian Block, evidenced by features such as grabens, strike-slip faults, and transpressive folds (Hancock and Kadhi, 1978; Vaslet et al., 1991; Weijermars, 1999). From the Late Cretaceous to the Eocene, dome formation commenced in the Arabian-African Shield, while rift formation and the separation of Africa from Arabia were during the Late Eocene to the Oligocene. Tectonic activity during the Late Miocene to the Pliocene led to Red Sea floor spreading, causing drainage from the uplifted Arabian Shield and depositing significant clastic sediments, resulting in the Miocene Hudruk and Mio-Pliocene Hofuf formations (Al-Saad et al., 2002b). The regional landscape, sloping eastward, facilitated sediment transport from west to east due to basement erosion.

Hydrogeologically, the area is recharged by the mountainous western part of Saudi Arabia, where fresh groundwater flowing to the east and northeast is observed in many monitoring wells (Figure 17a). A notable gradient in groundwater salinity is observed across the region, escalating from approximately 300 parts per million (ppm) in the west to more than

5000 ppm along the Arabian coast. Intriguingly, a discernible abrupt shift in salinity with depth reveals a distinct stratigraphic influence. Shallow aquifers exhibit comparatively better groundwater quality, whereas deeper (around 800 m) aquifers, particularly within the Aruma Formation, manifest exceedingly saline groundwater (Al Tokhais and Rausch, 2008).

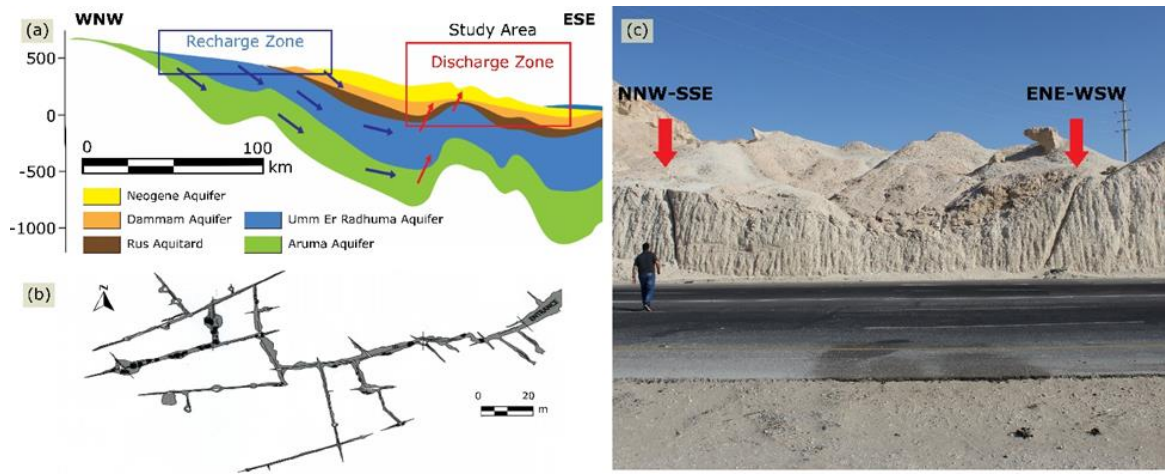


Figure 17: (a) W-E section showing the geologic formations, the groundwater flow (black and red arrows), and the subsurface deformation due to basement uplift beneath the study area (Al Tokhais and Rausch, 2008). (b) Fault zone pattern (Hussain et al., 2006) and (c) Fault zone field photo showing the major ENE-WSW and NNW-SSE directions observed at an outcrop within the study area.

The uplift and formation of the Ghawar anticline induced significant fracturing in the region. Some outcrops display joint systems trending in the NW-SE or NNW-SSE and E-W or ENE-WSW directions, eroded by wave-cut gorges (Figures 17b,c). Fluvial erosion later reshaped these features (Al-Sayari and Zötl, 1978).

3.3 Geophysical Survey Methods and Data Acquisition

Geophysical studies give indirect results about subsurface features. Thorough knowledge of the subsurface and its complexity is crucial for deep (e.g., natural resources exploration) and shallow surveys (e.g., preventing foundation failure and understanding ground

conditions). In general, geophysical data inversion results are interpreted to reveal underground structures. However, the geophysical data inversion is ill-posed and non-unique. To reduce the non-uniqueness problem, different types of geophysical methods are employed, such as MT, TEM, and gravity, and we apply joint inversion of the data or combined inversion (inverted separately) of 2D/3D geophysical models (Candansayar and Tezkan, 2008; Demirci et al., 2017; Edigbue et al., 2022). Thus, it is advisable to utilize many geophysical methods and combine their inversion results for optimal outcomes. Non-seismic geophysical technologies are important for enhancing the accuracy of scientific and technical evaluations in subsurface research. In comparison to seismic methods, these approaches offer cost-effective and practical solutions. Combining passive and active electromagnetic (EM) methods in both time and frequency domains with potential field methods (gravity and magnetic) can offer additional information that may lower field development expenses and enhance the comprehension of geological structures (Ashadi et al., 2024, 2022; Barajas-Olalde et al., 2023; Chavanidis et al., 2022; Hinojosa-Prieto et al., 2021; Kalisperi et al., 2018; Panagopoulos et al., 2021; Rani et al., 2020).

Magnetic surveys measure the distribution of induced and remanent magnetization produced by magnetic minerals in the crustal rocks belonging to all common lithological groups. The magnetic mineral accumulation in a rock is a function of its primary composition and geological history (Grant, 1985). Gravity surveys measure the lateral rock density distribution with depth; thus, we applied it to the Al-Hassa National Park study as the complex subsurface lithology and tectonic settings should provide significant density changes.

EM surveys are sensitive to subsurface resistivity structures. They are utilized to characterize the subsurface's electrical properties (conductivity or its inverse, resistivity) and create multidimensional models of the Earth's resistivity distribution. Resistivity often decreases when the measurements are collected over a basin, where fluids fill the pore spaces of porous materials, or when a fractured aquifer is detected with secondary porosity, where cracks are filled with fluids. There are time- and frequency-domain EM methods. The TEM method is an active time-domain EM method and is recognized for its near-surface application, reaching a depth of 500-600m below the surface (Hinojosa-Prieto et al., 2021; Panagopoulos et al., 2021; Rani et al., 2020). In the TEM method, we inject an alternating electric current inside the transmitter loop, which generates a vertical primary magnetic field. This magnetic field induces the conductive material and generates Eddy current, thus producing a secondary magnetic field. The secondary magnetic field derivative is measured as a function of time.

MT method is a natural source geophysical EM method (Chave and Jones, 2012). We mostly measure broadband MT data in the approximate frequency range between 0.01 Hz to 1000 Hz. Broadband MT data is used to reveal resistivity structures between 0.1 km and 10-20 km, depending on the resistivity of the area. Audio magnetotelluric (AMT) data have an approximate frequency range between 1 Hz to 80 kHz. These data reveal a shallower resistivity structure than broadband MT data. It must be highlighted that MT, AMT, and TEM data can be processed and interpreted individually or combined in a joint-inversion scheme to constrain uncertainties since those methods map different depths with different accuracies (Ashadi et al., 2024; Barajas-Olalde et al., 2023).

3.3.1 Magnetic Data

The magnetic data within the Al-Hassa National Park was collected in June 2021. The survey was conducted using a Geometrics G-858 cesium magnetometer that was set up as a gradiometer with two sensors positioned vertically apart. This configuration enabled the simultaneous measurement of the vertical magnetic gradient. The lower sensor was positioned at a height of 0.4 meters above the ground, whereas the upper sensor was at a height of 1.4 m. A G-857 proton magnetometer was used as the base station to correct diurnal variations. It was installed in a remote and noise-free area, and it continuously acquired data every 15 seconds during the measurements.

The survey was conducted in an East-West direction, as shown in Figure 16c (along the purple line), covering a total distance of 3.6 km, while the recording was continuous, collecting data every 0.3 seconds. The location of the magnetic stations was determined using the magnetometer's mounted GPS, while a handheld GPS was used for comparison. The two GPS datasets were similar; therefore, we kept the magnetometer's location data. It should be mentioned at this point that during the acquisition, three sources of cultural noise were encountered: a borehole, an abandoned truck, and two metallic pipes. The Oasis Montaj software was used to process data. Initially, the quality control for the base station and the rover magnetometer time series was applied. The three noise sites were identified in the rover measurements. The magnetic data were corrected for diurnal variation using the base station, and we derived the total magnetic field for both the top and the bottom sensors. The International Geomagnetic Reference Field (IGRF) correction was applied to the total field data afterward, and the noise on the recorded data was removed/masked (de-spiking).

3.3.2 Gravity Data

In this study, 210 gravity measurements were collected within the Al-Hassa National Park and the eastern area, covering approximately 53 km², using two Scintrex CG-5 AUTOGRAVTM gravimeters (Figure 16c). The gravimeters were set to account for the Earth's tide effect and the instrument's tilt during transportation and automatically make the necessary corrections to the measurements. The data were acquired during the morning to avoid the extra minor noise caused by the high air temperature typical for the area during the summer months when we measured (June 2021, June 2022). The measurements were made in sets of three or five, with a duration of 30-60 seconds, to eliminate noise produced by various artificial or natural sources. To further ensure good data quality, any set of measurements with a difference of more than 10 μ Gal and/or tilt greater than 15 arcsec was repeated with additional readings. The Trimble R10 Differential GPS location was used to determine the location and elevation of each station.

Coherent and non-coherent noise, topography, and geographic latitude impact gravity readings; hence, the raw data must be corrected for the effects of these factors. First, we corrected the measured data for the Earth's tide and the instrument's height and drift. The Earth's normal gravity at the survey's base station was computed using the 1980 International Gravity Formula (Moritz, 1980). Topographic correction (or terrain effect) reduces the impact of local topography on the measured gravity field at each station. This effect was reduced after applying the topographic correction algorithm of Oasis Montaj's Gravity and Terrain Correction extension. This algorithm creates a grid from a coarse regional elevation model, which is used as the "regional correction grid" for gravity corrections beyond a "local" distance. This distance is relevant to a more detailed elevation

model that covers the study area and is used to apply the correction within the limits of this area. As the local elevation model, we used the SRTM (Shuttle Radar Topography Mapping) topography at 30 m resolution, while the SRTM topography at 90 m was used as the regional elevation model. The Free Air and the Bouguer corrections were finally applied to the corrected data to calculate the complete Bouguer anomaly (CBA), which includes the effect of both large and deep-seated structures of regional scale and shallower local bodies. Modifications in this general workflow might be needed depending on the study's objective and the type of the survey (Fairhead, 2016).

To isolate the effect of the shallow structures, we derived the residual gravity field map by subtracting a first-order polynomial from the CBA map. To further proceed with identifying subsurface geotectonic structures (e.g., rock contacts, faults) with significant density contrast and correlate the gravity analysis results with the geology of the study area, we applied the terracing transformation and the tilt derivative (TDR) filters on the residual field data.

Terracing transformation (Cordell and McCafferty, 1989) can distinguish homogeneous domains of constant gravity field intensity with sharp boundaries (Li, 2016). Structural edges can be further enhanced using the zero contours of the TDR (Miller and Singh, 1994; Verduzco et al., 2004), while this filter also improves the signal of deeper and/or weaker gravity anomaly sources (Fairhead, 2016). TDR can be calculated by equation (1):

$$TDR = \arctan \left(\frac{\frac{dG}{dz}}{\sqrt{\left(\frac{dG}{dx}\right)^2 + \left(\frac{dG}{dy}\right)^2}} \right) \quad (1),$$

where dG/dx and dG/dy are the first-order derivatives of the gravity field in the x and y directions, and dG/dz is the first-order vertical derivative. It was applied to the residual gravity field data to clearly define the locations and the dip direction of structures' edges corresponding to faults and/or vertical/sloping rock contacts that act as the causative anomaly sources.

The variations in the anomaly sources' depth can also be studied using the tilt-depth method (Salem et al., 2007). Assuming vertical geologic contacts or faults, the burial depth of the upper surfaces of the sources is located at half the physical distance between the corresponding contours of $\pm 45^\circ$.

To study the subsurface distribution of the rock densities, we created 3D models using the VOXI Earth Modeling tool of Oasis montaj. Since one of the main focuses is to detect the subsurface formations that aid groundwater circulation, usually located within subsurface basins (Araffa et al., 2015; Silva-Ávalos et al., 2022), we selected to highlight structures that present negative density contrast compared to the Bouguer reduction density of 2.67 g/cm³ that we used as an average for our study. Moreover, we used the GM-SYS Advanced Profile Modeling extension of Oasis montaj to construct a 2D model along a W-E profile in the central-southern part of the National Park. The model was constrained using a 2D resistivity section obtained from the 3D M.T. data inversion result. Also, we calculated the gravity field along the 2D model and compared it with the observed field measured by the gravity stations, which was depicted in the complete Bouguer anomaly map.

3.3.3 Magnetotelluric Data

MT data were recorded using the KMS-820 acquisition unit from 52 stations. The LEMI-120 audio frequency and LEMI-118 low-frequency induction coils were used to measure the magnetic field for broadband MT and AMT data, respectively. LEMI-701 non-polarizable electrodes were used for electric fields in AMT and broadband MT frequency measurements. AMT measurements were set up for approximately 25 minutes with three different sampling frequencies of 4 kHz, 20 kHz, and 80 kHz. The recorded time of each MT station lasted about 6 hours with three different sampling frequencies of 1 kHz, 4 kHz, and 40 Hz. In total, we collected broadband MT data on 46 stations, and on six of those stations, we also collected audio MT data along three profiles.

The KMSPro software was used to process the time series of both MT methods using a robust statistical technique, as validated by Smirnov (2003). During data processing, the low-frequency filter parameters (short FFT window of 16, 32, and 64 samples) were chosen for data filtering to deal with 40 Hz sampling rate data, and the high-frequency parameter (FFT window of 65k samples) to filter other higher sampling rate data (i.e., 1 kHz, 4 kHz, 20 kHz, and 80 kHz). The notch filter was also used during data filtering to reject any narrow frequency bands, such as the 60 Hz noise from power lines, and leave the remaining spectrum unchanged. After applying proper static corrections, the AMT data were incorporated into the MT data.

After time series analyses and impedance estimation in the frequency domain, we prepared the data sets and a 3D initial resistivity model using 3D-Grid software (3D-Consulting Geo Inc.). We removed the data from 10 stations because of their high noise levels. We also

masked the MT data, which has a large standard deviation in some station data sets. We only used off-diagonal impedance components (Z_{xy} and Z_{yx}). Diagonal impedance components (Z_{xx} and Z_{yy}) are not used because of their low amplitude and high noise levels. Finally, we smoothed and resampled the M.T. data before the 3D inversion; for the latter, we used the ModEM software (Egbert and Keller, 2012; Kelbert et al. 2014). This software uses finite difference forward solution for modeling and Jacobian matrix calculation and regularized smoothing inversion with a conjugate solution solver for inversion. The model mesh and data information used in 3D inversion are given in Table 1. We obtained 3D inversion results after 130 iterations with a 1.74 RMS error.

Table 1: 3D inversion settings

Stations, periods	42, 51	Mesh dimensions (x, y, z - in km)	(400, 400, 404)
Number of data	1429	Survey area (x * y - in km)	35 km ² (5 x 7)
Period range (in seconds)	0.01 – 1000	Minimum mesh dimensions (dx, dy, dz - in meters)	(100, 100, 20)
Blocks added for boundary (nx, ny, nz)	(15, 15, 18)	Iterations	130
Total blocks (nx * ny * nz)	476000 (100 x 85 x 56)	Initial and final RMS	15.66 - 1.74

3.3.4 Transient Electromagnetic Data

The TEM data were acquired on 35 stations along three profiles supplementary to the MT data. The main purpose of the survey was to collect the TEM data along the three profiles and produce quasi-2D resistivity sections and quasi-3D resistivity depth slices reconstructing the subsurface, after the inversion of the acquired data.

The ABEM-WalkTEM system was used for the TEM survey. The employed transmitter loop was a single-turn wire about 400 meters long, with each side 100 meters. Two receiver

loops were utilized for data acquisition to cover shallow and deep subsurface layers simultaneously. The first receiver, RC-200, featured a wire length of 40 meters arranged in a 10 x 10 meter configuration. Internally, this wire comprised two turns, resulting in a total receiver area of 200 square meters, coupled with an amplitude gain factor of 7, leading to a cumulative amplitude gain factor of 1400. The second receiver, RC-5, constituted a square loop measuring 0.5 x 0.5 meters and encompassed 20 internal turns. This setup yielded a total receiver area of 5 square meters, with the amplitude gain factor also set at 7, resulting in a total coil amplitude gain factor of 35.

Three cycles (stacks) of measurements were applied at each location to improve the signal-to-noise ratio (SNR). An average current of 6.6 A was emitted. Employing a dual-moment setup, each measurement was concurrently conducted using low and high moments. The low moment, characterized by a current intensity of approximately 2 A, was optimized for detecting shallow subsurface layers during early time intervals. Conversely, the high moment, featuring a current intensity of approximately 13 A, was tailored to penetrate deeper subsurface layers, emphasizing late time intervals. The characteristics of the transmitter waveforms were regulated through user-defined script files comprising 39 receiver time gates. The total measuring time was 7953 μs , divided into 39 gates where the shortest and longest gates equal 2 μs and 1633 μs , respectively. At the time of measurements, the noise (natural background noise for both moments) is also recorded and used to determine the depth of investigation (DOI).

TEM data were filtered and inverted using the Aarhus SPIA software developed by Foged et al. (Foged et al., 2013) and SPIA (<https://hgg.au.dk/software/spia/>). The filtered data were processed by applying the efficient AarhusInv inversion code (Auken et al., 2015)

with varying levels of smoothing (low, normal, or high). The processed data and inversion models are stored in the SPIA database and can be directly imported into Aarhus Workbench (Vignoli et al., 2015) for convenient visualization of the results as cross-sections or depth slices.

3.4 Geophysical Data Results

3.4.1 Magnetic

The magnetic data are presented in Figure 18. More specifically, Figure 18a shows the data before the filtering for the cultural noise and the removal of the spikes, while Figure 18b shows the result after data processing. The magnetic response of the three main noise sources is highlighted with yellow circles in Figure 18a. They create high-amplitude spikes of very short wavelengths that do not match the general trend of the rest of the dataset. After removing the responses caused by the artificial magnetic sources, the data showed no significant anomalies that could be attributed to the shallow geologic structures identified using the gravity and EM methods. Thus, we did not integrate the analysis of the magnetic data into the rest of the models.

3.4.2 Gravity

Figure 19 presents the maps of the calculated CBA (Figure 19a) and the residual gravity field (Figure 19b). The CBA anomalies vary from 21.94 to 24.01 mGal, while in the residual field map, which represents the effects of the shallow structures on the measured gravity field, the anomalies vary from -1.47 to 0.97 mGal. This indicates a recorded signal with a total amplitude of 2.44 mGal. It should be highlighted that the gravitometer used has an accuracy of 0.001 mGal.

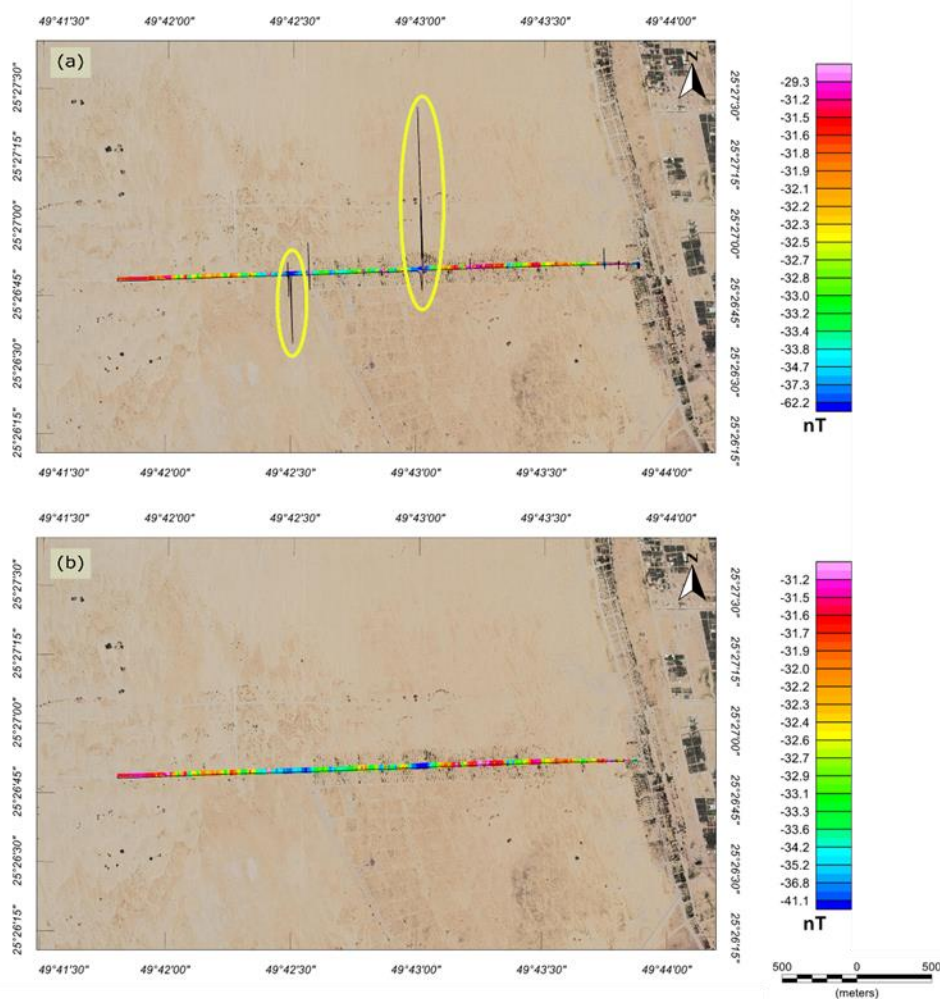


Figure 18: The magnetic response along the measured profile is indicated with the black line and the recorded magnetic field (color scale). (a) The data before noise filtering and spike removal. The three high-amplitude responses, marked with yellow circles, correspond to cultural noise sources. (b) The results after the data processing.

The residual gravity field shows low-gravity areas in the western and southern parts of the National Park (blue color), while high gravity values (red and pink colors) are encountered in the northern and southeastern parts. The largest portion of the National Park is characterized by mid-to-low gravity anomalies (around -0.12-0 mGal).

Figure 20 shows the TDR (Figure 20a) and the terracing (Figure 20b) map produced by the residual gravity field. The zero-value contours of the TDR were used to interpret the lineaments shown as black lines. The dip direction of the lineaments is also shown in Figure

20a (the direction of the semi-circles). The terracing filter enhanced the subsurface features (Figure 20b), indicating similar gravity response areas. The results of the tilt-depth method are shown as colorful circles overlain the terracing map of Figure 20b.

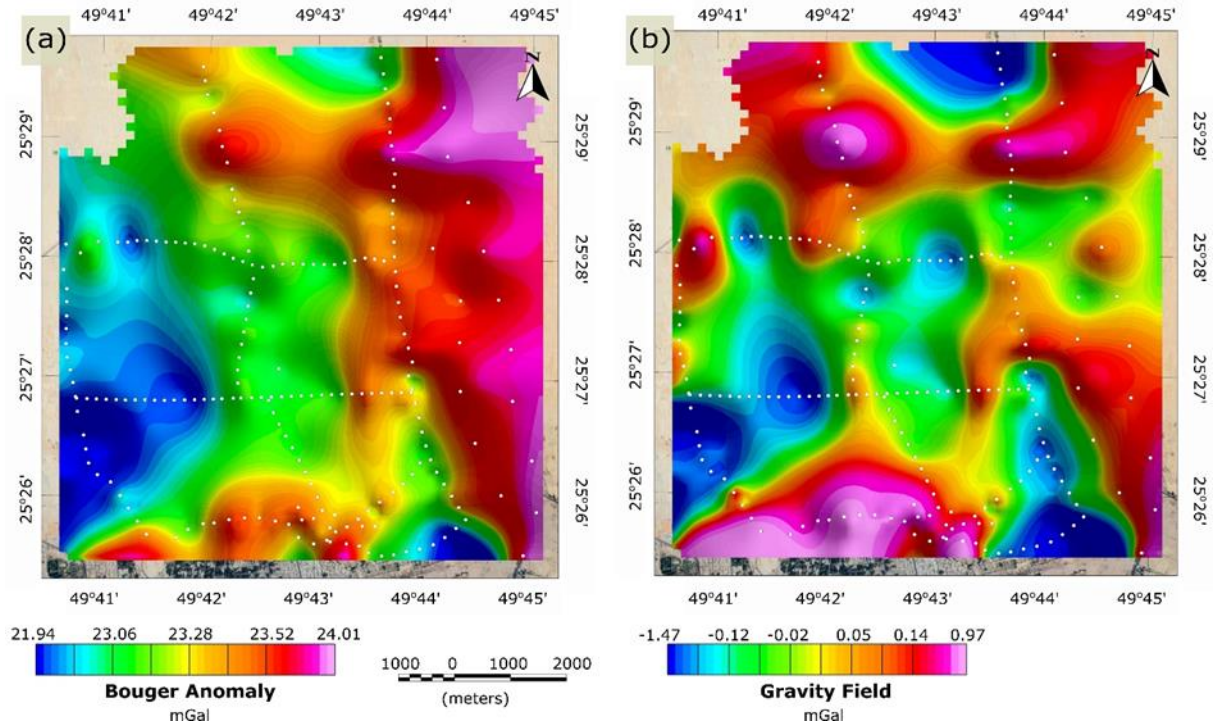


Figure 19: The results of the gravity data processing. The white dots correspond to the measured gravity stations. (a) The complete Bouguer anomaly map. (b) The residual gravity field map.

By applying 3D inversion to the gravity data, the 3D representation of the structures by voxel was constructed, representing the density contrast (positive or negative) as shown in Figure 21. We discretized the area in a mesh with 79x82x23 voxels in X (easting), Y (northing), and Z (depth), with a resolution of 100 m. This provided a maximum depth of 2.3 km for the inversion. Since we wanted to highlight the negative (low) density contrast bodies, we used the values of 0.1 g/cm³ and -1 g/cm³ as the upper and lower boundary on the inversion algorithm for visualizing the 3D gravity model (Figure 21b).

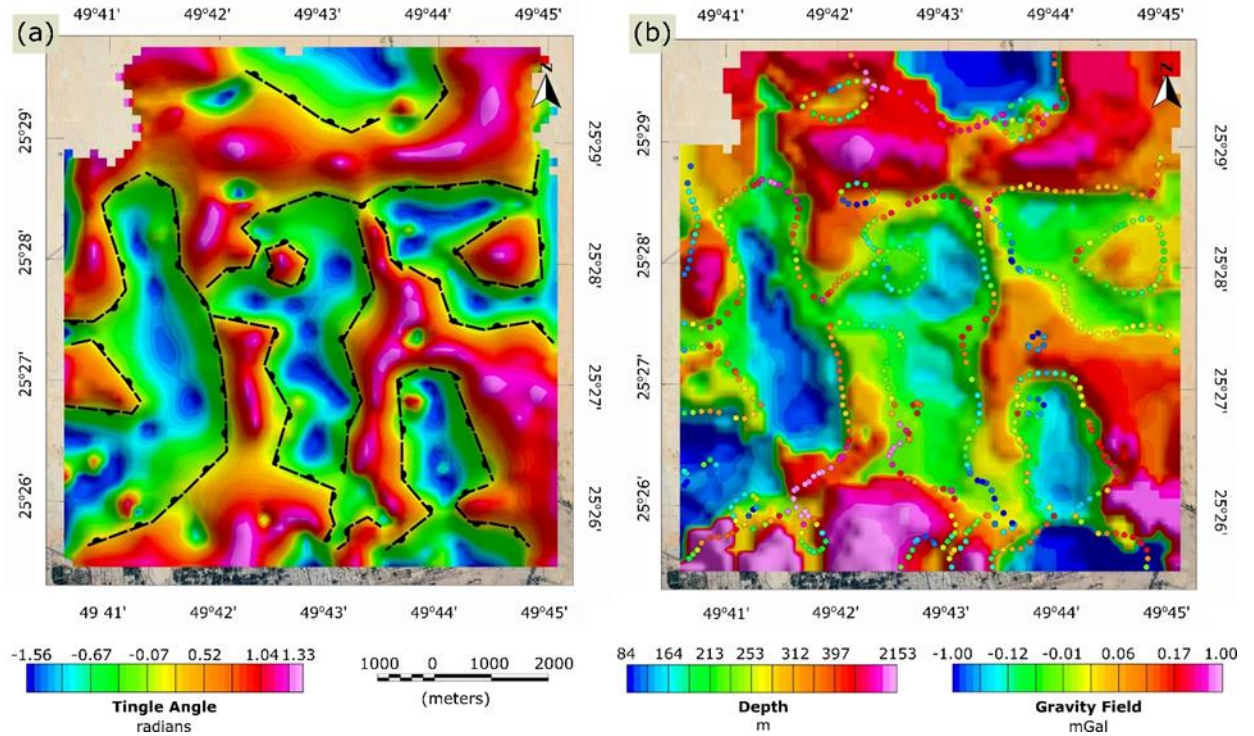


Figure 20: Enhancement filters on the gravity data. (a) The tilt derivative and the interpreted lineaments (black lines) correspond to structural edges. (b) The terracing map is overlaid by the results of the tilt-depth method and shown as colorful dots (the depth in the color bar is positive down).

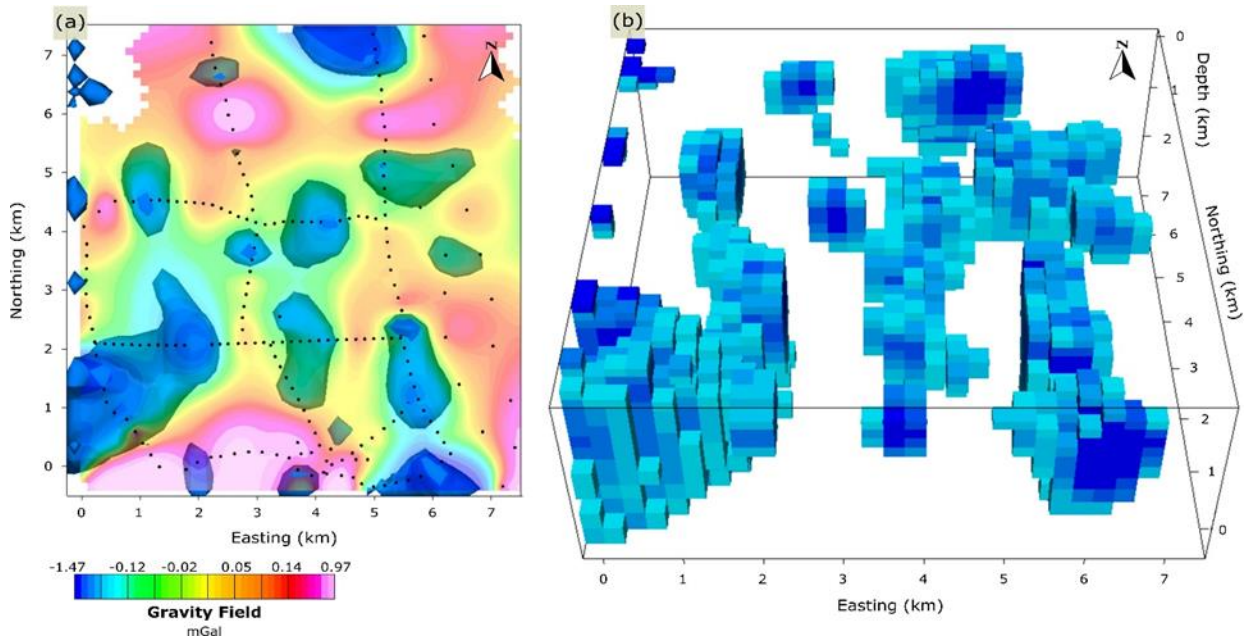


Figure 21: The 3D model of the Al-Hassa National Park survey area shows the negative density contrast bodies. (a) Top view of the model. The residual gravity field map overlays the anomaly sources, and the locations of the acquired gravity stations are shown as black points. (b) Side view of the model, in which the depth of the interpreted bodies can be studied. The directions of the geotectonic elements and their relative positions are also shown.

3.4.3 MT and TEM

The 3D inversion result of MT data is shown as six different depth slices (Figure 22) at 177-224 m, 500-596 m, 708-838 m, 987-1160 m, 1359-1589 m, and 1854-2161 m. Figure 23, presents three different 2D sections of the acquired EM data. One in the S-N direction (Figure 23a) and two profiles in the W-E direction (Figure 23b,c).

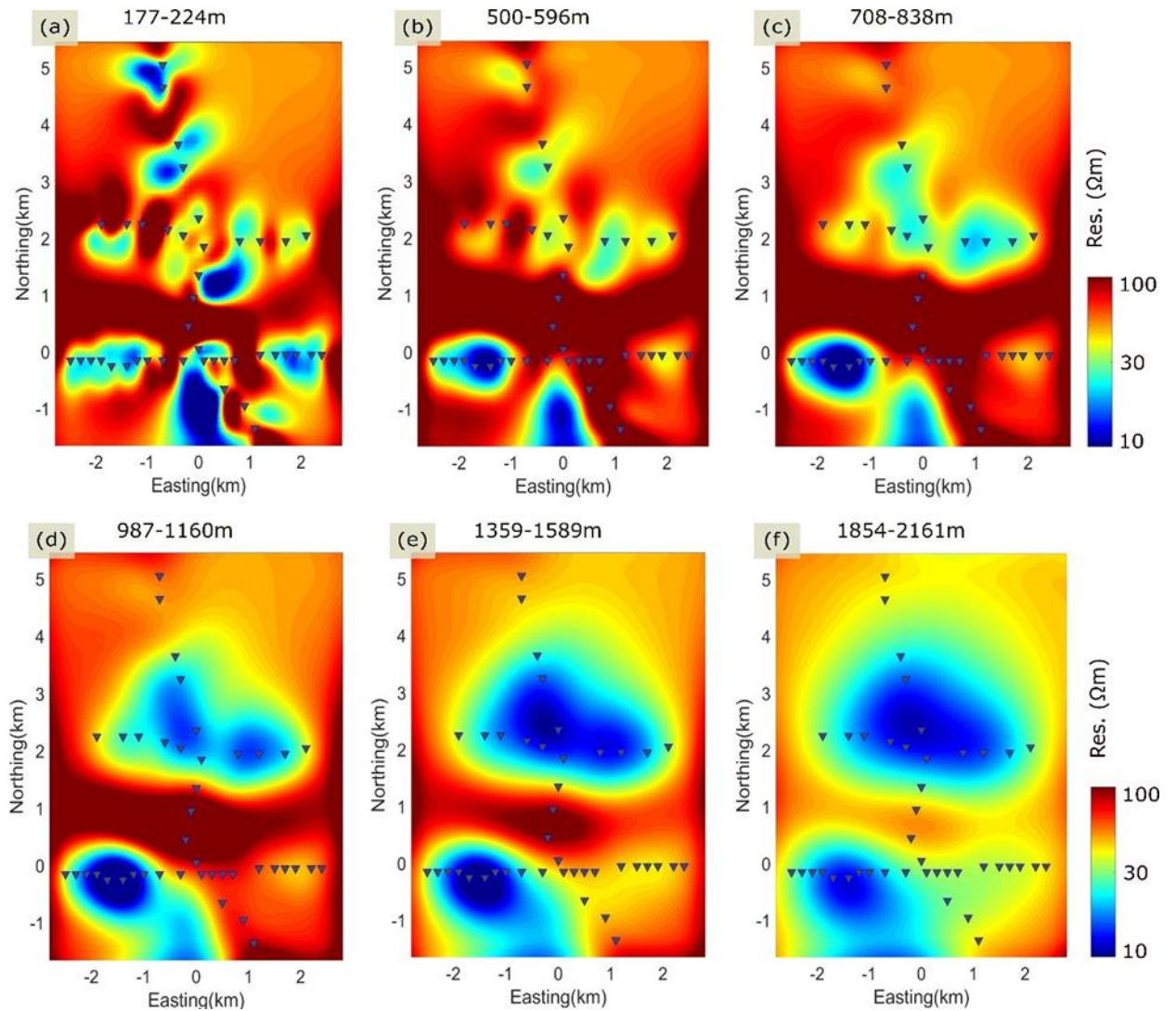


Figure 22: The 3D inversion results of MT data collected in the Al-Hassa National Park. The 3D resistivity model is presented as xy-sections for different depth ranges. The triangle symbols show the MT station locations. Depth increases from left to right and top to bottom.

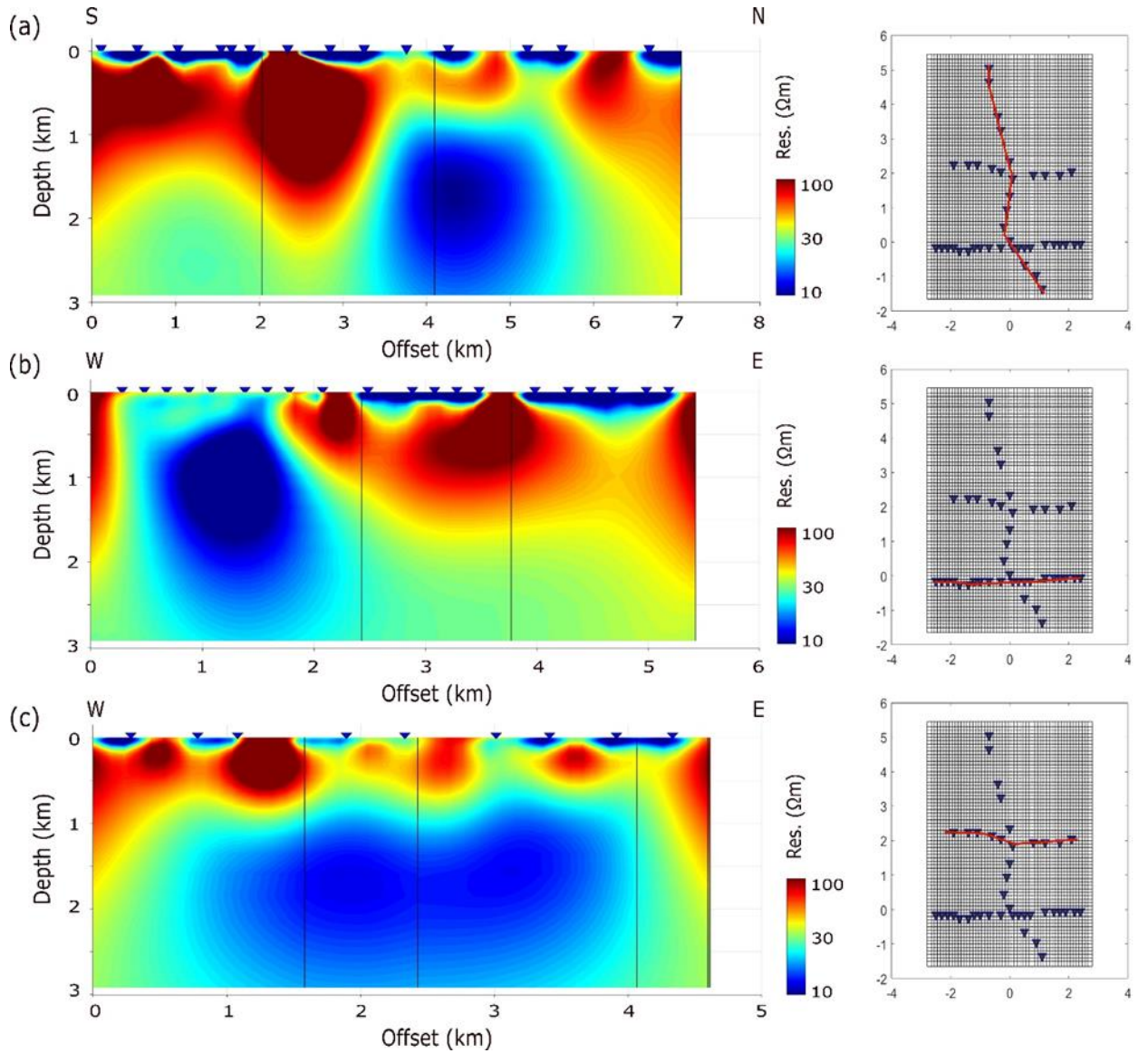


Figure 23: The 3D inversion results of MT data along three MT profiles. Each section line's location is shown on the plan view of the survey area given on the right side of the related 2D section.

All depth slices and cross sections were plotted using the same resistivity range (10-100 Ωm) and color scale, where the darker (blue) colors depict the low resistivity formations, and the brighter (red) colors represent the high resistivity areas.

Filtering and de-noising were automatically applied after importing the TEM data into the processing software. Any resultant inverse model can be an initial model for the subsequent

inversion process. The residual data averaged around 0.92. Two distinct resistivity models were computed for each acquired TEM sounding. A smoothed resistivity model is created based on a predefined number of layers with increasing thickness, while a layered resistivity model is developed with the fewest layers needed to achieve the best fit, assuming the mean resistivity within each layer is accurate. This method identifies minor and incremental variations in resistivity. The 1D inversion results of the TEM data are combined, and a pseudo-3D resistivity model is obtained. The Aarhus Workbench was utilized in this survey for visualizing the TEM data, and three (0-100 m, 100-200 m, and 200-300 m below the ground surface) quasi-2D depth slices were generated by interpolating the spatially distributed TEM soundings (Figure 24a,b,c). The comparison of the shallow 3D MT depth slice (170-220m below the ground, Figure 24d) with the TEM depth slices of 100-200m and 200-300m bgs (Figure 24b,c) are presented. The black circles depict the same anomalies indicating the agreement between the time and frequency domain EM data modeling for the same depth.

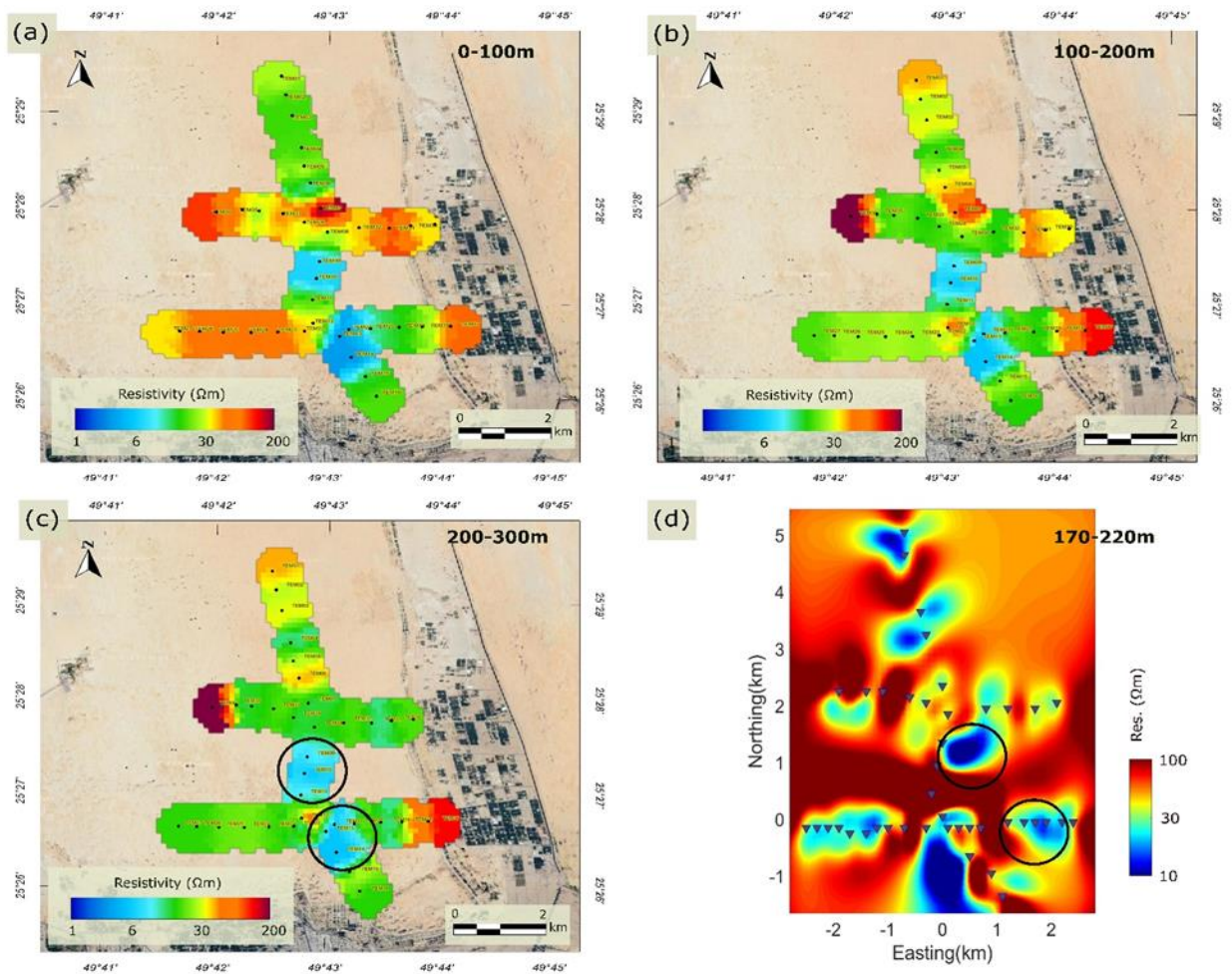


Figure 24: Quasi-3D TEM modeling. The depth slices for the depths of (a) 0-100 m, (b) 100-200 m, and (c) 200-300 m. (d) The depth slice for the depth of 170-220 m below the ground surface from the 3D MT data inversion.

CHAPTER 4

Reconstruction of the subsurface of Al-Hassa Oasis using gravity geophysical data

Khogali, A.; Chavanidis, K.; Kirmizakis, P.; Stampolidis, A.; Soupios, P. Reconstruction of the Subsurface of Al-Hassa Oasis Using Gravity Geophysical Data. Appl. Sci. 2024, 14, 3707. <https://doi.org/10.3390/app14093707>

4.1 Introduction

The Al-Hassa region in eastern Saudi Arabia is well-known for being home to the largest oasis in the world and the most extensive naturally irrigated lands on a global scale (Al Tokhais and Rausch, 2008). Al-Hassa is located next to Ghawar, which is the largest conventional oil field in the world. Due to its historical dependence on more than 280 natural springs, some of which provide warm water for agricultural irrigation (Al-Zarah, 2011), the area's diverse water quality indicates the existence of intricate underground geological formations that require careful investigation.

Prior research on the hydrochemistry and hydrogeology of the Al-Hassa region provides a thorough comprehension of the intricate subsurface conditions in the study area. Bakiewicz et al. (Bakiewicz et al., 1982) studied the hydrogeology of the Umm Er Radhuma aquifer. Subsequently, the authors Sen and Al-Dakheel (Sen and Al-Dakheel, 1986) assessed hydrochemical facies in the same aquifer. Sharaf (Sharaf, 2001) emphasized the hydrogeological and hydrochemical aspects of groundwater, specifically highlighting the risks of seawater intrusion. In their study, Al Tokhais and Rausch (Al Tokhais and Rausch, 2008) examined the hydrogeology of the Al-Hassa springs and predicted the future

availability and quality of water. They concluded that the situation will become increasingly dire if the current water extraction rates continue. In his 2009 study, Al-Dakheel (Al-Dakheel, 2009) introduced a spatial modeling approach to analyze changes in groundwater salinity over time. Al-Naeem (Al-Naeem, 2011) and Al-Zarah (Al-Zarah, 2011) expanded upon this by assessing groundwater suitability for irrigation purposes and analyzing the elemental compositions. Al-Omran et al. (Al-Omran et al., 2018) analyzed the quality of groundwater, while Dirks et al. (Dirks et al., 2018) provided further information on the geological aspects of the Umm Er Radhuma aquifer. In their recent studies, Abba, Yassin, Jibril, et al. (Abba et al., 2024a) and Abba, Yassin, Shah, et al. (Abba et al., 2024b) utilized advanced methodologies such as machine learning and spatial mapping to examine trace element pollution and nitrate concentrations, respectively. These studies provided state-of-the-art findings on groundwater susceptibility and pollution in Al-Hassa.

The Ghawar oil field was first discovered in 1948 and began production in 1951. This extensive oil field is projected to maintain its current maximum production capacity of 3.8 million barrels daily until at least 2050. Ghawar is the primary supplier of associated gas for Aramco, and the greater Ghawar area also contains several significant non-associated gas fields.

The genesis of the prolific Ghawar oil field can be traced back to the Amar Collision, occurring approximately between 640 and 620 million years ago (Ma). This collision initiated a series of structural events across the Arabian Plate, giving rise to distinct north-, northeast-, and northwest-oriented structural patterns, such as the En Nala Anticline, Qatar Arch, and Khurais-Burgan Anticline (Al-Husseini, 2000; Pollastro, 2003). After this,

an extensional regime between about 570 and 530 Ma catalyzed the development of the Najd fault system and engendered the formation of north-east-trending rift basins, laying the foundation for the creation of major subsidence zones during the Precambrian and Early Cambrian times (Al-Husseini, 2000; Geert et al., 2001; Martin, 2001; Oterdoom et al., 1999; Sharland et al., 2004). During this period, the proximity of the Arabian plate to the equator (Geert et al., 2001) facilitated the deposition of extensive salt layers within these basins, including the Hormuz, Ghaba, Fahud, and South Oman salt basins (Al-Husseini, 2000; Mattes and Conway Morris, 1990). Notably, the Hercynian Orogeny during the Devonian period was pivotal in reactivating pre-existing basement structures, thereby generating prominent north-south oriented horst blocks across central and eastern Saudi Arabia. These geological events and processes cumulatively contributed to the formation of structural traps favorable for hydrocarbon accumulation, amongst which Ghawar stands as a preeminent example (Pollastro, 2003).

Geophysical investigations are a set of techniques that are used to analyze and describe the properties of materials in the subsurface. These techniques are indirect and non-invasive, meaning they do not involve direct contact with the studied materials. A comprehensive understanding of the fundamental formations and their structures is essential for conserving natural resources through exploration and exploitation. Both seismic and non-seismic geophysical methods can be used to analyze and track the properties of the subsurface. However, relying solely on one geophysical method is inadequate; to achieve the most favorable result, it is advisable to utilize multiple methodologies and fully integrate their findings. Methods and data integration are not always applicable since sometimes the study

areas have cultural noise and the least susceptible to noise geophysical methods should be used to extract any information about the subsurface.

Gravity anomalies result from the heterogeneous distribution of densities within the Earth's crust. Consequently, profound and broad geological structures, including the delineation of sedimentary basins, hydrocarbon traps, and the boundaries of mineralized zones, can be effectively identified and mapped through gravity surveys. This geophysical method leverages variations in gravity to infer the subsurface structural composition, offering insights into both the depth and nature of geological features of interest (Zhang et al., 2019).

In the broader Ghawar structure, positive and negative gravity responses were observed by Edgell (Edgell, 1992), Saner et al. (Saner et al., 2005), and Mukhopadhyay et al. (Mukhopadhyay et al., 2020). Around 20 km east of the Ghawar structure, the Al-Hassa area in Saudi Arabia has not been extensively studied regarding its geological and geophysical characteristics, despite its importance in the field. Previous investigations by Al-Dakheel et al. (Al-Dakheel et al., 2008), Al Tokhais and Rausch (Al Tokhais and Rausch, 2008), and Mahmoudi et al. (Mahmoudi et al., 2011) have provided limited information on the subject.

This study aims to address the lack of research by creating an accurate and high-resolution 3D model of the subsurface using a robust geophysical method. Specifically, this research presents the results of a large-scale geophysical survey over urban, suburban, and agricultural sites using the gravity method to analyze intricate fracture networks and gain insights into the structural development and tectonic past of the Al-Hassa Oasis area in Saudi Arabia. The study area's subsurface model was acquired through the inversion of

three-dimensional (3D) gravity data, and the complex 3D subsurface structure of the Al-Hassa Oasis was reconstructed.

4.2 Study area - Geological and Tectonic settings

The study area is located about 60 kilometers west of the Arabian Gulf, in the eastern province of Saudi Arabia, known for its prominent geological characteristics. It is situated between latitudes 25.351462° and 25.547711° , and longitudes 49.557074° and 49.754603° , covering an area of approximately 350 km² (Figure 25a, b, c). The elevations in the area vary between 120 and 220 meters above sea level. A sand layer covers the study area and lacks any extended outcrops that can support any geological/tectonic study. Therefore, no geological maps have been published that include information about the types of rocks in the studied area (Figure 25a). Within the study area, there is a spot where rock outcrops, particularly the Hofuf formation, were found. These rock formations would probably extend to other areas in the eastern province.

The region is mainly characterized by sand dunes and Quaternary deposits, with occasional exposed sections that reveal the Upper Miocene to Lower Pliocene Hofuf Formation (Figure 25b). In general, there is a scarcity of published geological research in the area because it is located close to the Ghawar oilfield. Additionally, the groundwater wells in the area lack any information about the types of rocks present. The Hofuf Formation is distinguished by the presence of conglomerates, calcareous sandstones alternating with reddish mudstones, and limestones (Al-Saad et al., 2002). The Hofuf Formation is located above the Dam Formation and consists of limestone and reddish marls. The Hadrukh Formation follows, consisting of sandstones, limestones, and marls (Powers et al., 1966). Following that, the sequence comprises the dolomitic and lime-stone formations of the

Eocene Dammam Formation. The underlying formations include the early Eocene Rus Formation, which is made up of dolomitic limestone and gypsum, and the Paleocene Umm Er Radhuma Formation, which contains limestone and dolomite with quartz geodes and chert nodules (Al-Sayari and Zötl, 1978; Powers et al., 1966).

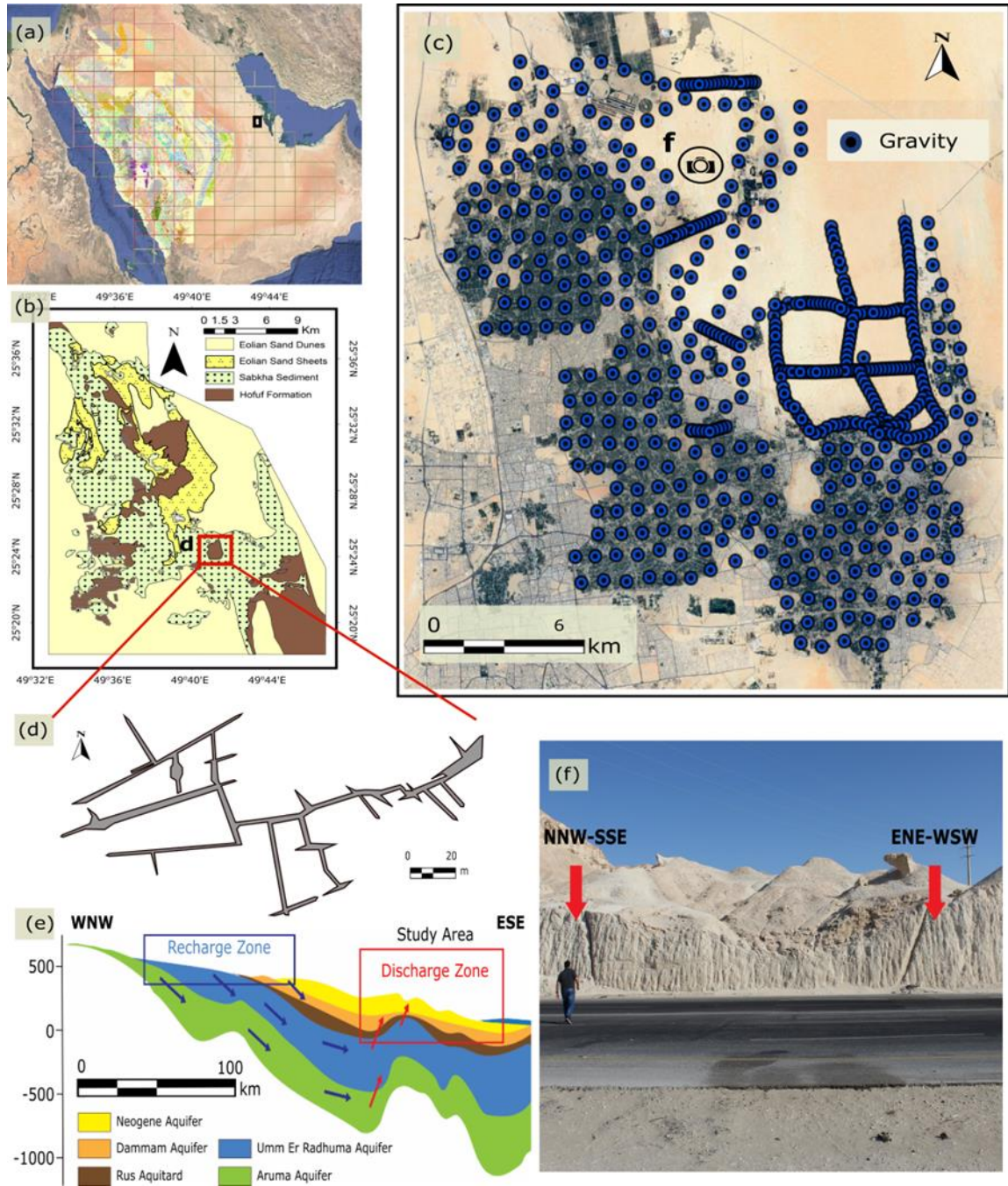


Figure 25: a) The coverage of Saudi Arabia by geological maps released by the Saudi Geological Survey is presented by the colored rectangles. A thick black square depicts the location of the study area. (b) Geological map of the wider area (modified from Al-Mahmoud (Al-Mahmoud, 1987)). A red rectangle shows the location of the caves map on Figure 1d. (c) The study area with all the acquired gravity geophysical measurements is presented. The camera icon shows the location of photo shown in Figure 1f (d) The fault zone pattern described by Hussain et al. (Hussain et al., 2006) is depicted. (e) W-E section shows the geologic formations, the groundwater flow (blue and red arrows), and the subsurface deformation due to basement uplift beneath the study area (modified from Al Tokhais and Rausch (Al Tokhais and Rausch, 2008)), and (f) Fault zone field photo showing the major ENE-WSW and NNW-SSE directions observed at an outcrop within the study area.

The Neogene sedimentary sequence in the Arabian Gulf area is distinguished by an elongated NW-SE asymmetrical basin called the Zagros Syncline, located within the East Arabian Block (Murriss, 1980; Powers et al., 1966). The basin area is thought to have diminished during the Neogene period, likely due to a global increase in sea levels during the Mid-Oligocene period, followed by the upward movement of the Earth's crust from the Oligocene to the Miocene epochs (Weijermars, 1999). The Hofuf Formation is formed due to the Neogene development of the East Arabian Block. This is supported by features such as grabens, strike-slip faults, and transpressive folds, as documented by Hancock and Kadhi in 1978 (Hancock and Kadhi, 1978), Vaslet et al. in 1991 (Vaslet et al., 1991), and Weijermars in 1999 (Weijermars, 1999). Dome formation in the Arabian-African Shield occurred from the Late Cretaceous to the Eocene, while rift formation and the separation of Africa from Arabia occurred during the Late Eocene to the Oligocene. Tectonic activity occurring from the Late Miocene to the Pliocene caused the Red Sea floor to spread, which resulted in the drainage of the uplifted Arabian Shield and the deposition of substantial clastic sediments. This process led to the formation of the Miocene Hudruk and Mio-Pliocene Hofuf formations (Al-Saad et al., 2002). The topography of the region, which slopes towards the east, allowed for the movement of sediment from west to east because of erosion of the underlying bedrock.

Hydrogeologically, the area is recharged by the mountainous western part of Saudi Arabia, where fresh groundwater flowing to the east and northeast is observed in many monitoring wells (Figure 25d). A notable gradient in groundwater salinity is observed across the region, escalating from approximately 300 parts per million (ppm) in the west to more than 5000 ppm along the Arabian coast. Intriguingly, a discernible abrupt shift in salinity with

depth reveals a distinct stratigraphic influence. Shallow aquifers exhibit comparatively better groundwater quality, whereas deeper (around 800 m) aquifers, particularly within the Aruma Formation, manifest exceedingly saline groundwater (Al Tokhais and Rausch, 2008).

The uplift and formation of the Ghawar anticline induced significant fracturing in the region. The Al-Shubaa outcrop and a southern one display joint systems trending in the NW-SE or NNW-SSE and E-W or ENE-WSW directions, eroded by wave-cut gorges (Figures 25e,f). Fluvial erosion later reshaped these features (Al-Sayari and Zötl, 1978).

4.3 Gravity survey

The gravity survey was carried out by the Geophysics lab of the King Fahd University of Petroleum & Minerals in three phases, taking place in the summer of 2021, the summer of 2022, and the spring of 2023. A total of 571 gravity stations were measured, at urban and semi-urban areas north and east of the Al Hofuf city, as well as within the Al Hassa National Park area. The data were collected in grids and profiles and cover an area of approximately 350 km², with varying station spacing (150-900 m) according to local conditions (gridded/profile data, remote/urbanized areas, accessibility, etc.). The characteristics of urban areas (e.g., roads, buildings, telecommunication cables, large metallic objects, buried pipes and cables, sewers) do not allow the usage of magnetic or electromagnetic methods, so the gravity method can be used to gain preliminary insights into the subsurface regime of such areas at a quick and cost-effective manner (Fairhead, 2016). However, due to the complexity of these areas, there are limitations in the application of the gravity method as well.

The measurements were acquired using two Scintrex CG-5 AUTOGRAVTM gravimeters, which have a high resolution of 1 μ Gal and using the optimum acquisition parameters depending on the natural and/or cultural noise of the area under investigation. We set the gravimeters to automatically detect and discard spikes caused by high external noise, as well as to consider the Earth's tide effect and the instrument's tilt during transportation and make the necessary corrections to the measurements. To avoid the extra minor noise caused by the high air temperature that is typical for the area during the summer months, the data were acquired during the morning hours and stopped before noon. The gravity measurements were taken in sets of three or five, with a duration of 30-60 seconds, according to the environmental or cultural noise in the nearby area. To ensure high-quality data, any set with a difference of more than 10 μ Gal was repeated with additional measurements. Stations with a tilt greater than 15 arcsec were not used and the gravity readings were repeated. The average standard deviation (SD) for all the acquired data was 0.037 mGal.

Three points were selected to be used as base stations (one for each measurement period), which were located in a central location near the rest of the measurements, in a relatively quiet area (with no external noise sources). Each day, an opening and a closing measurement were taken on the base station.

To estimate the gravimeter's height correction, the distance between the center of the instrument's mass and the elevation of the instrument's location was measured, so that every measurement refers to the actual elevation of the topographic relief. The geographic coordinates and elevation of each station were measured by Trimble's R10 Differential GPS (Global Positioning System), with an accuracy error of less than 1 cm, using either a

base station or the KSA-CORS (Kingdom of Saudi Arabia Continuously Operating Reference Station) network (for the measurements that cover wide areas within the city). The latter consists of a service provided for the entire country that increases the geographic and elevation accuracy of measured positioning.

For urban areas, there is a need to minimize the influence of buildings and other relevant constructions on gravity measurements. The mass, height, and vibrations of a tall construction cause the so-called “Building Effect”, which needs to be eliminated from the data by applying the “Building Correction” using information from detailed ground elevation datasets, such as LIDAR (Dilalos et al., 2018). A minimum distance of 75 m is proposed to exist between a large construction and the installed gravity station (Dilalos et al., 2018), while in many areas where a distance like this cannot be achieved, smaller distances might be used, up to 30 m (Chavanidis et al., 2022). In our survey, due to the densely constructed urban and semi-urban areas, the gravity station locations were selected so that there is a distance greater than 15 m from any small construction (e.g., stone wall) and 30 m from any larger building. This issue did not occur within the National Park and the surrounding area, where the stations were installed in remote locations.

4.3.1 Gravity data processing

After their acquisition, the data were imported to Seequent’s Oasis Montaj software for processing and enhancement. For the corrections to the raw data, the Gravity and Terrain Correction extension was used; a useful tool integrated within Oasis Montaj that handles gravity data obtained from ground surveys. The common gravity corrections of instrumental height and drift were applied to eliminate the factors affecting the

measurements' quality. Since no absolute gravity station was available to use its coordinates and elevation for the latitude correction, the base station of the 2021 survey was used as the reference point, and all gravity measurements were tied based on that point. Earth's normal gravity was calculated using the 1980 Geodetic Reference System (GRS80) (Moritz, 1980) so that the theoretical gravity value of the 2021 base station location was considered equal to zero.

Topographic highs and lows strongly affect the local gravity field, and this dependence should always be considered when processing gravity measurements (Chavanidis et al., 2022). The effect of the local topography was reduced after applying the topographic correction using the Oasis Montaj standard algorithm. To run the terrain correction algorithm, it is necessary to import detailed and coarser Digital Elevation Model (DEM) or gridded elevation data for the area of the survey and the wider area, respectively. The software produces a new grid that represents the terrain corrections, thus the correction at each gravity station location can be accurately calculated using the methods described by Kane (Kane, 1962) and Nagy (Nagy, 1966). In our study, the Shuttle Radar Topography Mapping (SRTM) at 30 m resolution was used as the local elevation model, and the SRTM at 90 m was used as the regional elevation model. The elevations of each gravity station were measured with high accuracy using the Trimble R10 Differential GPS system.

The Free Air and Bouguer corrections were applied to the corrected data to determine the complete Bouguer anomaly (CBA). This anomaly considers the influence of extensive and deep-seated regional structures, as well as shallower local bodies. Adjustments to this overarching workflow may be necessary based on the specific goals of the study and the nature of the survey (Fairhead, 2016). In order to separate the influence of the shallow

structures, we obtained the residual gravity field map by calculating and subtracting a 1st order polynomial that simulates deeper sources (regional field) from the CBA field.

To continue the process of identifying subsurface geotectonic structures such as rock contacts and faults that have a significant difference in density and to compare the results of the gravity analysis with the geology of the study area, we utilized the terracing transformation and the tilt derivative (TDR) filters on the residual field data. The technique of terracing transformation, as described by Cordell and McCafferty (Cordell and McCafferty, 1989), can identify distinct regions of uniform gravity field intensity with well-defined boundaries (Li, 2016). To produce the terracing transformation map, we run 30 iterations of the terracing algorithm using Oasis Montaj software. The zero contours of the TDR can be utilized to enhance structural edges (Miller and Singh, 1994; Verduzco et al., 2004). This technique can also improve the signal of gravity anomaly sources that are deeper or weaker. The calculation of TDR can be determined using equation (1):

$$TDR = \arctan \left(\frac{\frac{\partial G}{\partial z}}{\sqrt{\left(\frac{\partial G}{\partial x}\right)^2 + \left(\frac{\partial G}{\partial y}\right)^2}} \right)$$

where $\partial G/\partial x$ and $\partial G/\partial y$ are the first-order derivatives of the gravity field in the x and y directions, and $\partial G/\partial z$ is the first-order vertical derivative. It was applied to the residual gravity field data to define the locations of structures' edges corresponding to faults and/or vertical/sloping rock contacts that act as the causative anomaly sources. The dipping direction of the anomaly sources can also be estimated, which dips towards the negative tilt angles.

The tilt-depth method (Salem et al., 2007) can be utilized to analyze the variations in the depth of the anomaly sources. Given vertical geologic contacts or faults, the depth at which the upper surfaces of the sources are buried can be found by measuring half the physical distance between the corresponding contours of $\pm 45^\circ$.

To examine the distribution of rock densities beneath the surface, we generated three-dimensional models using the VOXI Earth Modeling tool within the Oasis montaj software. This software mainly uses the Cartesian Cut Cell method [42, 43] for the inversion process. This approach utilizes a Cartesian voxel comprising prismatic elements, which diminishes computational complexity and saves computation time, while also enabling highly accurate geometric depiction of geological surfaces. By integrating the method into inversion and forward calculations, well-known artifacts that arise from representing topography with prisms of fixed vertical extent are eliminated. To highlight the subsurface basins where tectonic features largely influence fluid circulation, we studied the 3D distribution of the negative density contrast bodies (density lower than the average crustal density of 2.67 g/cm³ that we used).

4.4 Results

Figure 26 presents the mapping of the resulting complete Bouguer anomaly (CBA). The CBA anomalies range from 20.893 to 24.276 mGal. It is shown that the southwestern part of the study area is dominated by lower CBA values than the rest of the area, whilst the highest values are measured in the south-eastern and northern part of the area under investigation.

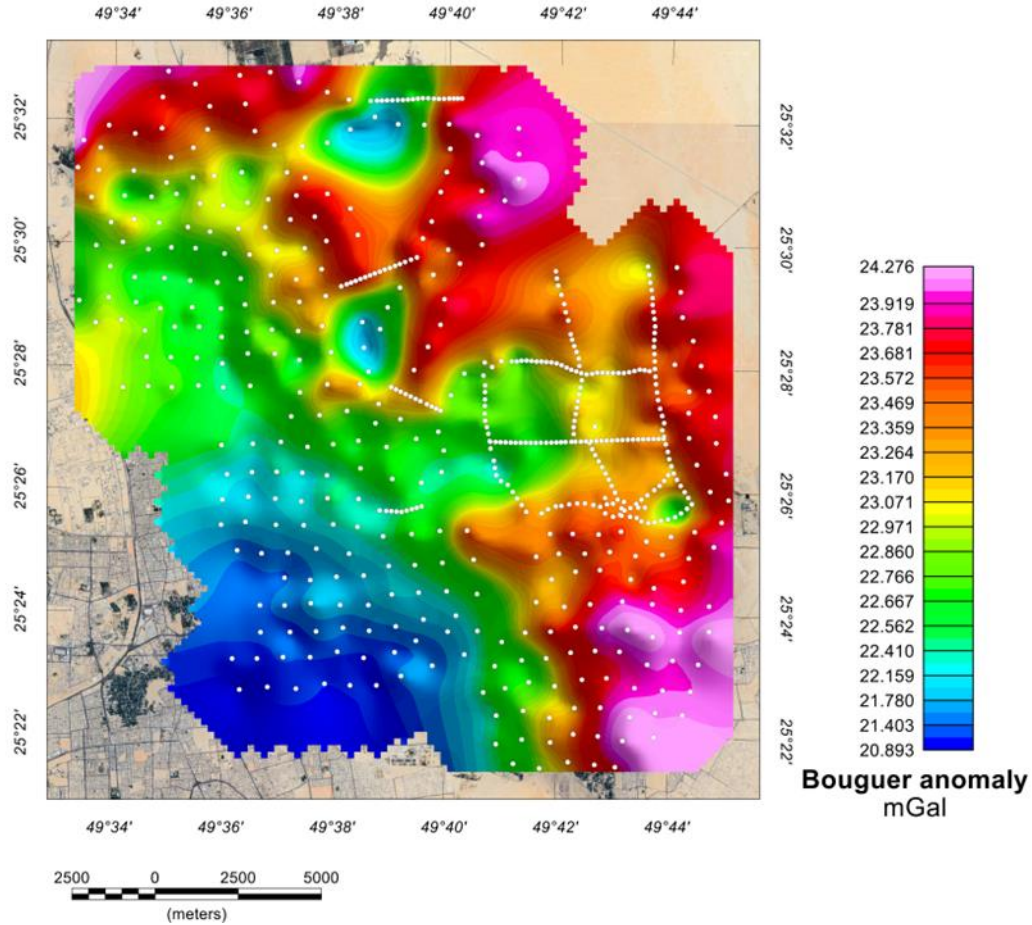


Figure 26: The complete Bouguer anomaly map of the Al-Hassa study area. The white points correspond to the locations of the gravity stations.

Figure 27 shows the residual gravity field. In the residual field map, which shows the influence of shallow structures on the gravity field, the anomalies range from -1.643 to 1.498 mGal. This indicates a measured signal with a cumulative amplitude of 3.141 mGals. Here, it is important to note that the gravitometer has a precision of 0.001 mGal.

The residual gravity field indicates regions of low gravity anomalies (lower densities) in the southwestern area and locally, in some spots supported by several stations, in the north, north-east, and central part of the study area, represented by the dark blue color. Conversely, areas of high gravity anomalies, depicted by the colors red and pink, are found

in the northwestern and southeastern parts of the study area. The rest of the study area is characterized by mid-to-low gravity anomalies, typically ranging from -0.4 to 0 mGal, represented by green and light-yellow colors.

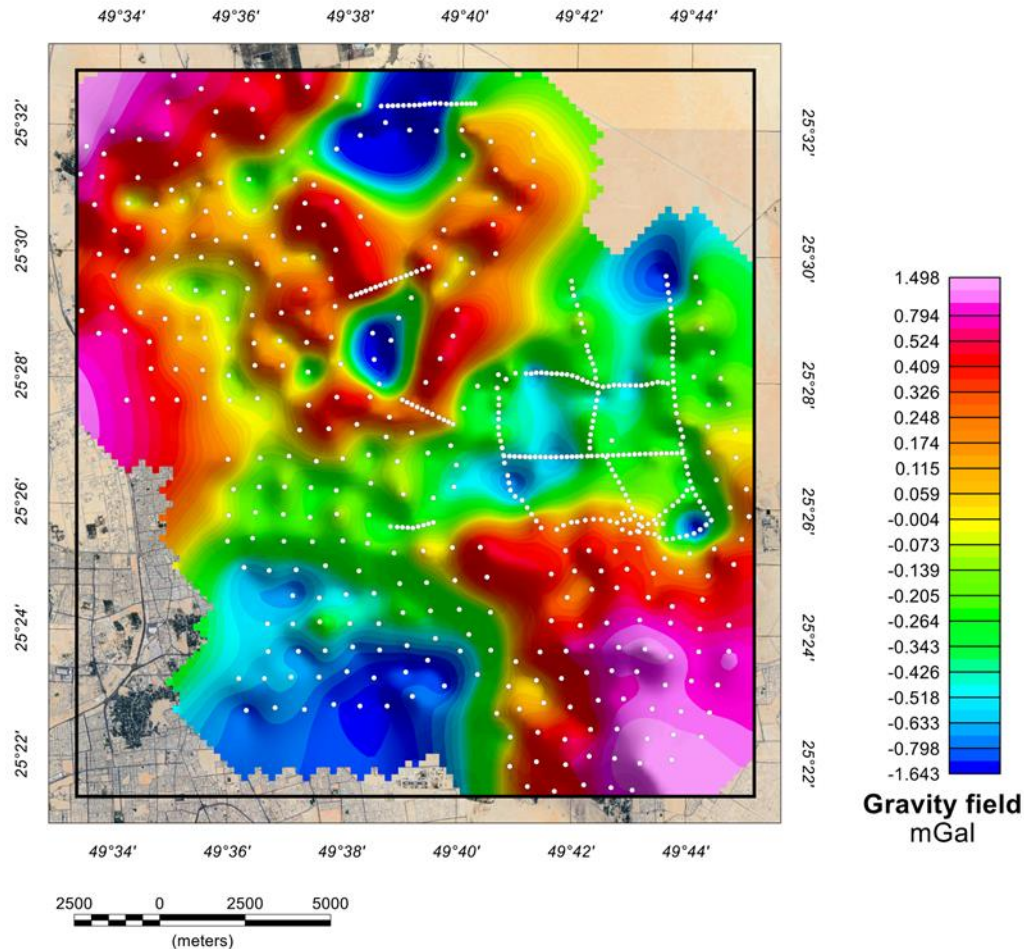


Figure 27: The residual gravity field map with the locations of the gravity stations (white points). The black rectangle indicates the boundaries of the 3D modeling area.

Figure 28a shows the TDR map generated using the residual gravity field. The TDR's contours at zero-value were employed to analyze the subsurface lineaments depicted as black lines. The dip direction of the lineaments is also indicated in Figure 28a, represented by the direction of the semi-circles. The subsurface lineaments can be considered as lateral geophysical (density) discontinuities and with low uncertainty can be assumed as fracture

zones. Based on this assumption, all lineaments were segmented in equal lengths and their orientation was recorded and used to prepare the rose diagram of Figure 28b, using the GeoRose software (<http://www.yongtechnology.com>).

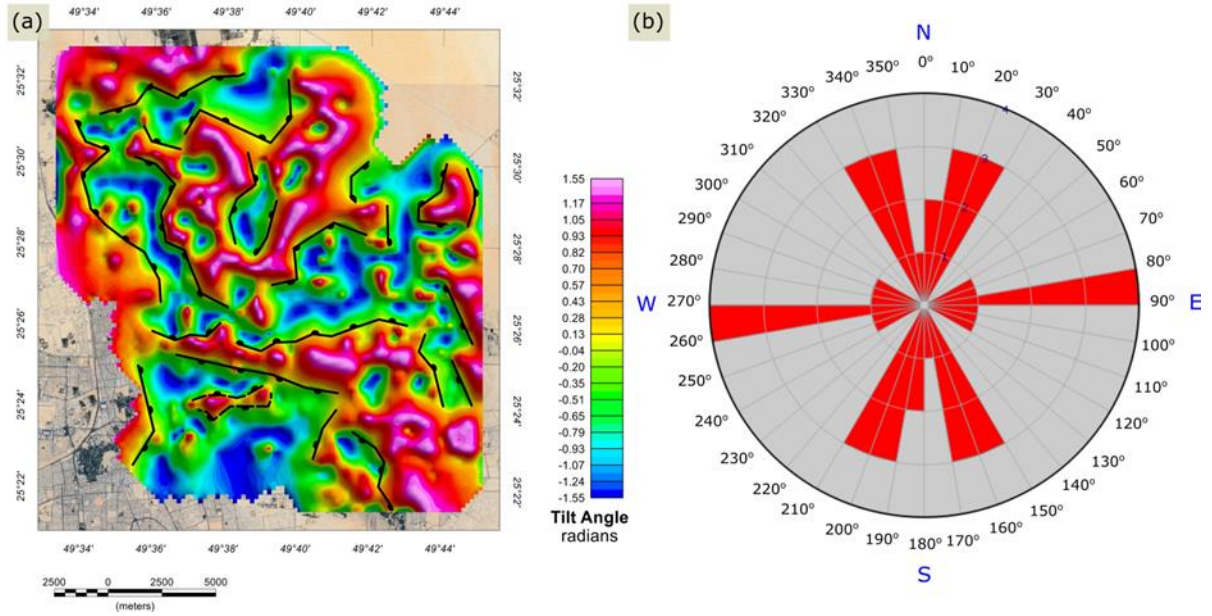


Figure 28: a) The tilt derivative and the interpreted lineaments (black lines), which correspond to structural edges (tectonic lineaments and/or rock contacts) are presented. b) Rose-diagram of the inter-preted lineaments (insert into the Figure with the tilt derivative and the lineaments).

Figure 29 displays the terracing transformation map, which improved the subsurface characteristics. This suggests the presence of similar areas with regard to gravity response. The depth solutions obtained from the tilt-depth method are displayed as colored circles according to their values over the residual gravity field (Figure 29).

3D inversion was applied to the gravity data, resulting in the construction of a voxel-based 3D representation of the subsurface density anomalies. This representation depicts the density contrast, which can be either positive or negative, as illustrated in Figure 30a. The area was divided into a mesh consisting of 41x43x12 voxels in the X (easting), Y (northing), and Z (depth) directions, with a resolution of 500 m. The inversion reached a

maximum depth of approximately 4.2 kilometers. To emphasize the presence of bodies with a low-density contrast, we employed upper and lower boundary values of 0.5 g/cm³ and -0.5 g/cm³, respectively, in the inversion procedure for the visualization of the 3D gravity model. The negative (green and blueish color) density anomalies are between -0.002 and -0.48 g/cm³ (Figure 30b).

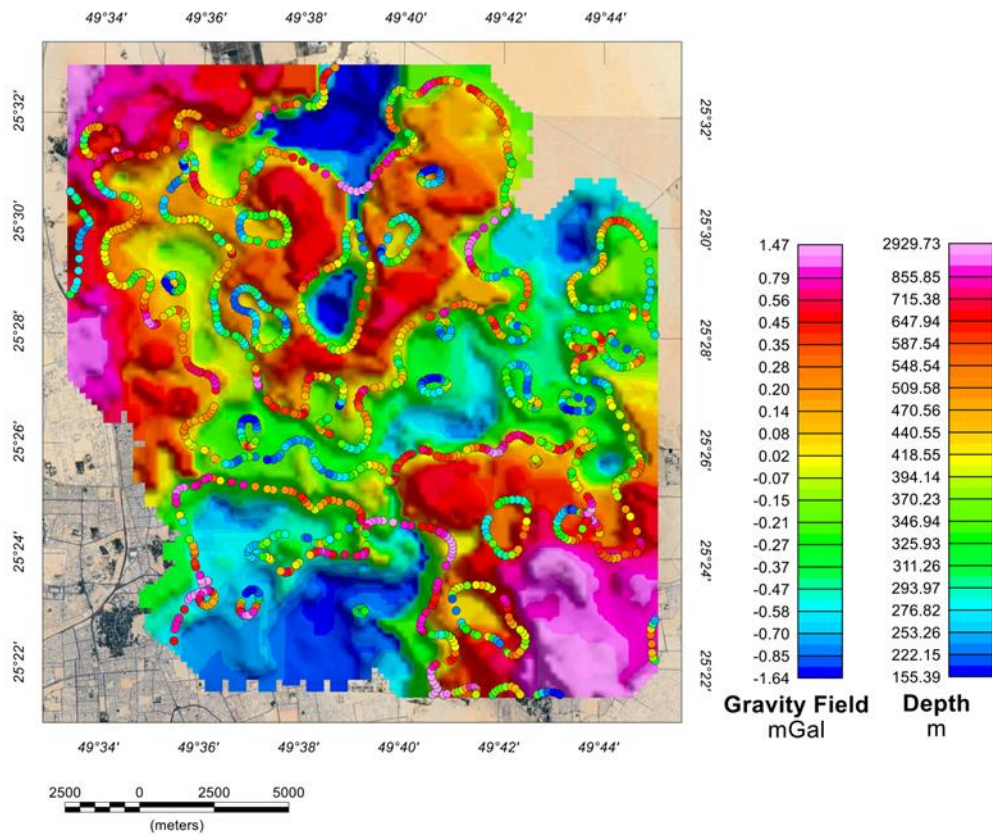


Figure 29: The terracing map overlaid by the results of the tilt-depth method (shown as colorful dots). The depth in the depth color bar is positive down.

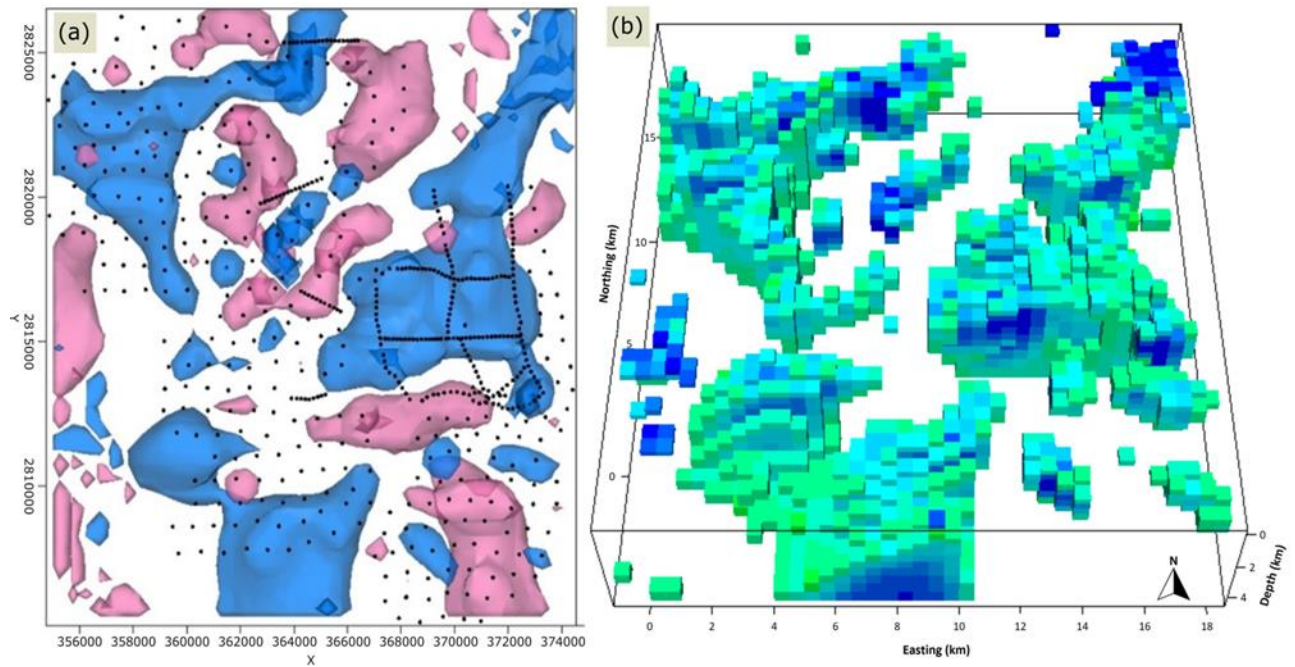


Figure 30: a) The top view of the 3D model of the Al-Hassa oasis area shows the positive (pink bodies) and negative (blue bodies) density contrast anomalies. b) 3D model of the study area, showing the negative density bodies, that correspond to subsurface basins.

CHAPTER 5

Subsurface complexity controls the aquifer heterogeneity: a case study from the Al-Hassa oasis, Eastern Saudi Arabia

***Khogali, A.;** Chavanidis K; Stampolidis, A.; Kirmizakis P; Yassin, M; Abu-Mahfouz, I.; Al-Shaibani A.; Soupios, P. Subsurface complexity controls the aquifer heterogeneity: a case study from the Al-Hassa oasis, Eastern Saudi Arabia. Submitted to the Groundwater for Sustainable Development Journal 2024, Under Review.*

5.1 Introduction

Al-Hassa region, eastern Saudi Arabia hosts the most extensive, naturally irrigated oasis in the world (Abderrahman and Ukayli, 1984), with an area of around 85.4 Km² and more than 2.5 million palm trees. In the past, date palms were cultivated in an area of around 120 km². Natural artesian pressure and springs have led to a massive amount of groundwater discharging from the underlying aquifers which have allowed for a great area of agricultural land (Al Tokhais and Rausch, 2008).

The irrigation water in the oasis is derived from 280 natural springs. The overall spring discharge was around 315 MCM/a in the mid-20th century (Abderrahman and Ukayli, 1984; Vidal, 1951). The discharge varied greatly, with some springs producing an enormous water supply of 3600 m³/h. Even though locals owned several minor springs many of them, including the major ones, were connected to a public irrigation system (Al-Dakheel et al., 2010). The innovative irrigation method implemented in the past utilized the natural force of gravity to transport and recycle water multiple times throughout the oasis, adapting to varying elevations with efficiency. However, the once abundant spring

discharge of approximately 10 m³/s has ceased, a direct result of the depletion of local aquifers. The excessive extraction of groundwater for agricultural use has led to a significant decline in groundwater levels (Al Tokhais and Rausch, 2008), highlighting the urgent need for sustainable water management practices in the region.

Generally, the water in these springs used to be warm, with temperatures ranging from 27 °C to 32 °C (e.g., Al-Haqel and Bahlah springs); nevertheless, some of them are called hot springs, with temperatures above 32 °C (e.g., Al-Harra, Al-Jawharia, Al-Khadoud, Um-Saba'a, and Najim springs). The presence of such spatial variability in spring water temperature within this limited area raises a question about the source/s of this groundwater.

Moreover, the Al-Hassa oasis has been the subject of limited research investigating subsurface geology, primarily focusing on its spatial hydrogeological distribution (Abba et al., 2024; Abderrahman and Ukayli, 1984; Al Tokhais and Rausch, 2008; Al-Dakheel, 2009; Al-Mahmoud, 1987; Simanek and Holden, 2020; Vidal, 1951). The present study mainly aims to integrate hydrochemical investigations and geophysical data (gravity survey) to correlate groundwater quality, subsurface anomalies based on gravity geophysical model, and temperature variations. It presents the first subsurface research in the Al-Hassa area, with broader implications for groundwater characterization and sustainable resource management in arid regions.

5.2 The study area

The study area is situated in the eastern province of Saudi Arabia, lying to the east of the well-known Ghawar oil field (Figure 31a). This region encompasses the most extensive

natural oasis globally, making it a unique and valuable site for geological exploration but also showing the high groundwater potential of this area. The total area under investigation in this study spans approximately 350 km² (Figure 31b). The elevations within the study area exhibit a range between 120 to 210 meters above sea level (masl). The area is characterized by a blend of urban and agricultural landscapes. The agricultural regions are primarily concentrated around the old natural springs that were being used for the irrigation of any nearby agricultural activities. The urban parts are concentrated in three main cities: Al-Hofuf, Al-Mubarraz, and Al-Uyun (Figure 31b). In terms of climate, the area falls

within a semi-arid region, characterized by a hot and dry climate during the summer and a cooler climate during the winter (Al-Omran et al., 2018).

5.3 Geological, hydrological, and tectonic setting

The Arabian Peninsula is considered an important geological region globally. It consists of igneous and metamorphic rocks in the Arabian Shield to the west and sedimentary deposits eastward across the Arabian platform (Khogali et al., 2020). The sedimentary part of the Arabian Plate is subdivided into distinct tectono-sedimentary units that contain most of the

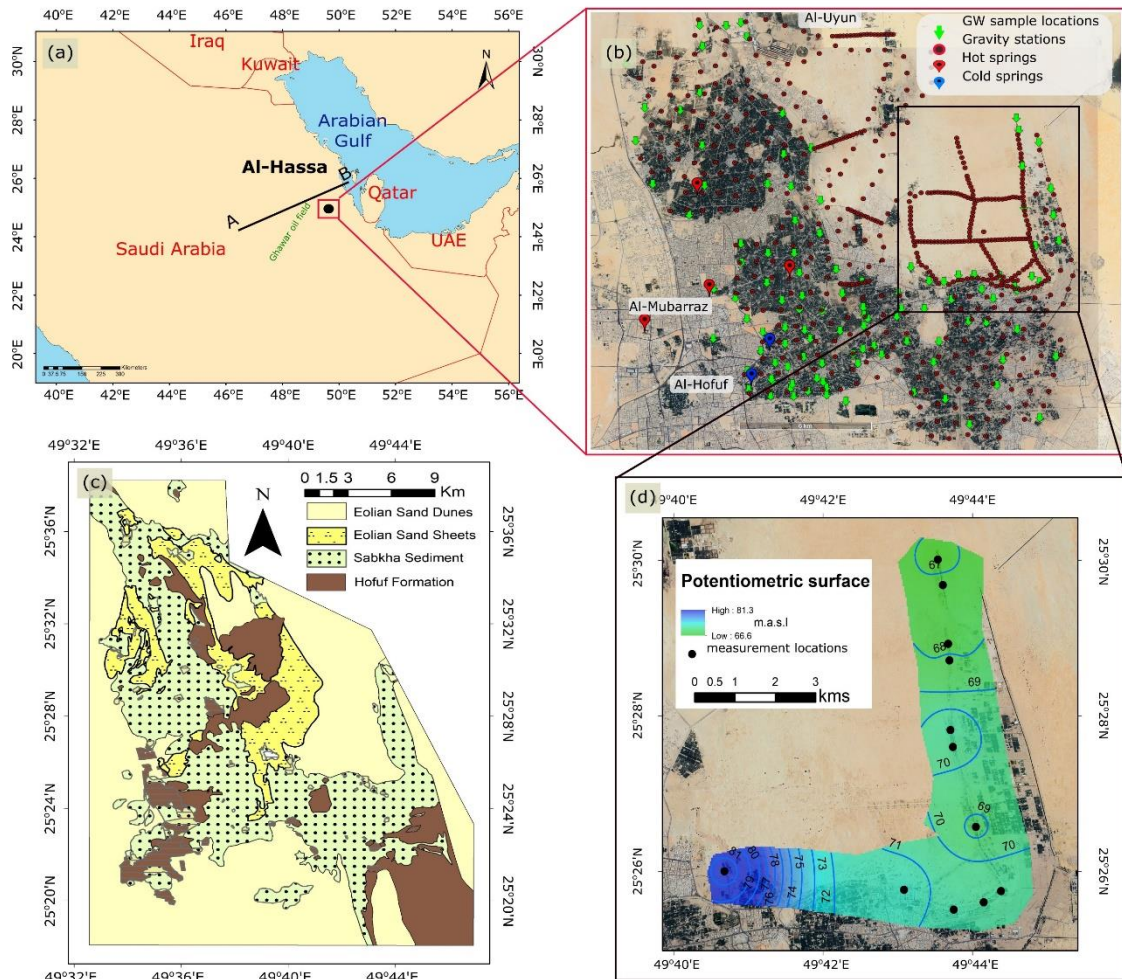


Figure 31: a) Location of the study area within the Arabian Peninsula. b) Sample locations and geophysical measurement stations. C) Geological map of study area. d) Potentiometric surface in the eastern section of the study area.

groundwater and hydrocarbon resources of Saudi Arabia. These units include the Wajid Basin, Wadi As Sirhan Basin, Rub al Khali Basin, Northeast Interior Homocline, East Interior Homocline, Arabian Platform, Arabian Gulf Margin, Widyan Basin Margin, and Tabuk Basin (Edgell, 1989).

The study area falls within the Eastern Platform, which is part of the Arabian Platform, along with smaller tectono-sedimentary units such as Summan Plateau, Dibdibah Trough, Khurais-Jauf Arch, Central Basin, and An Nala Trend (Edgell, 1989).

The study area is mostly covered by sand dunes/sheets and Quaternary deposits (Figure 31c). Only a few scattered outcrops reveal the Upper Miocene to Lower Pliocene Hofuf Formation, consisting of conglomerates, calcareous sandstone interbedded with reddish mudstone, and limestone (Al-Saad et al., 2002; Hussain, 2006; Kumar, 2013) (Figure 32a). Beneath the Hofuf Formation lies the limestone and reddish marls of the Dam Formation (Bashri et al., 2017). Then, there are the sandstone, limestone, and marl of the Hadrukh Formation, followed by the dolomite and limestone of the Eocene Dammam Formation (Al-Sayari and Zötl, 1978). Finally, the early Eocene Rus Formation, which is composed of dolomitic limestone and gypsum (Tleel, 1973), and the Paleocene Umm Er Radhuma Formation, which consists of limestone and dolomite with quartz geodes and chert nodules (Powers et al., 1966).

The complex multi-aquifer system in the study area contains four partially connected karstified fractured aquifers. These are, from bottom to top, the Aruma aquifer, the Umm Er Radhuma aquifer, the Dammam aquifer, and the Neogene aquifers (Al Tokhais and Rausch, 2008) (Figure 32b). The Rus Formation which consists of evaporites, marls, and

limestones, performs as an aquitard (brown color layer in Figure 32b), disconnecting hydrologically the Umm Er Radhuma from the Dammam aquifers in some parts. It also interconnects the two aquifers in other areas where fissures and the dissolution of the evaporite layer create secondary porosity and high permeabilities. The bottom portion of the Aruma Formation, composed of clay and shale, serves as an aquitard, dividing these aquifers from the Wasia aquifer underneath it. The natural springs have been formed because of the preferential flow routes that have emerged due to the uplift of the area and the development of the Ghawar anticline which caused intense fracturing. The fracturing interconnects the multiple aquifers and directs groundwater to surface discharge (Al Tokhais and Rausch, 2008). The groundwater level in the northeast part of the study area is between 66 to 82 masl following the regional groundwater flow direction to the east and northeast (Figure 31d).

Based on previous hydrochemical and hydrological studies in the area, the spring water is believed to be derived from the lower Umm Er Radhuma aquifer (Bakiewicz et al., 1982; BRGM, 1976). The Wasia groundwater has isotope characteristics distinct from those of the Umm Er Radhuma aquifer (Shampine et al., 1979).

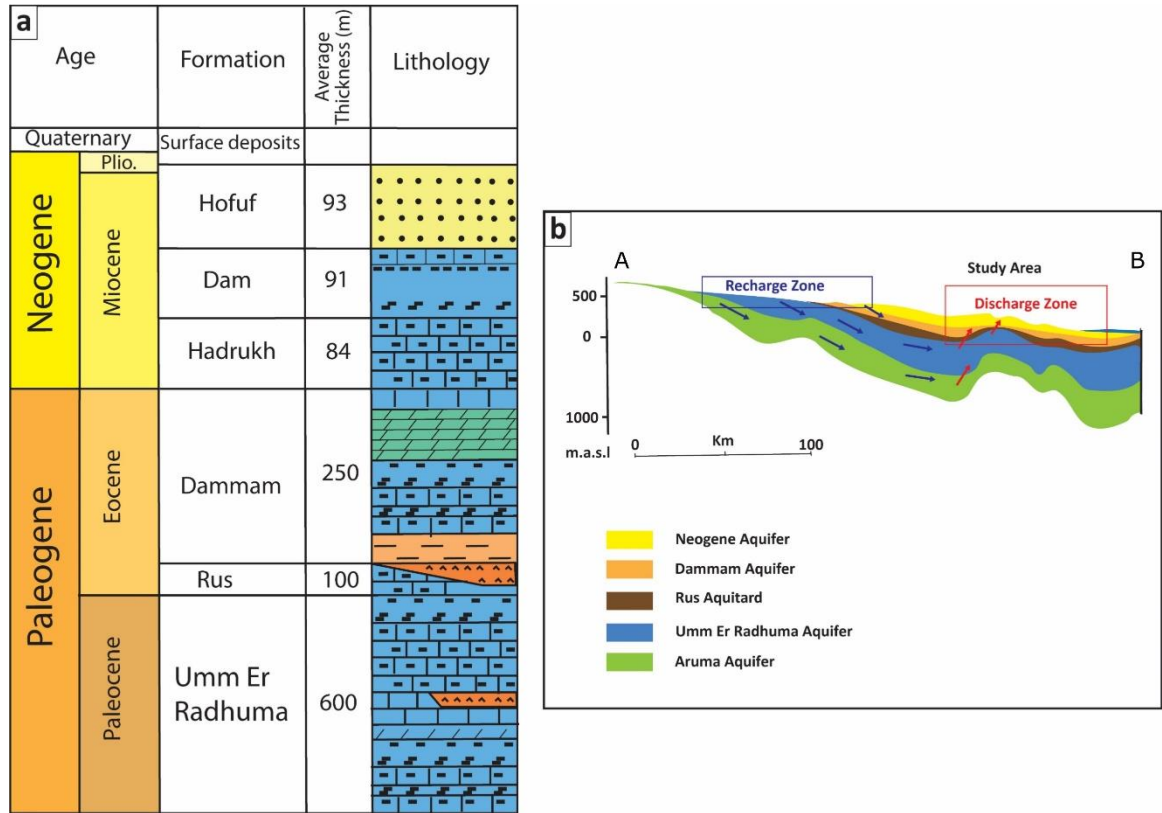


Figure 32: a) Stratigraphic column of the study area (modified after Al Tokhais and Rausch, 2008; Dirks et al., 2018; Powers et al., 1966). b) West-east geological section crossing the central Saudi Arabia to the Arabian Gulf showing major aquifers and the recharge and discharge zones. The extend of this cross-section is shown on Figure1a (modified from Al Tokhais and Rausch, 2008).

5.4 Methodology

The study consists of a total of 113 groundwater wells that were sampled from the Al-Hassa area in 2022. The data from 85 wells were provided by the Saudi Irrigation Organization (SIO), and 28 wells were sampled from distributed locations to cover the oasis. These wells were primarily used for irrigation and have depths ranging from 75m to 250m below the ground surface, tapping the Neogene and the Dammam aquifers. However, based on previous studies, all the aquifers in the study area are interconnected (Al Tokhais

and Rausch, 2008), the samples could be considered to represent a mixture of the three aquifers within the study area.

Two samples from each well were collected in polyethylene (PE) bottles for ionic concentrations and isotopic analyses. Eleven (11) wells were analyzed for oxygen and hydrogen isotopes. The PE bottles underwent a triple pre-rinsing process using deionized water to prevent any cross-contamination. The wells were subjected to an approximately one-hour purging period before sampling to obtain water samples that accurately represented the subsurface quality conditions. The piezometric water level was measured in 12 wells in the northeastern (known as, Al Hassa National Park) part of the study area. Electrical conductivity (EC), temperature, total dissolved solids (TDS), and pH were measured in situ using well-calibrated multi-parameter meters (Hanna HI 9828). The collected samples were transported to the lab in a cooling box below 4°C for preservation.

Ionic concentrations and isotopic analyses were carried out at King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia. Major ion concentrations within the milligrams per liter (mg/L) range were determined using the Dionex ICS-6000 Ion Chromatograph (IC) following the EPA 9056A standard method (US-EPA, 2007). Bicarbonate levels were determined using titration. Oxygen and hydrogen stable isotopes were analyzed using PICARRO cavity ringdown spectrometer L2130-I isotopic H₂O.

To understand the spatial distribution and differentiation of geochemical and physical parameters of the collected water samples within the study area, a total of 571 gravity stations were measured in both urban and semi-urban regions located to the north and east of Al Hofuf city, as well as within the confines of Al Hassa National Park covering the

whole Al-Hassa oasis. Specifically, the Geophysics laboratory of the King Fahd University of Petroleum & Minerals (KFUPM) conducted a gravity survey in three stages, occurring during the summers of 2021 and 2022, as well as the spring of 2023. The data were gathered within a 350 km² area using grids and profiles. The spacing between stations ranged from 150 to 900 meters, depending on factors such as local conditions, the type of data collected (gridded or profile), the level of urbanization, and accessibility. Due to the presence of various urban features such as roads, buildings, telecommunication cables, large metallic objects, buried pipes and cables, and sewers, magnetic or electromagnetic methods cannot be used effectively in urban areas. However, the gravity method can be employed to obtain initial information about the subsurface conditions in such areas quickly and at a reasonable cost (Fairhead, 2015a; 2015b). Nevertheless, the intricate nature of these regions imposes restrictions on the practical implementation of the gravity method.

The primary purpose of the geophysical survey was to process the gravity data and reconstruct the subsurface characteristics and complexity of the study area. The absence of geological maps (the area covered by a sand layer) or other available geological information (lithology, tectonic features, etc.) for the study area should be highlighted. The measurements were acquired using two Scintrex CG-5 AUTOGRAV TM gravimeters with a resolution of 1 µGal, after applying 2 days of measurements as a feasibility study and choosing the optimum parameters for acquisition depending on the natural and/or cultural noise of the area under investigation. The gravimeters were configured to autonomously identify and eliminate data anomalies caused by external noise interference. Additionally, they were programmed to account for the Earth's tidal variations and any potential instrument tilt caused by transportation. Subsequent requisite corrections were

applied to ensure the accuracy of the data acquired. To minimize interference from high air temperature prevalent in the summer months, data collection took place in the early morning hours and ended before noon. Gravity measurements were taken in sets of three or five, with a duration of 30-60 seconds, based on the level of environmental or man-made noise in the surrounding area.

Strict quality control measures were implemented to guarantee the reliability of the data, including repeating any measurement sets that deviated by more than 10 μGal . Stations exhibiting a tilt greater than 15 arcsec were excluded, and gravity readings were repeated as needed. The average standard deviation, error, and variance were calculated at 0.036, 0.002, and 0.001, respectively.

Three base stations were chosen, one for each measurement period and positioned in a central area of each field campaign. The base stations were always situated in a quiet area without any external sources of noise. Every day, the base station was measured at the beginning and end of the day. Additionally, an extra measurement was taken every 2-3 hours to investigate if there was a non-linear drift in the data that needed to be eliminated.

In order to determine the gravimeter's height correction, the distance between the center of the instrument's mass and the elevation of the instrument's location was measured. This ensures that each measurement accurately reflects the elevation of the topographic relief. The precise geographic coordinates and elevation of each gravity station were determined using Trimble's R10 Differential Global Positioning System (GPS), enabling accurate topographic corrections during the analysis and modelling of the gravity data. The accuracy error of the measurements was less than 1 cm using the base station.

Following the acquisition, the data were imported into Seequent's Oasis Montaj software to process and improve its quality. The Gravity and Terrain Correction extension was utilized to rectify the raw data. The standard gravity corrections (Earth tide, instrumental height, and drift) were implemented to mitigate the factors that impact the quality of the measurements. Due to the unavailability of an absolute gravity station, the base station of the 2021 gravity survey was used as the reference point. All gravity measurements were then connected to this point. The 1980 Geodetic Reference System (GRS80) was used to determine the normal gravity of Earth. This system established that the theoretical gravity value at the 2021 base station location is considered to be zero. The impact of the local topography was diminished following the implementation of the Oasis Montaj standard algorithm for topographic correction. To execute the terrain correction algorithm, a highly detailed Digital Elevation Model (DEM) for the specific survey area and less detailed gridded elevation data for the surrounding region have to be used. The Shuttle Radar Topography Mapping (SRTM) at a resolution of 30 m was utilized as the local elevation model, while the SRTM at a resolution of 90 m was employed as the regional elevation model. The corrected data underwent the application of the Free Air and Bouguer corrections to calculate the complete Bouguer anomaly (CBA).

To identify subsurface geotectonic structures (e.g., rock contacts, faults) with significant density contrast and correlate the gravity analysis results with the geology of the study area, the total horizontal derivative (THDR) and the terracing transformation filters on the residual field data were applied. THDR is given by equation (1):

$$THDR = \sqrt{\left(\frac{dG}{dx}\right)^2 + \left(\frac{dG}{dy}\right)^2} \quad (1),$$

where dG/dx and dG/dy are the first-order derivatives of the gravity field in the x and y directions, respectively.

The terracing transformation technique, as outlined by Cordell and McCafferty (1989), can be used to identify specific areas with consistent gravity field intensity that have clearly defined boundaries (Li, 2016). The peaks of the THDR are centrally located over structural edges and vertical rock contacts. However, in cases of sloping contacts, the peaks were displaced in the down-dip direction (Fairhead, 2015b). We used the curvature analysis method of Phillips et al. (2007) to detect the locations of the THDR peaks, which are shown as black dots in the map of Figure 41.

5.5 Results

5.5.1 Hydrochemical investigations

Table 2 presents a statistical analysis, including minimum, maximum, mean, and standard deviation, of the major ions in the study groundwater samples, alongside a comparison with the local Saudi Standards, Metrology and Quality Organization (SASO) and international standards like the U.S. Environmental Protection Agency (EPA) and the World Health Organization (WHO) water quality standards.

The results indicate that the average E.C. is 5169.7 ($\mu\text{S}/\text{cm}$), surpassing the permissible limit set by the WHO for all samples. The pH averaged as 7.3, while the mean values for TDS, sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), nitrate (NO_3^-)

Table 2: Summary of descriptive statistics for hydrochemical parameters, comparison with international and local drinking water standards, and proportion of parameters surpassing permissible thresholds.

Variable	Units	Minimum	Maximum	Mean	Std. deviation	WHO	EPA	SASO	Samples exceeding the WHO permissible drinking limits (%)
E.C	μS/cm	1856.0	12200.0	5169.7	2689.5	1500	1500	2300	100
TDS	mg/L	928.0	7808.0	3100.6	1599.3	500	500	1000	100
pH	pH unit	6.5	8.0	7.3	0.3	6.5-8.5	6.5-8.5	6.5-8.5	0.0
Na	mg/L	105.0	1930.0	605.5	379.2	200	200	-	92.9
K	mg/L	6.3	85.0	29.8	13.6	12	12	-	92.9
Ca	mg/L	93.0	748.0	248.8	120.1	75	75	75	100
Mg	mg/L	33.6	390.0	124.7	76.6	50	50	-	93.8
NO₃	mg/L	0.9	102.9	16.7	12.8	50	45	50	0.9
HCO₃	mg/L	140.0	420.9	216.3	53.6	500	500	-	0.0
Cl	mg/L	256.2	3527.5	1129.2	701.6	250	250	250	100
SO₄	mg/L	70.6	1786.0	669.9	378.3	250	500	250	94.7
NH₃	mg/L	0.0	2.7	0.2	0.4	-	-	-	0.0
PO₄	mg/L	0.0	5.6	0.4	0.9	-	-	-	0.0
CO₃	mg/L	0.0	30.0	2.0	6.4	-	-	-	0.0

), bicarbonate (HCO_3^-), chloride (Cl^-), sulfate (SO_4^{2-}), ammonia (NH_3), phosphate (PO_4^-), and carbonate (CO_3^{2-}) are recorded in mg/l as 3100.6, 605.5, 29.8, 248.8, 124.7, 16.7, 216.3, 1129.2, 669.9, 0.2, 0.4, and 2.0, respectively (Table 2).

Furthermore, the percentages of samples exceeding the WHO permissible drinking limits for various ions are as follows: TDS (100%), pH (0.0%), Na^+ (92.9%), K^+ (92.9%), Ca^{2+} (100%), Mg^{2+} (93.8%), NO_3^- (0.9%), HCO_3^- (0.0%), Cl^- (100%), and SO_4^{2-} (94.7%) (Table 2).

The Piper diagram (Figure 33) is a useful tool for classifying different groundwater hydrochemical facies (Piper, 1944). The cation's triangle exhibits a predominant trend observed towards the alkali metals ($\text{Na}^+ + \text{K}^+$) area, with a subset of samples positioned within the no-dominance area. Similarly, on the anion's triangle, most samples are clustered within the Cl^- area, with only a minor proportion falling within the no-dominance zone. In the diamond-shaped portion of the Piper diagram, the prevailing hydrochemical facies are identified as Na-Cl water, encompassing most of the samples, while a subset of samples exhibits characteristics indicative of a mixed water type.

Statistical analyses were conducted on the chemical constituents, encompassing correlation and cluster analysis to elucidate the relationships between different hydrochemical parameters and classify groups of clusters exhibiting comparable properties.

Utilizing Pearson's correlation coefficient (r) (Table 3), the relationships between various parameters were categorized as follows: strong ($r > 0.7$), medium ($r = 0.5-0.7$), and weak ($r < 0.5$). A strong correlation was observed between total dissolved solids (TDS) and Na^+ , K^+ , Ca^{2+} , Mg^{2+} , HCO_3^- , Cl^- , and SO_4^{2-} , indicating that these ions are primary contributors

to elevated TDS amounts. Additionally, the impact of gypsum dissolution was evident from the good correlation between Ca^{2+} and SO_4^{2-} , while halite dissolution was inferred from the strong relationship between Na^+ and Cl^- .

The cluster analysis, employing dendrogram technique, discerned four distinct groups within the dataset, as illustrated in Figure 34. This classification was based on the varying concentrations of the analyzed groundwater parameters. The clustering process aimed to uncover distinct patterns in water quality, highlighting areas with similar characteristics,

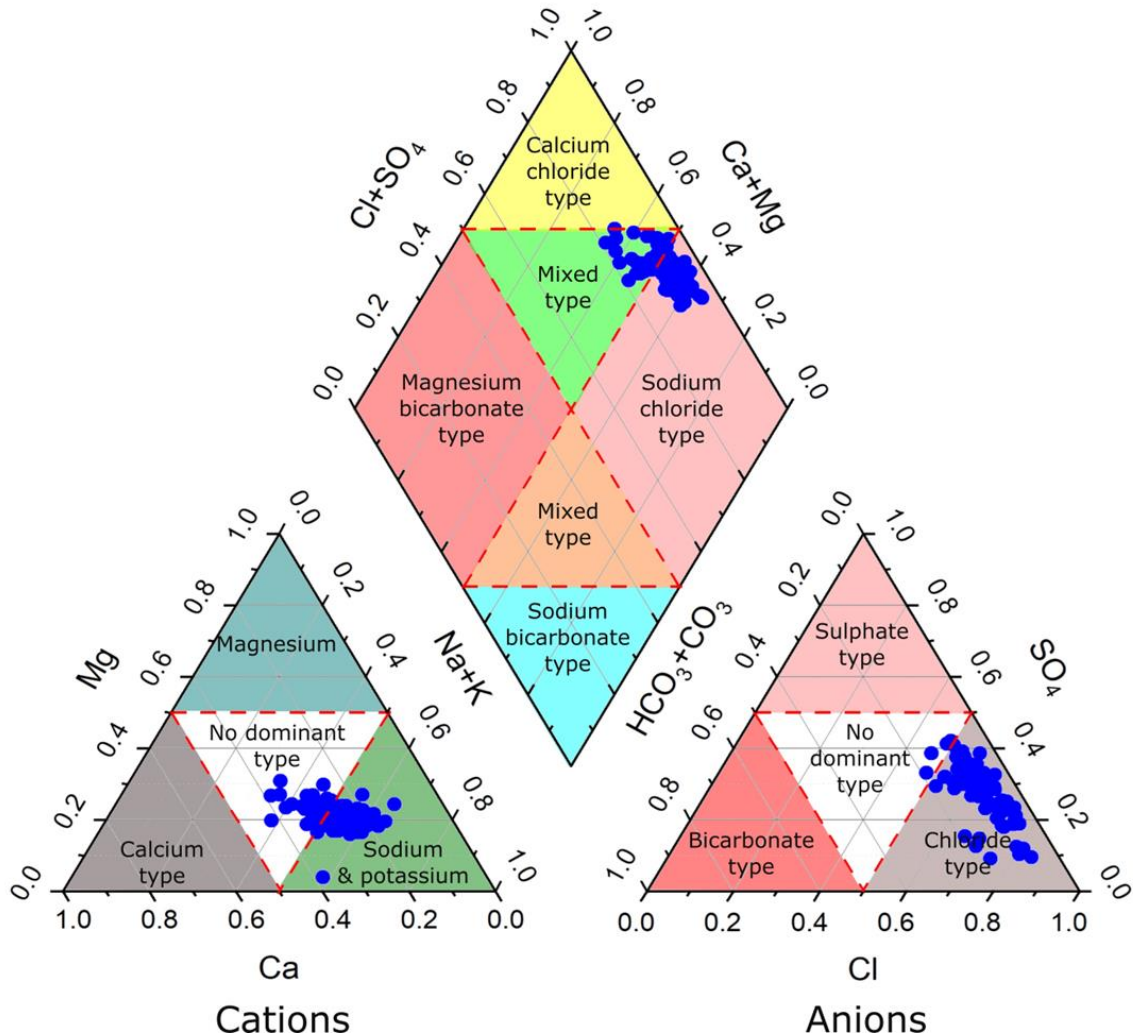


Figure 33: Hydrochemical facies classification of the groundwater of Al-Hassa oasis using Piper diagram,

Table 3: Correlation matrix of chemical parameters of the groundwater in the study area. The strong correlation between different parameters is highlighted in bold.

	E.C	TDS	pH	Na	K	Ca	Mg	NO ₃	HCO ₃	Cl	SO ₄	NH ₃	PO ₄	CO ₃
E.C	1													
TDS	0.972	1												
pH	-0.360	-0.238	1											
Na	0.936	0.958	-0.242	1										
K	0.783	0.845	-0.009	0.842	1									
Ca	0.844	0.862	-0.300	0.833	0.692	1								
Mg	0.895	0.906	-0.290	0.920	0.797	0.758	1							
NO ₃	0.369	0.276	-0.501	0.258	0.112	0.416	0.235	1						
HCO ₃	0.715	0.729	-0.068	0.699	0.711	0.729	0.703	0.002	1					
Cl	0.932	0.955	-0.307	0.971	0.817	0.867	0.921	0.306	0.684	1				
SO ₄	0.830	0.845	-0.165	0.869	0.766	0.802	0.858	0.228	0.747	0.788	1			
NH ₃	0.000	0.067	0.170	0.072	0.147	0.021	-0.020	-0.007	-0.063	0.076	-0.011	1		
PO ₄	-0.076	-0.028	0.271	-0.026	0.098	-0.092	-0.027	-0.126	0.046	-0.036	-0.013	0.578	1	
CO ₃	0.193	0.249	-0.057	0.225	0.191	0.213	0.297	0.016	0.067	0.294	0.118	-0.001	-0.099	1

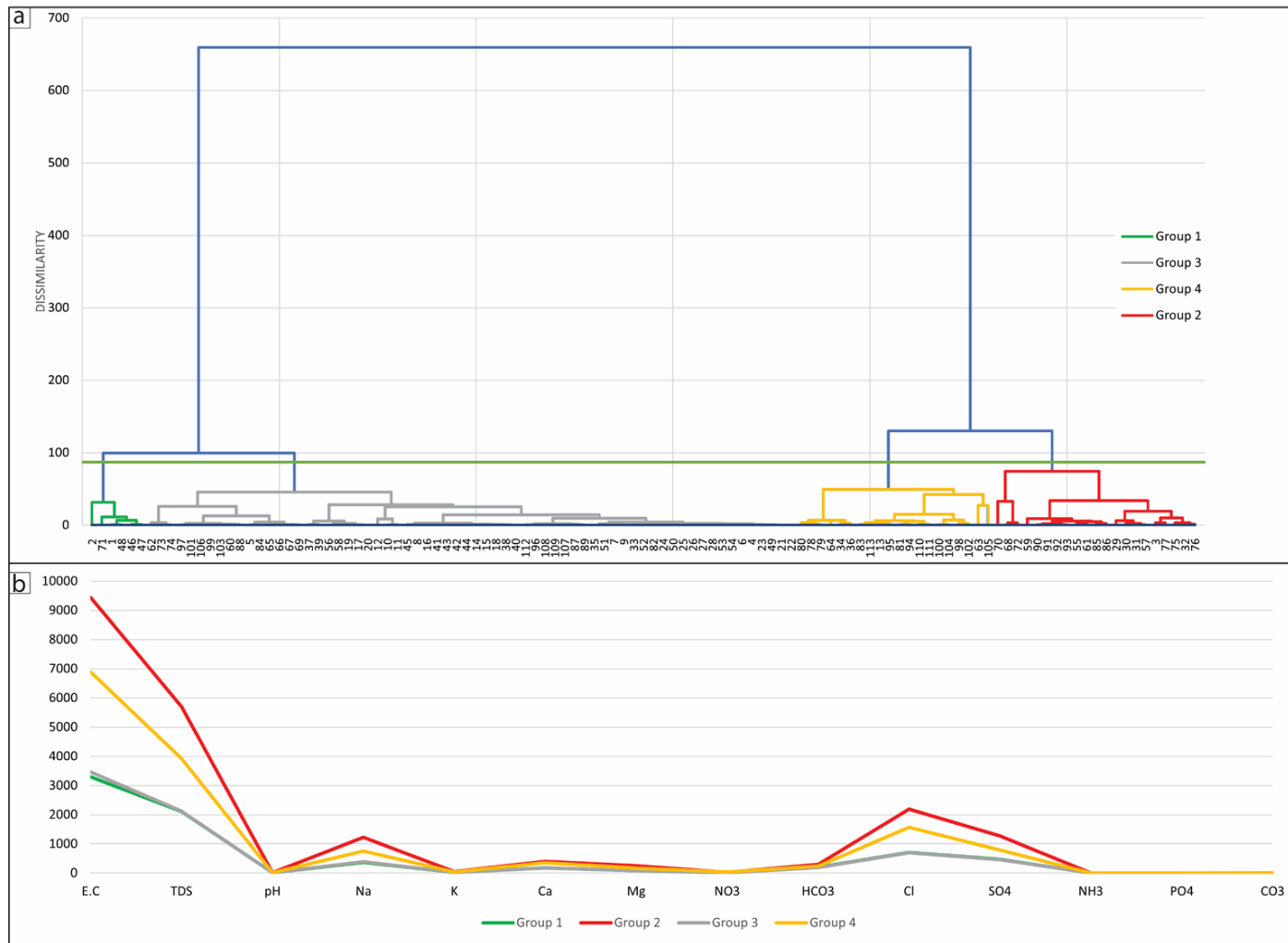


Figure 34: a) Dendrogram clustering based on the chemical parameters of 113 groundwater samples in the study area. b) The relationship between the clustered groups based on the chemical characteristics of the sampled groundwater.

linking distinct groups to their unique isotopic signatures to trace pollution sources and understand hydrological processes for targeted environmental management and further investigative research.

Table (4) presents the oxygen and hydrogen isotopic compositions for 11 samples, alongside their respective total well depths, compared to their total dissolved solids (TDS). The graphical representation in Figure (35a) shows the relationship between TDS and well depth.

Table 4: Oxygen and hydrogen isotopic ratios of 11 selected samples along with the total well depths and TDS.

SN	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	Well Depth (m)	TDS (ppm)
86	-4.3955	-34.212	75	4968
87	-4.8615	-36.68	90	2377
88	-4.958	-37.1575	75	1546
89	-4.6015	-35.0645	90	2600
90	-4.288	-33.42	120	4700
91	-4.0585	-32.153	80	5300
92	-3.9955	-31.7665	90	5400
93	-4.1275	-32.6345	120	5800
94	-4.326	-33.6255	90	3686
95	-4.4505	-33.7675	70	3371
96	-4.5135	-33.919	75	2270

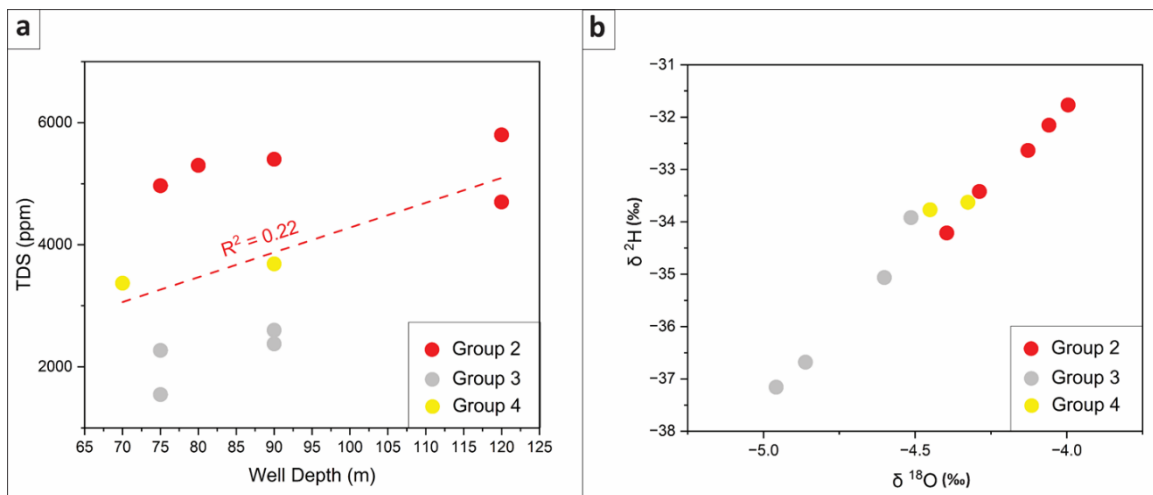


Figure 35: a) The relation between the TDS and well depths of 11 selected groundwater samples. b) Plot of $\delta^2\text{H}$ vs $\delta^{18}\text{O}$ of the selected samples.

Spatial distribution maps were generated using ArcMaps 10.8.2 software using the inverse distance weighted (IDW) interpolation method to evaluate the lateral deviations in the hydrochemical properties in the study area (Figure 6).

Generally, the maps depicting TDS, EC, Ca^{2+} , Cl^- , Mg^{2+} , Na^+ , and SO_4^{2-} (Figure 6a, b, c, d, g, h, j) exhibit a consistent trend, with higher concentrations observed in the southeastern section of the study area and relatively lower concentrations in the western section.

The spatial distribution maps for HCO_3^- and K^+ (Figure 36e and f) reveal increased concentrations in the northwestern part of the study area, alongside overall elevated concentrations in the southeastern area. Interestingly, the NO_3^- map (Figure 36i) exhibits slight deviations from the patterns observed in other elements, with areas displaying low NO_3^- concentrations despite having high TDS.

To elucidate the natural processes governing water chemistry, the Gibbs diagram (Figure 37) (Gibbs, 1970), offers valuable insights. This diagram assesses three fundamental mechanisms: Evaporation, Rock-water interaction, and atmospheric precipitation. As depicted in Figure 37, all samples are clustered near the evaporation zone.

Furthermore, the saturation index (SI) is utilized to anticipate interactions between water and surrounding rock units based on groundwater geochemical data, eliminating the need for rock sample analysis (Figure 38). PHREEQC 3.0 speciation code was employed to calculate the SI of calcite, dolomite, gypsum, halite, and anhydrite (Parkhurst, 1995). A positive SI indicates mineral precipitation in groundwater (supersaturation), while a negative SI suggests mineral dissolution (undersaturation), with zero SI showing equilibrium with groundwater (Appelo and Postma, 2004).

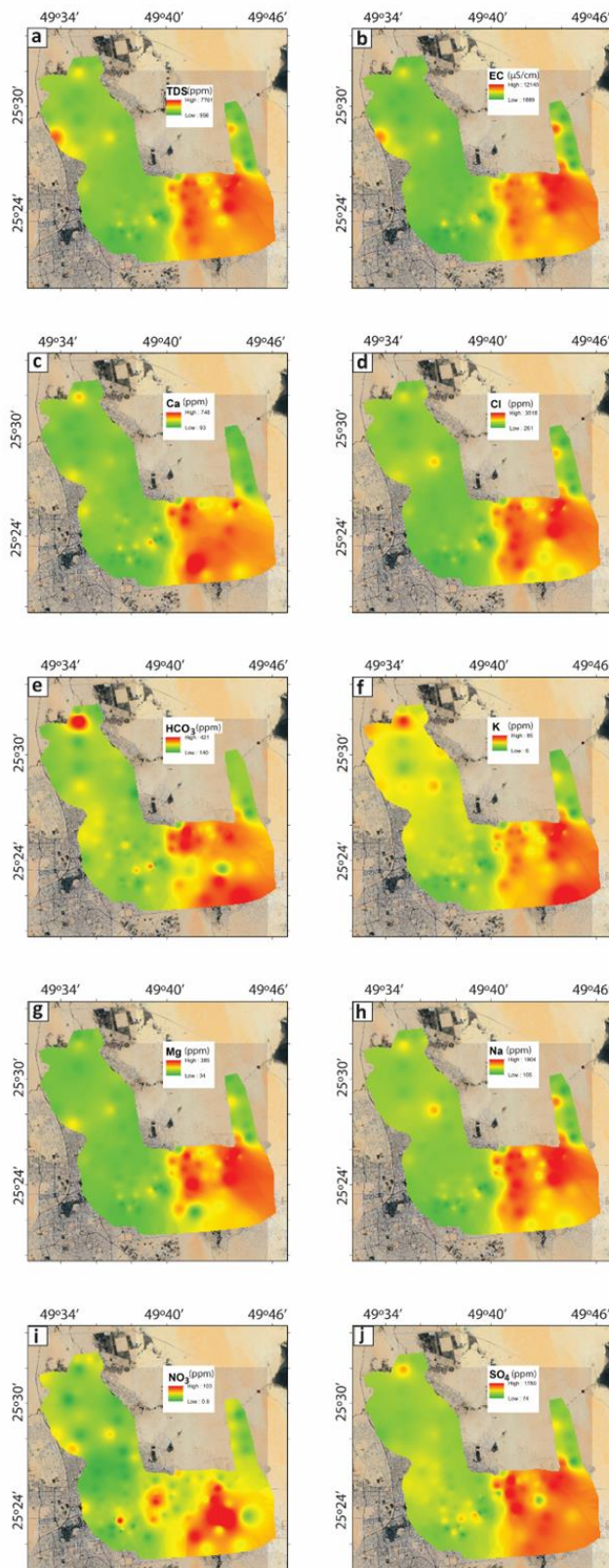


Figure 36: Spatial distribution maps of a) TDS b) EC c) Ca^{2+} d) Cl^- e) HCO_3^- f) K^+ g) Mg^{2+} h) Na^+ i) NO_3^- j) SO_4^{2-} .

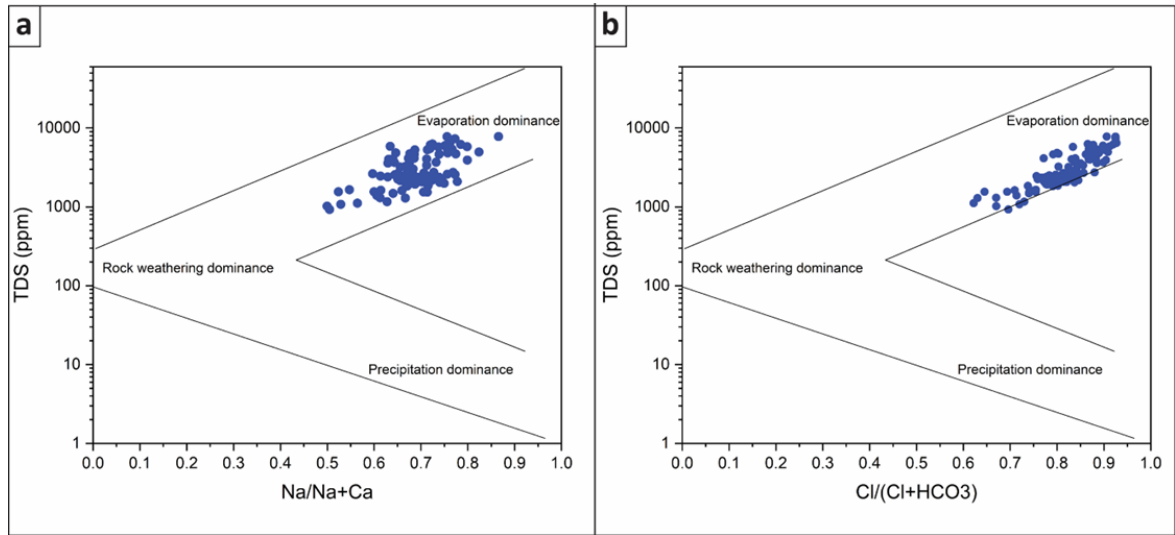


Figure 37: Gibbs diagrams illustrating the mechanisms controlling hydrochemical evolution of the analyzed groundwater based on a) Na^+ to Ca^{2+} and b) Cl^- to HCO_3^- ratios.

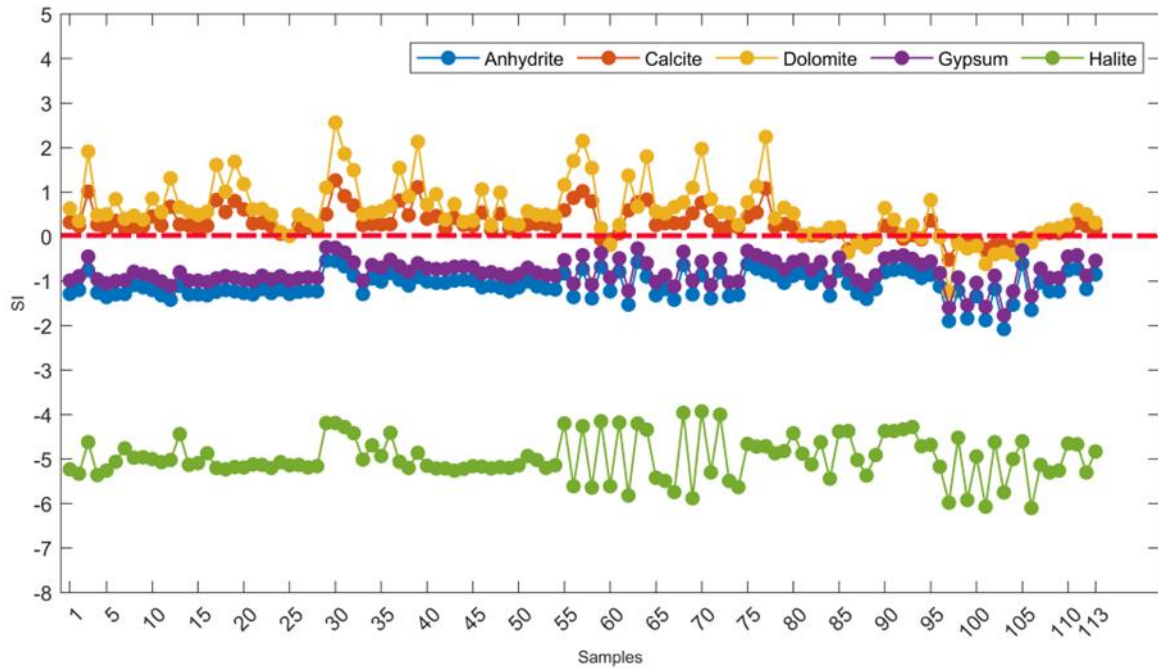


Figure 38: Scatter plots displaying the relationship between the saturation indices of calcite, dolomite, anhydrite, halite, and gypsum in the present study.

Results indicate oversaturation of calcite and dolomite in most tested groundwater samples, with some exhibiting undersaturation (Figure 8). Conversely, all samples show undersaturation of anhydrite, gypsum, and halite.

Plotting $\text{HCO}_3^- + \text{SO}_4^{2-}$ versus $\text{Ca}^{2+} + \text{Mg}^{2+}$ (Figure 39a) provides insights into whether these ions result from the dissolution of calcite, dolomite, and gypsum. Plotting Na^+ versus Cl^- provides insights into the dissolution of halite (Figure 39b). Plots of Ca^{2+} versus HCO_3^- and Ca^{2+} versus SO_4^{2-} (Figure 39c and d) may confirm the probability of calcite or gypsum dissolution in these samples.

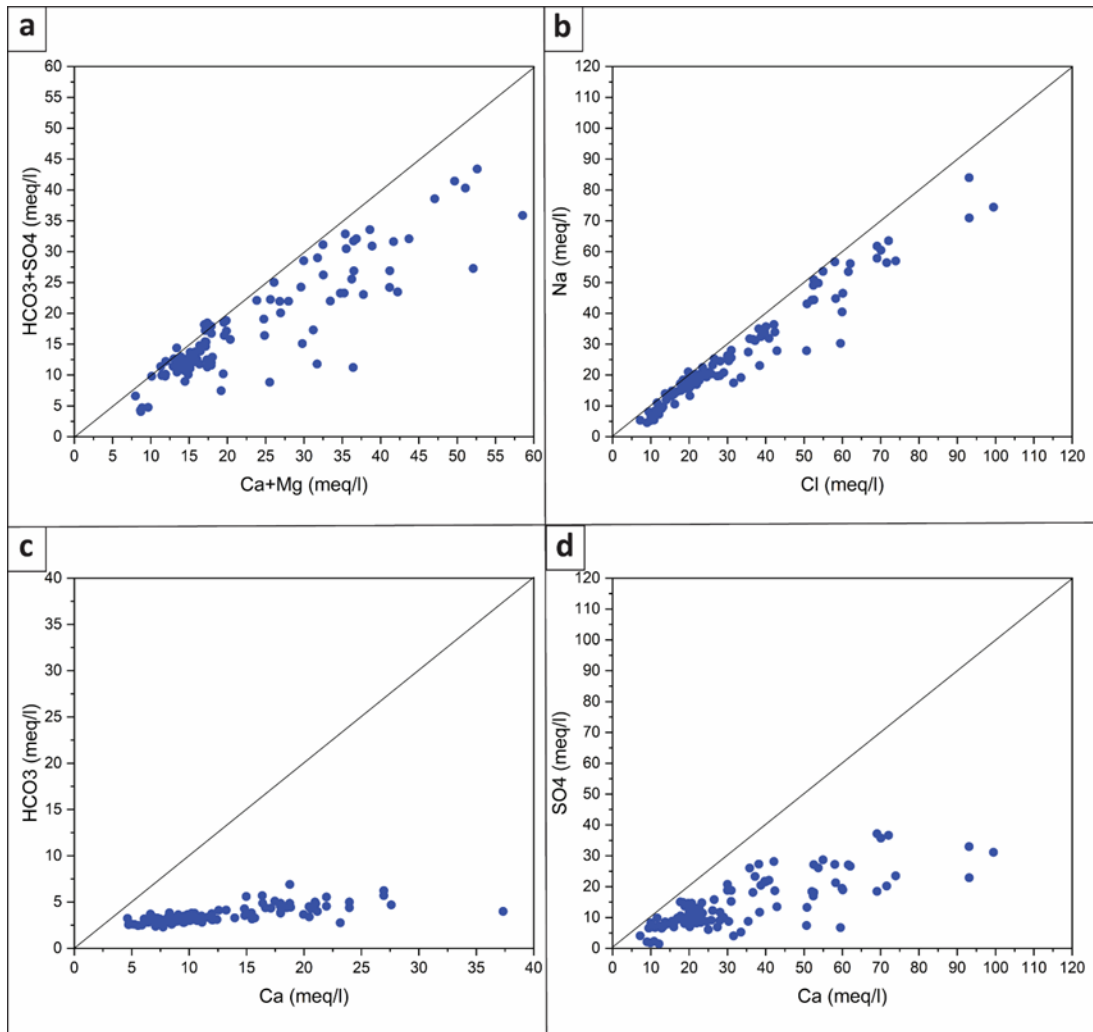


Figure 39: Scatter plots of the relationship between a) $\text{HCO}_3^- + \text{SO}_4^{2-}$ and $\text{Ca}^{2+} + \text{Mg}^{2+}$, b) Na^+ and Cl^- , c) Ca^{2+} and HCO_3^- , d) Ca^{2+} and SO_4^{2-}

5.5.2 Gravity Survey

Since the subsurface model for the study area was unknown and the spatial distribution of geochemical parameters from the collected water samples (Figure 36) was unexplained and irregular, gravity measurements were conducted and processed to highlight the subsurface complexity (Figure 40 and 41). The modelling of the gravity data would delineate subsurface geotectonic structures such as rock contacts, faults, domes, and basins with significant density contrast.

Figure 40 presents the residual gravity field. The residual field map displays the impact of shallow structures on the gravity field, with anomalies ranging from -1.643 to 1.498 mGal. The red color represents low-density anomalies associated with basins filled with loose sediments. The blue anomalies indicate areas with high-density anomalies, indicative of hard or more cohesive geological units. This indicates a measured signal with a total amplitude of 3.141 mGals. It is crucial to emphasize that the gravitometer has a precision of 0.001 mGal. The location of all the measuring points is shown as green squares.

Figure 41 shows the terracing filter map with the maximum horizontal gradient. The map presents an improvement of the subsurface characteristics, suggesting the presence of similar areas with regards to gravity response showing areas with distinct border between low- and high-density geological units. The location of the maximum of the THDR is depicted by the black dots over the terracing map (Figure 35).

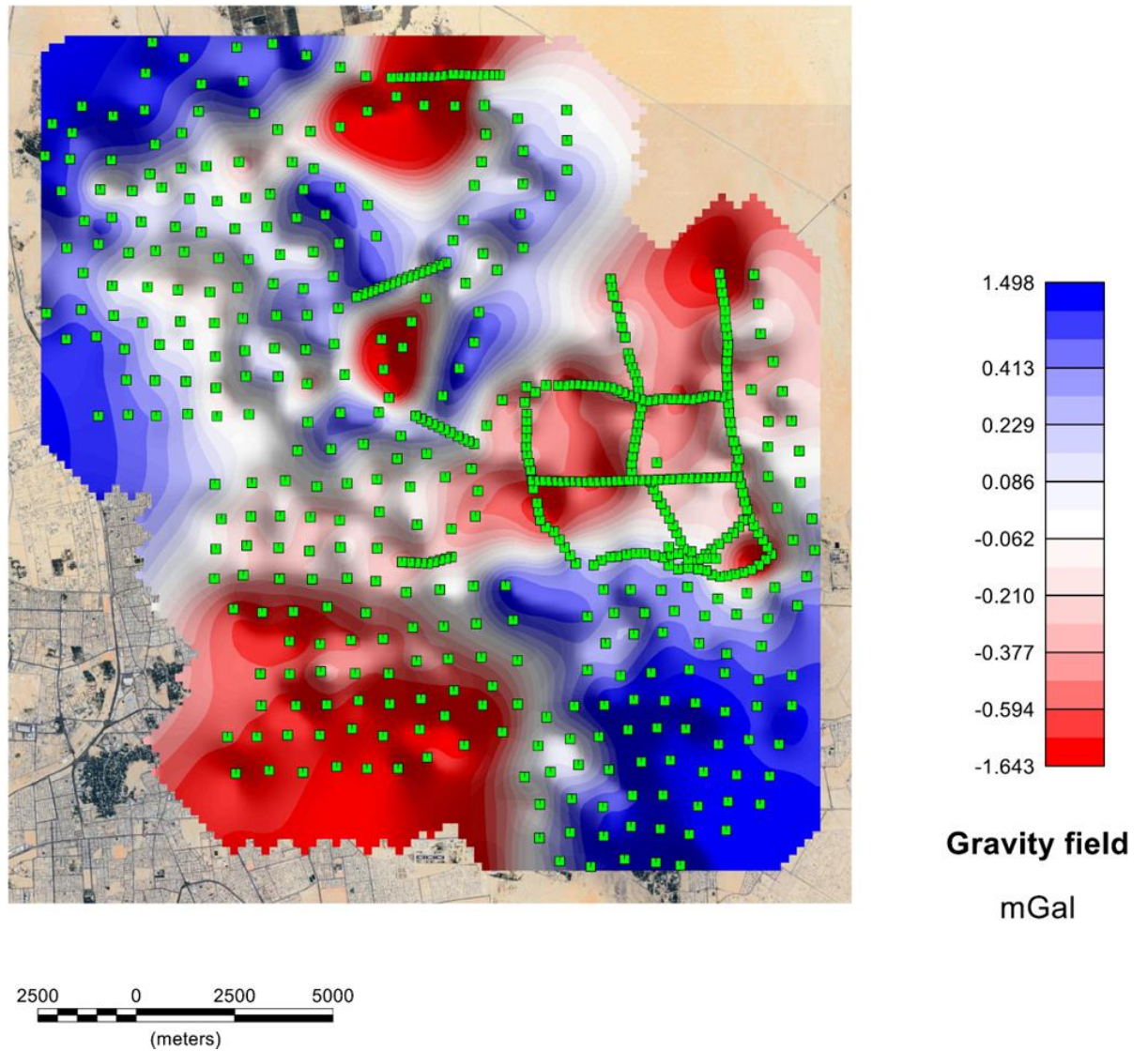


Figure 40: Residual Bouguer anomaly map of the study area based on 571 gravity stations, as depicted by green squares.]

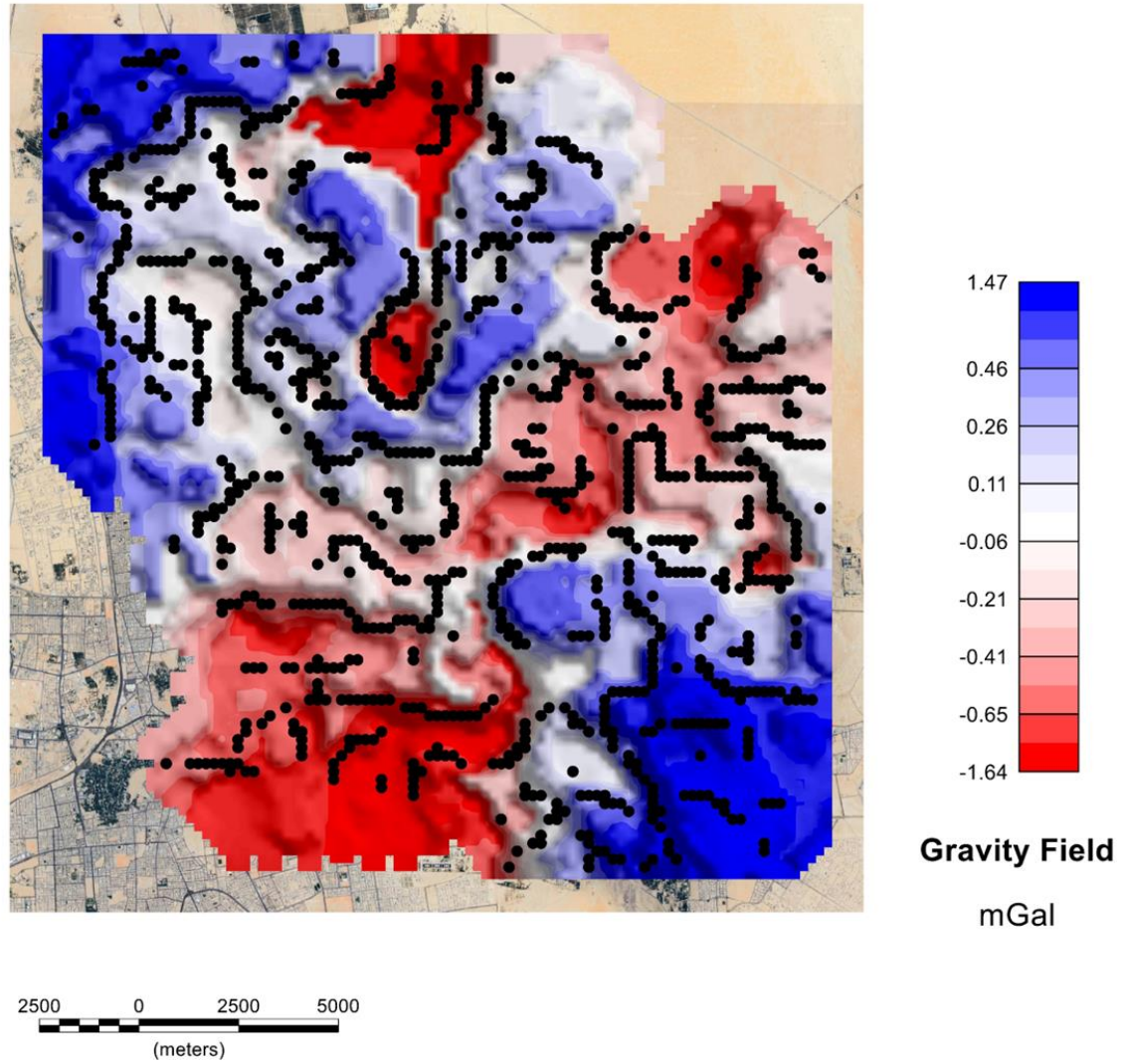


Figure 41: Total horizontal derivative (THDR) and terracing map.

CHAPTER 6

DISCUSSION

6.1 Structural analysis of Neogene sandstone sequence through integrated digital outcrop modeling and field investigations

6.1.1 Fracture characteristics

The comprehensive digital outcrop modeling of the Upper Miocene to Lower Pliocene Hofuf Formation in Saudi Arabia has yielded significant insights into the structural characteristics of the region. Main finding is the pronounced dominance of fracture orientations from the DOM along the WNW-ESE axis (Figure 12a), which were consistent with the orientations from traditional fieldwork (Figure 13a). This persistent directional tendency is not merely a local anomaly but resonates with the broader structural style of the Arabian Peninsula. Such orientations reflect the principal stress direction imprinted on the geological strata in the region over ages, likely due to the sustained compressional forces (Tranos et al., 2024). This compression is most likely attributed to the ongoing oblique collision between the Arabian and Eurasian Plates, a monumental tectonic interaction that has shaped much of the Middle Eastern geology (Ziegler, 2001).

Secondary fracture orientations (e.g., 120° and 80°) suggest episodic or phased tectonic stress, possibly indicating a complex interplay of forces in the Hofuf area over the geological timeline. Caution should be taken in interpreting these secondary orientations,

as they may represent localized adjustments or minor reactivations of pre-existing structures, rather than entirely new tectonic regimes (Maerten et al., 2002).

A notable feature in the fracture characterization is the predominance of nearly vertical dip angles, predominantly ranging between 88 to 90 degrees from the DOM (Figure 12b) and 87 to 90 degrees from the fieldwork (Figure 13b). This verticality typically indicates an extensional regime or tensional stresses, a somewhat counterintuitive finding given the region's known compressional history. This suggests a more nuanced tectonic evolution, possibly involving phases of local extension intermixed with the dominant compressional regime (Tranos, 2015). Such a revelation underscores the intricate interplay of tectonic forces that have shaped the Hofuf Formation, hinting at a complex succession of stress environments over time.

The diversity of fracture dip angles further complicates the structural story. The interpretation of fracture dip angles requires a nuanced understanding that goes beyond simple categorization into tensional or compressional regimes (Ferrill and Morris, 2003; Schöpfer et al., 2007). The observation that fractures with a wide range of dip angles exist across various geological settings challenges the interpretation. While vertical fractures are more common in tensional regimes (Gudmundsson, 1992), non-vertical fractures suggest a more variegated history of stress and deformation. This diverse fracture geometry can be attributed to various factors, including regional tectonic realignments, localized faulting dynamics, or even the original depositional environment's influence on subsequent stress responses (Zeng et al., 2023).

The presence of fractures of various heights, predominantly less than 100 cm (Figure 14), is indicative of a history of brittle deformation (Volatili et al., 2022). These short fractures, typically resulting from localized stress concentrations, paint a picture of a dynamic subsurface, periodically reworked by tectonic and possibly even climatic forces (Volatili et al., 2022).

The fracture aperture analysis within the Hofuf Formation (Figure 15) offers insights into its complex deformation history yet requires careful interpretation within the structural context of the Hofuf formation. While the presence of narrow fractures, predominantly less than 3 cm, might be interpreted as indicative of brittle deformation under relatively low to moderate stress conditions (Hooker et al., 2013), the existence of wider fractures, with apertures reaching up to 22 cm, suggests intermittent periods of elevated stress, potentially linked to significant tectonic activities or faulting (De Jossineau and Petit, 2006). However, it's crucial to acknowledge that using fracture apertures to estimate stresses—without accounting for block displacements and deformations, besides local stress alteration—can introduce substantial inaccuracies (Agheshlui et al., 2018).

The comparison between fracture height and aperture in the DOM shows a linear relationship (Figure 42). The data implies that for each centimeter increase in fracture aperture, there is a corresponding increase in fracture height, with a constant offset of 2.19 cm. The results also suggest that the model explains approximately 42% of the variability in fracture aperture. While this relationship is not exceptionally strong, it contributes to our understanding of the subsurface processes responsible for fracture formation within the Hofuf Formation. This highlights the interplay between fracture height and aperture as a significant factor in its deformation history (Renshaw and Park, 1997). These variations in

fracture height and aperture have implications for hydrocarbon reservoir quality, groundwater flow dynamics, and geotechnical stability. Moreover, the large aperture sizes of most of the fractures measured (Figure 42) indicate that the fractures have undergone further dilation (opening) derived by late tectonic stresses associated with uplift unloading (Hooker et al., 2013). Another factor that may have contributed to accelerated fracture opening is erosional processes (Eppes and Keanini, 2017).

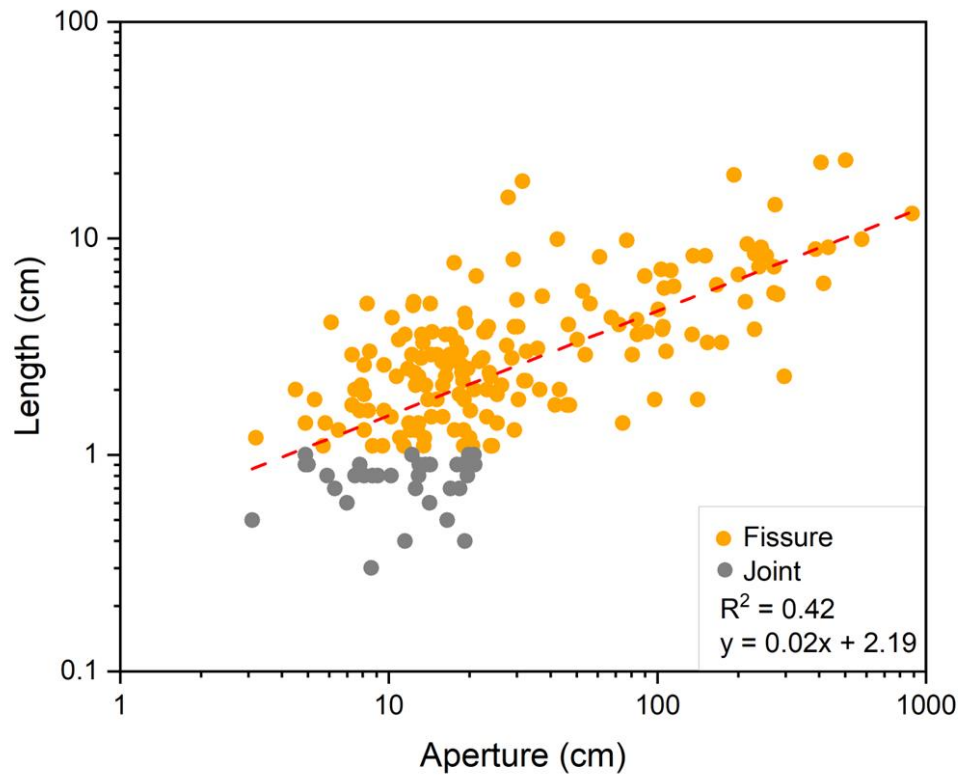


Figure 42: Fracture aperture size vs length measured from the DOM. Fissure: open fracture with an aperture size > 1 cm. Joint: open fracture with an aperture size <1 cm.

6.1.2 Implications for hydrocarbon exploration

The structural insights gathered from this study bear profound implications for hydrocarbon exploration. Understanding the dominant WNW-ESE fracture orientation provides a valuable predictive tool for mapping potential hydrocarbon conduits and optimizing extraction strategies. Such fractures, which are well-aligned with regional stress fields, can significantly enhance reservoir permeability, ensuring pathways for hydrocarbon migration and entrapment. The proximity of the Hofuf area to the Ghawar field, the world's largest conventional oil field, magnifies the significance of these structural insights for sustainable resource exploitation and regional development. Hence, all this will augment the economic and strategic value of the subsurface assets in the region.

In summary, the digital outcrop modeling of the Hofuf Formation provides a multifaceted view of its structural characteristics. The predominant fracture orientations align with regional tectonic forces, while the diversity in orientation, dip angles, heights, and apertures of fractures reveals a complex geological history marked by varied stress regimes. These insights are invaluable for furthering our understanding of the Arabian Peninsula's geological evolution and enhancing the exploration and efficient exploitation of its natural resources. Future studies should aim to integrate this structural characterization with other geological, geophysical, and geochemical data, providing a more holistic view of the subsurface and its potential resources.

6.2 Subsurface characterization of the Al-Hassa national park, eastern Saudi Arabia, using multi-geophysical methods

Five different geophysical methods were applied over the Al-Hassa National Park to characterize the subsurface. Most of the data was very valuable, and their interpretation helped me understand the complexity and uniqueness of the study area.

The magnetic data contained no significant geologically induced signal that could be used to extract information about the subsurface. All the high-amplitude recordings, with a total amplitude difference of 32.9 nT (Figure 18a), came from nearby metallic objects. When these anomalies were identified and removed by filtering the data, the total amplitude difference was down to 9.9 nT (Figure 18b), showing no important magnetic properties of the subsurface rocks.

The residual gravity field (Figure 19b), which represents the contribution of the shallow structures to the recorded signal, shows low gravity anomalies in the western, southern, and northern parts of the National Park, while high gravity anomalies are encountered mainly in the north and the southeastern parts. Mid-to-low gravity anomalies characterize the largest extent of the National Park. Low-density anomalies can be considered as basins/valleys filled with low-density loose materials of unconsolidated sediments that follow a general N-S orientation and are interrupted locally by high-density saddles. The assumption above about the N-S or NNW-SSE basins was confirmed by applying the enhancement filters in Figure 5. The drawn lines on the TDR map (Figure 20a) could be interpreted as tectonic lineaments and/or geologic contacts. Their dip direction is also indicated in the exact Figure. The lineament analysis distinguished the boundaries of the

geologic structures and highlighted the areas where small basins (low density, blue areas) of the suggested N-S direction are created. The tilt-depth method was applied to improve the understanding of the development and evolution of the basins (Figure 20b). This analysis provided information about the depths in which the geologic contacts and/or tectonic features are expected and offered valuable insights for subsurface modeling. The structural basins within the Al-Hassa National Park are located at greater depths in the southwestern part, where the rim of the basin is between 300-500 m below the ground surface. In the central part, the geologic structures should be expected to be situated at shallower depths, between 100 and 350 m. 3D inversion was also applied to the acquired data to incorporate and present the study area's complexity (in-depth and lateral density change). Figure 21a presents low-density (blue colors) and high (red colors) density areas. The low-density (basins) structure appears with an N-S arrangement, which is also indicated in Figure 21b, where only the low-density anomalies are depicted, creating N-S elongated basins interrupted by higher-density areas located in the in-between space (white areas). Finally, the assumption that the southwestern basin is the deepest is also supported by the 3D model, in which a large structure that continues beyond the area's limits and the maximum depth of the model (3 km) is observed.

3D inversion was also applied to the MT data, achieving high accuracy for the shallow layers (around 200 m depth) till the maximum depth of 2.1 km below the ground surface. Several scattered low-resistivity (below 20 Ω m, blue colors) anomalies were identified in the first depth slice, between 0.177 and 0.224 km (Figure 22). These low-resistivity areas are connected and becoming more extensive as we move deeper, from 0.5 to 0.838 km. After the depth of 1 km, these low-resistivity anomalies cover the central and southwestern

parts of the National Park until the maximum depth of 2.161 km. The first anomaly, in the southwest part of the survey area, has its top part at a depth of 500m and average lengths in the x, y, and z directions of 200 m, 600 m, and 1300 m, respectively; thus, an average volume is 0.156 km³ (Figures 22 and 23b). The second deep low-resistivity anomaly can be seen in the center of the area, with its top part at a depth of 980 m and average lengths in x, y, and z directions of 1400 m, 900 m, and 1350 m, respectively (Figures 22 and 23a, c). The second deep conductive anomaly volume is 1.7 km³. The geometrical characteristics of the low-resistivity and high-resistivity structures can also be extracted from Figures 23a, b, and c, where the three cross sections are presented.

Similar to the MT, resistivity models were also extracted from the 1D inversion of the TEM data, and the construction of the quasi-3D resistivity model and the representation of its depth slices are shown in Figure 24. The same color scale (blue and red for low and high resistivity anomalies, respectively) and resistivity range (10-100 Ω m) were applied to compare the shallow MT and TEM depth slices. The TEM models are presented as three depth slices, separated every 100 m, and reach a maximum depth of 300 m (Figure 24). Lateral and in-depth resistivity variations were observed where the main resistivity features are two low-resistivity (below 20 Ω m) anomalies depicted from the surface (Figure 9a) till the last depth slice (Figure 24c) and are shown as white circles. By comparing the third depth slice (200-300 m, Figure 24c) with the depth slice from the 3D MT resistivity model (177-224 m, Figure 24d), it is shown that there is a good agreement between the final resulted model by the different geophysical methods.

Figure 43 presents the comparison between the MT and gravity 2D models. A 2D section (Figure 43a) was extracted from the 3D MT model and used as the initial model for

applying 2D constrained inversion of the gravity data acquired along the same profile. It should be mentioned that MT and gravity are possibly the only methodologies that can get deep information about the surface, and their integration can be beneficial for characterizing complex areas. The MT model reaches a depth of 4.5 km, while the gravity model reaches a depth of 1.8 km. A low-resistivity (less than 20 Ωm) anomaly is shown in the western part of the profile, with a total thickness of 1 km (from -2 to -1 along the easting direction). This anomaly could be interpreted as a sedimentary basin filled with saturated sediments due to its low resistivity and the fact that a high-potential aquifer characterizes the area. The high-resistivity (around 100 Ωm , red colors) anomalies are extended over the rest of the profile, representing the basement of the study area. A sudden lateral discontinuity at 1.7 km Easting is found and could be considered as a small basin with lower resistivities. All this information was incorporated as an input constraint for the 2D inversion of the gravity data, as shown in Figure 10b. The gravity model consists of four density units based on the subsurface structures. The first unit with brown color is the basement, with an average density of 2.69 gr/cm^3 covering most of the profile. The second and third basins are filled with low-resistivity sediments and are light pink. The basin in the west is more extensive and deeper and produces a recorded gravity signature. The smaller and shallower basin is interpreted at the profile's eastern end. Due to their depth and expected compaction effects, the basins have slightly different densities, 2.55 gr/cm^3 for the western and 2.50 gr/cm^3 for the eastern. The final inverted gravity model has a very

low RMS error (0.033), indicating that the conceptual model used for the subsurface represents a realistic depiction of the subsurface.

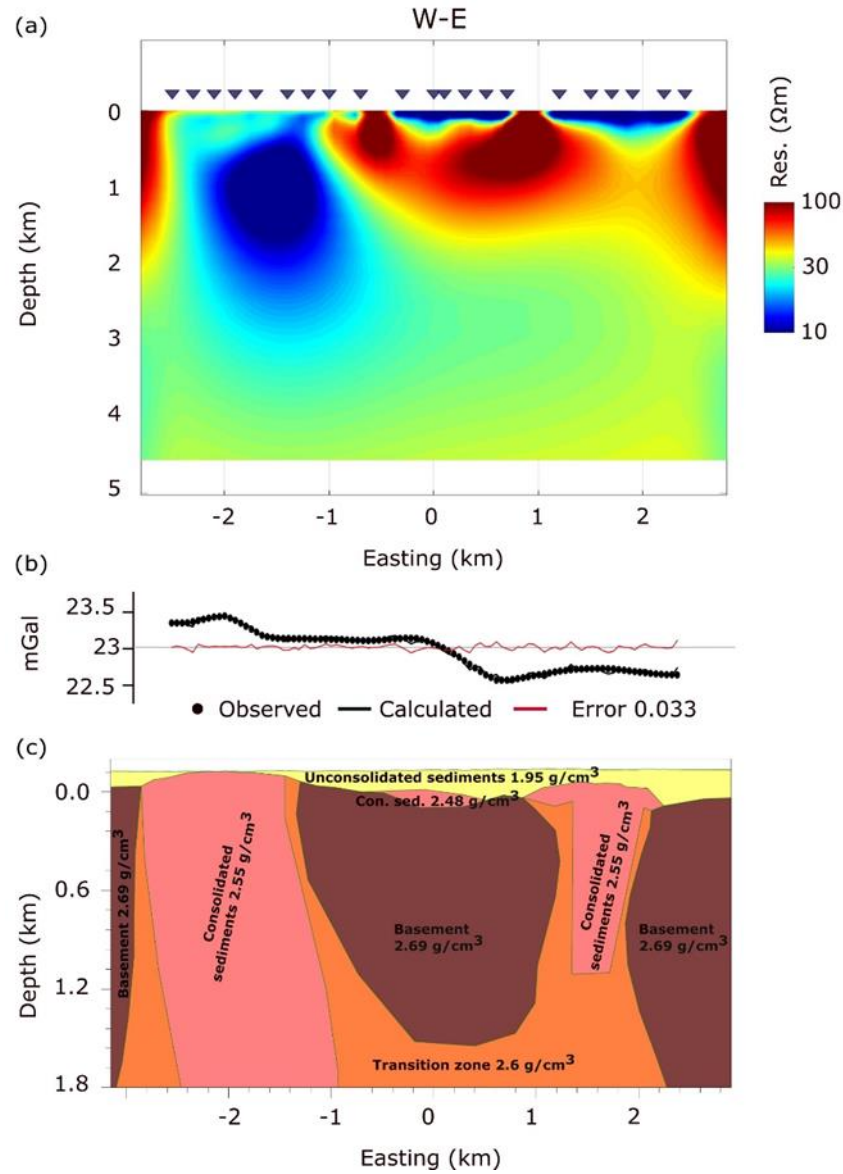


Figure 43: A comparison between the 2D MT and gravity models along the W-E direction. (a) The 2D MT cross-section of the 3D resistivity model (Figure 8b). (b) root mean square (rms) interpretation as the discrepancy between the observed and calculated values of the gravity measurements, and (c) the 2D model is based on the inversion of gravity data.]

Summarizing all the findings mentioned above by applying different geophysical methods and incorporating additional information, such as the proximity of the study area to the Ghawar oilfield and the expected tectonic features in the area, we could reach the following conclusions.

One possible scenario for the geologic regime of the study area is that the resulting 3D resistivity structure from the MT data, as shown in Figure 44 and confirmed by the TEM and gravity measurements, consists of four main elements: a very low resistivity clayed sand layer, a low-resistivity (less than 20 Ωm) suprasalt formation, the resistive (around 100 Ωm) salt body and low resistivity, around 20-50 Ωm , subsalt formation. Stewart (Stewart, 2018) documented these elements.

Specifically, very low resistivity (less than 1 Ωm) is probably related to high concentration clayed horizons covering the top layer of the study area. It should be mentioned that in some areas, clayed materials were observed during the scouting and fieldwork supporting our interpretation. The next unit is the Meso-Cenozoic suprasalt strata consisting of, from top to bottom, the Hofuf, Dam, Hadrukh, Dammam, Rus, and Umm Er Radhuma Formations with resistivities ranging from 1 to 20 Ωm (Ashadi et al., 2022). The total thickness of this unit reaches a maximum of 2 km, which agrees with the resulting 3D resistivity images. The resistive salt formation appears next to the suprasalt low-resistivity structures in very steep contact, as shown in Figure 11. The top of the salt formation ranges from 200-300 m and extends to a depth of 1.5-2 km. Below all three units, the subsalt unit is observed with an average resistivity of 30 Ωm , which may be linked to either carbonate sequences or effusive rocks. The subsalt formation is found from the 2-2.5 km depth and continues till the end of the model at the depth of 4.5 km.

It is useful to observe that suprasalt sediments can be considered as an oil reservoir, as oil moves upward from the subsalt formations (Berdichevsky et al., 2015). Seismic imaging is frequently ineffective for imaging subsalt strata due to the significant differences in velocity within the salt formation. Moreover, the seismic methods are costly and time-

consuming. MT method can capture a detailed image of the intricate arrangement of the salt structure with all of its components.

The other possible geologic scenario is that the observed low resistivity zone, ranging from 20 to 50 Ωm , could be attributed to geothermal fluids circulating through fractures induced by tectonic activity on the broader region. This hypothesis is bolstered by historical records of hot springs in the Al-Hassa area, suggesting a geothermal influence on the subsurface resistivity profile. Similar interpretations have been made in studies of other similar regions, such as the Kumamoto area in Japan (Asaue et al., 2012). In this scenario, the tectonically fractured zones act as conduits for geothermal fluids, altering the resistivity characteristics of the surrounding rock formations. The presence of these fluids could significantly impact the resistivity response, offering an alternative explanation to purely lithological factors. This scenario not only underscores the complexity of subsurface resistivity patterns but also highlights the potential for geothermal resources in the Al-Hassa area, necessitating further investigation to delineate the extent of geothermal influence on the observed resistivity characteristics.

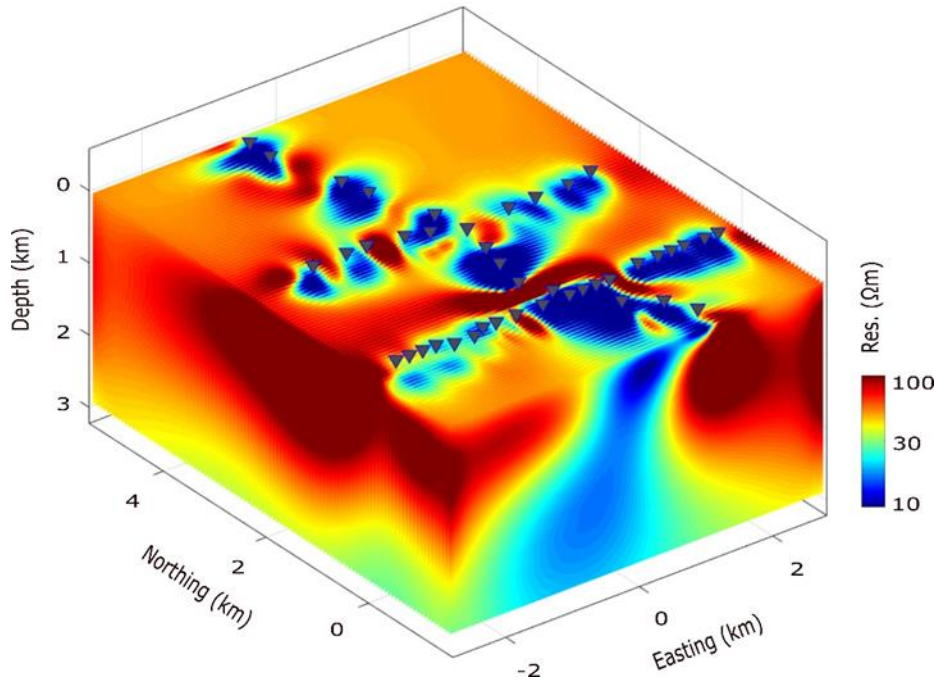


Figure 44: The 3D resistivity model for the study area of the Al-Hassa National Park.

6.3 Reconstruction of the subsurface of Al-Hassa Oasis using gravity geophysical data

A detailed and extensive gravity survey was applied over the Al-Hassa oasis to characterize the subsurface and reveal any tectonic or geological information. The data possessed significant value, and their analysis aided in my comprehension of the study area's intricacy and distinctiveness.

The residual gravity field (Figure 27) indicates the influence of shallow structures on the recorded signal. It reveals low gravity anomalies in the southwestern part of the study area and in some other areas, in the north, north-east, and central parts of the area under investigation. Low-density anomalies (blue and dark blue colors) are usually represented by fractured/eroded rocks and semi-cohesive sediments and sedimentary rocks, and sometimes loose sediments. On the other hand, areas of high gravity anomalies, depicted

by the colors red and pink, are found in the north-western and south-eastern parts of the study area. Hard sediments and rock formations usually produce such high anomaly densities. The rest of the study area is characterized by mid-to-low gravity (density) anomalies, typically ranging from -0.4 to 0 mGal, represented by green and light-yellow colors.

Based on the above, the low-density anomalies can be considered as deep basins where only the area they cover can be calculated. Other information, such as the thickness of the sedimentary basin, can be extracted from other results. The high-density anomalies appear next to the basins, with very sharp, NNW-SSE and W-E, contacts. Assuming that the lateral density change can be considered as a fault and the proximity of the study area to the Ghawar anticline, the high-density anomalies are probably uplifted rock formations.

The previous assumption regarding the N-S or NNW-SSE basins and the E-W discontinuities was verified by utilizing the enhancement filters and the produced map showing the TDR, seen in Figure 4a. The lines depicted on the TDR map could be interpreted as either tectonic lineaments or geologic contacts. The dip direction is also specified (Figure 28a). The lineament analysis identified the borders of the geological structures and emphasized the regions where basins (characterized by low density and appearing blue) of the predicted north-south and west-east general orientation are formed. A rose diagram is created to interpret the lineaments (Figure 28b). All linear features (black lines in Figure 28a) were segmented into 100m length lines, and the strike for each one was recorded. From the total number of linear segments, the rose diagram was constructed where the dominant lineaments in NNW-SSE, NNE-SSW and E-W orientations, were

determined. Although those orientations are depicted from the subsurface, they show a good agreement with surface features documented by Saner et al. (Saner et al., 2005).

The tilt-depth approach was utilized, and the terracing map was estimated to enhance comprehension of the formation and progression of the basins (Figure 29). This investigation presented data on the depths at which geologic contacts and/or tectonic structures are anticipated and provided useful insights for subsurface modeling. The structural basin in the southwestern area of Al-Hassa Oasis is situated at significant depths, with the basin rim being approximately 200 meters below the ground surface and extending to a depth of almost 1.8 km. The rest of the basins are shallower.

The obtained data was subjected to 3D inversion to incorporate and portray the complexity of the research area, including changes in density both in-depth and later-ally. Figure 30a displays regions with low density (shown by blue colors) and high density (indicated by pink colors). The low-density structures are observed in a north-south pattern. This is much clearer in Figure 30b, where only the low-density anomalies are shown, represented by the sedimentary basins covering the study area. The figure shows that almost all three basins are formed in the main N-S orientation. These basins are interrupted by higher-density areas, which are represented by the white spaces in between. Furthermore, the 3D model provides additional evidence to corroborate the notion that the southwestern basin is indeed the deepest. The model reveals a substantial structure that extends beyond the boundaries of the area and reaches a maximum depth of 4.2 kilometers.

By utilizing several geophysical techniques and considering additional factors, such as the proximity of the research area to the Ghawar oilfield and the anticipated tectonic

characteristics in the region, we can draw the following conclusions based on the findings. The presence of fractures with distinct orientations both at the surface and in the subsurface offer insights into the complex geodynamic history of the region. Surface observations reveal predominantly E-W oriented fractures, as indicated by Khogali et al. (Khogali et al., 2024). Conversely, subsurface data obtained from gravity surveys show the coexistence of both N-S and E-W fracture sets. The orientation of the principal stress (σ_1), resulting from the Arabian-Eurasian plate collision along the Zagros belt, provides a plausible explanation for the genesis of E-W fractures. This tectonic interaction, characterized by significant compressive forces, will likely induce fracturing perpendicular to the σ_1 direction, aligning with the observed E-W fractures.

Conversely, the presence of N-S fractures, particularly noted in the subsurface and absent on the surface, suggests a different mechanism at play. These fractures may be associated with an extensional regime responsible for developing the Najd fault system. Furthermore, the general N-S orientation of outcrop belts and subsurface basins in the Al-Hassa area may derive from the Amar Collision's imprint, which established N-S trending structural patterns such as Al Nala anticline. This Precambrian event's legacy, coupled with subsequent reactivation during the Hercynian Orogeny in the Devonian period, could have further accentuated the N-S structural predisposition. Acknowledging the limitation of the outcrop data derived from a single outcrop study, which may not fully represent the area's complex fracture network is crucial. A comprehensive examination of additional outcrops could yield further insights into the interplay of tectonic forces and the development of fractures in the Al-Hassa area. This expanded analysis would enhance our understanding

of the subsurface fracture patterns and their implications for hydrocarbon exploration and extraction in the region.

Moreover, the observed density variations contributing to gravity anomalies may also be attributed to salt domes or diapirism, a hypothesis supported by the presence of such structures in the region, such as the Dammam Dome and the North Gulf Salt Basin (Pollastro, 2003). This scenario underscores the multifaceted geological processes influencing the area's subsurface characteristics, further complicating the geophysical interpretation and emphasizing the need for a multi-disciplinary approach in unraveling the geological history and potential resource opportunities in the Al-Hassa region.

6.4 Subsurface complexity controls the aquifer heterogeneity: a case study from the Al-Hassa oasis, eastern Saudi Arabia

Understanding the hydrochemical characteristics of groundwater is essential for effective management and sustainable utilization of water resources (Costa Santos et al., 2024; Rezaei et al., 2020). However, it is challenging to understand subsurface factors that control groundwater chemistry or quality (Khogali et al., 2020). In this study, we conducted a comprehensive analysis encompassing hydrochemical facies, statistical analysis, isotopic composition, spatial distribution maps, and an extended geophysical investigation by collecting gridded gravity data. By integrating findings from these diverse analyses, valuable insights into the factors controlling groundwater heterogeneity in the Al-Hassa Oasis region are gained.

The analysis of the chemistry of major ions provided a foundational dataset on the chemical composition of groundwater samples (Table 2). High levels of various ions, exceeding

permissible limits set by regulatory standards, raise concerns about water quality and highlight potential anthropogenic influences. These findings set the stage for further exploration into the sources and processes driving ion concentrations in groundwater. The subsequent hydrochemical facies analysis, utilizing the Piper diagram (Figure 33), revealed distinct patterns of ion associations, and provided insights into hydrological processes shaping groundwater chemistry. The predominance of alkali metals ($\text{Na}^+ + \text{K}^+$) and Cl^- suggests influences from the evaporation and dissolution of evaporite rocks.

Statistical analysis further explained relationships between hydrochemical constituents, revealing strong correlations between TDS and Na^+ , K^+ , Ca^{2+} , Mg^{2+} , HCO_3^- , Cl^- , and SO_4^{2-} (Table 3). This underscores the crucial role of specific ions in shaping overall water quality and highlights potential sources of enrichment (Laonamsai et al., 2023). Cluster analysis based on dendrogram analysis revealed the formation of four distinct groups (Figure 34). Group 1, comprising 6 samples, exhibited lower TDS, EC, and ion concentrations compared to other groups, albeit with exceptions for pH, NO_3^- , and PO_4^{3-} . Group 2, encompassing 21 samples, was characterized by the highest TDS, pH, EC, and ion concentrations. Group 3, comprising the majority of samples (66 samples), displayed the lowest NO_3^- concentrations and overall values slightly higher than Group 1. Finally, Group 4, consisting of 20 samples, exhibited the lowest pH and highest NO_3^- values, with overall values marginally lower than Group 2. Comparing the TDS to the total well depths showed a very low correlation ($R^2 = 0.22$) (Figure 35a), which may indicate that the groundwater depth is not the main control of the water quality in this area. On the other hand, the isotopic composition analysis (Figure 35b, Table 4) offered additional insights into hydrological processes and water sources, with distinct isotopic signatures for groundwater groups that

indicate the variation in recharge mechanisms and groundwater flow paths of those groups. These findings underscore the complex interplay between geological, hydrological, and climatic factors in determining groundwater chemistry (Farid et al., 2015; McEachern et al., 2006).

The observed trends from spatial distribution maps, such as higher concentrations of certain ions in specific regions, may suggest localized influences from geological formations, land use practices, and hydrological processes (Ashraf et al., 2022; Dwarakish and Ganasri, 2015; Wang et al., 2007). In the study area, we noticed higher concentrations of most of the ions in the southeastern part and relatively lower concentrations in the western part (Figure 36). The factors governing groundwater chemistry in the study area, explored through Gibbs diagram (Figure 37), saturation index calculations (Figure 38), and ionic relationships (Figure 39). All samples are clustered near the evaporation zone in Gibbs diagram, characterized by high salinity and the dominance of Na^+ and Cl^- . Those observations suggest the involvement of evaporites in enriching the groundwater of Al-Hassa oasis. The saturation indexes indicate oversaturation of calcite and dolomite in most tested groundwater samples, with some exhibiting undersaturation (Figure 38). Conversely, all samples show undersaturation of anhydrite, gypsum, and halite, indicating the potential for further dissolution of these minerals. Plotting $\text{HCO}_3^- + \text{SO}_4^{2-}$ versus $\text{Ca}^{2+} + \text{Mg}^{2+}$ (Figure 39a) suggested a partial dissolution of calcite, dolomite, and gypsum as some samples align along the 1:1 equiline. Moreover, a significant contribution from halite dissolution is evident, as most samples align along the 1:1 equiline with a strong correlation (Figure 39b). Plots of Ca^{2+} versus HCO_3^- and Ca^{2+} versus SO_4^{2-} (Figure 39c and d) suggest a minor probability of calcite or gypsum dissolution in these samples. Overall, the results

showed that evaporation and halite dissolution are the main factors that enriched the groundwater of the Al-Hassa oasis.

The integration of high-accuracy geophysical data from the gravity survey provides additional context by delineating subsurface geological structures (Mohamed et al., 2023; Omollo and Nishijima, 2023). The residual gravity field (Figure 40) reveals areas of low gravity anomalies (corresponding to lower densities) in the southwestern region and, in specific locations supported by multiple stations, in the study area's northern, north-eastern, and central portions. Low-density anomalies are commonly identified by the presence of fractured or eroded rocks, semi-cohesive sediments, sedimentary rocks, and occasionally loose sediments. A prominent basin or depression is observed in the southwestern part, indicated by a strong negative anomaly as aforementioned. Additionally, smaller elongated sub-basins are discernible in the eastern and northern regions of the study area. In contrast, regions with elevated gravity anomalies, represented by light to dark blue colors, are located in the northwestern and southeastern sections of the study area. Hard sediments and rock formations typically result in elevated anomaly densities. Specifically, the rectangular-shaped, positive density anomaly in the southeastern part of the study area suggests the presence of evaporites. It has to be mentioned that evaporites (halite, anhydrite, and gypsum) are less dense than most rocks in the study area. The positive anomaly comes from comparing the evaporites and the sediments filling the basins (low-density anomalies) in the west and north of the evaporitic positive response. The high-density anomalies are situated next to the basins, displaying clear and precise boundaries oriented in the NNW-SSE and W-E directions (Figure 40 and 41). Considering the geological fault represented by the lateral variation in density and the proximity of the

study area to the Ghawar anticline, it is probable that the high-density anomalies correspond to rock formations that have been uplifted. The remaining portion of the study area is distinguished by moderate to low gravitational anomalies, typically varying from -0.4 to 0 mGal, depicted by green and light-yellow hues.

In addition, the terracing map and the maximum of the THDR were calculated (Figure 41). These filters yielded information on the expected geological boundaries and/or tectonic formations, providing valuable knowledge for creating subsurface models.

The black dots on the THDR map can be interpreted as tectonic lineaments or geologic contacts.

The presence of features such as diapirism, basins, and faults (as lateral changes of the measured geophysical property) revealed by the gravity survey offers insights into potential controls on groundwater flow and chemistry (Bajc et al., 2018; Hiebing et al., 2018; Scott, 2022). The observed correlation implies that the probable presence of a diapirism structure in the southeastern part of the study area may underlie the compromised groundwater quality in this area while having a relatively better water quality in the southwestern part of the probable basin area (Figure 45). Moreover, the correlation of gravity anomalies with groundwater temperature distribution (Figure 45) across the study area suggests that cooler water originates from basin areas (low-density anomalies) characterized by loose sediments, potentially facilitating the cooling of upwelling hot groundwater from deeper aquifers. Conversely, areas with hotter water correspond to regions with dense rock formations or doming, possibly stimulating shorter flow pathways for upwelling hot groundwater through fractured geological formations.

The correlation between hydrochemical characteristics and geological structures underscores the interconnected nature of hydrogeological processes and geological features. The findings of this study highlight the complex interplay of geological, hydrological, and tectonic factors in shaping groundwater chemistry in the Al-Hassa oasis region. By integrating findings from diverse analyses, we comprehensively understand the complex processes governing hydrochemical variability. Moving forward, interdisciplinary approaches combining hydrogeological, geochemical, geophysical, and climatological techniques will be essential for advancing our understanding of groundwater dynamics and developing sustainable water resource management strategies in arid regions.

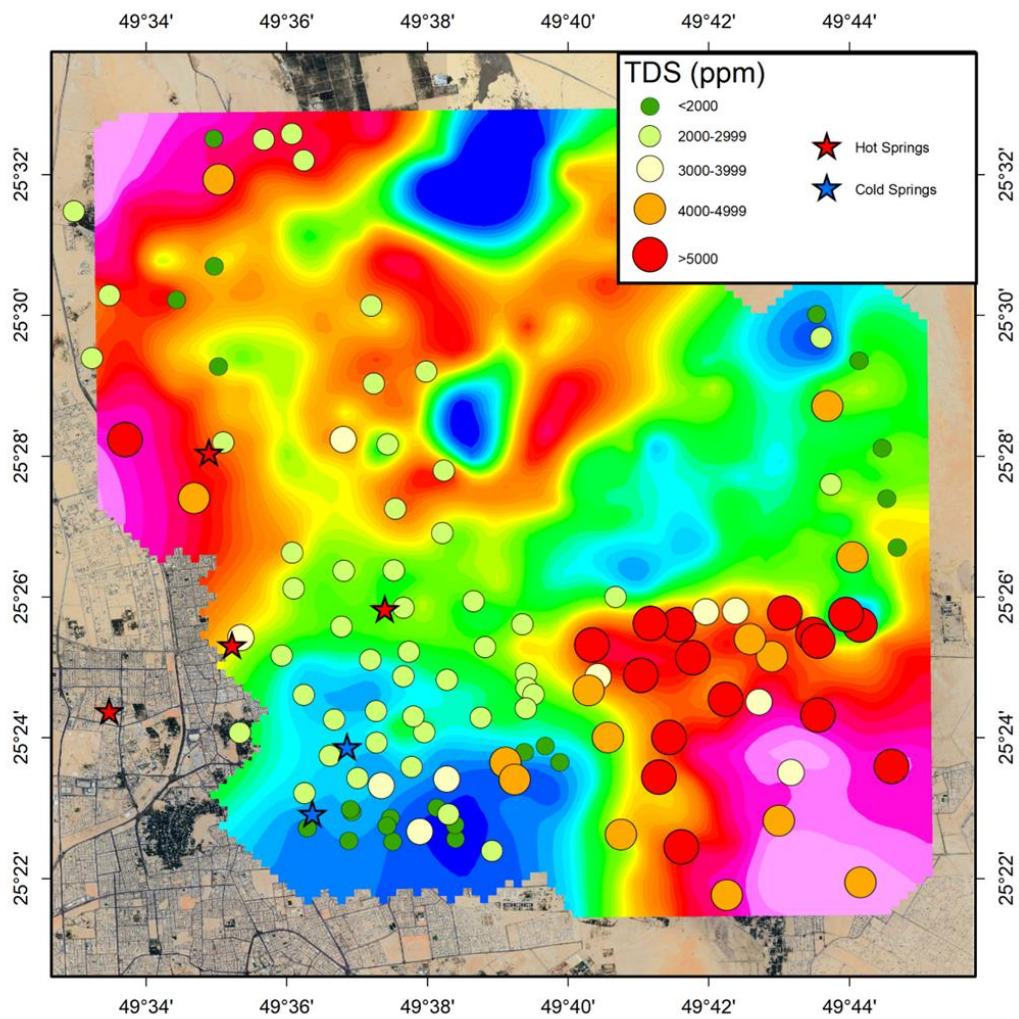


Figure 45: Spatial distribution of TDS and water temperature and their relation to density variations in the subsurface.

CHAPTER 7

CONCLUSION

The Al-Hassa area, renowned for its geological and hydrogeological significance, historically boasted over 280 natural springs that irrigated the world's largest oasis. Situated near the Ghawar oil field, the largest conventional oil field globally, this region holds immense geological importance. This study employed a combination of geophysical, geological, and hydrogeological methods to understand and reconstruct the subsurface heterogeneity in the Al-Hassa oasis area, covering more than 350 km².

The investigation divided the region into two parts based on the acquired data for a comprehensive understanding of the subsurface. The first part, approximately 40 km², focused on the Al-Hassa National Park in the northeast of the oasis. Five geophysical methods were employed: 210 gravity stations, a 3.6 km magnetic profile, 46 magnetotelluric, six audio-magnetotelluric, and 35 transient electromagnetic stations. These were integrated to create a detailed 3D subsurface model. The second part encompassed the entire Al-Hassa oasis, covered by 571 gravity stations and hydrochemical data from 113 groundwater wells.

In Al-Hassa National Park, electromagnetic soundings were processed to achieve maximum resolution. Gravity and electromagnetic data were combined to construct a 3D model revealing a complex underground structure, while magnetic data offered minimal additional insights. The resulting 3D geophysical subsurface model highlighted lateral

resistivity discontinuities, a possible salt dome structure, and fracture zones that facilitate or impede groundwater flow.

Across the broader Al-Hassa oasis, 3D subsurface modeling unveiled an intricate subterranean configuration with lateral variations in density, indicating the presence of potential salt dome structures and fracture zones that serve as conduits or barriers to subsurface fluid flow. Hydrochemical and geophysical results aligned well with groundwater quality and gravity anomaly distributions. Positive gravity anomalies in the southeastern part indicated denser rock formations and higher TDS values, reflecting poor water quality. In contrast, significant negative gravity anomalies in the southwest suggested loose sediments or basins and low TDS values, signifying good water quality.

Groundwater temperature distribution revealed a consistent pattern, with cooler waters in areas of negative gravity anomalies (basins) and hotter waters in regions of positive gravity anomalies. These findings suggest that groundwater quality variations are linked to interactions with distinct geological substrates and varying sub-basins. Temperature differences may also be attributed to different subsurface flow pathways.

Structural investigations identified a dominant WNW-ESE trending fracture system and secondary NW-SE and NE-SW oriented fracture systems, suggesting a complex interplay of tectonic stresses that shaped the region over geological timescales. This thesis provides a comprehensive explanation of the controlling factors behind subsurface heterogeneity in the Al-Hassa oasis, emphasizing the roles of geological, tectonic, and hydrogeological elements in shaping the region's subsurface patterns

References

- Abba, S.I., Yassin, M.A., Jibril, M.M., Tawabini, B., Souplos, P., Khogali, A., Shah, S.M.H., Usman, J., Aljundi, I.H., 2024a. Nitrate concentrations tracking from multi-aquifer groundwater vulnerability zones: Insight from machine learning and spatial mapping. *Process Safety and Environmental Protection* 184, 1143–1157. <https://doi.org/10.1016/j.psep.2024.02.041>
- Abba, S.I., Yassin, M.A., Shah, S.M.H., Egbueri, J.C., Elzain, H.E., Agbasi, J.C., Saini, G., Usaman, J., Khan, N.A., Aljundi, I.H., 2024b. Trace element pollution tracking in the complex multi-aquifer groundwater system of Al-Hassa oasis (Saudi Arabia) using spatial, chemometric and index-based techniques. *Environ Res* 249, 118320. <https://doi.org/10.1016/j.envres.2024.118320>
- Abderrahman, W., Ukayli, M., 1984. Strategy of Groundwater Use in Al-Hassa Region of Saudi Arabia. *Int J Water Resour Dev* 2, 45–59. <https://doi.org/10.1080/07900628408722307>
- Agheshlui, H., Sedaghat, M.H. and Matthai, S., 2018. Stress influence on fracture aperture and permeability of fragmented rocks. *Journal of Geophysical Research: Solid Earth*, 123(5), pp.3578-3592.
- Agyemang, V.O., 2020. Application of magnetotelluric geophysical technique in delineation of zones of high groundwater potential for borehole drilling in five

- communities in the Agona East District, Ghana. *Appl Water Sci* 10, 1–6.
<https://doi.org/10.1007/s13201-020-01214-2>
- Al Tokhais, A.S., Rausch, R., 2008. The Hydrogeology of Al Hassa Springs. The 3rd International Conference on Water Resources and Arid Environments 1, 16–19.
- Alabdula'aly, A.I., Al-Rehaili, A.M., Al-Zarah, A.I., Khan, M.A., 2010. Assessment of nitrate concentration in groundwater in Saudi Arabia. *Environ Monit Assess* 161, 1–9. <https://doi.org/10.1007/s10661-008-0722-7>
- Alfarhan, M., Salem Alhumimidi, M., Reuben Cline, J., Stuart White, L., Lynn Aiken, C., 2020. 3D digital photorealistic models from the field to the lab. *Arabian Journal of Geosciences*. <https://doi.org/10.1007/s12517-020-05517-1/Published>
- Al-Dakheel, Y., 2009. Spatial Modeling for Groundwater Salinity: Neogene Aquifer, Al-Hassa, Saudi Arabia. *Journal of Environmental Hydrology* 17.
- Al-Dakheel, Y.Y., Hussein, A.H.A., El-Mahmoudi, A.S., Massoud, M.A., 2010. Soil, water chemistry and sedimentological studies of Al Asfar evaporation lake and its inland sabkha, Al Hassa Area, Saudi Arabia. *Asian Journal of Earth Sciences* 3, 142–162. <https://doi.org/10.3923/ajes.2009.1.21>
- Al-Garni, M.A., El-Kaliouby, H.M., 2011. Delineation of saline groundwater and sea water intrusion zones using transient electromagnetic (TEM) method, Wadi Thuwal area, Saudi Arabia. *Arabian Journal of Geosciences* 4, 655–668.
<https://doi.org/10.1007/s12517-009-0094-5>

- Al-Mahmoud, M., 1987. Hydrogeology of the Al-Hassa Oasis. King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia.
- Al-Naeem, A., 2011. Evaluation of Groundwater of Al-Hassa Oasis, Eastern Region Saudi Arabia. *Res J Environ Sci* 5, 624–642. <https://doi.org/10.3923/rjes.2011.624.642>
- Al-Omran, A.M., Mousa, M.A., AlHarbi, M.M., Nadeem, M.E.A., 2018. Hydrogeochemical characterization and groundwater quality assessment in Al-Hasa, Saudi Arabia. *Arabian Journal of Geosciences* 11. <https://doi.org/10.1007/s12517-018-3420-y>
- Al-Saad, H., Nasir, S., Sadooni, F., Alsharhan, A.S., 2002. Stratigraphy and sedimentology of the Hofuf Formation in the State of Qatar in relation to the tectonic evolution of the East Arabian Block, *Geol. Palaont. Mh.*
- Al-Sayari, S.S., Zötl, J.G., 1978. Quaternary Period in Saudi Arabia. Springer Vienna, Vienna. <https://doi.org/10.1007/978-3-7091-8494-3>
- Al-Zarah, A., 2011. Elemental Composition of Groundwater and Spring Waters in Al-Ahsa Oasis, Eastern Region Saudi Arabia. *Trends Appl Sci Res* 6, 1–18. <https://doi.org/10.3923/tasr.2011.1.18>
- Appelo, C.A.J., Postma, D., 2004. Geochemistry, groundwater and pollution. CRC press.
- Araffa, S.A.S., Helaly, A.S., Khozium, A., Lala, A.M.S., Soliman, S.A., Hassan, N.M., 2015. Delineating groundwater and subsurface structures by using 2D resistivity, gravity and 3D magnetic data interpretation around Cairo–Belbies Desert road, Egypt.

- NRIAG Journal of Astronomy and Geophysics 4, 134–146.
<https://doi.org/10.1016/j.nrjag.2015.06.004>
- Árnason, K., Eysteinnsson, H., Hersir, G.P., 2010. Joint 1D inversion of TEM and MT data and 3D inversion of MT data in the Hengill area, SW Iceland. *Geothermics* 39, 13–34. <https://doi.org/10.1016/j.geothermics.2010.01.002>
- Asaue, H., Kubo, T., Yoshinaga, T., Koike, K., 2012. Application of Magnetotelluric (MT) Resistivity to Imaging of Regional Three-Dimensional Geologic Structures and Groundwater Systems. *Natural Resources Research* 21, 383–393.
<https://doi.org/10.1007/s11053-012-9184-2>
- Ashadi, A.L., Martinez, Y., Kirmizakis, P., Hanstein, T., Xu, X., Khogali, A., Paembonan, A.Y., AlShaibani, A., Al-Karnos, A., Smirnov, M., Strack, K., Soupios, P., 2022. First High-Power CSEM Field Test in Saudi Arabia. *Minerals* 12, 1236.
<https://doi.org/10.3390/min12101236>
- Ashadi, A.L., Tezkan, B., Yogeshwar, P., Hanstein, T., Kirmizakis, P., Khogali, A., Chavanidis, K., Soupios, P., 2024. Magnetotelluric Case Study from Ain Al-Harrah Hot Spring, Al-Lith, Saudi Arabia. *Arab J Sci Eng* 49, 899–912.
<https://doi.org/10.1007/s13369-023-08293-8>
- Ashraf, S., Ali, M., Shrestha, S., Hafeez, M.A., Moiz, A., Sheikh, Z.A., 2022. Impacts of climate and land-use change on groundwater recharge in the semi-arid lower Ravi River basin, Pakistan. *Groundw Sustain Dev* 17, 100743.
<https://doi.org/https://doi.org/10.1016/j.gsd.2022.100743>

- Auken, E., Christiansen, A.V., Kirkegaard, C., Fiandaca, G., Schamper, C., Behroozmand, A.A., Binley, A., Nielsen, E., Effersø, F., Christensen, N.B., Sørensen, K., Foged, N., Vignoli, G., 2015. An overview of a highly versatile forward and stable inverse algorithm for airborne, ground-based and borehole electromagnetic and electric data. *Exploration Geophysics* 46, 223–235. <https://doi.org/10.1071/EG13097>
- Bai, D., Meju, M.A., Liao, Z., 2001. Magnetotelluric images of deep crustal structure of the Rehai geothermal field near Tengchong, southern China. *Geophys J Int* 147, 677–687. <https://doi.org/10.1046/j.0956-540x.2001.01568.x>
- Bajc, A.F., Marich, A.S., Priebe, E.H., Rainsford, D.R.B., 2018. Evaluating the groundwater resource potential of the Dundas buried bedrock valley, southwestern Ontario: an integrated geological and hydrogeological case study. *Can J Earth Sci* 55, 659–676.
- Bakiewicz, W., Milne, D.M., Noori, M., 1982. Hydrogeology of the Umm Er Radhuma aquifer, Saudi Arabia, with reference to fossil gradients. *Quarterly Journal of Engineering Geology* 15, 105–126. <https://doi.org/10.1144/gsl.qjeg.1982.015.02.03>
- Barajas-Olalde, C., Adams, D.C., Curcio, A., Davydycheva, S., Klapperich, R.J., Martinez, Y., Paembonan, A.Y., Peck, W.D., Strack, K., Soupios, P., 2023. Application of Electromagnetic Methods for Reservoir Monitoring with Emphasis on Carbon Capture, Utilization, and Storage. *Minerals* 13, 1308. <https://doi.org/10.3390/min13101308>

- Bashri, M., Abdullatif, O., Salih, M., 2017. Sedimentology and facies analysis of Miocene mixed siliciclastic–carbonate deposits of the Dam Formation in Al Lidam area, eastern Saudi Arabia. *Arabian Journal of Geosciences* 10, 472. <https://doi.org/10.1007/s12517-017-3244-1>
- Berdichevsky, M.N., Bubnov, V., Aleksanova, E., Alekseev, D., Yakovlev, A., Yakovlev, D., 2015. Magnetotelluric Studies in Russia: Regional-Scale Surveys and Hydrocarbon Exploration, in: *Electromagnetic Sounding of the Earth's Interior*. Elsevier, pp. 379–401. <https://doi.org/10.1016/B978-0-444-63554-9.00013-1>
- Bilmes, A., D'Elia, L., Lopez, L., Richiano, S., Varela, A., Alvarez, M. del P., Bucher, J., Eymard, I., Muravchik, M., Franzese, J., Ariztegui, D., 2019. Digital outcrop modelling using “structure-from-motion” photogrammetry: Acquisition strategies, validation and interpretations to different sedimentary environments. *Journal of South American Earth Sciences* 96, 102325. <https://doi.org/https://doi.org/10.1016/j.jsames.2019.102325>
- BRGM, 1976. Hydrogeological Investigation of the Al Wasia Aquifer in the Eastern Province of Saudi Arabia. Riyadh.
- Buckley, S.J., Howell, J.A., Enge, H.D., Leren, B.L.S., Kurz, T.H., 2006. Integration of terrestrial laser scanning, digital photogrammetry and geostatistical methods for high-resolution modelling of geological outcrops. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science* 36, B5.

- Cagniard, L., 1953. Basic theory of the magneto-telluric method of geophysical prospecting. *Geophysics* 18, 605–635.
- Candansayar, M.E., Tezkan, B., 2008. Two-dimensional joint inversion of radiomagnetotelluric and direct current resistivity data. *Geophys Prospect* 56, 737–749. <https://doi.org/10.1111/j.1365-2478.2008.00695.x>
- Chapman, R.W., 1974. Calcareous Duricrust in Al-Hasa, Saudi Arabia. *Bulletin of the Geological Society of America* 85, 119–130. [https://doi.org/10.1130/0016-7606\(1974\)85<119:CDIASA>2.0.CO;2](https://doi.org/10.1130/0016-7606(1974)85<119:CDIASA>2.0.CO;2)
- Chapman, R.W., 1971. Climatic changes and the evolution of landforms in the eastern province of Saudi Arabia. *Bulletin of the Geological Society of America* 82, 2713–2728. [https://doi.org/10.1130/0016-7606\(1971\)82\[2713:CCATEO\]2.0.CO;2](https://doi.org/10.1130/0016-7606(1971)82[2713:CCATEO]2.0.CO;2)
- Chavanidis, K., Stampolidis, A., Kirmizakis, P., Tranos, M., Fedi, M., Pasteka, R., Al-Ramadan, K., Kaka, S., Tsokas, G.N., Soupios, P., 2022. Gravity Survey on the Oil-Bearing Dammam Dome (Eastern Saudi Arabia) and Its Implications. *Remote Sens (Basel)* 14, 735. <https://doi.org/10.3390/rs14030735>
- Chave, A.D., Jones, A.G., 2012. *The Magnetotelluric Method*. Cambridge University Press. <https://doi.org/10.1017/CBO9781139020138>
- Cordell, L., McCafferty, A.E., 1989. A terracing operator for physical property mapping with potential field data. *Geophysics* 54, 621–634.
- Costabel, S., Siemon, B., Houben, G., Günther, T., 2017. Geophysical investigation of a freshwater lens on the island of Langeoog, Germany – Insights from combined HEM,

- TEM and MRS data. *J Appl Geophy* 136, 231–245.
<https://doi.org/10.1016/j.jappgeo.2016.11.007>
- Costa Santos, R., Aguilar da Silva, R., Moreira dos Santos, M., Botelho Bovo, A., Furtado da Silva, A., 2024. Assessing nitrate contamination in groundwater for public supply: A study in a small Brazilian town. *Groundw Sustain Dev* 25, 101084.
<https://doi.org/https://doi.org/10.1016/j.gsd.2024.101084>
- Demirci, İ., Candansayar, M.E., Vafidis, A., Soupios, P., 2017. Two dimensional joint inversion of direct current resistivity, radio-magnetotelluric and seismic refraction data: An application from Bafra Plain, Turkey. *J Appl Geophy* 139, 316–330.
<https://doi.org/10.1016/j.jappgeo.2017.03.002>
- Demirci, İ., Gündoğdu, N.Y., Candansayar, M.E., Soupios, P., Vafidis, A., Arslan, H., 2020. Determination and Evaluation of Saltwater Intrusion on Bafra Plain: Joint Interpretation of Geophysical, Hydrogeological and Hydrochemical Data. *Pure Appl Geophys* 177, 5621–5640. <https://doi.org/10.1007/s00024-020-02573-2>
- De Joussineau, G., Petit, J.-P., 2006. Variations in fracture aperture above normal faults: a numerical investigation in 2-D elastic multilayers. *Journal of Structural Geology* 28, 669–681. <https://doi.org/https://doi.org/10.1016/j.jsg.2006.01.011>
- Dilalos, S., Alexopoulos, J.D., Tsatsaris, A., 2018. Calculation of Building Correction for urban gravity surveys. A case study of Athens metropolis (Greece). *J. Appl. Geophys.* 159, 540–552. <https://doi.org/10.1016/j.jappgeo.2018.09.036>

- Dirks, H., Al Ajmi, H., Kienast, P., Rausch, R., 2018. Zur Hydrogeologie des Umm Er Radhuma Aquifers (Arabische Halbinsel). *Grundwasser* 23, 5–15. <https://doi.org/10.1007/s00767-017-0388-6>
- Dwarakish, G.S., Ganasri, B.P., 2015. Impact of land use change on hydrological systems: A review of current modeling approaches. *Cogent Geosci* 1, 1115691.
- Edgell, H.S., 1992. Basement Tectonics of Saudi Arabia as Related to Oil Field Structures, in: Rickard, M.J. (Ed.), *Basement Tectonics* 9. Kluwer Academic Publishers, Dordrecht, pp. 169–193. https://doi.org/10.1007/978-94-011-2654-0_10
- Edigbue, P., Demirci, I., Hamdan, H., Al-Shuhail, A., Akca, I., Soupios, P., Candansayar, E., 2022. Joint Inversion of Seismic and DC Geophysical Data Using Local and Global Optimization Algorithms, in: *International Petroleum Technology Conference*. IPTC, Riyadh, Saudi Arabia. <https://doi.org/10.2523/IPTC-21877-MS>
- Eltom, H.A., Yassin, M.A., Cline, J., Alghamdi, M.H., Kusuma, L., Al-Mahfoudh, A.E., 2023. Incorporating outcrop observations and laboratory measurements in 3D reservoir models: An integrated study to enhance the workflow of modeling bioturbated carbonate reservoirs. *Marine and Petroleum Geology* 152. <https://doi.org/10.1016/j.marpetgeo.2023.106259>
- El Asa'ad, G.M.A., 1984. The paleobiogeographic distribution of the late Cretaceous fauna of Arabia and surroundings areas. *Arab Gulf journal of scientific research* 2, 105–121.
- El Asa'ad, G.M.A., 1983a. Bio-and chronostratigraphy of the Aruma Formation in central Saudi Arabia, in: *Proc 1st Jordanian Geol Conf Spec Publ.* pp. 87–111.

- El Asa'ad, G.M.A., 1983b. Lithostratigraphy of the Aruma Formation in Central Saudi Arabia, in: Proc 1st Jordanian Geol Conf Spec Publ. pp. 72–86.
- Eppes, M.C. and Keanini, R., 2017. Mechanical weathering and rock erosion by climate-dependent subcritical cracking. *Reviews of Geophysics*, 55(2), pp.470-508.
- Erdoğan, E., Candansayar, M.E., 2017. The conductivity structure of the Gediz Graben geothermal area extracted from 2D and 3D magnetotelluric inversion: Synthetic and field data applications. *Geothermics* 65, 170–179.
<https://doi.org/10.1016/j.geothermics.2016.09.007>
- Fairhead, J.D., 2015a. Advances in gravity and magnetic processing and interpretation. *Earthdoc*. <https://doi.org/10.3997/9789462821774>
- Fairhead, J.D., 2015b. Generating a high-resolution global gravity model for oil exploration: Part 1—Land data compilations. *The Leading Edge*, 34(3), pp.326-330.
<https://doi.org/10.1190/tle34030326.1>
- Fairhead, D., 2016. Advances in Gravity and Magnetic Processing and Interpretation. EAGE Publications bv. <https://doi.org/10.3997/9789462821774>
- Farid, I., Zouari, K., Rigane, A., Beji, R., 2015. Origin of the groundwater salinity and geochemical processes in detrital and carbonate aquifers: Case of Chougafiya basin (Central Tunisia). *J Hydrol (Amst)* 530, 508–532.
<https://doi.org/https://doi.org/10.1016/j.jhydrol.2015.10.009>
- Farzamian, M., Alves Ribeiro, J., Khalil, M.A., Monteiro Santos, F.A., Filbandi Kashkouli, M., Bortolozo, C.A., Mendonça, J.L., 2019. Application of Transient Electromagnetic

- and Audio-Magnetotelluric Methods for Imaging the Monte Real Aquifer in Portugal. *Pure Appl Geophys* 176, 719–735. <https://doi.org/10.1007/s00024-018-2030-7>
- Ferrill, D.A. and Morris, A.P., 2003. Dilational normal faults. *Journal of structural geology*, 25(2), pp.183-196.
- Foged, N., Auken, E., Christiansen, A.V., Sørensen, K.I., 2013. Test-site calibration and validation of airborne and ground-based TEM systems. *Geophysics* 78, E95–E106. <https://doi.org/10.1190/geo2012-0244.1>
- Geert, K., Afifi, A.M., Al-Hajri, S.A., Droste, H.J., 2001. Paleozoic Stratigraphy and Hydrocarbon Habitat of the Arabian Plate. *GeoArabia* 6, 407–442. <https://doi.org/10.2113/geoarabia0603407>
- Gibbs, R.J., 1970. Mechanisms controlling world water chemistry. *Science* (1979) 170, 1088–1090.
- Grant, F.S., 1985. Aeromagnetism, geology and ore environments, I. Magnetite in igneous, sedimentary and metamorphic rocks: An overview. *Geoexploration* 23, 303–333. [https://doi.org/10.1016/0016-7142\(85\)90001-8](https://doi.org/10.1016/0016-7142(85)90001-8)
- Gudmundsson, A., 1992. Formation and growth of normal faults at the divergent plate boundary in Iceland. *Terra Nova*, 4(4), pp.464-471.
- GTZ/DCO, 2006. Investigations of Updating Groundwater Mathematical Model(s) for the Umm Er Radhuma and Overlying Aquifers – Review of Monitoring Network. Riyadh.

- Gudmundsson, A., 1992. Formation and growth of normal faults at the divergent plate boundary in Iceland. *Terra Nova*, 4(4), pp.464-471.
- Hancock, P.L., Kadhi, A., 1978. Analysis of mesoscopic fractures in the Dhurma-Nisah segment of the central Arabian graben system. *Journal of the Geological Society* 135, 339–347.
- Hiebing, M., Doser, D.I., Avila, V.M., Ma, L., 2018. Geophysical studies of fault and bedrock control on groundwater geochemistry within the southern Mesilla Basin, western Texas and southern New Mexico. *Geosphere* 14, 1912–1934.
- Hinojosa-Prieto, H.R., Soupios, P., Barsukov, P., 2021. Subsurface Geological Characterization of the Late Neogene–Quaternary Argive Basin, Peloponnese, Greece Using Transient Electromagnetic Data and Vintage Stratigraphic Logs. *Geosciences (Basel)* 11, 317. <https://doi.org/10.3390/geosciences11080317>
- Hussain, M., 2006. The Jabal Qarah Caves Of The Hofuf Area, Northeastern Saudi Arabia: A Geological Investigation.
- Kalbus, E., Oswald, S., Wang, W., Kolditz, O., Engelhardt, I., Al-saud, M.I., Rausch, R., 2011. Large-scale Modeling of the Groundwater Resources on the Arabian Platform 1, 38–47.
- Kalisperi, D., Kouli, M., Vallianatos, F., Soupios, P., Kershaw, S., Lydakis-Simantiris, N., 2018. A Transient ElectroMagnetic (TEM) Method Survey in North-Central Coast of Crete, Greece: Evidence of Seawater Intrusion. *Geosciences (Basel)* 8, 107. <https://doi.org/10.3390/geosciences8040107>

- Kane, M.F., 1962. A Comprehensive System of Terrain Correction using a Digital Computer. *Geophysics* 27, 455–462. <https://doi.org/10.1190/1.1439044>
- Khogali, A., Abu-Mahfouz, I., Arrofi, D., AlGhamdi, M., Souprios, P., 2024. Structural analysis of Neogene sandstone sequence through integrated digital outcrop modeling and field investigations.
- Khogali, A., Birkle, P., Al-Shaibani, A., Keller, M., Tawabini, B., Makkawi, M., 2020. Geochemical assessment of potential sources for nitrate in the wasia aquifer, Al Kharj Area, central Saudi Arabia. *Water* (Switzerland) 12. <https://doi.org/10.3390/w12051479>
- Kumar, A., 2013. Geological and environmental observations on “Ali Baba” (al Qarah) caves and al Hasa oasis of al Hofuf in the eastern province of Saudi Arabia and an overview of Quaternary climate history of the Arabian Peninsula. VI, 1–19.
- Laonamsai, J., Julphunthong, P., Chipthamlong, P., Pawana, V., Chomchaewchan, P., Kamdee, K., Tomun, N., Kimmany, B., 2023. Hydrochemical characteristics and salt intrusion in groundwater of the lower Chao Phraya river basin: Insights from stable isotopes and hydrochemical analysis. *Groundw Sustain Dev* 23, 101044. <https://doi.org/https://doi.org/10.1016/j.gsd.2023.101044>
- Laubach, S.E., Lander, R.H., Criscenti, L.J., Anovitz, L.M., Urai, J.L., Pollyea, R.M., Hooker, J.N., Narr, W., Evans, M.A., Kerisit, S.N. and Olson, J.E., 2019. The role of chemistry in fracture pattern development and opportunities to advance

- interpretations of geological materials. *Reviews of Geophysics*, 57(3), pp.1065-1111.
<https://doi.org/10.1029/2019RG000671>
- Le Nindre, Y.M., Vaslet, D., Maddah, S.S., Al-Husseini, M.I., 2008. Stratigraphy of the Valanginian? To early paleocene succession in central Saudi Arabia outcrops: Implications for regional Arabian sequence stratigraphy. *GeoArabia* 13, 51–86.
- Li, X., 2016. Terracing gravity and magnetic data using edge-preserving smoothing filters. *Geophysics* 81, G41–G47. <https://doi.org/10.1190/geo2015-0409.1>
- Maerten, L., Gillespie, P., Pollard, D.D., 2002. Effects of local stress perturbation on secondary fault development. *Journal of Structural Geology* 24, 145–153.
[https://doi.org/https://doi.org/10.1016/S0191-8141\(01\)00054-2](https://doi.org/10.1016/S0191-8141(01)00054-2)
- Mahmoudi, A., Al-Barrak, K., Massoud, M., 2011. 2-D Electrical Tomography for Mapping of Aquifers at the New Campus of King Faisal University, Al Hassa, KSA. *International Journal of Water Resources and Arid Environments* 397–410.
- Martin, A.Z., 2001. Late Permian to Holocene Paleofacies Evolution of the Arabian Plate and its Hydrocarbon Occurrences. *GeoArabia* 6, 445–504.
<https://doi.org/10.2113/geoarabia0603445>
- Massoud, U., Qady, G. El, Metwaly, M., Santos, F., 2009. Delineation of Shallow Subsurface Structure by Azimuthal Resistivity Sounding and Joint Inversion of VES-TEM Data: Case Study near Lake Qaroun, El Fayoum, Egypt. *Pure Appl Geophys* 166, 701–719. <https://doi.org/10.1007/s00024-009-0463-8>

- Mattes, B.W., Conway Morris, S., 1990. Carbonate/evaporite deposition in the Late Precambrian — Early Cambrian Ara Formation of Southern Oman. Geol. Soc. London, Spec. Publ. 49, 617–636. <https://doi.org/10.1144/GSL.SP.1992.049.01.37>
- McEachern, P., Prepas, E.E., Chanasyk, D.S., 2006. Landscape control of water chemistry in northern boreal streams of Alberta. J Hydrol (Amst) 323, 303–324. <https://doi.org/https://doi.org/10.1016/j.jhydrol.2005.09.016>
- Miller, H.G., Singh, V., 1994. Potential field tilt—a new concept for location of potential field sources. J Appl Geophy 32, 213–217. [https://doi.org/10.1016/0926-9851\(94\)90022-1](https://doi.org/10.1016/0926-9851(94)90022-1)
- Mohamed, A.K., Meju, M.A., Fontes, S.L., 2002. Deep structure of the northeastern margin of the Parnaiba Basin, Brazil, from magnetotelluric imaging. Geophys Prospect 50, 589–602. <https://doi.org/10.1046/j.1365-2478.2002.00338.x>
- Moritz, H., 1980. Geodetic reference system 1980. Bulletin Géodésique 54, 395–405. <https://doi.org/10.1007/BF02521480>
- Mukhopadhyay, M., Mogren, S., Mukhopadhyay, B., Venkatesh, K.D., Elawadi, E., 2020. Crustal control on basement uplift beneath the Ghawar Anticline, Saudi Arabia—gravity modeling with receiver function constraints. Arab. J. Geosci. 13, 463. <https://doi.org/10.1007/s12517-020-05433-4>
- Murris, R.J., 1980. Middle East: stratigraphic evolution and oil habitat. AAPG Bulletin 64, 597–618.

- Nabulsi, Y.A., 1987. Control of the irrigation water resources of the Al-hasa oasis. King Faisal University.
- Nagy, D., 1966. The Gravitational Attraction of a Right Rectangular Prism. *Geophysics* 31, 362–371. <https://doi.org/10.1190/1.1439779>
- Nesbit, P.R., Durkin, P.R., Hugenholtz, C.H., Hubbard, S.M., Kucharczyk, M., 2018. 3-D stratigraphic mapping using a digital outcrop model derived from UAV images and structure-from-motion photogrammetry. *Geosphere* 14, 2469–2486. <https://doi.org/10.1130/GES01688.1>
- Omollo, P., Nishijima, J., 2023. Analysis and Interpretation of the gravity data to delineate subsurface structural geometry of the Olkaria geothermal reservoir, Kenya. *Geothermics* 110, 102663.
- Ortega, O.J., Marrett, R.A. and Laubach, S.E., 2006. A scale-independent approach to fracture intensity and average spacing measurement. *AAPG bulletin*, 90(2), pp.193-208.
- Oterdoom, W.H., Worthing, M.A., Partington, M., 1999. Petrological and Tectonostratigraphic Evidence for a Mid Ordovician Rift Pulse on the Arabian Peninsula. *GeoArabia* 4, 467–500. <https://doi.org/10.2113/geoarabia0404467>
- Panagopoulos, G., Soupios, P., Vafidis, A., Manoutsoglou, E., 2021. Integrated use of well and geophysical data for constructing 3D geological models in shallow aquifers: a case study at the Tymbakion basin, Crete, Greece. *Environ Earth Sci* 80, 142. <https://doi.org/10.1007/s12665-021-09461-5>

- Panara, Y., Chandra, V., Finkbeiner, T., Petrovic, A., Zühlke, R., Khanna, P., Vahrenkamp, V., 2023. Fracture intensity and associated variability: A new methodology for 3D digital outcrop model analysis of carbonate reservoirs. *Marine and Petroleum Geology* 158. <https://doi.org/10.1016/j.marpetgeo.2023.106532>
- Parkhurst, B.D.L., 1995. User's guide to PHREEQC a computer program for speciation, reaction-path , advective-transport, and inverse geochemical calculations.
- Patro, P.K., 2017. Magnetotelluric Studies for Hydrocarbon and Geothermal Resources: Examples from the Asian Region. *Surv Geophys* 38, 1005–1041. <https://doi.org/10.1007/s10712-017-9439-x>
- Philip, J.M., Roger, J., Vaslet, D., Cecca, F., Gardin, S., Memesh, A.M.S., 2002. Sequence stratigraphy, biostratigraphy and paleontology of the (Maastrichtian-Paleocene) Aruma Formation in outcrop in Saudi Arabia. *GeoArabia* 7, 699–718.
- Piper, A.M., 1944. A graphic procedure in the geochemical interpretation of water-analyses. *Eos, Transactions American Geophysical Union* 25, 914–928.
- Pollastro, R.M., 2003. Total petroleum systems of the Paleozoic and Jurassic, Greater Ghawar Uplift and adjoining provinces of central Saudi Arabia and northern Arabian-Persian Gulf. *U.S. Geol. Surv. Bull.* 52. <https://doi.org/10.3133/b2202H>
- 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.

- Prabhakaran, R., Bruna, P.O., Bertotti, G., Smeulders, D., 2019. An automated fracture trace detection technique using the complex shearlet transform. *Solid Earth* 10 (6), 2137–2166.
- Rani, P., Soupios, P., Barsukov, P., 2020. Regional tectonic model of Southern, Central part of the Mygdonian basin (Northern Greece) by applying 3D Transient Electromagnetic Modeling. *J Appl Geophy.* <https://doi.org/10.1016/j.jappgeo.2020.104008>
- Renshaw, C.E., Park, J.C., 1997. Effect of mechanical interactions on the scaling of fracture length and aperture. *Nature* 386, 482–484. <https://doi.org/10.1038/386482a0>
- Rezaei, A., Hassani, H., Tziritis, E., Fard Mousavi, S.B., Jabbari, N., 2020. Hydrochemical characterization and evaluation of groundwater quality in Dalgan basin, SE Iran. *Groundw Sustain Dev* 10, 100353. <https://doi.org/https://doi.org/10.1016/j.gsd.2020.100353>
- Salem, A., Williams, S., Fairhead, J.D., Ravat, D., Smith, R., 2007. Tilt-depth method: A simple depth estimation method using first-order magnetic derivatives. *The Leading Edge* 26, 1502–1505. <https://doi.org/10.1190/1.2821934>
- Saner, S., Al-Hinai, K., Perincek, D., 2005. Surface expressions of the Ghawar structure, Saudi Arabia. *Mar Pet Geol* 22, 657–670. <https://doi.org/10.1016/j.marpetgeo.2004.12.006>
- Schöpfer, M.P., Childs, C. and Walsh, J.J., 2007. Two-dimensional distinct element modeling of the structure and growth of normal faults in multilayer sequences: 2.

- Impact of confining pressure and strength contrast on fault zone geometry and growth. *Journal of Geophysical Research: Solid Earth*, 112(B10).
- Scott, D., 2022. Characterization And Evolution Of The Professor Valley Pennsylvanian Salt Body (paradox Basin, Ut) Using Gravity And Magnetotellurics.
- Sen, Z. and Al-Dakheel, A., 1986. Hydrochemical facies evaluation in Umm Er Radhuma Limestone, Eastern Saudi Arabia. *Groundwater*, 24(5), pp.626-635. <https://doi.org/10.1111/j.1745-6584.1986.tb03711.x>
- Shampine, W.J., Dincer, T., Noory, M., 1979. An evaluation of isotope concentrations in the groundwater of Saudi Arabia, in: *Isotope Hydrology 1978*.
- Sharaf, M.A.M., 2001. Review of the hydrogeological and hydrochemical aspects of groundwater in the Umm-Er-Radhuma aquifer system, Arabian Peninsula. *Journal of African Earth Sciences* 33, 349–362. [https://doi.org/10.1016/S0899-5362\(01\)80068-3](https://doi.org/10.1016/S0899-5362(01)80068-3)
- Sharland, P.R., Casey, D.M., Davies, R.B., Simmons, M.D., Sutcliffe, O.E., 2004. Arabian Plate Sequence Stratigraphy – revisions to SP2. *GeoArabia* 9, 199–214. <https://doi.org/10.2113/geoarabia0901199>
- Siemon, B., Christiansen, A.V., Auken, E., 2009. A review of helicopter-borne electromagnetic methods for groundwater exploration. *Near Surface Geophysics* 7, 629–646. <https://doi.org/10.3997/1873-0604.2009043>
- Silva-Ávalos, R.U., Júnez-Ferreira, H.E., González-Trinidad, J., Bautista-Capetillo, C., 2022. Non-Linear 3D Satellite Gravity Inversion for Depth to the Basement

- Estimation in a Mexican Semi-Arid Agricultural Region. *Applied Sciences* 12, 7252.
<https://doi.org/10.3390/app12147252>
- Simanek, D.E., Holden, John., 2020. Evaluation of Groundwater of Al-Hassa Oasis, Eastern Region Saudi. *Science Askew* 76–88.
<https://doi.org/10.1201/9781420033564-12>
- Smirnov, M.Y., 2003. Magnetotelluric data processing with a robust statistical procedure having a high breakdown point. *Geophys J Int* 152, 1–7.
<https://doi.org/10.1046/j.1365-246X.2003.01733.x>
- Steineke, M., Bramkamp, R.A., Sander, N.J., 1958. Stratigrafic Relations of Arabian Jurassic Oil.
- Stewart, S.A., 2018. Hormuz salt distribution and influence on structural style in NE Saudi Arabia. *Petroleum Geoscience* 24, 143–158. <https://doi.org/10.1144/petgeo2017-011>
- Tikhonov, A.N., 1950. On determination of electric characteristics of deep layers of the earth's crust. *Doklady* 73, 295–297.
- Thomas, H., Brigaud, B., Blaise, T., Saint-Bezar, B., Zordan, E., Zeyen, H., Andrieu, S., Vincent, B., Chirol, H., Portier, E., 2021. Contribution of drone photogrammetry to 3D outcrop modeling of facies, porosity, and permeability heterogeneities in carbonate reservoirs (Paris Basin, Middle Jurassic). *Marine and Petroleum Geology* 123, 104772.

- Thralls, H.W., Hasson, R.C., 1956. Geology and oil resources of eastern Saudi Arabia. Symposium Sobre Yacimientos de Petroleo y Gas: 20th Internat. Geol. Cong., Mexico. 14–32.
- Tleel, J.W., 1973. Surface Geology of Dammam Dome, Eastern Province, Saudi Arabia. Am Assoc Pet Geol Bull 57, 30–33. <https://doi.org/10.1306/819a4304-16c5-11d7-8645000102c1865d>
- Tranos, M.D., 2015. TR method (TRM): A separation and stress inversion method for heterogeneous fault-slip data driven by Andersonian extensional and compressional stress regimes. Journal of Structural Geology 79, 57–74. <https://doi.org/https://doi.org/10.1016/j.jsg.2015.07.006>
- Tranos, M.D., Xu, X., Wang, Z., 2024. Paleostress reconstruction of the Chaling-Yongxing basin in the central South China Block: Bulk (areal or multisite) vs. site stress tensors. Journal of Structural Geology 178, 105002. <https://doi.org/https://doi.org/10.1016/j.jsg.2023.105002>
- Ueda, T., Mitsuhashi, Y., Uchida, T., Marui, A., Ohsawa, K., 2014. A new marine magnetotelluric measurement system in a shallow-water environment for hydrogeological study. J Appl Geophy 100, 23–31. <https://doi.org/10.1016/j.jappgeo.2013.10.003>
- US-EPA, 2007. SW-846 Test Method 9056A: Determination of Inorganic Anions by Ion Chromatography.

- Uzkeda, H., Poblet, J., Magán, M., Bulnes, M., Martín, S., Fernández-Martínez, D., 2022. Virtual outcrop models: Digital techniques and an inventory of structural models from North-Northwest Iberia (Cantabrian Zone and Asturian Basin). *Journal of Structural Geology* 157. <https://doi.org/10.1016/j.jsg.2022.104568>
- Valkaniotis, S., Papathanassiou, G., Ganas, A., 2018. Mapping an earthquake-induced landslide based on UAV imagery; case study of the 2015 Okeanos landslide, Lefkada, Greece. *Engineering Geology* 245, 141–152. <https://doi.org/10.1016/j.enggeo.2018.08.010>
- Vaslet, D., Al-Muallem, M.S., Maddeh, S.S., Brosse, J.M., Fourniquet, J., Breton, J.P., Le Nindre, Y.M., 1991. Explanatory notes to the geologic map of the Ar Riyad Quadrangle, Sheet 24 I, Kingdom of Saudi Arabia. Saudi Arabian Deputy Ministry for Mineral Resources, Jeddah, Geosciences Map, GM-121 54.
- Verduzco, B., Fairhead, J.D., Green, C.M., MacKenzie, C., 2004. New insights into magnetic derivatives for structural mapping. *The Leading Edge* 23, 116–119. <https://doi.org/10.1190/1.1651454>
- Vidal, F.S., 1951. The Oasis of Al Hassa. ARAMCO. Water Atlas of Kingdom of Saudi Arabia, 1985. MoAW; Riyadh.
- Vignoli, G., Fiandaca, G., Christiansen, A.V., Kirkegaard, C., Auken, E., 2015. Sharp spatially constrained inversion with applications to transient electromagnetic data. *Geophys Prospect* 63, 243–255. <https://doi.org/10.1111/1365-2478.12185>

- Villarreal J, C.A., Rojas D, J.D., Ríos R, C.A., 2020. 3D digital outcrop modelling of the Lower Cretaceous Los Santos formation sandstones, Mesa de Los Santos region (Colombia): Implications for structural analysis. *Journal of Structural Geology* 141. <https://doi.org/10.1016/j.jsg.2020.104214>
- Volatili, T., Agosta, F., Cardozo, N., Zambrano, M., Lecomte, I., Tondi, E., 2022. Outcrop-scale fracture analysis and seismic modelling of a basin-bounding normal fault in platform carbonates, central Italy. *Journal of Structural Geology* 155, 104515. <https://doi.org/https://doi.org/10.1016/j.jsg.2022.104515>
- Wang, G., Liu, J., Kubota, J., Chen, L., 2007. Effects of land-use changes on hydrological processes in the middle basin of the Heihe River, northwest China. *Hydrological Processes: An International Journal* 21, 1370–1382.
- Weijermars, R., 1998. Plio-Quaternary movement of the East Arabian block. *GeoArabia* 3, 509–540.
- Yang, C.-H., Tong, L.-T., Huang, C.-F., 1999. Combined application of dc and TEM to sea-water intrusion mapping. *Geophysics* 64, 417–425. <https://doi.org/10.1190/1.1444546>
- Zeeb, C., Gomez-Rivas, E., Bons, P.D., Virgo, S. and Blum, P., 2013. Fracture network evaluation program (FraNEP): A software for analyzing 2D fracture trace-line maps. *Computers & Geosciences*, 60, pp.11-22.

- Zeeb, C., Gomez-Rivas, E., Bons, P.D. and Blum, P., 2013. Evaluation of sampling methods for fracture network characterization using outcrops. AAPG bulletin, 97(9), pp.1545-1566.
- Zeng, L., Song, Y., Liu, G., Tan, X., Xu, X., Yao, Y., Mao, Z., 2023. Natural fractures in ultra-deep reservoirs of China: A review. Journal of Structural Geology 175, 104954. <https://doi.org/https://doi.org/10.1016/j.jsg.2023.104954>
- Zhang, P., Chouteau, M., Mareschal, M., Kurtz, R., Hubert, C., 1995. High-frequency magnetotelluric investigation of crustal structure in north-central Abitibi, Quebec, Canada. Geophys J Int 120, 406–418. <https://doi.org/10.1111/j.1365-246X.1995.tb01828.x>
- Ziegler, M. a, 2001. Late Permian to Holocene Paleofacies Evolution of the Arabian Plate and its Hydrocarbon Occurrences. 6, 445–504.

Vitae

Name :Abid Khogali |

Nationality :Sudanese |

Date of Birth :1/31/1992|

Email :abid.gasm8@gmail.com|

Address :Khartoum North, Sudan, P.O. 11111|

Academic Background : **Master of Science in Geology**

King Fahd University of Petroleum and Minerals, 2019

Dhahran, Saudi Arabia

Bachelor of Science in Geology

University of Khartoum, 2013

Khartoum, Sudan

Professional **Research Assistant**

Experience King Fahd University of Petroleum and Minerals

Jan 2017- Present

Dhahran, Saudi Arabia

Teaching Assistant

University of Khartoum

Jan 2014- Jan 2017

Khartoum, Sudan

Publications

1. **Khogali, A.**; Chavanidis, K.; Kirmizakis, P.; Stampolidis, A.; Soupios, P. Reconstruction of the Subsurface of Al-Hassa Oasis Using Gravity Geophysical Data. Appl. Sci. 2024, 14, 3707. <https://doi.org/10.3390/app14093707>
2. Abba, S.I., Yassin, M.A., Jibril, M.M., Tawabini, B., Soupios, P., **Khogali, A.**, Shah, S.M.H., Usman, J. and Aljundi, I.H., 2024. Nitrate concentrations tracking from multi-aquifer groundwater vulnerability zones: Insight from machine learning and spatial mapping. Process Safety and Environmental Protection, <https://doi.org/10.1016/j.psep.2024.02.041>
3. Ashadi AL, Tezkan B, Yogeshwar P, Hanstein T, Kirmizakis P, **Khogali, A.**, Chavanidis K, Soupios P. Magnetotelluric Case Study from Ain Al-Harrah Hot Spring, Al-Lith, Saudi Arabia. Arabian Journal for Science and Engineering. 2024. <https://doi.org/10.1007/s13369-023-08293-8>
4. Ashadi, A.L.; Martinez, Y.; Kirmizakis, P.; Hanstein, T.; Xu, X.; **Khogali, A.**; Paembonan, A.Y.; AlShaibani, A.; Al-Karnos, A.; Smirnov, M.; et al. First High-Power CSEM Field Test in Saudi Arabia. Minerals 2022, 12, 1236. <https://doi.org/10.3390/min1210123>
5. **Khogali, A.**; Birkle, P.; Al-Shaibani, A.; Keller, M.; Tawabini, B.; Makkawi, M. Geochemical Assessment of Potential Sources for Nitrate in the Wasia Aquifer, Al Kharj Area, Central Saudi Arabia. Water 2020, 12, 1479. <https://doi.org/10.3390/w12051479>

6. Yassin, M.A., Abba, S.I., Shah, S.M.H., Usman, A.G., Egbueri, J.C., Agbasi, J.C., **Khogali, A.**, Baalousha, H.M., Aljundi, I.H., Sammen, S.S. and Scholz, M., 2024. Toward Decontamination in Coastal Regions: Groundwater Quality, Fluoride, Nitrate, and Human Health Risk Assessments within Multi-Aquifer Al-Hassa, Saudi Arabia. *Water*, 16(10), p.1401.
<https://doi.org/10.3390/w16101401>