

Characterization of Minjur Aquifer using Geophysical Methods for Future CO₂ storage, North of Riyadh, KSA

Adam Ahmed

MASTER OF SCIENCE IN GEOPHYSICS

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BY

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DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
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MASTER OF SCIENCE

In

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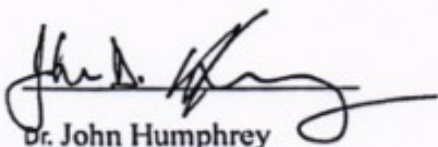
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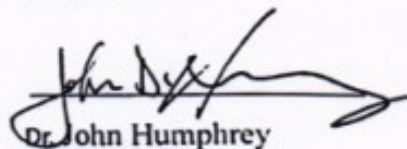
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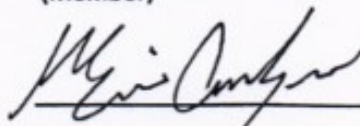
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For everyone who has helped me at any level of my academic career

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TABLE OF CONTENTS

ACKNOWLEDGMENTS	V
TABLE OF CONTENTS.....	VI
LIST OF TABLES	VIII
LIST OF FIGURES	IX
LIST OF ABBREVIATIONS	XIII
ABSTRACT	XIV
ملخص الرسالة	XV
CHAPTER 1 INTRODUCTION.....	1
1.1. IMPORTANCE OF THE STUDY & RESEARCH GAP	1
1.2. OBJECTIVES	2
1.3. GEOLOGY.....	3
1.4. HYDROGEOLOGY.....	7
1.5. CO ₂ STORAGE.....	9
CHAPTER 2 LITERATURE REVIEW	16
CHAPTER 3 METHODOLOGY	27
3.1. HISTORICAL BACKGROUND.....	27
3.2. BASIC THEORY.....	27
3.3. MAXWELL'S EQUATIONS	29
3.3.1 SCHELKUNOFF POTENTIALS	30
3.3.2 THE TRANSIENT REACTION ACROSS A STRATIFIED HALF-SPACE.....	32
3.3.3 THE TRANSIENT REACTION OF A HALF SPACE.....	34
3.4. FUNDAMENTAL PRINCIPLE AND MEASUREMENT METHODOLOGY	35
3.5. DATA APPROACH.....	37
3.6. NOISE AND RESOLUTION	38
3.6.1 AMBIENT NATURAL NOISE	38
3.6.2 NOISE AND MEASUREMENTS.....	40

3.6.3	DEPTH OF PENETRATION	41
3.7.	MODELLING.....	43
3.7.1	INTRODUCTION.....	43
3.7.2	THE ONE-DIMENSIONAL MODEL.....	44
3.7.3	THE TWO-DIMENSIONAL MODEL.....	44
3.7.4	ADVANTAGES, AND LIMITATIONS	45
3.8.	FIELD MEASUREMENT AND CONFIGURATION	46
3.9.	ABEM-WALKTEM INSTRUMENTS	47
3.10.	SPIA PROCESSING AND INVERSION OF TEM	48
3.11.	THE AMT METHOD.....	49
3.12.	AMT INSTRUMENTS AND CONFIGURATION	50
3.13.	FIELD PROCEDURES	51
3.14.	HALF-SPACE MODEL AND EMPIRICAL DATA	53
3.15.	SOURCE OF THE CURRENTS	54
 CHAPTER 4 DATA ACQUISITION		58
4.1.	TIME DOMAIN ELECTROMAGNETIC METHOD	59
4.2.	AUDIO FREQUENCY MAGNETOTULLERIC	60
 CHAPTER 5 RESULTS AND DISCUSION		65
5.1.	TRANSIENT ELECTROMAGNETIC RESULT	65
5.1.1	1D MODEL OF TEM	65
5.1.2	2D MODEL OF TEM	66
5.1.3	2D GEOELECTRIC SECTION WITH RELATED TO GEOLOGY OF STUDY AREA	67
5.1.4	3D MODEL OF TEM	68
5.2.	AUDIO-FREQUENCY MAGNETOTULLERIC RESULT	69
5.3.	AMT METHOD AND CO2 STORAGE	71
5.4.	CONCLUSION:	72
 REFERENCES:		73
 VITAE		76

LIST OF TABLES

Table 1 Depleted oil and gas reserves and saline aquifers in Saudi Arabia are prime examples of sedimentary rocks with estimated probability ranges of carbon dioxide storage capabilities, according to (Ye et al., 2023).....	14
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LIST OF FIGURES

Figure 1.1 Depth map of the Minjur aquifer, illustrating the proximal depocenters and stratigraphic thinning zones (Issautier et al.,2019).....	2
Figure 1.2 A depiction of the stratigraphic map of the Minjur Formations: Upper and Lower Minjur appear in the chronostratigraphic chart, which has been revised based on research and comparative stratigraphy from the region (Stewart et al., 2016)	5
Figure 1.3 In this composite topography and sedimentology section of the Minjur Sandstone, the vertical history of the depositional settings illustrated (Issautier, Nindre, et al., 2012).	6
Figure 1.4 The geological terrains of the Arabian Plate that are favorable for carbon capture and storage and carbon cycle use (modified). (Vahrenkamp et al., 2021).....	11
Figure 1.5 The Eastern Arabian Peninsula's sedimentary formations offer prospects for CCS and CCUS. Numerous stacked aquifer/seal pairings present potential with different characteristics. For CCS maintain the supercritical state of CO ₂ , a minimum depth of 800 metres is necessary. A minimum temperature of 100°C is required for geothermal CCUS, which is based on the circulation of stored CO ₂ [9].....	12
Figure 1.6 The results of the basin study for overall acceptability geological CO ₂ sequestration are represented on this map [8].....	14
Figure 2.1 Stratigraphy of Riyadh Area. The proportion of sandstone comprises between sixty and ninety percent of the entire deposit. The percentage of shale comprises between 10 and 40 percent of a formation [6].....	17
Figure 2.2 Estimated Minjur aquifer potentiometric surface After 1974 pumping. Groundwater flowed northeast from the outcrop (Williams and Al-Sagaby, 1982).	18
Figure 2.3 Flat sequence boundaries linked with coarse proximal deposits in the model show depositional circumstances changing. The flat structure is attributable to large-scale deposition and progressive basin infill, which permits sedimentary processes to migrate laterally (Issautier et al., 2012b).	19
Figure 2.4 A) Reflection seismic data and interpretation illustrate the onlap connection of the Minjur sandstone onto the Jilh Formation in the eastern sector of the Qatar arch. B) The understanding of geological boundaries[7].	21
Figure 2.5 Evaluation of a sedimentary features of Khashm al Khalta Minjur Sandstone. The map illustrates depositional ecosystems and their lateral	

	and vertical development. Green, blue, and pink denote coastal to shallow marine layers; yellow and orange signify proximal deposits [1].	22
Figure 2.6	The two-dimensional representation of the Ghawar field displays continuous curves for horizons and dotted lines, both vertical and subvertical, to indicate faults [12].	23
Figure 2.7	(A) A geological cross-sectional of southern and eastern Saudi Arabia demonstrating the Interior Homocline-Wajid and Rub'Al-Khali Basin structure and strata (adapted from Stewart et al., 2016). Dotted lines signify ambiguity in the formation summit. (B) illustrates the location of the portion. The hydrogeologic cross-section analysis reveals source rocks, hydrocarbon reservoirs, saline aquifers, significant regional aquitards/aquicludes, primary and secondary groundwater aquifers, and water salinity levels. Georgia groundwater aquifer.	24
Figure 2.8	An illustration of the highlights of the Arabian Plate can be found on a map that depicts the depth of the basement. There are a total of seventeen basins and subbasins in Saudi Arabia, including the Tabuk Basin, the Widyan Basin, the Interior Homocline-Central Arch (IHCA), the Eastern Arabian Basin (EAB) both onshore and offshore, the Rub'Al-Khali Basin (RAKB), the Interior Homocline-Wajid (IHW), six western coastal basins, and three offshore Red Sea segments (2003)).	25
Figure 2.9	Construction of a model for the Minjur reservoir using the CMG-GEM program [13].	26
Figure 3.1	Illustration of the components in Equation 20.	33
Figure 3.2	The basics of Transmission Electron Microscopy (TEM). (a) show sender loop current. (b) represents the ground's induced electromotive force (Christiansen, et al., 2006), and (c) represents the receiver coil's secondary magnetic field. For the induced electromotive force and secondary magnetic field graphs, the receiving coil is assumed to be at the center of the transmitting loop.	35
Figure 3.3	Setting up the TEM. both a) and b) are examples of central and offset loops. In the equation, Tx represents the transmitter, Rx represents the receiver (Christiansen et al., 2006), l represents the side length of the loop, and h represents the offset between the centers of the Tx loop and the Rx coil.	36
Figure 3.4	Black lines represent the a) impulse reactions (db/dt) for a homogeneous half-space with various resistivities. b) shows the same area-wise curves. The grey line represents the reaction of a two-layer earth comprising ten meters of layer 2 and one hundred meters of layer 1. Layer 1 spans forty meters.	38

Figure 3.5 50 transients (grey) and 5,000 transients (black) are superimposed on TEM sounding curves.	39
Figure 3.6 Transmission Electron Microscopy sounds and noise assessments.....	41
Figure 3.7 TEM configurations, (a) A single loop transmitter and receiver or referred to as one-loop. (b) Coincident transmitter-receiver loops and In-loop (or central loop) or dipole receiver configuration. (c) Separated transmitter-receiver circuits. (d) Dipole receiver. (e) Dual loop single wire for transmitter and receiver and dual loop separate wires for transmitter and receiver (f) Large stationary transmitter, mobile receiver (Nabighian & Macnae, 1991).....	47
Figure 3.8 Standard field setup and measurement for MT/AMT	51
Figure 3.9 The values of E and H are displayed as a function of the experimental response parameter. The alignment of theory and model is superb. Along the y-axis, there was a model-theoretic correlation identified between the electric and magnetic fluxes. At frequency of 150 kHz, the values are 0.074 ohms, which is equivalent to volts per meter and ampere-turns per meter. (Goldstein & Strangway, 1975).	54
Figure 3.10 Plane electromagnetic wave incident upon Earth's surface. 55	
Figure 4.1 Show workflow for the geophysical methods, Transient Electromagnetic TEM and Audio Frequency Magnetotelluric AMT	58
Figure 4.2 Standard TEM field configuration and measurement.	59
Figure 4.3 Showing TEM device that use the conducting the measurement.....	60
Figure 4.4 A profile of 29 TEM geophysical soundings incorporated to the different geological formations and tectonic zones.	60
Figure 4.5 Standard field setup and measurement for AMT.	61
Figure 4.6 The unit of the AMT setup and measurement.	62
Figure 4.7 The Whole unit of the AMT four electrode, three coils, cables and PC to run the unit.....	62
Figure 4.8 Leveling and fixing the cable.....	63
Figure 4.9 NE – SW Profile of 31 TEM and 2 AMT sounding of 136 Km.	63
Figure 4.10 The King Khalid airport in the Riyadh area and the study area profile.	64
Figure 5.1 The Raw data of the TEM field Shallow moment and Deep moment and the noise (TEM 01) and the 1D model of the TEM field resistivity and depth (TEM 01).	66
Figure 5.2 The 2D inversion result profile of the TEM field resulted from 30 stations with 136 km length targeting deferent formations and geological features. North of Riyadh area.....	66

Figure 5.3 The 2D inversion result profile of the TEM with related to the geology of the study area.....	68
Figure 5.4 The results of the quasi-2D TEM inversion performed using the time-domain electromagnetic (TEM) data belonging to the research region are shown in Parts A–E. The 2D resistivity model is composed of X- and Y-sections that are spaced exactly 100 meters apart. You will notice an increase in depth as you move from left to right and from top to bottom.	69
Figure 5.5 The Audio-magnetotelluric sounding curves and inversion 1D model for A and B.....	71

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LIST OF ABBREVIATIONS

AMT	:	Audio Magnetotelluric
TEM	:	Transient Electromagnetic
MT	:	Magnetotelluric
EM	:	Electromagnetic
1D	:	One Dimension
2D	:	Two Dimension
3D	:	Three Dimension
EMAP	:	Electromagnetic Array Profiling
MD	:	Millidarcy.
CCS	:	Carbon Capture and Storage
CCUS	:	Carbon Capture, Utilization
GCC	:	Gulf Cooperation Council
DOI	:	Depth of Investigation
IP	:	Induced Polarization
Tx	:	Transmitter loop
Rx	:	Receiver loop
(S/N)	:	Signal to noise ratio

ABSTRACT

Full Name :[Adam Ahmed Abaker Ahmed]

Thesis Title :Characterization of Minjur Aquifer using Geophysical Methods for Future CO₂ storage, North of Riyadh, KSA.

Major Field :[Geophysics]

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This work presents the analysis of the electromagnetic geophysical methods conducted to utilizing transient electromagnetic (TEM) and audio magnetotelluric (AMT) methods to characterize the subsurface geology of the study area. The TEM data processed using Aarhus SPIA software and inverted via the AarhusInv method yielded high resolution insight into the subsurface geoelectric characteristics. The inverted 1D, 2D and 3D (depth slice) resistivity models have delineated the primary lithological and structural characteristic of stratigraphic units include Dhurma, Tuwaiq, Hanifa, Jubaila, Sulaiy, Aruma, and Umm er Radhuma Formations. At the SW end of the profile, there is a low resistivity zone delineated by saline aquifers, while the relatively high resistivity one beneath the previously mentioned zone signified carbonate deposited or potential freshwater aquifer zone. The utilization of KMSPro software to analyze AMT data expanded the depth of research and provided additional resistivity and phase information, hence improving stratigraphic and structural interpretation. This work demonstrates the effective integration of the TEM and AMT methods in delineating substantial resistivity differences, tectonic characterization and hydrogeological patterns. Despite the limitations of the TEM, combined with AMT, it successfully yielded sufficient subsurface models. This indicates the multi-methodological methods in geophysical surveys are essential. The finding has significance for groundwater exploitation and regional geology. The study validates the efficacy of TEM and AMT in the subsurface characterization and advocates for the enhanced integration of geophysical techniques to augment the resolution and depth of the studied area.

ملخص الرسالة

الاسم الكامل: ادم احمد ابكر احمد

عنوان الرسالة: استخدام الطرق الجيوفيزيائية في توصيف خزان منجور بغرض تخزين ثاني اكسيد الكربون

التخصص: جيوفيزياء]

تاريخ الدرجة العلمية: 2024

يقدم هذا البحث استخدام الطرق الجيوفيزيائية الكهرومغناطيسية وهي طريقتي الحقل المغناطيسي في المجال الزمني والحقل المغناطيسي في المجال التردد او الصوتي لدراسة تم معالجة البيانات الكهرومغناطيسية في الطبقات تحت سطحية لجيولوجيا منطقة الدراسة للحصول على رؤية عالية AarhusInv و تحويل Aarhus المجال الزمني بواسطة تطبيق الدقة لخصائص الجيوكهربية وقد وجدت النتائج في ثلاثة أبعاد، أحادية، ثنائية وثلاثية الأبعاد لمظاهر الجيولوجية الرئيسية بما في ذلك تكوين دورما، طويق، حنيفة، جبيلة، السلي، وأم الردوما. في الجزء الشمالي الغربي من القطاع الجيولوجي وجدت المقاومة منخفضة مما يشير إلى وجود خزانات مياه جوفية مالحة، بينما نطاقات المقاومة العالية نسينا تعلق نفس الموقع المذكور بتكوين الكربونيت او المياه العذبة المحتملة. أما بيانات المجال الكهرومغناطيسي في نطاق العمق المستكشف وفرت معلومات KMSPro النطاق الترددي تم معالجتها باستخدام إضافية عن المقاومة مما عزز تفسير الطبقات والتراكيب الجيولوجية، رغم المحدوديات في أثبت فعاليتها في إنتاج AMT و TEM الطرق المستعملة ولكن اثبت استخدام التكامل لتقنيتي نموذج متكامل لطبقات تحت السطحية مما يبرر أهمية المنهج الجيوفيزيائي متعدد الطرق، لهذه النتائج تأثيرات مهمة في استكشاف المياه الجوفية وفهم الجيولوجية الإقليمية، تؤكد الدراسة عن إمكانية الطريقتين في توصيف الطبقات تحت السطحية وتدعو إلى دمج مزيد من الأساليب الجيوفيزيائية المتقدمة لتحسين الدقة والعمق في البحوث والدراسات المستقبلية.

CHAPTER 1

INTRODUCTION

1. Introduction

A comprehensive geophysical study investigated the Minjur Aquifer, located north of Riyadh, covering an extensive 136-kilometer profile. The study employed cutting-edge geophysical methods, including 2 audio-magnetotelluric (AMT) stations and 30-time domain electromagnetic (TEM) stations, to characterize the lower saline aquifer and evaluate its potential for CO₂ storage. This initiative represents a critical and essential step toward developing sustainable energy solutions, aligning with global efforts to mitigate climate change through effective carbon sequestration. This research aimed to map and characterize the thickness, geometry, and other key properties of the Minjur Aquifer using advanced geophysical techniques. To enhance the accuracy of the results, calibration tests were conducted near two deep groundwater boreholes, with depths of 1.6 km and 1.5 km, providing valuable reference data for geophysical interpretations. While significant information exists on the aquifer's porosity, permeability, and lithology, much of this knowledge is derived from outcrop studies and data from remote boreholes.

These sources often lack crucial details about the aquifer's true thickness and subsurface geometry, essential for assessing its capacity and suitability for CO₂ storage. The lower Minjur Aquifer exhibits characteristics that make it a promising candidate for CO₂ storage. The aquifer lies at depths exceeding 800 meters, meeting the critical requirement for efficient and safe CO₂ storage under high-pressure conditions. Its saline nature reduces its value for conventional groundwater use, making it more viable for industrial purposes such as CO₂ sequestration. Preliminary findings suggest favorable conditions for CO₂ trapping, including adequate porosity for storage and caprock integrity to prevent leakage. The geophysical data collected from the AMT and TEM surveys will be used to construct a conceptual model of the aquifer.

1.1. Importance of the Study & Research Gap

Extensive research has been conducted on the Minjur aquifer, focusing on its porosity permeability, lithology, stratigraphy, and storage capacity. However much of this work is

based on data from surface outcrops and distant boreholes, as illustrated in Figure 1.1. While these studies have provided valuable insights, they do not offer a comprehensive understanding of the aquifer's actual subsurface thickness and geometry, which are critical for evaluating its potential as a CO₂ storage reservoir [1].

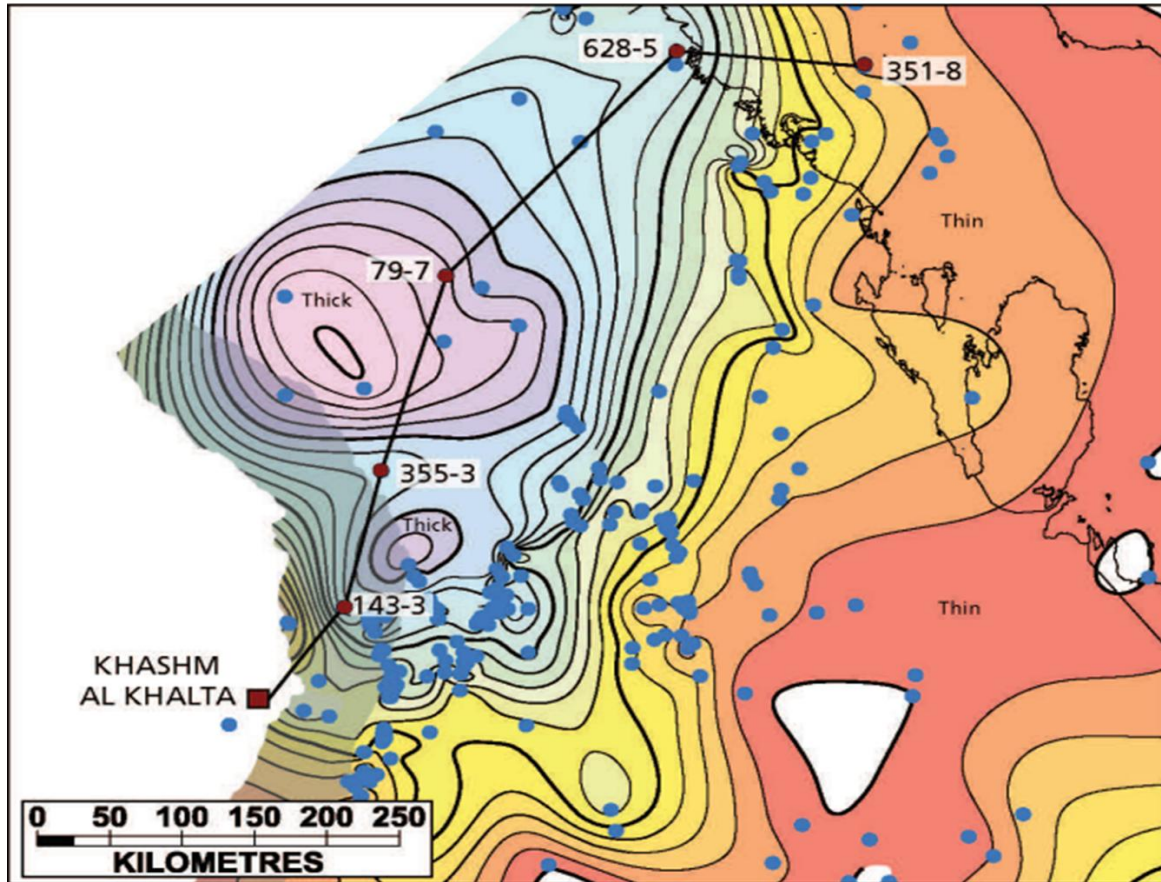


Figure 1.1 Depth map of the Minjur aquifer, illustrating the proximal depocenters and stratigraphic thinning zones (Issautier et al., 2019).

1.2. Objectives

This study aims to analyze and characterize a section of the Minjur Aquifer, specifically the lower saline region, as a possible CO₂ storage reservoir. To achieve this goal, a combination of time and frequency domain electromagnetic soundings were conducted along a southwest-northeast (SW-NE) profile located north of Riyadh in Saudi Arabia. These geophysical surveys enable detailed subsurface imaging, which is essential for mapping the subsurface and identifying key geological and geophysical features. The

geophysical data was calibrated using two nearby deep boreholes, ensuring improved accuracy and reliability of the interpretation. This study is guided by three main objectives:

- Construct a 2D deep geophysical section of the study area, which will provide a clear depiction of the subsurface structure and aquifer characteristics.
- Identify and delineate lateral subsurface geophysical and geological variations. These variations are influenced by tectonic activity in the region, which may have created structural discontinuities or compartmentalized the aquifer.
- Develop a conceptual model of the study area. This model will integrate geophysical and geological data, offering a comprehensive representation of the aquifer system for any future research.

1.3. Geology

The Minjur Sandstone derives its name from Khashm al Minjur (Latitude 24° 42' 15 N Longitude 46° 12' 2 E), where the upper section of the formation is prominently exposed. Initially, Max Steineke (unpublished data, 1937) did not differentiate the Minjur Sandstone from other Triassic units. Instead, he grouped it together with strata now recognized as Jilh and Sudair Formations under what was then called the Es Sirr Member. Over time, the Es Sirr Member was reclassified, leading to the formal subdivision and refinement of Triassic nomenclature, which is further elaborated in the definition of the Jilh Formation. The specified section of the Minjur Sandstone spans from the eastern edge of the dip slope created by the uppermost layer of the Jilh Formation (latitude 23°34'33" N, longitude 46°07'15" E) to the base of the overlying Marrat Formation at Khashm al KhaHa' (latitude 23°35'24" N, longitude 46°10'36" E), as delineated by Powers et al. (1966). This section delineates a precise stratigraphic framework for identifying the Minjur Sandstone and contextualizes it within the broader geological framework of the Triassic rock units in the region. The Arabian Peninsula, one of the driest regions on Earth, hosts Riyadh as its center. The city has historically faced acute water shortages due to its arid climate and rapidly expanding population. In 1956, a strategic effort was initiated to enhance groundwater recharge in the aquifers beneath the city. A 1,200 m well was drilled into the Minjur Aquifer, which supplies approximately 80–90% of Riyadh's water. This vital aquifer remains under active development. The Minjur Formation outcrops approximately

80 km west of Riyadh, forming east-facing curved arcs with a gentle eastward dip ranging between 1° and 1.5°. The outcrop zone spans up to 33 km in width and extends more than 640 km in length. Surrounding dunes facilitate additional water infiltration into the aquifer by capturing rainfall. A sieve analysis conducted on formation near Riyadh revealed that the sand grain sizes, predominantly quartz with minor rock fragments, ranged from 0.55 to 0.74 mm, indicative of coarse sand. Rainfall infiltration in the 6,500 km² outcrop region primarily recharges two sandstone units within the formation [3].

The lithological model of the Minjur Sandstone reflects complex depositional processes driven by regional geodynamics. The formation comprises sandstone, shale, and evaporites, with key lithographic divisions including the Upper Jilh Formation and the Lower Minjur Member. Deposition during the Triassic–Jurassic boundary was influenced by significant tectonic and climatic events, including high clastic influx resulting from hinterland uplift and the initial rifting associated with the opening of the NeoTethys Ocean. Shale and carbonate deposition occur at maximum flooding intervals, marking periods of reduced clastic input and deeper marine conditions. Sandstone and conglomerates deposited under high-energy conditions are linked to fluctuating sediment supplies and sea-level shifts. Passive sedimentation in the lower member is associated with low sediment supply and minor sea-level fluctuations. This phase produced isolated, narrow sand ribbons, typically deposited in intertidal zones governed by tidal processes and river-dominated coastal plains. These features are rare and create limited reservoir bodies. In contrast, periods of substantial sediment supply and increased platform accommodation enabled the development of thick, amalgamated sandstone bodies. Such reservoir units were deposited under high-energy conditions characterized by fluvial and deltaic processes. These units exhibit enhanced connectivity and porosity, crucial for aquifer storage and fluid flow (Issautier et al., 2012).

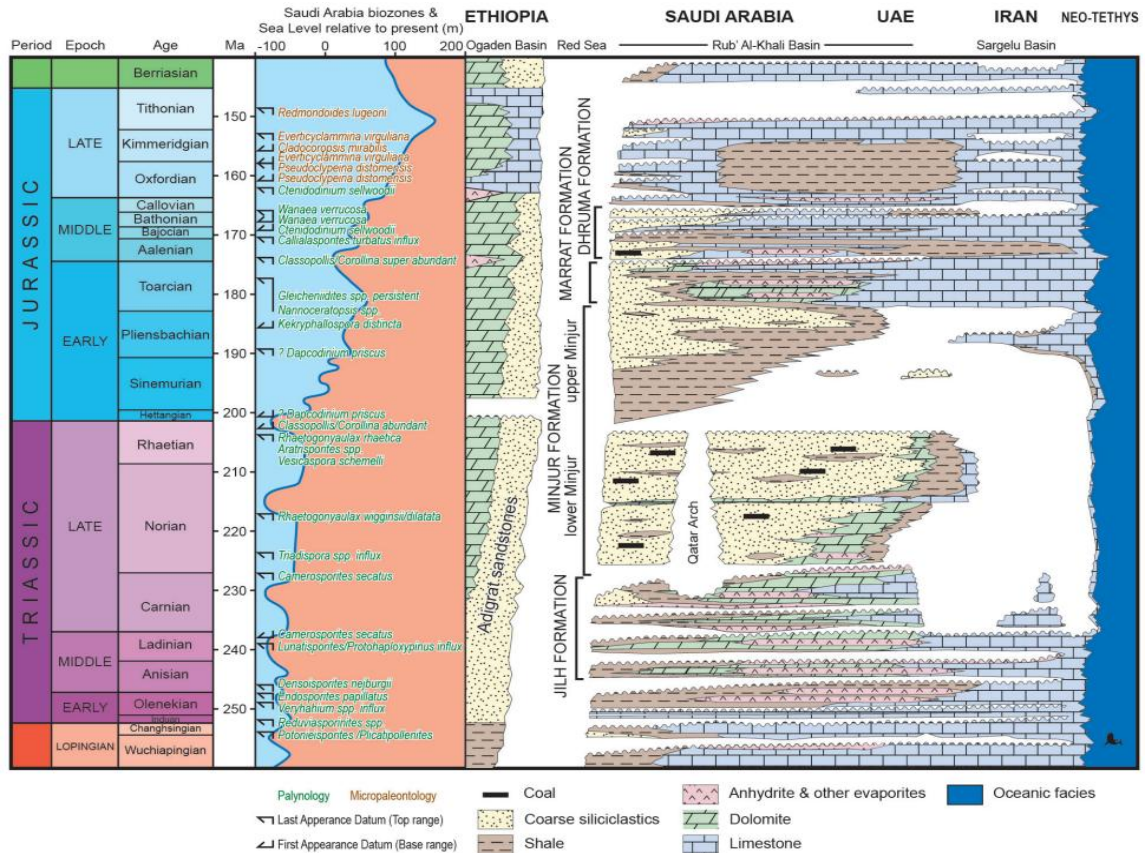


Figure 1.2 A depiction of the stratigraphic map of the Minjur Formations: The Upper and Lower Minjur appear in the chronostratigraphic chart, which has been revised based on research and comparative stratigraphy from the region (Stewart et al., 2016)

The Minjur Sandstone is a quartz-dominated sandstone characterized by significant crossbedding, indicative of aeolian (wind-driven) deposition processes. This sandstone is predominantly poorly sorted, through local variations ranging from fair to well-sorted. It is friable to well-indurated, with a color spectrum that varies from white to brown, and grain sizes that are medium to coarse. Sandstone comprises approximately 60-90% of the formation, while shale constitutes about 10-40%, with their proportions varying geographically. The quartz grains in the Minjur Sandstone are believed to be derived primarily from the hard crystalline rocks of the Arabian Shield. The larger grains are typically subangular to the surrounding and exhibit high sphericity, reflecting transport and depositional dynamics. Shale beds are interbedded with the sandstone and exhibit transitional grading both upward and downward. These shale beds can reach up to 5 m thick and are interspersed within the sandstone layers. According to Powers et al. (1966),

limestone beds associated with the formation are grey to purple in colour with gypsum layers often present at their base. The stratigraphy of the Minjur Sandstone reveals greater complexity than previously recognized. The formation is now understood to comprise eight depositional sequences, which are divided into (upper and lower Minjur) separated by a maximum flooding surface. Sequence 1 is assigned to the upper Jilh formation.

The lower Minjur formation appears to have limited sediment availability, as it predominantly consists of shaly deposits interspersed with sporadic, narrow sandstone bodies. This suggests a depositional environment where sandstone accumulation was restricted, possibly due to limited sediment supply or prevailing depositional conditions. Based on current interpretations, Sequence 1 of the Upper Jilh and Sequences 2 and 3 of the Minjur represent a thick coastal plain system. This system is characterized by interbedded deposits reflecting intertidal zones transitioning into more continental settings. In the other hand, the upper Minjur formation is defined by thick, coarse-grained sedimentary units that extend horizontally over several kilometers. The architectural framework of Sequences 5 through 9 reveals a range of depositional settings, transitioning from vast river plains to shallow marine supratidal and intertidal zones [3].

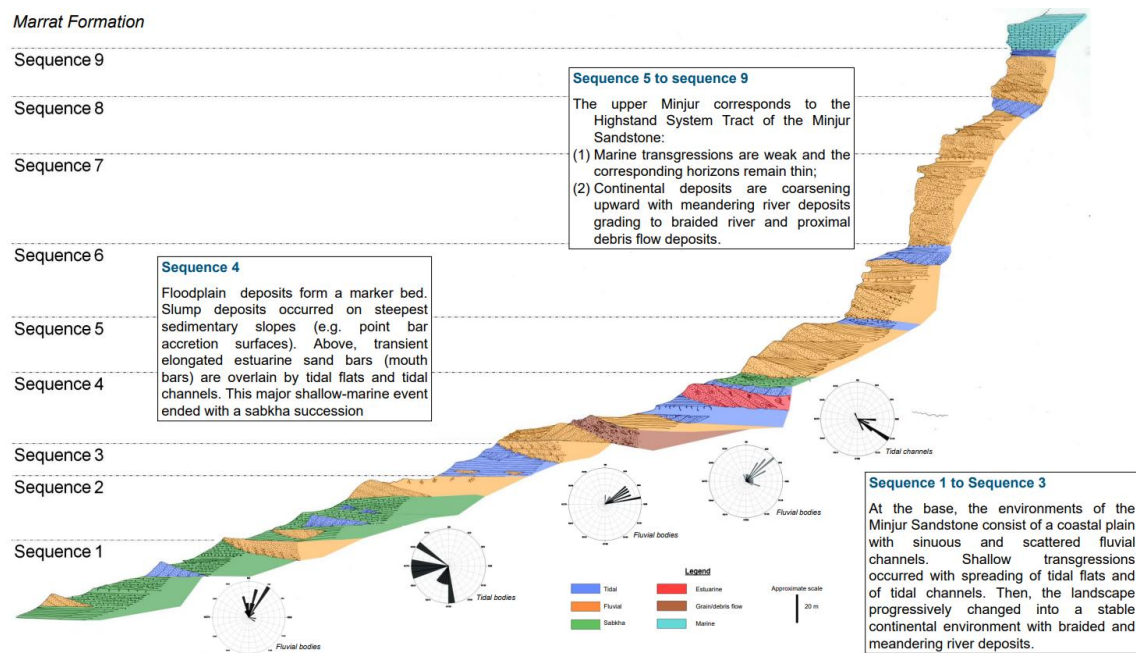


Figure 1.3 In this composite topography and sedimentology section of the Minjur Sandstone, the vertical history of the depositional settings is illustrated (Issautier, Nindré, et al., 2012).

The lithofacies and reservoir characteristics of the Late Triassic Minjur outcrop in central of the Kingdom Saudi Arabia west of Riyadh area, have been studied, focusing on establishing a link between outcrop and subsurface sandstone reservoir quality on regional and global scales. These outcrop studies are particularly significant because the Minjur Formation shares stratigraphic and chronological parallels with the prolific sandstone reservoirs found in hydrocarbon-rich fields of the Persian Gulf. A variety of sandstone lithofacies were identified in the Minjur Formation, and their reservoir properties, such as permeability and porosity, were investigated in detail. Permeability values varied significantly across different lithofacies, reaching up to 3000 millidarcies (md), while porosity ranged as high as 34%. The differences were caused by interior texture and composition, including grain size, sorting, and form in fine- to coarse in texture sandstones. Porosity correlates directly with permeability. Petrographic analysis revealed that reservoir quality is influenced by the degree of cementation, sorting, and grain morphology. Weak to moderate cementation, poor sorting, and suboptimal grain morphologies were associated with reduced reservoir quality. Weak to moderate cementation, poor sorting, and suboptimal grain morphologies were associated with reduced reservoir quality. Conversely, reservoir quality improved in sandstones with reduced cementation and better grain roundness and sorting, highlighting the critical role of depositional and diagenetic processes in controlling reservoir potential [3]

1.4. Hydrogeology

The Minjur Aquifer, a vital groundwater resource in the broader study area, plays a critical role in supporting the future expansion of Riyadh. In addition to the Minjur, Riyadh can also utilize shallow boreholes tapping into unconfined aquifers, providing supplementary water sources. However, the Minjur Aquifer remains the primary focus due to its significant water-bearing capacity. In Riyadh, the upper boundary of the Minjur aquifer lies approximately 1,200 m below the land surface. Within the 40,000 km² research area, the aquifer's thickness varies between 74 and 138 m. Hydraulic characteristics used in groundwater modeling for the aquifer include transmissivity values ranging from 0.001 to 0.0062 m²/sec and storage coefficients of 0.07 for the unconfined portion and 0.0004 for

the confined portion. The vertical conductivity of the overlying confining layer was modeled as 0.2 m/sec.

The Minjur aquifer is essentially a restricted aquifer, and it receives its replenishment from leakage that occurs through the confining layers that lie above it. Over the course of twenty-three years, from 1957 to 1979, a historical simulation of aquifer behavior was carried out in order to get an understanding of its dynamics and to make predictions regarding its future behavior. This simulation replicated groundwater pumping and recharge circumstances. This was then divided into pumping intervals of one year, and the model calibration was accomplished by comparing the water-level reductions that were computed using the model with those that were observed throughout these intervals. The calibrated model extended over a 160,000 km² area, using the same transmissivity and storage coefficients described above and a vertical conductivity value for the confining bed of 2×10^{12} m²/sec.

Every year, there is an intrusion of up to 20 millimeters. A total of 166 additional areas has an invasion rate of approximately 7 millimeters per year. It is expected that the rate will be as low as 1.5 millimeters per year for 167 additional sites. The natural slopes in the aquifer cause water to flow downward in the aquifer. The water well usage zone of Minjur is characterized by the formation of a number of different gradients, which ultimately results in the formation of cones of depression on the piezometric surface. Within the confines of the Minjur Aquifer, artesian conditions are found to be particularly abundant. The range of aquifer transmissibility in the Riyadh Area is from $1.5 \times 10^{(-3)}$ to $72 \times 10^{(-3)}$ m²/sec, as stated by [3]

The samples taken from the two wells that are located in close proximity to Riyadh were classified as coarse sand because they had an average grain size of 0.64 millimeters. They ranged from very fine to coarse sand in terms of grain size. It is common for this kind of sand to have a porosity that ranges between thirty and forty percent. It is anticipated that the porosity will be decreased as a result of the composition of the formation, which consists of sand, sandstone, shale, and mudstone. When it comes to porosity, sandstones typically range between 10 and 20 percent. The porosity of shale falls somewhere between 1 and 10 percent. The aquifer contains clay and mudstone, both of which have a porosity that can reach up to an approximate forty percent. It has been documented that the Upper Minjur in Riyadh is composed of between forty and seventy percent, with sand and

sandstone accounting for an average of fifty-five percent. The sand content of Samples 3 and 4 was around 99 percent, while the sand content of Samples 1 and 2 was approximately 67%. It is evident from the well logs that the shales and mudstones make up between 30 and 60 percent, with an average of 45 percent, of the Upper Minjur. They are arranged in an orderly fashion; accordingly, the porosity of the Upper Minjur Aquifer in the Riyadh Region may reach between 25 and 30 percent, depending on the texture of the aquifer. There was a range of 3×10^{-3} to 7.2×10^{-3} meters per second for the transmissibility that was observed, with the Upper Minjur Aquifer having a mean value of 4×10^{-3} meters per second. An average of 7.7×10^{-5} meters per second was observed for the permeability, which ranged from 2.5×10^{-5} to 1.6×10^{-4} meters per second [6].

The sandstones exhibit a porosity ranging from 7% to 20% and possess substantial intergranular and moldic macropores. The sand bodies grow progressively prevalent as the basin accumulates, constituting 70% of the overall stratigraphic thickness. Because of the sandy facies that are present in the Marrat rock formation, it is difficult to demarcate the top boundary of the Minjur Formation in the western part of the Rub' Al-Khali [7].

1.5. CO₂ Storage

The member countries of the Arabian Peninsula are one of the most world's biggest emitters of CO₂. Despite this, only a limited number of experimental CCS (Carbon Capture and Storage) and CCUS (Carbon Capture, Utilization, and Storage) projects have been implemented in the region. Rapid advancement in CCS and CCUS technologies is essential for these nations to achieve their ambitious climate goals, such as Saudi Arabia's Vision 2030, which aims to mitigate the detrimental effects of CO₂ emissions on the environment [8]. Reducing CO₂ emissions from hydrocarbon usage is crucial not only for addressing climate change but also for ensuring the long-term sustainability, and competitiveness of hydrocarbon resources in the face of a global transition towards cleaner energy. Thus, expediting the advancement and implementation of CCS and CCUS technologies is an immediate imperative. These technologies can help maintain the economic viability of hydrocarbons, which remain the primary source of revenue for Gulf Cooperation Council (GCC) countries. The Arabian Peninsula offers promising opportunities for large-scale CCS and CCUS due to its favorable geological settings. The region is endowed with a

variety of deep geological formations that can serve as potential CO₂ storage sites. These include extensive, layered aquifers with effective sealing structures along the eastern margin of the Arabian Plate, particularly near the Persian Gulf. These aquifers enable long-term CO₂ storage. Decades of exploration and extraction of hydrocarbons have generated an abundance of underground geological information. The Mesozoic carbonate aquifers are particularly well-documented, with detailed information on their lateral extent, depth, lithological composition, and petrophysical properties. In addition to the aquifers, several reliable caprocks and sealing formations have been identified, which are crucial for preventing CO₂ migration. Notable examples include the Nahr Umr Shales and Hith Anhydrite, both of which have demonstrated extensive coverage and excellent sealing and capabilities.

A setting with many stacked aquifers, suitable seals, and a favourable arrangement of mild anticlinal structures and CO₂ point sources can be ideal for geothermal heat extraction. Future hydrocarbon reservoir recovery from late-stage CO₂ EOR phases will be improved and a steady revenue stream from stored CO₂ will be produced through the development and broad deployment of CCUS technology. The lack of subsurface data is ultimately a major barrier to conducting in-depth research on the potential of CCS and CCUS, as well as to establishing the groundwork for pilot projects and economic growth. Information regarding the discovery and extraction of hydrocarbons throughout the last fifty years will prove crucial in the development of geologically based methods to decrease, recover, reuse, and recycle carbon dioxide.

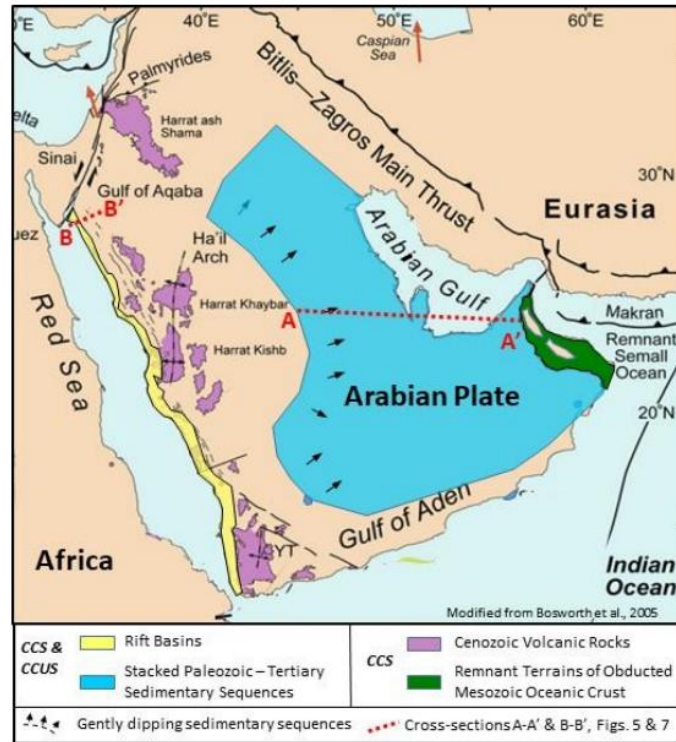


Figure 1.4 The geological terrains of the Arabian Plate that are favorable for carbon capture and storage and carbon cycle use (modified). (Vahrenkamp et al., 2021).

Diverse models have been suggested to depict the subsurface characterization of Minjur, each based on interpretations derived from isopach (thickness) maps and depth contour maps, as shown in Figure 1.1. The Upper and Lower Minjur Formations are detailed within a revised chronostratigraphic framework, reflecting updated research findings. This framework is further enriched by comparative stratigraphic correlations with other regional formations, offering a clearer picture of the temporal and depositional relationships. These stratigraphic comparisons are visualized in Figure 1.2, highlighting Minjur's position within the broader geological history of the region.

Figure 1.4 presents a detailed geological cross-section that provides additional insights into the vertical and lateral facies changes within the Minjur Aquifer. This section illustrates the stratigraphic interplay between the Upper and Lower Minjur units and their bounding formations, aiding in understanding their reservoir characteristics and hydrogeological significance.

Moreover, a seismic model mapping sedimentary sequences in the eastern province, shown in Figure 1.6, offers a dynamic perspective on Minjur's subsurface architecture. This model

integrates seismic reflection data to delineate key stratigraphic boundaries, structural features, and sedimentary facies variations. It also serves as a critical tool for assessing the aquifer's hydrocarbon and groundwater potential and planning sustainable resource utilization.

There are some of the largest oil reserves in the world located in the eastern part of the Arabian Plate. These oil reservoirs are composed of stacked and layered limestone sequences that are primarily Jurassic to late Cretaceous in age. At the time, the Arabian Plate was located at a passive continental margin, which resulted in the deposition of carbonate material over broad areas. A shallow marine lagoon behind a platform margin was the location where the sediments were deposited, and over time, they have been aggrading and prograding. A more complicated architecture may be found in the platform margin and slope deposits that are located near the Tethys Ocean. These deposits feature cyclic carbonate deposition as well as intermittent intrusions. These structures are perfect for entrapping hydrocarbons that are moving through porous sequences beneath seals since they are excellent for the purpose. There are, however, some formations that are not filled with hydrocarbons because they contain salty waters that come from subterranean aquifers in the region [9].

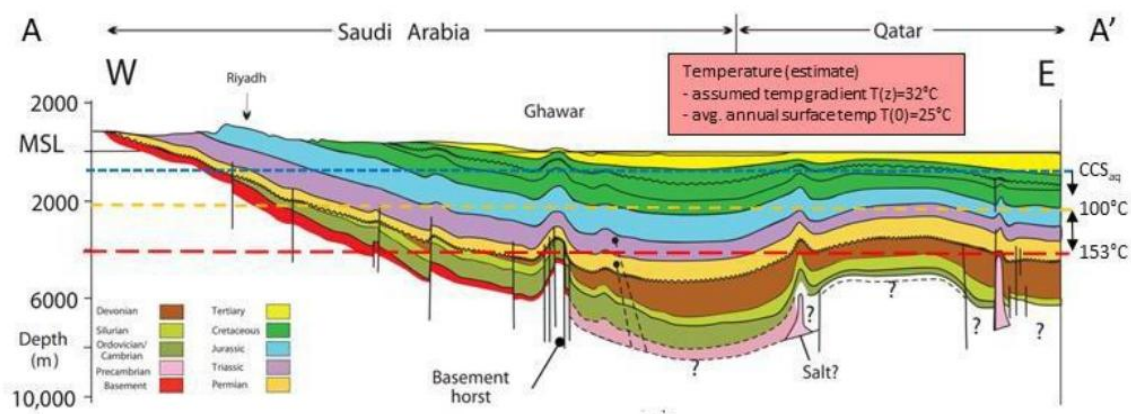


Figure 1.5 The Eastern Arabian Peninsula's sedimentary formations offer prospects for CCS and CCUS. Numerous stacked aquifer/seal pairings present potential with different characteristics. For CCS to maintain the supercritical state of CO₂, a minimum depth of 800 metres is necessary. A minimum temperature of 100°C is required for geothermal CCUS, which is based on the circulation of stored CO₂ [9].

When it comes to the platform margin and slope deposits that are located on the edge of the Tethys Ocean, the depositional architecture becomes exceedingly complicated. The region is distinguished by the presence of cyclic carbonate deposition, which is occasionally disrupted by layers of interbedded siliciclastic shale or argillaceous limestone (for example, the Albian Nahr Umr Formation) and thick evaporite deposits (for example, the Tithonian Hith Formation and the Eocene Rus Formation). The interaction of stratigraphic features has led to the construction of an ideal geological system that is composed of various porous sequences of carbonate rocks that are stacked on top of each other and are covered by impermeable seals for protection. These particular geological structures offer favourable conditions for the capture of hydrocarbons that are in the process of migrating. In the permeable formations beneath the seals, the later Cretaceous/Early Tertiary tectonic activity caused gentle folding of the strata, creating several structural traps ideal for hydrocarbon accumulation. However, not all such structures contain hydrocarbons. Some serve as potential targets for injecting and securely storing light fluids, such as supercritical CO₂, as they only contain high saline water from subsurface aquifers. Aquifers in the region exhibit remarkable reservoir characteristics, including Darcy-scale permeabilities reaching up to 1,000 mD and porosities up to 40%. These properties are representative of the optimal range for reservoir-quality aquifers. The formation fluids are highly saline, with salinities five to seven times that of seawater or higher, making them unsuitable for direct use but ideal for fluid storage applications. Temperatures in these formations can exceed 150°C at depths of several kilometers, driven by advantageous conditions of relatively high porosity and permeability. The existence, extent, and characteristics of the region's aquifers, reservoirs, traps, and seals are well-documented in numerous scientific publications. These works provide a foundation for understanding the subsurface geological framework. Nevertheless, the extensive, site-specific data necessary for assessing suitable sites for CO₂ sequestration or storage experiments is predominantly proprietary and exists within the confidential databases of National Oil Companies.

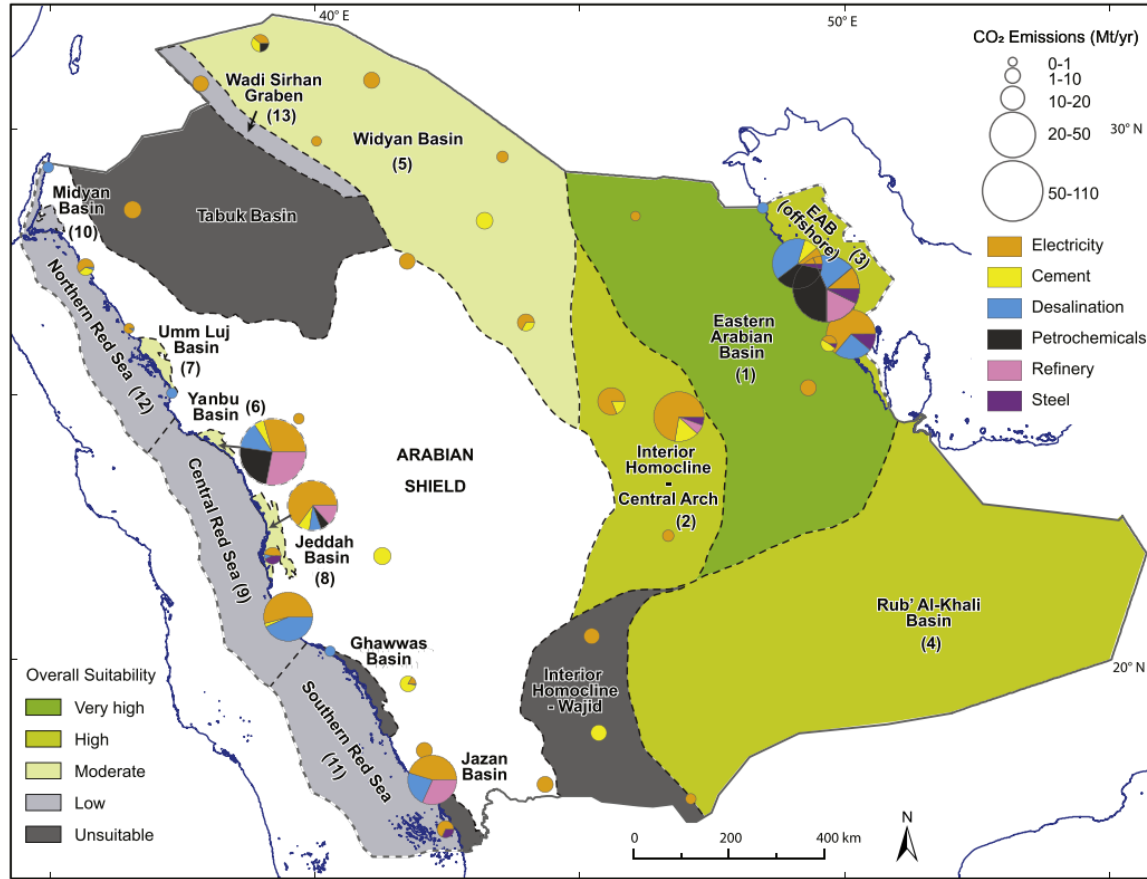


Figure 1.6 The results of the basin study for overall acceptability for geological CO₂ sequestration are represented on this map [8].

Table 1 Depleted oil and gas reserves and saline aquifers in Saudi Arabia are prime examples of sedimentary rocks with estimated probability ranges of carbon dioxide storage capabilities, according to (Ye et al., 2023).

Formation storage capacity	P10	P50	P90
Deep aquifers (Gt)	275	432	654
Gas reservoirs (Gt)	3.8	5.1	6.5
Oil reservoirs (Gt)	8.1	9	9.7

Metrics like the P10, P50, and P90 are useful for understanding how values are distributed within a sample. The optimal application of statistical techniques' results in decision-

making processes might be complicated by the large number of data they create. This strategy is based on "simulating" potential outcomes, as we mentioned in our article about the Monte Carlo method. The calculation of potential lifespan to forecast asset performance is one instance of its application in the oil and gas sector. Analysts occasionally run simulations with more than 1000 lifecycles when running models with a lot of variation. We are essentially recording tens of thousands of years of simulation when we multiply this figure by the time frame needed to replicate the asset performance [21].

CHAPTER 2 |

LITERATURE REVIEW

2. Literature Review

Originally belonging to the Es Sirr Member, the Minjur Sandstone is a Triassic unit named for Khashm al Manjur. This portion extends from the foot of the Marrat group near Khashm al KhaHa to the eastern edge of the dip slope induced by the Jilh Formation's top bed. In the Minjur, cross-bedded, medium, poorly sorted quartz-grained sandstone (white, tan, or brown) weathers into jet-black quartzite masses. On the other hand, the sand crumbles quickly and is often loose. Red, purple, and green shale thin layers are intercalated across the various strata of conglomeratic sandstone lenses. Fossilized dunes, along with sandbar structures, mud cracks, and ripple lines, can be seen at the upper level. No marine fossils have been found; nonetheless, various forms of petrified plant material are present throughout. The Minjur Formation is predominantly a coastal continental sandstone, containing trace amounts of shale and conglomerate. The lithologic character of the unit is highly persistent along strike. The sandstone has a color spectrum from off-white to tan, brown, red, and black as a result of weathering. It is frequently cross-bedded, medium to coarse-grained, and typically friable. The shale, occurring as thin interbeds within the sequence, is distinguished by grey, purple, and red tones and is often silty or sandy. The maximum thickness of an individual shale stratum seldom exceeds 5 meters [2].

The Minjur Aquifer System, which is the primary supply of groundwater for Riyadh, the most important metropolis in the central region of the Arabian Peninsula, is the main focus of this research. Due to the fact that the Minjur is an essential source of water for Riyadh, it will be required to accumulate information regarding this system in order to design changes to it. Furthermore, Riyadh is able to draw water from a variety of sources, including shallow wells that draw water from unconfined aquifers. During the course of this study, a number of aspects of the Minjur Aquifer, including its characteristics, water presence, hydraulic features, wells, recharge and outflow mechanisms, water quality, and sustainable yield, will be explored [6].

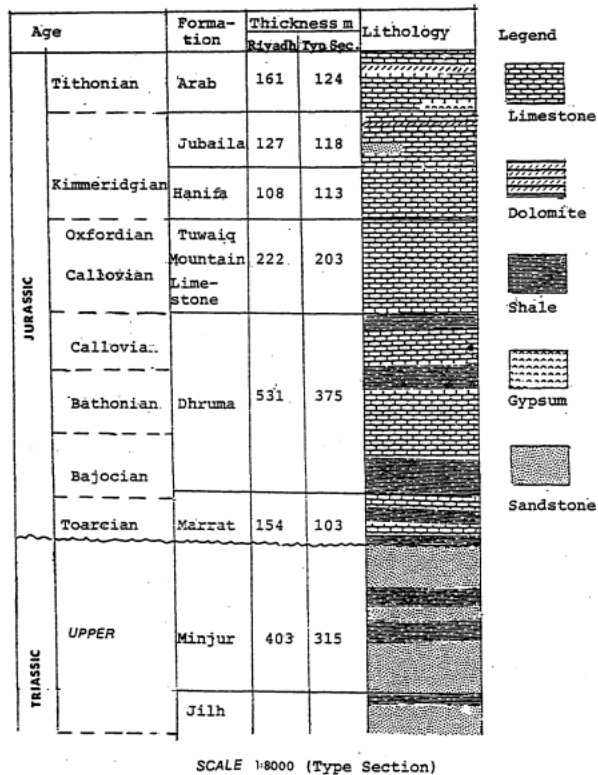


Figure 2.1 Stratigraphy of Riyadh Area. The proportion of sandstone comprises between sixty and ninety percent of the entire deposit. The percentage of shale comprises between 10 and 40 percent of the formation [6].

A 2D computer model of the Minjur aquifer, which is located close to Riyadh in the Kingdom of Saudi Arabia, was developed in order to simulate and forecast the decline that is caused by groundwater withdrawals. Riyadh, the capital of Saudi Arabia, gets a significant portion of its municipal water supply from the aquifer, which is a deposit that dates back to the Late Triassic period. The calibration of the model was accomplished by recreating the historical pump age from 1957 to 1979 and comparing it to the observed decline in water level across a variety of time periods. In the event that the Minjur aquifer is subjected to pressure as a result of anticipated future pump ages, it is anticipated that water levels will drop by ten to ninety meters between the years 1980 and 1999, as indicated by some predicted estimates. Additionally, during the years 1980 and 1981, the pumping volumes in the new Buwayb well field will experience a large drop (Williams and Al-Sagaby, 1982).

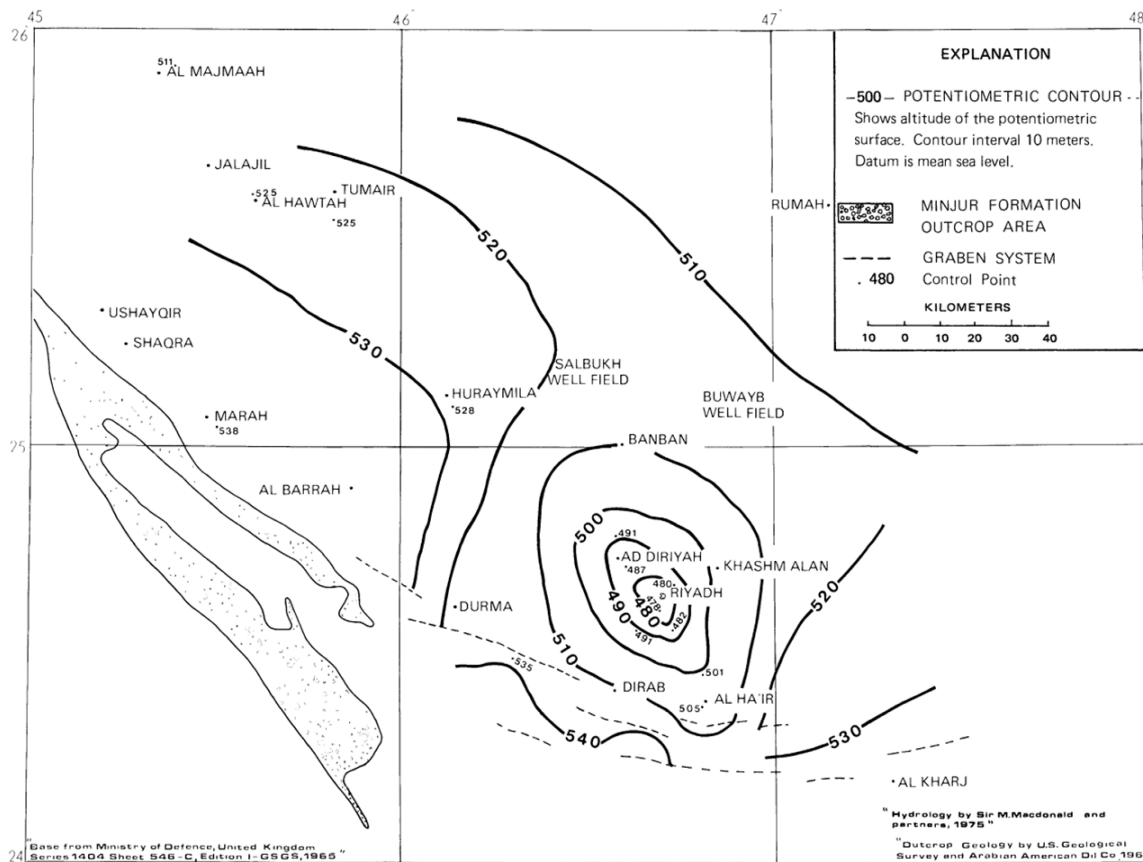


Figure 2.2 Estimated Minjur aquifer potentiometric surface After 1974 pumping. Groundwater flowed northeast from the outcrop (Williams and Al-Sagaby, 1982).

An example of a case study that can be used to comprehend and simulate the spatial distribution of sand bodies in a fluvial-deltaic system is the Minjur Sandstone, which was formed during the Triassic period. Specifically, it has been investigated in relation to the sequestration of carbon dioxide in complex heterogeneous forms. Sedimentological mapping of the vertical and lateral variations of the formation at Khashm al Khalta provides a thorough understanding of the sequence stratigraphy at that location (Issautier et al., 2012a). Sabkha, tidal, estuarine, and fluvial continental habitats are these four types of depositional settings that are represented in the nine depositional sequences that make up the formation. While sequences 4 and 5 display the highest levels of flooding and meander systems, sequences 6 to 9 display an increasing amount of clastic influx into the system.

In light of the growing demand for geological reservoirs, such as those used for geothermal energy and CO₂ storage, questions have been raised regarding the potential impact that

reservoir heterogeneity may have on performance. The Minjur Formation, which is located in the Central Kingdom, is utilized in this work for the purpose of complicated reservoir modeling, simulation, and prediction of the spatial distribution of sand bodies within a fluvial-deltaic system. As part of the research, a deterministic three-dimensional model is constructed in order to investigate the connectivity of the Minjur Sandstone and to depict a typical fluvio-deltaic reservoir along with the heterogeneity that is connected with it. Sequences 1 through 9 are included. While the lower half is made up of sandstone reservoir bodies that are not well connected to one another, sequences 1 to 4 (which make up the Upper Minjur Member) are made up of sandstone reservoirs that are well connected to one another. The Upper Minjur Member has the most substantial potential, and the best reservoir bodies in the Minjur Sandstone can be found near the base of each sequence (Issautier et al., 2012b).

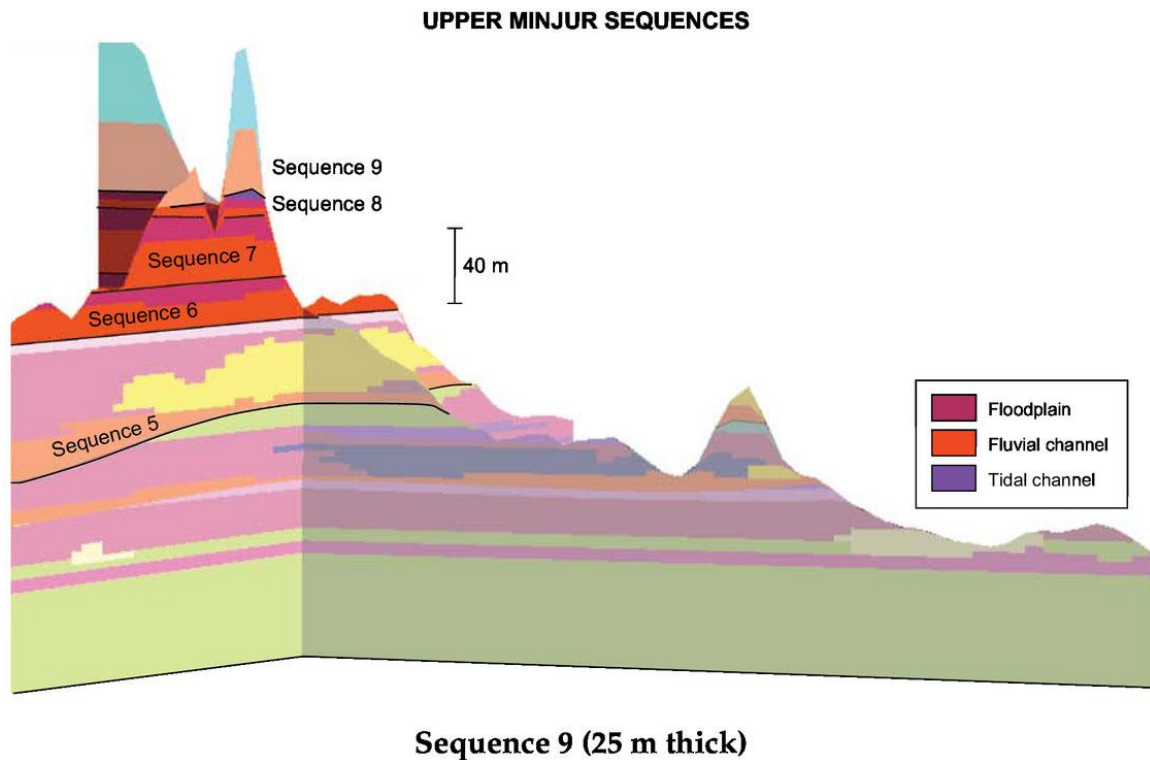


Figure 2.3 Flat sequence boundaries linked with coarse proximal deposits in the model show depositional circumstances changing. The flat structure is attributable to large-scale deposition and progressive basin infill, which permits sedimentary processes to migrate laterally (Issautier et al., 2012b).

Heterolithic with lignitic siltstone, very fine-grained argillaceous sandstone, and finely stratified, kerogen-rich silty mudstone, the upper Minjur in the Rub' Al-Khali basin of Saudi Arabia is characterized by its composition. Mica, chamositic ooids, quartz grains, and other rare heavy minerals can be discovered in muddy sandstones that occasionally contain blocky coal layers. Despite the fact that spore-pollen assemblages are discovered at muddy intervals, palynomorphs are almost nonexistent. Well-defined strata of fine-to-medium-grained and extraordinarily coarse-grained sandstones that are between 5 and 20 meters thick are the sites where weak to bimodal sorting takes place. Subangular to well-rounded quartz grains, feldspar, coal pieces, mica, and muddy, high-gamma facies are contained within these sandstones. Blocky sandstones that have not been changed contain pore porosity ranging from 7 to 20 percent and have well-connected intergranular and moldic macropores. Determining the top border of the Minjur Formation in western Rub' Al-Khali is made more complicated by the sandy Marrat Formation. Recent finds of hydrocarbons have been reported in siliciclastic reservoirs that date back to the Middle Jurassic to the Upper Triassic in the Rub' Al-Khali basin. These reservoirs are located in the accommodation space that was created by crustal-scale basins that date back to the

Triassic and early Jurassic periods. These basins have a frequency of around 100 kilometers and a depth of a few hundred meters.

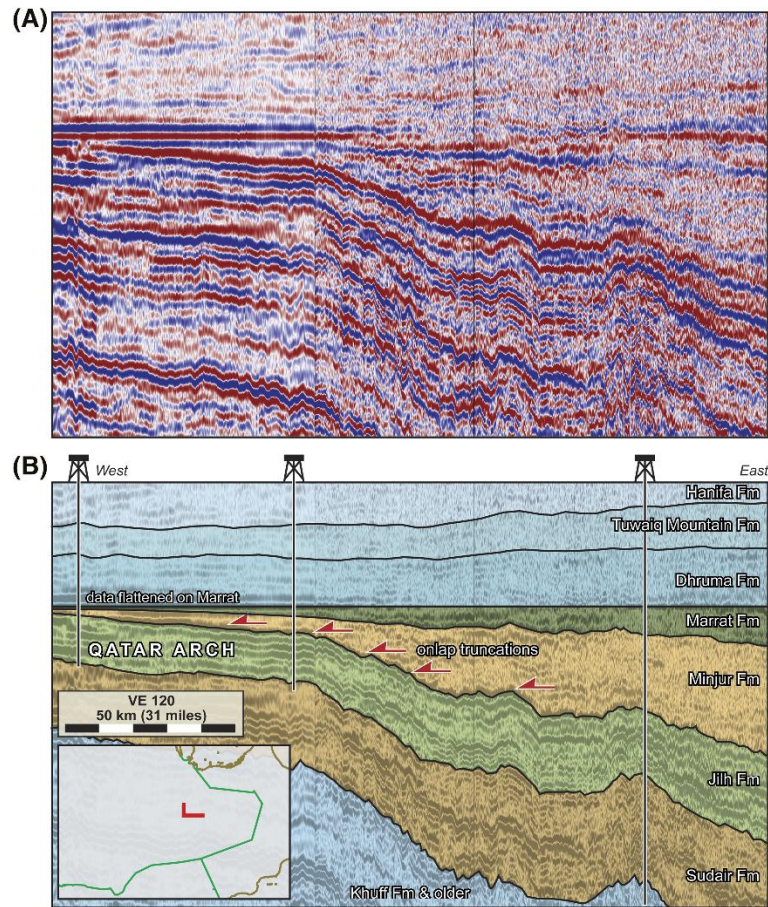


Figure 2.4 A) Reflection seismic data and interpretation illustrate the onlap connection of the Minjur sandstone onto the Jilh Formation in the eastern sector of the Qatar arch. B) The understanding of geological boundaries[7].

This study advances Minjur stratigraphic comprehension and proposes a surface-subsurface correlation depositional model. The Minjur Formation, discovered at the eastern Arabian Shield, has alternating sandstone and shale layers with modest carbonate deposits. The Minjur Formation, categorized into lower and upper strata, comprises alluvial to marginal marine deposits featuring tidally influenced channels. The accumulation patterns indicate delta or shoreline progradation and retrogradation, accompanied by a coarsening upward tendency. Conodonts located at the base of the outcrop have dated the Minjur Formation to the Norian period. Palynology has established a four-tier subsurface biostratigraphic classification from the terminal Carnian early Norian to the latest Rhaetian

Pliensbachian. This analysis suggests a surface-subsurface correlation depositional model and advances our understanding of Minjur stratigraphy [1].

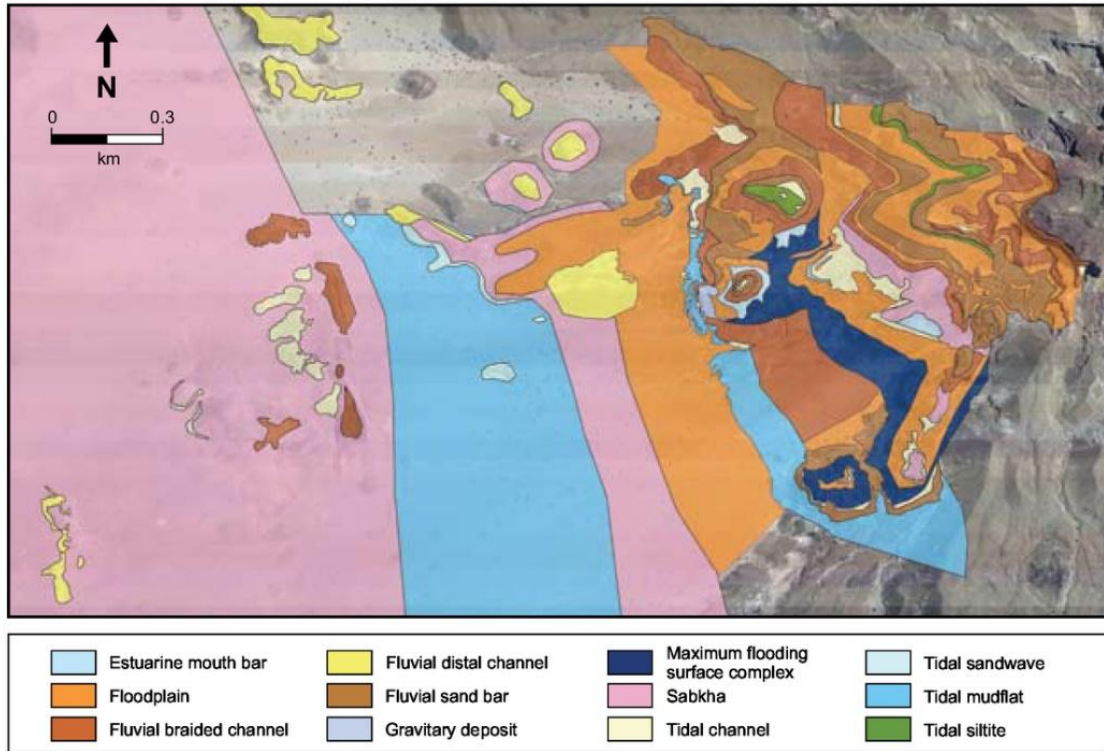


Figure 2.5 Evaluation of the sedimentary features of Khashm al Khalta Minjur Sandstone. The map illustrates depositional ecosystems and their lateral and vertical development. Green, blue, and pink denote coastal to shallow marine layers; yellow and orange signify proximal deposits [1].

This study examines the Late Triassic Minjur Formation outcrop's sandstone lithofacies and reservoir characteristics. Five lithofacies classes were discerned based on their textures, porosity, and permeability. Variographic analyses revealed a robust link between porosity and permeability. The analysis utilized sandstone outcropping data as a representative equivalent for the related underground reservoir, successfully identifying a significant correlation between the characteristics of the outcrop and those of the subsurface reservoir. It is necessary to collect additional qualitative and quantitative data in order to achieve enhanced correlation (Abdelkarim, et al., 2019).

Ghawar, the largest oil field globally, lacks modern geological models and synthetic seismic data. Utilizing P-wave velocities, densities, and quality factors, a 2D viscoelastic

model was created and a multi-component artificial seismic data set was assembled. The models and datasets were openly disseminated to encourage scholars to evaluate their concepts and progress in hydrocarbon exploration seismology. The researchers share their findings to inspire others to make contributions to the geoscience community [12].

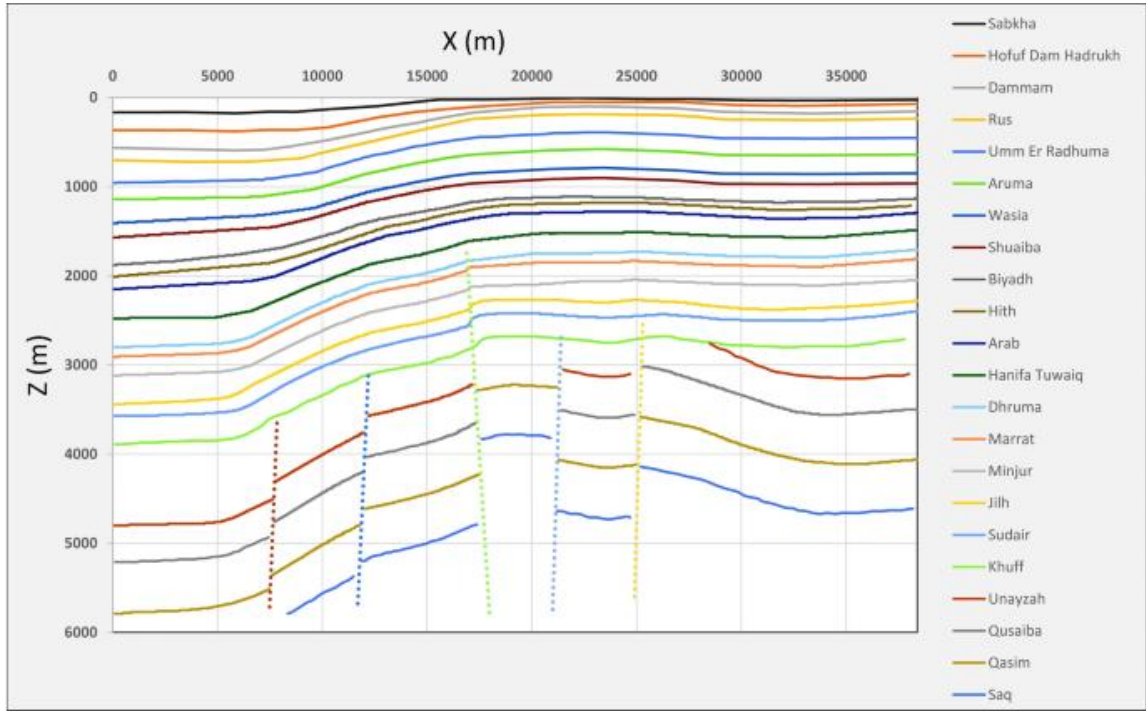


Figure 2.6 The two-dimensional representation of the Ghawar field displays continuous curves for horizons and dotted lines, both vertical and subvertical, to indicate faults [12].

Both carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCUS) are crucial technologies that must be implemented in order to cut down on carbon emissions and perhaps generate geothermal energy. A comprehensive analysis has determined that there are four geological formations in Arabia that are suitable for (CCS) and (CCUS): an eastern segment of superimposed Mesozoic aquifers along the Arabian Gulf coast and inland, rift basins with deep saline aquifers near the Red Sea, Cenozoic volcanic formations located inland from the Red Sea coast, and a perimeter of Cretaceous abducted marine crust (ophiolites) in Northeastern Oman and throughout the United Arab Emirate [9]. Because it has a large number of supergiant oil reserves in stacked, layered limestones that are largely Mesozoic in age, the Northeast region has the potential to be used for the underground sequestration of carbon dioxide for energy purposes. It is

anticipated that the rift basins that are next to the coast of the Red Sea would experience favorable conditions that are comparable.

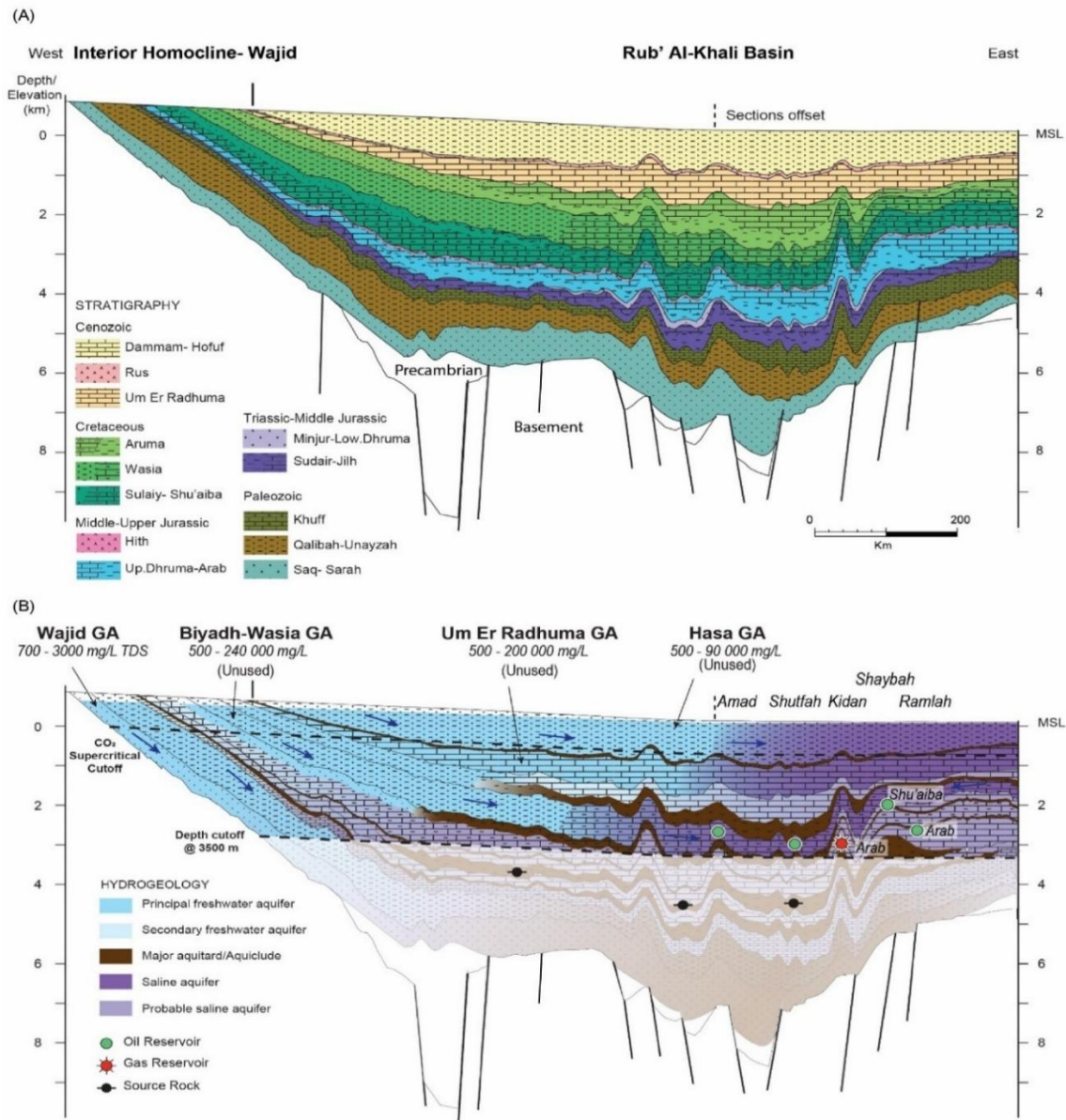


Figure 2.7 (A) A geological cross-sectional of southern and eastern Saudi Arabia demonstrating the Interior Homocline-Wajid and Rub'Al-Khali Basin structure and strata (adapted from Stewart et al., 2016). Dotted lines signify ambiguity in the formation summit. (B) illustrates the location of the portion. The hydrogeologic cross-section analysis reveals source rocks, hydrocarbon reservoirs, saline aquifers, significant regional aquitards/aquicludes, primary and secondary groundwater aquifers, and water salinity levels. Georgia groundwater aquifer.

This study evaluates the geological potential for CO₂ sequestration in 17 basins and sub-basins in Saudi Arabia, focusing on deep saltwater aquifers and potentially drained oil and gas reservoirs. The most appropriate basins are found in the country's eastern portion, such as the Eastern Arabian Basin and the Interior Homocline-Central Arch. Western Saudi Arabia possesses few advantageous basins, except for three somewhat promising onshore basins. The projected total effective storage capacity is roughly 432, 5, and 9 gigatons, respectively. The work underscores the necessity for further research, including prospect-level evaluations, to enhance comprehension of oilfield and trap properties, assess injectivity efficiency, and elucidate CO₂ behavior. [8].

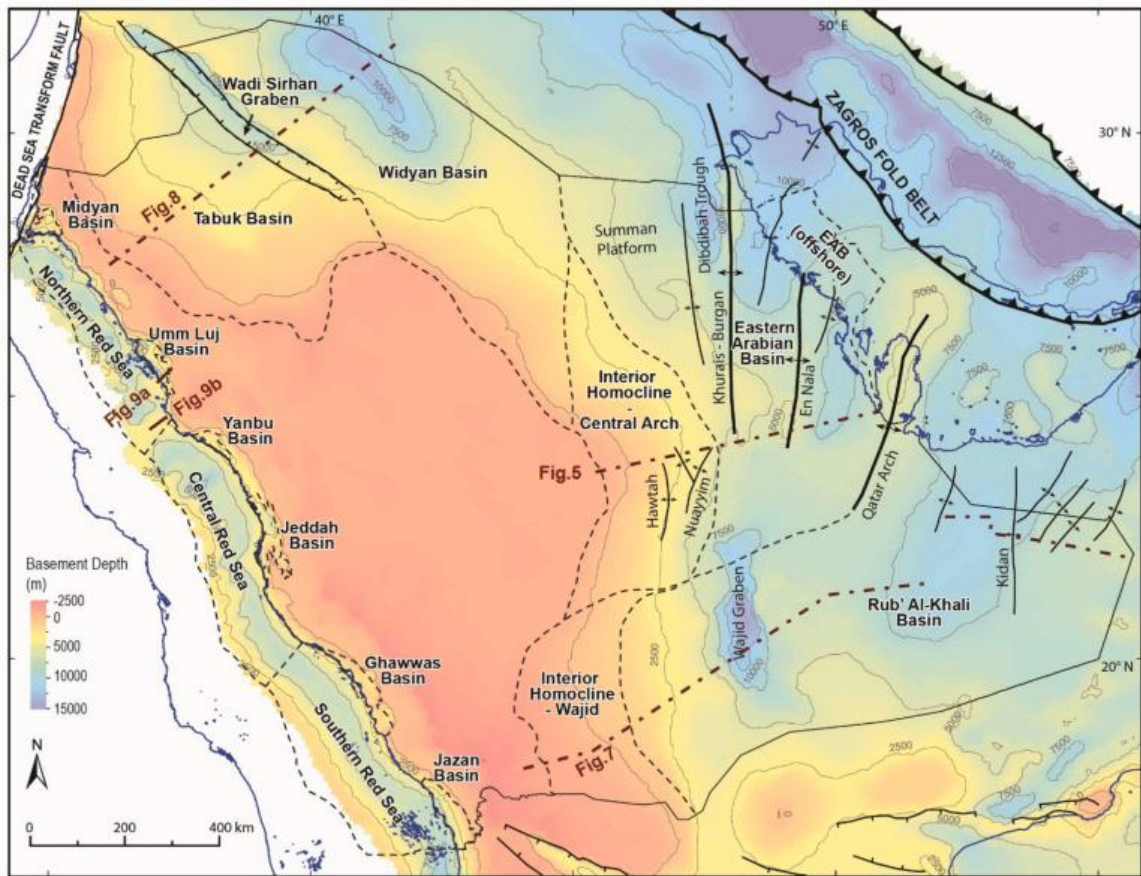


Figure 2.8 An illustration of the highlights of the Arabian Plate can be found on a map that depicts the depth of the basement. There are a total of seventeen basins and subbasins in Saudi Arabia, including the Tabuk Basin, the Widyān Basin, the Interior Homocline-Central Arch (IHCA), the Eastern Arabian Basin (EAB) both onshore and offshore, the Rub'Al-Khali Basin (RAKB), the Interior Homocline-Wajid (IHW), six western coastal basins, and three offshore Red Sea segments (2003)).

The emission of substantial amounts of CO₂ into the atmosphere is a primary contributor to global warming. The most effective approach to managing this issue is to absorb and permanently sequester surplus CO₂ in subterranean geological formations. Monitoring increasing pore pressure is essential to avert potential reservoir failure and the resultant release of stored CO₂ into overburden layers and the atmosphere. Khan et al. evaluated the Minjur sandstone reservoir's stability using a coupled geomechanical model in eastern Saudi Arabia. A fault intersecting the Minjur and Marrat strata is geomechanically modeled to determine injection-induced pore pressure and ground uplift profiles for fault-free and fault-present scenarios. Stability is assessed using Mohr–Coulomb failure criteria. The atmospheric CO₂ concentration is 410 ppm and expected to climb to 600–1550 ppm by 2030. CCS involves capturing CO₂ emissions from power stations and refineries in flue gasses and storing them in deep geological formations. CO₂ injection into impermeable caprock-filled deep sedimentary reservoirs increases storage capacity and reduces leakage. This study examines the Minjur reservoir's viability and safe CO₂ injection criteria in geological faults [13].

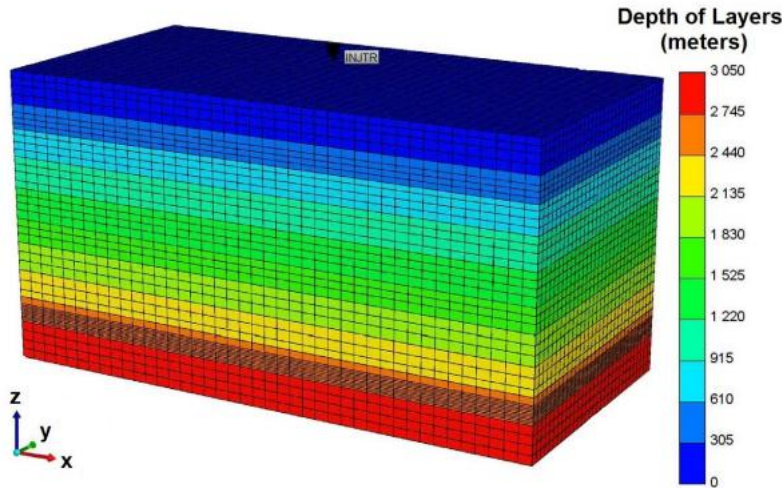


Figure 2.9 Construction of a model for the Minjur reservoir using the CMG-GEM program [13].

CHAPTER 3

METHODOLOGY

3. Methodology

The methods used in this study are different electromagnetic methods: TEM (Transient electromagnetic) and AMT (Audio-Magnetotelluric). In this chapter, I discuss the theoretical background behind these methods, the quality of the data, enhancement and inversion.

3.1. Historical Background

Since the mid-1980s, the time domain electromagnetic (TEM) technique has seen significant advancements, improving reliability and applicability. TEM is considered relatively novel compared to geoelectric methods, frequency domain electromagnetic (FDEM), and magnetotelluric (MT) methods. The broad dynamic range of TEM responses makes accurate quantification challenging, requiring sophisticated instruments to capture both strong early-time and weaker late-time signals. Processing TEM data typically demands more computational power than frequency-domain and geoelectric methods. However, recent developments in computing technology have transformed the field, allowing for interactive processing and real-time interpretation of TEM data (Christiansen, et al; 2006). This democratization of computational power means that TEM surveys can be conducted efficiently in the field, enhancing data accuracy and survey effectiveness.

3.2. Basic theory

All activities involving electromagnetic fields are governed by the Maxwell equations. One of the fundamental phenomena of electromagnetic (EM) is that a fluctuating magnetic field causes an electric field to be induced, which then causes another magnetic field to be generated. Electromagnetic radiation is controlled by these mechanisms as well as others. Light bulbs, microwave ovens, and long-wave radio transmitters are all examples of devices that emit electromagnetic radiation. The equations developed by Maxwell, which demonstrate that changes in the magnetic field cause electrical current to flow through conductive materials like the earth, are the foundation upon which electromagnetic

geophysical techniques are built. Secondary fields are a term that is occasionally used to refer to the current as well as its electrical and magnetic fields. For the purpose of researching electrical and magnetic fields, a spear that is inserted into the ground and a coil that is placed on the ground are both utilized. There is no differentiation made between primary and secondary fields when counting the total number of fields. The secondary field segment of the overall field indicates the subsurface conductivity of the material. This is due to the fact that current induction varies depending on the geological material. Data is extracted and images of subsurface resistivity are created through the use of electromagnetic geophysics. TEM, which stands for time-domain, and FEM, which stands for frequency-domain, are the two fundamental electromagnetic techniques.

The in-phase (real) and out-of-phase (quadrature) fields of a harmonic main signal that is transmitted at a specific frequency are quantified by a receiver to determine their magnitude. In this manner, the FEM operates as usual. When compared to the quadrature component, which is 90 degrees out of phase with the primary field, the real component is in phase with the primary field. Synchronous detection, which is accomplished by monitoring a frequency in order to eliminate background electromagnetic noise, is one of its advantages. During the measuring process, the primary matter of concern is the primary field. The primary field is superior to the secondary field, which is responsible for the majority of the ground's conductivity structure data. As a result, reliable measurements are difficult to get or require adjustments to be made for the primary field before beginning the measurement. In order to accomplish this, the coil arrangement of the device must be precise, which is a difficult task to accomplish away from the laboratory. The TEM observes the amplitude of the signal over time. The transmission electron microscope (TEM) is only used to measure the secondary fields after the primary fields have been eliminated.

A transmitter generates a pulse, usually a quick switched-off current. This concerns FEM setup geometry intricacies. To allow for considerable signal strength changes, the secondary field must be assessed over a long period. The dynamic range is wide. The variance is often 1,000,000, hence this parameter must be checked between 0.00001 and 0.001 seconds. The signal's properties prevent direct filtration to reduce adjacent electromagnetic interference. This is solved by measuring the transient signal in gates and

stacking gate values to average. The fundamental electromagnetic theory behind the transient response expression is examined here. The goal is to present the core components needed to understand the TEM process, not to derive the equations. The Schelkunoff potentials derivation is broad and fits all electromagnetic methods, however the TEM method needs source characteristics to use them. The theory is explained in detail in [15].

3.3. Maxwell's equations

The following five vector functions are used to define an electromagnetic field: E , which represents the intensity of the electric field; B , which represents the induction of the magnetic field; D , which represents the dielectric displacement; H , which represents the electric current density; and J , which indicates the electric current density. All electromagnetic phenomena can be characterized by Maxwell's equations, which regulate the interactions between the elements. These equations govern the electromagnetic waves. Maxwell's equations, which are first-order linear differential equations that are uncoupled, are shown as follows in the time domain:

$$\nabla \times E + \frac{\partial b}{\partial t} = 0 \quad (1)$$

$$\nabla \times h - \frac{\partial d}{\partial t} = j \quad (2)$$

$$\nabla \cdot b = 0 \quad (3)$$

$$\nabla \cdot d = \rho \quad (4)$$

Where ρ represents electric charge density [C/m³]. To characterize the fields thoroughly, boundary conditions are necessary, as shown by the differential equation representation of Maxwell's equations. The conversation here will not cover boundary conditions. The following is an expression for frequency domain constitutive relations applicable to earth materials that can be used to shorten these five field quantity equations to two:

$$D = [\varepsilon'(\omega) - i\varepsilon''(\omega)]E = \varepsilon E \quad (5)$$

$$J = [\sigma'(\omega) - i\sigma''(\omega)]E = \sigma E \quad (6)$$

$$B = \mu_0 H \quad (7)$$

It is generally believed that the magnetic permeability is equal to the free-space value, despite the fact that electric conductivity and dielectric permittivity are complex functions of angular frequency. Christiansen et al et al. (2006) state as much. Equations 6 and 7 define constitutive relations that, when applied to the Fourier transformation of Equations 1 and 2, yield the frequency domains applicable Maxwell equations.

$$\nabla \times E + i\omega u_o H = \nabla \times E + zH = 0 \quad (8)$$

$$\nabla \times H - (\sigma + i\omega)E = \nabla \times H + yE = 0 \quad (9)$$

The impedivity $z = i\omega u_o$ and the admittivity $y = \sigma + i\omega$ will be utilized for practicality. The homogeneous Maxwell equations in Equations 8 and 9 are applicable just in source-free zones. In areas with sources, they are substituted by the heterogeneous equations:

$$\nabla \times E + zH = -J_m^s \quad (10)$$

$$\nabla \times H - yE = J_e^s \quad (11)$$

where J_m^s represents magnetic source current and J_e^s denotes electric source current (Christiansen, et, al; 2006).

3.3.1 Schelkunoff potentials

The heterogeneous frequency-domain Maxwell equations delineated in Equations 10 and Equations 11 can be resolved for regions of homogeneity if J_m^s and J_e^s are definable. E and H can be derived by differentiation by representing them with the Schelkunoff potentials A and F. Differential equation which more simply manageable when potentials are employed rather than the fields themselves, as the potentials correspond with the source fields. Typically, the electric and magnetic fields of each homogeneity zone are represented as an arrangement of either electric or magnetic characteristics.

$$\begin{aligned} E &= E_m + E_e \\ H &= H_m + H_e \end{aligned} \quad (12)$$

As a consequence of this, an electromagnetic field is characterized by a combination of vector variables named E_m , H_m and E_e , H_e . For the initial pair, J_e^s is presumed to be zero for the first pair, and on the other hand, it is assumed that the value of J_m^s is also presumed

to be zero for the succeeding pair. The fact that this is the case demonstrates that the electric source current is not present for electric and magnetic fields that originate from a magnetic source, and vice versa. Even while all of the equations that have been discussed up until this point are, for the most part, accurate, we are going to focus our attention on the TEM approach in particular. Transmission electron microscopy (TEM) is a technique that utilizes a magnetic source (J_m^s). To transmit a transverse electric field. This simplifies the problem because the Schelkunoff capacity F is the only thing that is required for computations. F is defined as $F = E_m$ is the definition of the Schelkunoff potential, which may be found in equation 13.

$$E_m = -\nabla + F \quad (13)$$

Employing this relation in Equation 10 facilitates the formulation of the inhomogeneous Helmholtz equation

$$\nabla^2 F + k^2 F = J_m^s \quad (14)$$

where the wave number k is delineated as:

$$k^2 = \mu_o \epsilon \omega^2 - i \mu_o \epsilon \omega = zy \quad (15)$$

For terrestrial materials and frequencies below $10^5 Hz$, the movement of current significantly less than the conduction current. Therefore, $\mu_o \epsilon \omega^2 \ll i \mu_o \epsilon \omega$ so that $k \approx -i \mu_o \epsilon \omega$. This is referred to as the quasi-static approximation. The Schelkunoff potential can now be used to figure out the full electric and magnetic fields that come from a magnetic source.

$$E_m = -\nabla \times F \quad (16)$$

$$H_m = yF + \frac{1}{z} \nabla(\nabla \cdot F) \quad (17)$$

Assuming a 1D layered earth, F has a single component, the z -component, expressed as

$$F_m = F_z u_z ; TE_z \quad (18)$$

where F_z is a scalar function of x, y and z , and u_z is the unit vector in the z -direction. TE_z signifies the longitudinal electric field, which propagates within the xy -plane. Inserting Equations 18 into Equations 16 and 17 facilitates the representation of the field components.

$$\begin{aligned} H_x &= \frac{1}{z} \frac{\partial^2 F_z}{\partial x \partial z} & E_x &= -\frac{\partial F_z}{\partial y} \\ H_y &= \frac{1}{z} \frac{\partial^2 F_z}{\partial y \partial z} & E_y &= \frac{\partial F_z}{\partial x} \\ H_z &= \frac{1}{z} \left(\frac{\partial^2}{\partial z^2} + k^2 \right) F_z & E_z &= 0 \end{aligned} \quad (19)$$

3.3.2 The transient reaction across a stratified half-space

The TEM method transmits longitudinal electric field. Therefore, just the F-potential is required to compute the upward magnetic field at the center of an equilateral loop. A circular loop closely resembles a square loop of equivalent area. The former is utilized more frequently in practice. Determining the relevant Schelkunoff potential in a one-dimensional model with parallel planes that includes both source-free and source-containing regions necessitates defining source features. By integrating vertical magnetic dipoles, one may determine the area of a transmitter loop, whether it is square or circular. The vertical magnetic dipole in this instance is subject to the Schelkunoff potential, which is displayed as:

$$F(\rho, z) = \left(\frac{zm}{4\pi} \int_0^\infty [e^{-u_o|z+h|} + r_{TE} e^{u_o|z-h|}] \lambda / u_o J_0(\lambda \rho) d\lambda \right) \quad (20)$$

In this context, the symbol m represents the magnetic moment of the dipole, while the symbol J_0 represents the Bessel function of size zero. $\lambda = \sqrt{k_x^2 + k_y^2}$ where k_x and k_y represent the spatial frequencies in the x and y directions, $u_n = \sqrt{\lambda^2 + k_n^2}$ where k_n^2 signifies the wavenumber in layer n , which, according to Equations 15, is determined in the quasi-static approximation, $k^2 = -i\mu_o\sigma_n\omega$ receiver. There is a radial distance between the source and the receiver, which is represented by this ρ . r_{TE} , also referred to as the reflection coefficient, is a unit of measurement that quantifies the degree to which the

layered half space modifies the source field. In Equation 20, the first term of the integral represents the free-space response from the source dipole to the receiver. This response is represented by the term. As can be seen in the figure, the second one is made up of three different components. After being modified by the reflection coefficient in the second term, the field is next transferred from the source dipole to the boundaries of the Earth in the first part of the process. Finally, the field is given to the receiver in the third and final portion of the process. A recursive computation of the reflection coefficient is shown in Figure 3.1. This coefficient is derived from the basis of the model.

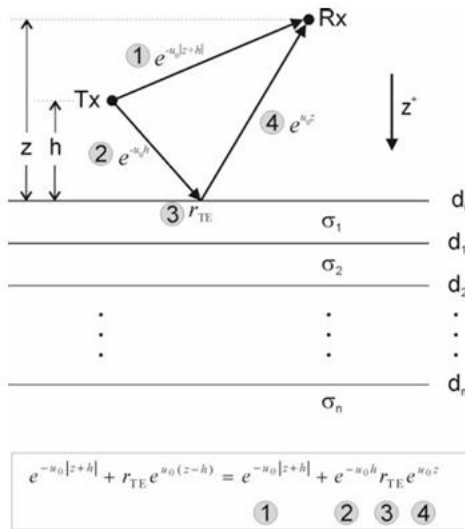


Figure 3.1 Illustration of the components in Equation 20.

Figure 3.1. Depiction of the elements in Equation 20. z is orientated positively in a downward direction. Rx is positioned at an elevation h above the Earth. Therapeutic intervention at altitude z . The surfaces of the layers in the model are flat, parallel, and uniform. The phrase "one-dimensional model" characterizes this model. Equation 20 revolves around a circular loop with radius I and current. Subsequent to some modifications, in the expression:

$$F(\rho, z) = z_0 I_a \int_0^\infty \frac{1}{u_0} \left[e^{-u_0|z+h|} + r_{TE} e^{u_0|z-h|} \right] J_1 \lambda_a J_0 \lambda_\rho d\lambda \quad (21)$$

J_1 The Bessel function of the first order is represented here. Consider a circular transmitter loop in which the dipole receiver is positioned at a distance from the center of the loop.

Equation 21 applies to this situation. The expression for the vertical magnetic field is obtained by using Equation 17 and further simplifying the equation. This expression is obtained when the receiver is positioned in the middle of the transmitter loop (central-loop setup).

$$H_z = \frac{I_a}{2} \int_0^\infty [e^{-u_0|z+h|} + r_{TE} e^{u_0|z-h|}] \lambda^2 / 2 \lambda_a J_1 d\lambda \quad (22)$$

To describe Equation 22, the frequency domain is used, with r_{TE} as a function of frequency. The inverse Laplace transform, or inverse Fourier transform, is used to calculate the transient response, also known as the time-domain response. Equation 22 contains the Hankel integral, which is known by that name. It is necessary to perform a calculation and evaluation of this integral using numerical methods because it is not calculable and cannot be resolved using analytical methods.

3.3.3 The transient reaction of a half space

The complexity of integrals in general and Bessel functions in particular prevents any analytical expression from being produced in the general situation. However, r_{TE} occurs for the Central loop arrangement on an equal half-space area.

$$r_{TE} = \frac{\lambda - u}{\lambda + u} \quad (23)$$

Equation 22 simplifies to

$$H_z = I_a \int_0^\infty \frac{\lambda^2}{\lambda - u} J_1 \lambda_a d\lambda \quad (24)$$

By employing the straightforward connection $b = 0$, Equation 24 may now be resolved for b . assessing the integral and utilizing an inverse Laplace transform

$$b_z = \frac{\mu_0 I}{2a} \left[\frac{3}{\pi^2 \theta a} e^{-\theta^2 a^2} + \left(1 - \frac{3}{2\theta^2 a^2} \right) \text{erf}(\theta a) \right] \quad (25)$$

In this equation, t is equal to 4, and erf represents the error function. If b_z is evaluated at time $t=0$, then b_z is equal to $I/2a$. The dimensions of the major area in unoccupied space, specifically the magnetic intensity prior to deactivating the current, are indicated by this.

The determination of the temporal derivative, also known as the impulse response $\frac{\partial b_z}{\partial z}$, is accomplished by the utilization of the differentiation process.

$$\frac{\partial b_z}{\partial z} = -\frac{I}{\sigma a^3} \left[3 \operatorname{erf}(\theta a) - \frac{2}{\pi^2} \theta a (3 + 2\theta^2 a^2) e^{-\theta^2 a^2} \right] \quad (26)$$

These are the essential equations for the TEM methodology, and we will review them again. Thereafter, to them. The previously given equations apply solely to the vertical field at the center of the transmitter loop.

3.4. Fundamental Principle and Measurement Methodology

It is common practice for TEM operations to make use of direct current, which is typically transmitted over an ungrounded loop. Through the use of an induction coil, one may determine the rate of change of the secondary field that is generated by eddy currents following the sudden termination of the current. The measurement does not take place in the presence of the primary field. Figure 3.3 provides a breakdown of the basic concepts and vocabulary phrases.

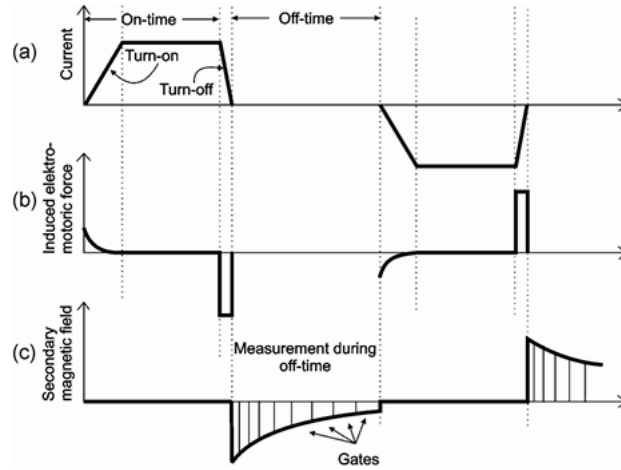


Figure 3.2 The basics of Transmission Electron Microscopy (TEM). (a) shows sender loop current. (b) represents the ground's induced electromotive force (Christiansen, et al., 2006), and (c) represents the receiver coil's secondary magnetic field. For the induced electromotive force and secondary magnetic field graphs, the receiving coil is assumed to be at the center of the transmitting loop.

Standard ground-based system characteristics include a ramp of 50–200, an on-time of 1–40 ms, a turn-on duration of 1–30 s, a turn-off ramp, and an off-time of 1–40 ms for measurement. This is a square waveform. In airborne systems, sine and triangle waveforms are common. Gates record data at set intervals. A logarithmically growing gate time improves (S/N) ratio at successive intervals. Log gating uses 8–10 gates every decade. Figure 3.3 shows the stream's direction changes with each pulse. An average sounding has 1,000–10,000 pulses. There is a reduction in both power line noise and amplifier static fluctuations when the repeated frequency is a subharmonic of the power line frequency. The signal changes are responsible for this reduction. The term for this is synchronized detection. 25 Hz is the standard repetition frequency for a line that operates at 50 Hz. For the purpose of attenuating the frequency of the 50 Hz power line, high the repeated frequency requires coordinated transient frequency and number coordination. To transient sounding in the field, a wire that is arranged in a square loop on the ground can be utilized. For examining the upper 150 meters of the ground, it is customary to utilize a $40 \times 40 \text{ m}^2$ area. In the center of the transmitting loop, after the wires have been linked, is the receiving coil, which has a diameter of about one meter. For the transmitter and receiver to be in sync with each other, the receiving coil must be attached to the receiver before it can be linked to the transmitter (Figure 3.3).

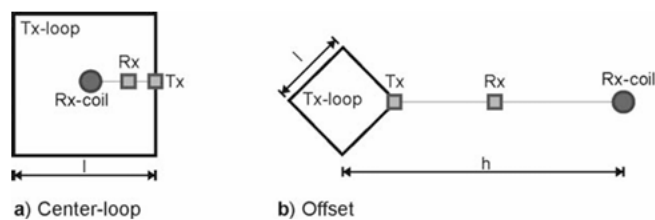


Figure 3.3 Setting up the TEM. both a) and b) are examples of central and offset loops. In the equation, Tx represents the transmitter, Rx represents the receiver (Christiansen et al., 2006), l represents the side length of the loop, and h represents the offset between the centers of the Tx loop and the Rx coil.

The Tx-loop allows direct current to flow for the purpose of conducting measurements. This causes the main magnetic field to become static. When the current is abruptly cut off, an electric field is created nearby, as stated by Faraday's Law. An electric current will be generated within the Earth by this electric field, leading to the production of a secondary magnetic field. In the case that the transmitter is turned off, the strength of the ground-

based secondary magnetic field will match that of the absent main field. For the time being, the early phase of the current is completely independent of the ground's conductivity configuration. This means that the magnetic field changes gradually when the current is turned off, instead of suddenly. Over time, the earth's resistance will cause the current to decrease, leading to the conversion of energy into heat. The maximum current density after the transformation will alter as a result of this.

3.5. Data Approach

Apparent resistivity at late time

Equation 25 displays the step response, which is also referred to as the falling secondary magnetic field. The step response is denoted by the Greek symbol b . Because field measurements are performed with an induction coil, the actual measurement is tied to the db/dt ratio. This is because the induction coil does the measurements. This is due to the fact that the time derivative of the magnetic flux that is proceeding through the coil is proportional to the induced electromotive force that is being generated. In situations where A is coming closer to zero, particularly during late periods, the impulse response, which is represented by the equation 26 (db/dt), can be approximated by the following calculations:

$$\frac{\partial b_z}{\partial t} \approx -\frac{I\sigma^{\frac{3}{2}}\mu_0^{\frac{5}{2}}a^2}{\pi^{\frac{1}{2}}}t^{-5/2} \quad (27)$$

There is a reduction in the time derivative of b that is proportionate to the time value of $t^{-5/2}$. The examination of the curve that depicts the diminishing magnetic field in Figure 3.4a is not useful, and the same can be said for the sounding curves that were acquired using empirical means. An apparent resistivity graph, denoted by the letter a , offers additional information. This can be obtained from the late time estimate of the impulse response in Equation 27, which ultimately leads to the following:

$$\rho_a = \left(\frac{Ia^2}{20\partial b_z/\partial t}\right)^{1/2} \frac{\mu_0^{\frac{5}{2}}}{\pi^{\frac{1}{2}}}t^{-5/3} \quad (28)$$

There are curves in Figure 3.4b that are representations of the response curves that can be seen in Figure 3.4a. It is of the utmost importance to acknowledge that oscillations on an

apparent resistivity curve do not naturally imply geological changes and should not be construed as such. An example of this would be a reduction and conversely (refer to the overshoot in Figure 3.4b at 2 a-curve), which regularly ascends prior to reaching 10-5s. Despite the fact that it provides a large amount of normalization of data concerning the source and measurement arrangement, the apparent resistivity does not accurately reflect the actual resistivity in a stratified ground.

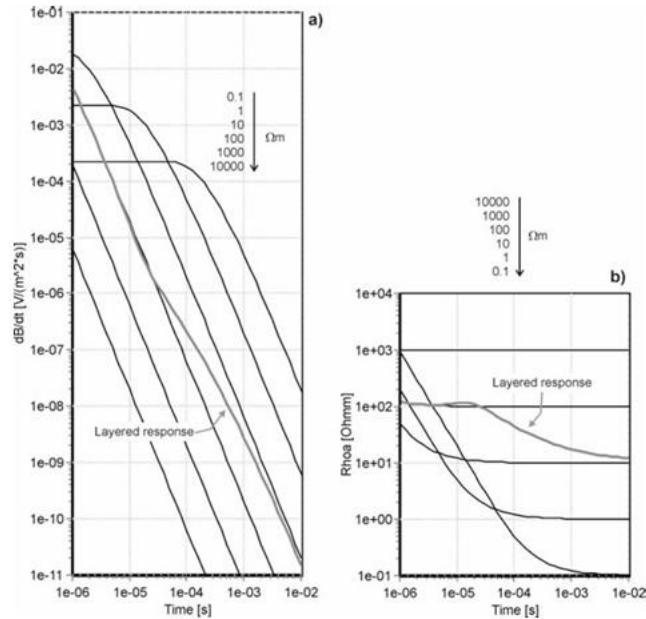


Figure 3.4 Black lines represent the a) impulse reactions (db/dt) for a homogeneous half-space with various resistivities. b) shows the same area-wise curves. The grey line represents the reaction of a two-layer earth comprising ten meters of layer 2 and one hundred meters of layer 1. Layer 1 spans forty meters.

3.6. Noise and Resolution

3.6.1 Ambient Natural Noise

Two numerical values are simultaneously displayed as a geophysical datum, which is comprised of a reading and the uncertainty that is associated with it. All of the measurements are inaccurate since the data that was collected takes into account both the response of the Earth and the background noise. A single transient's effectiveness can frequently be significantly impacted by the presence of noise in a transmission electron microscopy (TEM) sounding. The signal is improved by conducting tests on a regular basis,

which simultaneously minimizes the amount of noise. There are between one thousand and ten thousand different transients that are present in a typical TEM sounding. When compared to trying to interpret a sound that contains five thousand transients, the task of interpreting a sound that contains fifty stacked transients would be substantially more difficult. When using a log-gating technique, the signal-to-noise ratio is directly proportional to the quantity of data that is stored in the stack, which is denoted by the letter N. The assumption that we are making is that the noise follows a Gaussian distribution. When the number of stacked readings increases, the signal-to-noise ratio increases by a factor of 1.41, which indicates that the ratio is becoming better.

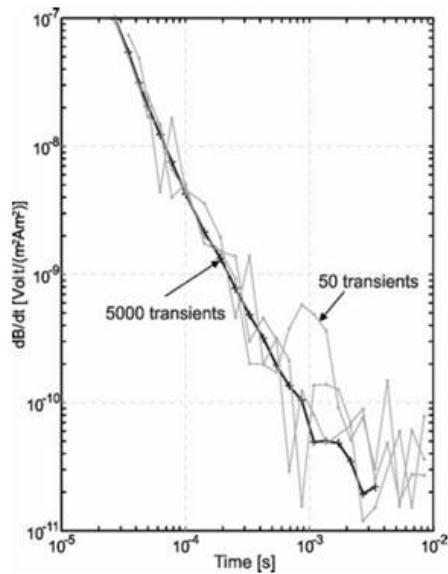


Figure 3.5 50 transients (grey) and 5,000 transients (black) are superimposed on TEM sounding curves.

Electromagnetic field interference in the environment can arise from numerous sources. Some sources, such as lightning, are situated in close proximity, while others are positioned at a longer distance. The electromagnetic radiation emitted by these sources traverses the entire planet, from the Earth's surface to the ionosphere. This cavity serves as an effective waveguide throughout the electromagnetic spectrum. Fluctuations in the Earth's magnetic field, induced by solar winds, establish a foundation for electromagnetic noise. Nevertheless, their frequencies are sufficiently low to avoid impacting the transient measurement. The spherics generated are more pronounced from lightning strikes during thunderstorms globally, particularly in tropical regions. Approximately 100 lightning

strikes impact the Earth per second. This noise exhibits randomness and is more prominent during the day than at night, as well as more intense in summer than in winter. Noise also emanates from the power supply and its associated infrastructure. The signal consists of a deterministic harmonic component at 50 or 60 Hz, in addition to transient magnetic fields that display random properties, produced by current fluctuations during the activation or deactivation of electrical systems. Moreover, the EM fields produced by communication devices (radio, television, telephone, etc.) will act as sources of interference. When the equipment operates optimally, the noise generated by the instrument's electronics is negligible relative to the overall noise.

3.6.2 Noise and measurements

The random noise will diminish in accordance with $t^{1/2}$ when employing the log-gating technique. Figure 6 illustrates the fundamental components of a TEM sounding. Post-stacking, the resultant noise fluctuates between 0.1 and 10 nV/m², averaging roughly 1 nV/m². In Figure 3.6, the value is approximately 3 nV/m²·s at 1 ms. The image illustrates a series of noise measurements in gray. A correlation exists between the curve trends and the expected $t^{-1/2}$ relationship, illustrated by the grey dotted line. A significant disparity exists between the noise level and the initial time measurements. This indicates that the signal-to-noise ratio is adequate, hence enhancing the dependability of the data at beginning intervals. In scenarios where the measured signal exceeds the noise level, the correlation is often proportional to $t^{-5/2}$. This signifies that the shift from a good signal-to-noise ratio to a markedly unfavorable one occurs abruptly. To obtain data at successive intervals, especially from higher depths, two procedures may be employed: One approach is to diminish the noise through stacking, while the alternative is to enhance the transmitter's moment. N represents the quantity of measurements in the array, and the efficacy of noise reduction via stacking is directly proportional to N . The impact of increasing the strength of the instant is illustrated in Figure 3.6 by the black dotted line. Furthermore, subsequent periods exhibit a significantly greater ratio of signal to noise compared to previous periods. The line depicts the intensity of a hearing that transpires at the same location but with a tenfold greater moment.

3.6.3 Depth of Penetration

Regarding TEM soundings, as with all other geophysical techniques, it is difficult to have a clear and mathematical discussion of penetration depth. Several guidelines will now be presented. The diffusion depth is the extent to which the current system penetrates.

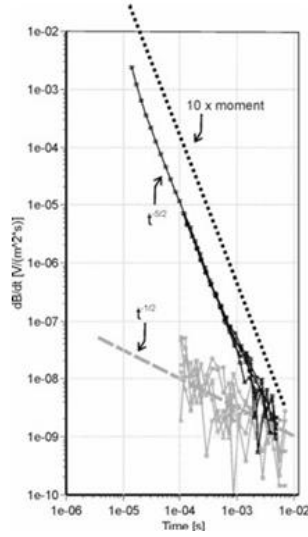


Figure 3.6 Transmission Electron Microscopy sounds and noise assessments.

$$z_d = \sqrt{\frac{2t}{\mu\sigma}} \approx 1.26\sqrt{\rho t} \text{ [m]}, \quad \rho[\text{ohmm}], t[\mu\text{s}] \quad (29)$$

The depth, z_d , is delineated by noise measurements are represented by the grey curves, and the thick dashed grey line shows the $t^{-1/2}$ trend. The error bars indicate 5%. The black curves show how the Earth responded. The estimated level of a sound with a moment ten times greater is indicated by the black dotted line. This formula only applies to planar fields. When it comes to sources that are quadratic loop, the estimated diffusion depth is approximately 1.8 times less than the estimate that is provided by Equation 29. The diffusion time, which is the length of time required for the current to reach a specific depth, is represented by the following equation:

$$t_d = \frac{\mu\sigma z_d^2}{2} \approx 0.628 \times \frac{z_d^2}{\rho} [\mu\text{s}], \quad \rho[\text{ohmm}], z_d[\text{m}] \quad (30)$$

When t_L is comparable to the diffusion time t_d

$$V_{noise} = \frac{dB}{dt} = \left(\frac{M}{20}\right) \left(\frac{\sigma}{\pi}\right)^{\frac{3}{2}} \left(\frac{\mu}{t_L}\right) \Rightarrow$$

$$t_L = \mu \left(\frac{M}{20V_{noise}}\right)^{\frac{2}{5}} \left(\frac{\sigma}{\pi}\right)^{\frac{3}{5}} \quad (31)$$

$$t_L = \mu \left(\frac{M}{20V_{noise}}\right)^{\frac{2}{5}} \left(\frac{\sigma}{\pi}\right)^{\frac{3}{5}} = t_d = \frac{\mu \sigma z_d^2}{2} \Rightarrow$$

$$z_d = \left(\frac{2}{25\pi^3}\right)^{\frac{1}{10}} \left(\frac{M}{\sigma V_{noise}}\right)^{\frac{1}{5}} = 0.551 \left(\frac{M}{\sigma V_{noise}}\right)^{\frac{1}{5}} \quad (32)$$

The signal attenuates in a homogeneous half-space according to $t^{-5/2}$, and once the signal is beyond the threshold of natural noise, the measurements become invalid. The depth to which the current can penetrate the earth is therefore influenced by the strength of naturally occurring noise, which also sets limitations on the time of our observations. The signal attenuates in a homogeneous half-space according to $t^{-5/2}$, and once the signal is beyond the threshold of natural noise, the measurements become invalid. The depth to which the current can penetrate the earth is therefore influenced by the strength of natural noise, which also sets limitations on the time of our observations. We establish a correlation between the background noise and signal, V_{noise} and the latest measurement time, t_L , using the equation given for dB/dt during late times (Equation 27). The maximum diffusion depth, which represents the penetration depth, is proportional to the fifth root of the current loop moment to the product of noise level and conductivity.

The only way to improve penetration depth is to increase the transmitter's moment or decrease the effective noise level. Generally, the ambient noise does not change, but our data collecting and processing strategy, which aggregates several observations, reduces the effective noise. According to equation 32, the effective noise must be reduced, or the transmitter's moment must be increased by a factor of 32 in order to double the penetration depth, V_{noise} and the latest measurement time, t_L , by the equation given for dB/dt during late times (Equation 27). The maximum diffusion depth, which represents the penetration depth, is directly proportional to the fifth root of the current loop moment to the product of noise level and conductivity. The only way to improve investigation depth is to increase the transmitter's moment or decrease the effective noise level. Generally, ambient noise

does not change, but our data collecting and processing strategy, which aggregates several observations, reduces the effective noise. According to equation 32, the effective noise must be decreased, or the transmitter's moment must be increased by a factor of 32 in order to double the penetration depth.

3.7. Modelling

3.7.1 Introduction

The introduction highlights that the need for precise data with a high spatial density is a crucial component of applying the TEM method for hydrogeological applications. Establishing a trustworthy geophysical model for hydrogeological study is hampered by poor data accuracy. It is essential to identify and integrate the subsequent instrument parameters into the data modeling methodology to ensure the generation of data of sufficient quality: Characteristics of the broadcast waveform include the specific time interval between the transmitter and receiver, as well as the various configurations of the ramps that are currently being used for turning off and turning on the signal. As a result of the significant influence that timing parameters have on early-time data, it is necessary to establish them with a precision of one hundred nanoseconds. Early-time data is often greatly affected by the receiver transfer function, which is made up of one or more low-pass filters. Integrated within the receiver system are low-pass filters, which are used to reduce the amount of noise that is caused by long-wave radio signals and to stabilize the amplifiers. Regarding the design of the offset array, it is imperative that the shape of the transmitter-receiver set up be precise.

Central-loop data exhibit relative insensitivity to geometric modifications, provided the transmitter area remains constant. The measuring of high spatial density data achieves two objectives: 1) enhancement of geological structure resolution and 2) identification and elimination of erroneous data resulting from instrument malfunctions and transmitter-induced coupling with artificial conductors. The latter is undoubtedly the most significant.

3.7.2 The One-Dimensional Model

Currently, routine inversions of TEM data in several dimensions are not feasible. Recent advancements in 3D inversion codes have occurred; nonetheless, they remain computationally demanding and necessitate densely sampled data sets. Consequently, geological noise is unavoidable when representing a three-dimensional reality with a one-dimensional model. The degree of geological noise is determined by the configuration of 2D and 3D structures.

3.7.3 The Two-Dimensional Model

An exponential function summation can be used to express a transitory reaction that can be exhibited by a horizontal circular cylinder that is applied to a uniform magnetic field along its axis. The (TEM) response of a conducting circular cylinder of radius is determined by the following equation: A uniform emission field B_0 directed orthogonal to the axis [15].

$$b_r(t) = 4B_0 \frac{a^2}{r^2} \cos \varphi C(t),$$

and

(33)

$$b_\varphi(t) = 4B_0 \frac{a^2}{r^2} \sin \varphi C(t),$$

where r, φ, z are the cylindrical coordinates. Equation (34) is clearly analogous to the field of a linear magnetic dipole aligned along the cylinder's axis, with its moment decaying over time. In equation (34), the function $C(t)$ is delineated as follows:

$$C(t) = \sum_{n=1}^{\infty} \frac{e^{-t/\tau_k}}{n_k^2} \quad (34)$$

where $\tau_k = \frac{\sigma \mu a^2}{n_k^2}$ and n_k represents the successive roots of the equation $J_0(x) = 0$ (i.e., $n_1 = 2.40$, $n_2 = 5.52$, etc.). During late periods, the cylinder's time constant is calculated as

$$\tau = \tau_1 = \frac{\sigma \mu a^2}{n_1^2} \approx \frac{\sigma \mu a^2}{5.52} . \quad (35)$$

In a coil, the induced electromotive force can be expressed by the function $C(t)$ and its derivative, $C'(t)$. The 2D example is the one with an infinite line current perpendicular to a two-dimensional conductive geometry; the 2D-and-a-half-dimensional situation is the one with 2D conductivity and a 3D source. Two-dimensional models are only beneficial from a pragmatic standpoint if they are able to accurately portray situations that take place in three dimensions.

3.7.4 Advantages, and Limitations

Ground-based TEM systems often utilize a transmitter loop measuring between 40 and 100 meters in length. Extensive loops are advantageous as they facilitate measurements within the loop and exhibit a considerably bigger magnetic moment. However, they possess limitations, including limited field efficiency and a significant cultural connection. Although a smaller transmitter loop with increased current exhibits superior field efficiency, the design configuration faces four obstacles. Saturation of receiver amplifiers transpires in the central-loop configuration when a narrower transmitter loop is employed with an augmented output current. The substantial voltages produced upon deactivation of the primary field lead to saturation of the receiver amplifiers. The distorted signals generated by amplifiers persist for several hundred microseconds following saturation. Furthermore, when the current is deactivated, nanometer-scale currents are emitted from the transmitter coil. These currents interact with the Earth's response to produce data distortion. Geometry is utilized to mitigate the adverse impacts of utilizing either a low output current with an extensive transmitter loop or a significant offset between the transmitter and reception coils. Consequently, data pertaining to low current may be assessed within the central-loop structure, whereas data concerning large output current must be examined in the offset array. The influence of induced polarization (IP) is a significant environmental phenomenon, particularly in sedimentary environments. The intrinsic power (IP) effect, especially noticeable in the arrangement of the center loop, decreases as the distance between the receiving coils and the transmitter coils increases. The offset design is particularly sensitive to small variations in near-surface resistivity in the early phases of the design process. The comprehensive three-dimensional modeling of these inaccuracies substantially influences the measured fields. Before the installation of

the current system, it was located beneath the receiving coil. Under some conditions, it is impractical to assess this data with a one-dimensional model, despite the section being primarily 1D. Consequently, the effects of the existing system, which are distorting, will diminish over time. The central-loop arrangement is significantly less vulnerable to alterations in near-surface resistivity. This offset pattern may be influenced by minor alterations to the array structure. A thirty percent mistake in the response at the sign change arises in a fundamental sixty-meter half-space model when the receiver coil is situated at 71 meters instead of 70 meters from the transmitter. The typical field setting does not facilitate such precision, rendering it practically hard to attain. Modifying the sign central-loop system is analogous to the offset configuration in their respective manners. This role does not influence the layout of the center loop. The receiver site is situated within the transmitter circuit. The deployment of a high-power system with a minimum current of one to three during the initial phases analyzed in the configuration of the central loop serves as a source of equilibrium. Subsequently, measurements are conducted in the offsetting array utilizing the maximum achievable output currents. A high level of field output has been sustained due to the resolution of four challenges, [15]

3.8. Field Measurement and Configuration

All current inductive time-domain methods have a shared trait: they utilize a primarily square grounded loop as the transmitter. The most common TEM arrays, based on the transmitter-receiver array [16].

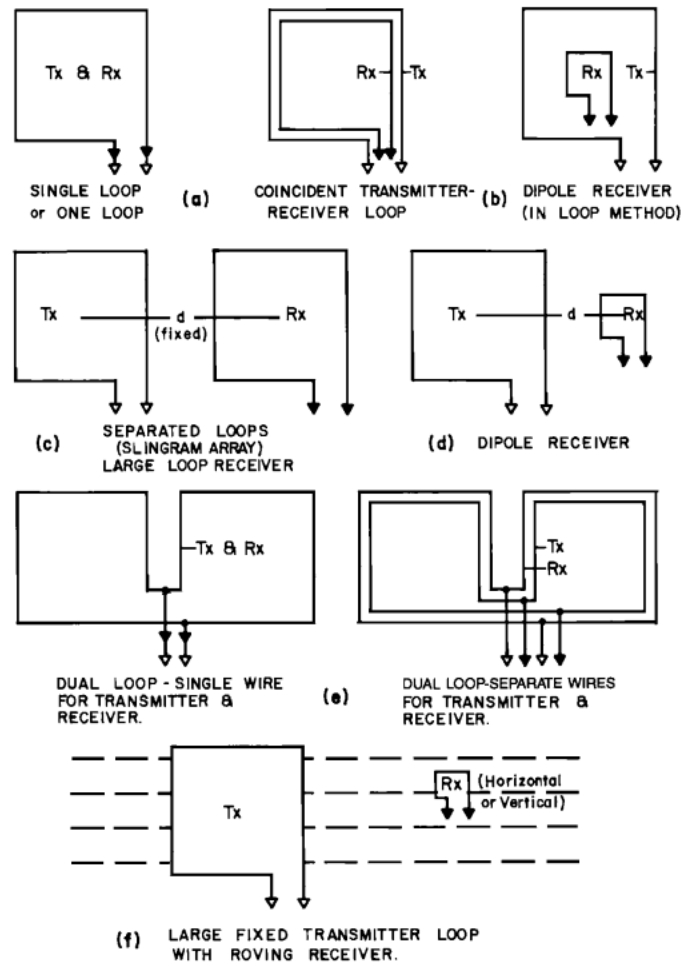


Figure 3.7 TEM configurations, (a) A single loop transmitter and receiver, also referred to as one-loop. (b) Coincident transmitter-receiver loops and In-loop (or central loop) or dipole receiver configuration. (c) Separated transmitter-receiver circuits. (d) Dipole receiver. (e) Dual loop single wire for transmitter and receiver and dual loop separate wires for transmitter and receiver (f) Large stationary transmitter, mobile receiver (Nabighian & Macnae, 1991).

3.9. ABEM-WalkTEM Instruments

In order to conduct the TEM survey, the ABEM-WalkTEM equipment was utilized. The loop that was used for the transmitter was a single turn wire that measured around 400 meters in length and had 100 meters on each side. The installation of two receiver loops allowed for the simultaneous collection of data on both the shallow and the deep underground strata. The primary receiver, the RC-200, made use of a cable that was forty meters long and was arranged in a layout that was ten meters by ten meters. The wire achieved an overall amplitude gain factor of 1400 by utilizing a total receiver area of 200

square meters, an amplitude gain factor of 7, and two twists. The secondary receiver, labelled RC-5, included a rectangular circuit spanning 0.5 meters by 0.5 meters, with twenty turns. The design yielded a total receiver area of 5 square meters, with the amplitude gain factor established at 7. This resulted in a total coil amplitude gain factor of 35. Three distinct measurement rounds were performed at each location to get an enhanced (SNR). The average current generated was 6.6 amperes.

All measurements were conducted simultaneously, incorporating both low and high points. In the initial periods, the low moment, defined by a current intensity of around 2 A, was calibrated for the detection of shallow subsurface strata. Conversely, the increased instant, possessing a current intensity of approximately 13 A, was designed to penetrate deeper geological strata to elucidate later temporal periods. User-defined script files were employed to alter the waveform characteristics of the transmitter. The script files included 39 receiver time gates. The overall measurement time was 7953 microseconds, which was divided into 39 gates. The shortest duration of each gate was 2 microseconds, while the longest duration was 1633 microseconds. During the measuring technique, ambient noise, which is a representation of natural background noise in both cases, is recorded and used to estimate the depth of investigation (DOI).

3.10. SPIA Processing and Inversion of TEM

TEM data were processed and inverted with the assistance of the Aarhus SPIA program, which was developed by Foged et al. (Foged et al., 2013), as well as SPIA (<https://hgg.au.dk/software/spia/>). Processing and inversion of TEM data were carried out with the assistance of SPIA. The effective AarhusInv inversion approach (Auken et al., 2015) was applied for the purpose of processing the filtered data with varied smoothing levels (low, normal, or high). This was done in order to achieve the desired results. The SPIA database is where the processed data and inversion models are kept after they have been stored. The findings can be viewed in the form of depth slices or cross-sections, and these models can be imported into Aarhus Workbench (Vignoli et al., 2015) immediately after they have been created.

3.11. The AMT Method

Simpson and Bahr (2005) describe the AMT process as an electromagnetic passive-source induction technique employed to ascertain the subterranean electrical conductivity of the Earth. The quantification of subsurface electrical conductivity is achieved through the use of transient magnetic (H) and electric (E) field measurements. The approaches of AMT and MT can capture electromagnetic waves through "passive methods" derived from global lightning events and the interaction between solar activity and the magnetosphere. Low-frequency signals, which are less than one hertz, are produced by the magnetosphere of the Earth, solar wind, sunspot activity, and auroras. Lightning strikes on a global scale generate audio sources with frequencies greater than one hertz, which are utilized in AMT surveys. Telluric currents that move horizontally through the Earth's crust as a result of electromagnetic radiation exchanges are tracked by MT and AMT surveys, which collect magnetic signals from these currents. Electric and magnetic fields are measured using sensors that have a variety of orientations, including magnetic and electric sensors. Within the context of data processing, the data is initially recorded as an interval sequence, and then it is translated to the frequency domain of interest. It is possible to calculate the transfer function, also known as the complex impedance matrix, by using the observed field in the frequency domain, as demonstrated by Equation 35. Utilizing the impedance components enables the determination of apparent resistivity and phase at appropriate frequencies. Upon completion of the MT data collection and processing, forward modeling and inversion yield mathematical models of resistivity distribution (1D, 2D, and 3D). Equation 36 illustrates the correlation between the vectors of the electric (E) and magnetic (H) fields. The impedance tensor (Z) denotes the ratio of the magnetic (H) and electric (E) fields. Equation 37 facilitates the calculation of the relationship among the impedance tensor components Z_{xx} , Z_{xy} , Z_{yx} , and Z_{yy} , as well as the electric and magnetic fields observable in the x (north-south) and y (east-west) directions [17].

$$E = ZH \quad (36)$$

$$\begin{pmatrix} Z_{xx}(\omega) & Z_{xy}(\omega) \\ Z_{yx}(\omega) & Z_{yy}(\omega) \end{pmatrix} \begin{pmatrix} H_x(\omega) \\ H_y(\omega) \end{pmatrix} = \begin{pmatrix} E_x(\omega) \\ E_y(\omega) \end{pmatrix} \quad (37)$$

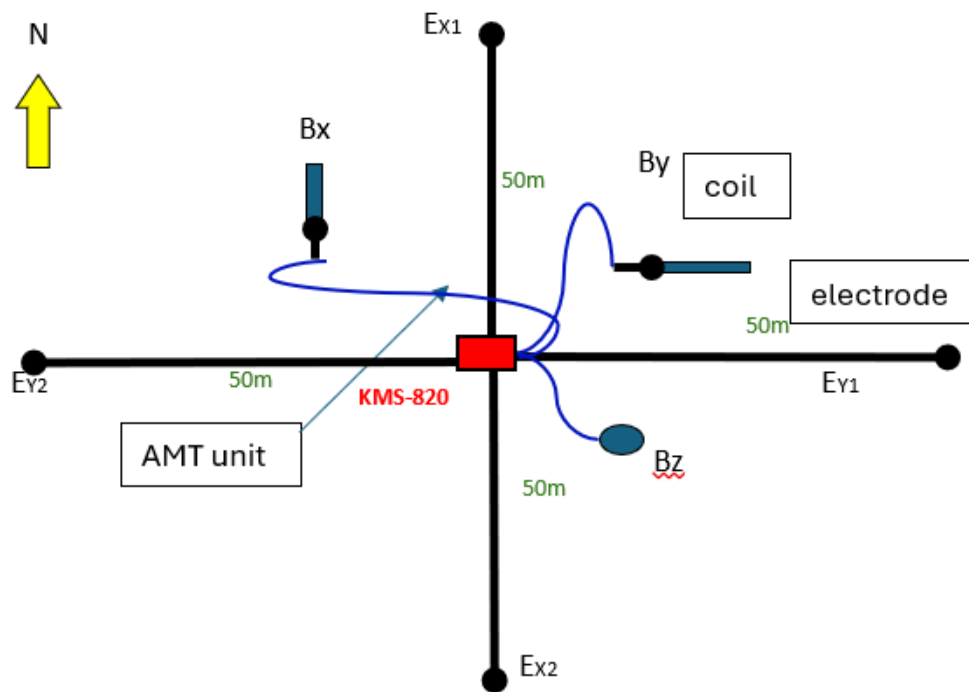
In order to get the apparent resistivity (ρ_a) and phase (φ) based on the impedance components, the formula that is utilized is as follows:

$$\rho_{a,i,j} = \frac{1}{\omega\mu} |Z_{ij}|^2, \varphi_{i,j} = \tan^{-1} \frac{\text{Im}Z_{ij}}{\text{Re}Z_{ij}}, i, j = x, y \quad (38)$$

In this context, ω signifies the angular frequency ($\omega = 2\pi f$, where f is the frequency in Hz), μ indicates the magnetic permeability of free space (1.2566×10^{-6} H/m), Z_{ij} relates to the element of Z , and $\text{Im}Z_{ij}$ and $\text{Re}Z_{ij}$ indicate the imaginary and real components of the impedance, consequently

3.12. AMT Instruments and Configuration

The AMT data were obtained via KMS-820 acquisition apparatus. The AMT data were gathered via LEMI-118 audio-MT induction coils. Nonpolarizable electrodes of the LEMI-701 type were utilized for the electric field in AMT tests. The KMSPro program was employed to analyze the time series of both MT techniques utilizing a stringent statistical methodology sanctioned by Smirnov (2003). Data was filtered at a sampling rate of 40 Hz using low-frequency filter settings and small FFT windows of 16, 32, and 64 samples. A high-frequency parameter employing a 65,000-sample FFT window was utilized to filter data at elevated sampling rates of 1 kHz, 4 kHz, 20 kHz, and 80 kHz. The notch filter was employed in data filtration to eliminate specific narrow frequency bands, such as 60 Hz interference from power lines, while preserving the integrity of the remaining bandwidth [18].



[Figure 3.8 Standard field setup and measurement for MT/AMT]

3.13. Field Procedures

The detailed field procedures are crucial for achieving excellent results in Audio frequency magnetotelluric methods (AMT) due to the small scale of the fields involved. Site selection and sensor placement are the primary determinants of data quality, with AMT surveys costing less than transient EM measurements under optimal recording conditions. TEM excels in scenarios necessitating tensor measurements, but AMT efficiently acquires tensor information across a broad area. Powerlines, pipelines, electric trains, electric fences, welding operations, smelters, irrigation pumps, radio and radar transmitters, urban areas, traffic, pedestrian activity, metal structures, large, grounded conductors, and other sources that affect the electric field all have an impact on the site selection structure. Equipment should be packed and taken out before leaving the place overnight, with the exception of electrodes that are meant to be used the next day. Magnetometers necessitate shielding from wind and sunlight, and the installation of horizontal, permeable core induction coils may be difficult based on soil conditions. Electrodes should be positioned several hours before utilization in shallow water saturation for cavities and insulated to reduce evaporation and temperature variations. Increased contact resistance may lead to noise and

signal degradation; hence, impedance-matching amplifiers are advised to enhance resistance. In remote reference acquisition, assessing the reference site's location and the applied methodologies is crucial. Data gathering can be accomplished by radio telemetry, hardwired connections, or synchronized recording. The features of the main noise source determine the distance between the reference and data sites. The distance between locations and the duration required for data collection affect the cost of the survey.

The optimal proposal for the minimal duration is derived from the inversion of presumed models. This inversion can rapidly yield, with noise hypotheses, the requisite frequency band and recording period to detect a specified target. The durations for petroleum exploration recordings range from half a day to two days. In geothermal contexts, a length of half to one day is standard; however, in AMT surveys, we designate 2 to 6 hours on field, based on intensity of the signal. The small station interval depends on the conductivity structure and the required degree of horizontal resolution. Traditional tensor investigations utilize intervals of 10 km for reconnaissance, whereas 0.5-1 km or less are used for greater level of detail. It became evident that MT, similar to the reflection seismic method, sometimes encountered what are now referred to as "statics" issues as the technique gained traction and reduced spacings were employed for enhanced lateral resolution. The lateral conductivity fluctuations might be significant but superficial, causing complete apparent resistivity curves to move vertically. This topic is discussed in this chapter. Protocols have been established to mitigate this issue. The EMAP (stands for Electromagnetic Array Profiling) technique is the most complex, requiring constant measurements of the electric field along a profile. This is accomplished by utilizing a multiconductor seismic cable with takeouts to electrodes situated roughly 100 meters distant. The longitudinal fluctuations in the electric field diminish over distances that align with the skin depth at the designated frequency and location, employing a spatial filter on the electric field data array. EMAP employs a single local and a single remote magnetometer for pragmatic reasons. A later section will address how EMAP data is processed and presented. By the late 1990s, broad multichannel receivers emerged, enabling the simultaneous digital recording of several channels. These developments will undoubtedly impact field methodologies, facilitating data collecting at more proximate

sites at a manageable cost. Theoretically, the same apparatus can be used for applied field measurements, reducing the expenses related to the static correction procedures [19].

3.14. Half-space Model and Empirical Data

For the purpose of evaluating the approach, two distinct scenarios were studied. With regard to both of these instances, the soundings were performed over a fundamental half-space. The first incident took place in a precise scale tank, while the second occurrence took place at the Bonneville Salt Flats in Utah, which is an area where a low and consistent resistivity has been proved to cover a vast territory. Both of these occurrences occurred in Utah. This particular model was tested in a big tank that had dimensions of 300 centimeters by 300 centimeters by 75 centimeters and was filled with a solution of ammonium chloride. A measurement of the solution's resistivity was taken at a value of 0.074 ohm-m. For the experiments that were carried out at a frequency of 150 kHz, the phase-lock amplifier (HR-8) manufactured by Princeton Applied Research served as both the source and the receiver devices. Platinum was used to construct the transmitting and receiving electrodes, and a high-frequency choke coil that was designed to be compact was used to construct the receiving coil. Electromagnetic and electric field measurements were carried out with the required degree of caution, which led to a significant degree of congruence between the actual results and the theoretical predictions [20].

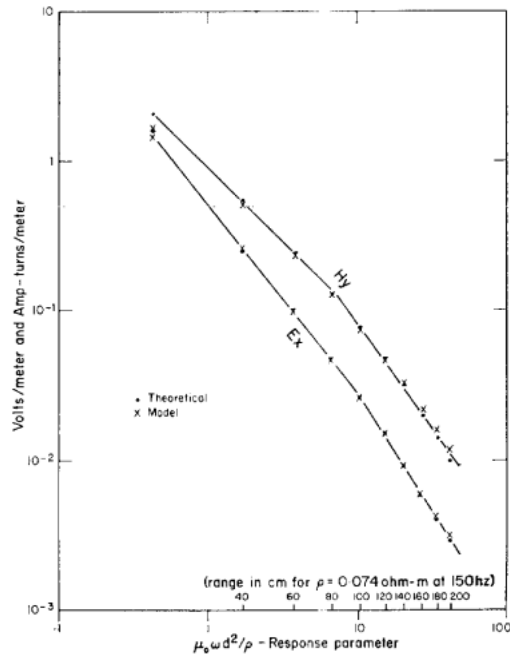


Figure 3.9 The values of E and H are displayed as a function of the experimental response parameter. The alignment of theory and model is superb. Along the y-axis, there was a model-theoretic correlation identified between the electric and magnetic fluxes. At a frequency of 150 kHz, the values are 0.074 ohms, which is equivalent to volts per meter and ampere-turns per meter. (Goldstein & Strangway, 1975).

3.15. Source of the Currents

The explanation does not address the origin of the relevant currents. Regardless of whether the origins of these currents are internal to the Earth's crust or ionospheric, and whether they are natural (genuine telluric currents) or manufactured (vagrant currents), the electromagnetic phenomena within the Earth remain consistent in all instances. The rationale relies solely on the necessity for the telluric current sheet to be adequately uniform. This uniformity is contingent upon experience. Telluric prospecting demonstrates that in extensive sedimentary basins, this consistency approximately spreads over a significant area, often over ten kilometers in breadth. Such homogeneity should be anticipated even more when one considers the highly limited scope involved in a magneto-telluric comparison. Vagrant currents, due to the closeness of their sources and the inadequate regularity of the associated sheets, are regarded with apprehension by telluric prospectors. Conversely, magneto-telluric prospectors regard them as advantageous, as

they provide adequate regularity to satisfy the criteria of the novel method and effectively broaden the frequency band.

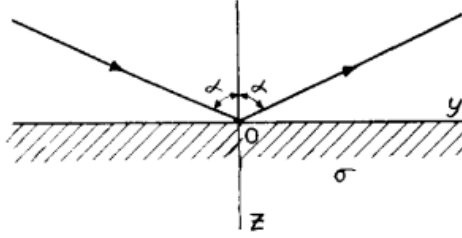


Figure 3.10 Plane electromagnetic wave incident upon Earth's surface.

Geophysics readers, including this author, primarily focus on subterranean phenomena and exhibit minimal interest in aerial occurrences. Nevertheless, it may be beneficial to contemplate for a brief period the characteristics of the electromagnetic phenomena encompassing the environment. In the atmosphere, where we set $\sigma = 0$, equation (16) simplifies to $\frac{\partial^2 E_z}{\partial z^2} = 0$. E_z manifests as a linear function of z , whereas H_y remains constant:

$$E_z(z) = E_z(o) + i\omega z H_y; \quad E_z = E_y = 0 \quad (39)$$

$$H_y(z) = H_y(o); \quad H_x = H_z = 0 \quad (40)$$

This type of solution may astonish the reader. It is known that the E_z component, which is right angle to the surface of the magnetic field experiences rapid fluctuations, which are correlated with the horizontal one of the same fields. However, the actual solution indicates that it is null. It is important to remember that, in expression (13) of Maxwell's equations, we have first regarded the speed V of electromagnetic waves in the ground, as well as the speed c of those waves in a vacuum, as infinite. We have initially replaced the genuine phenomenon of propagation with a fictional stationary phenomenon. The approximation was enough for our computations, but it did not provide a precise representation of the underlying physical events. Assume that in the oyz plane strikes the ground surface at an angle of incidence α (Figure 3.4). To fulfill the boundary conditions at the ground surface, the equations for the characteristic vectors of the three waves (incident, reflected, and refracted) must include the following factors,

respectively: The coefficient of i in the imaginary component of K must uphold an optimistic perspective. We first defend the form of the phrases (17) that we initially picked as a starting point. Subsequently, we observe that an infinite array of potential waves in the atmosphere may correlate to a provided wave in the substrate. (Y is entirely arbitrary since it does not manifest in (zz) , although the polarization condition of the incident wave persists completely random. One is permitted to conceive various atmospheric occurrences, with no specific requirement the E_z component, which is at right angle to the surface of the magnetic field be null or insignificant. In accordance with the aforementioned strategy, the comprehensive statement for firstly, it is essential that the formulations for the characteristic vectors of the three waves (incident, reflected, and refracted) encompass, respectively, the following factors:

Incident Wave:

$$e^{-i\omega(t-y\sin\alpha+\cos\alpha/c)} \quad (41)$$

Reflected Wave:

$$e^{-i\omega(t-y\sin\alpha-\cos\alpha/c)} \quad (42)$$

Refracted Wave:

$$e^{-i\omega(t-y\sin\alpha+K/c)} \quad (43)$$

The constant K is selected to fulfill the equation.

$$\nabla^2\Pi + \Pi\left(4\pi\sigma\omega i + \frac{\omega^2}{v^2}\right) = 0 \quad (44)$$

Consequently, it is imperative that:

$$K^2 = \frac{c^2}{v^2} - \sin^2\alpha + i\frac{4\pi\sigma c^2}{\omega} \quad (45)$$

However, while $(\frac{c^2}{v^2} - \sin^2\alpha)$ reaches its maximum value of one, it occurs that the coefficient of i is substantial. For example, when $\rho = 10 \text{ } \Omega\text{m}$ and $T = 30$ seconds, it is equivalent 5.4×10^{10} , allowing for a practical and very accurate approximation.

$$K^2 = 2\sigma c^2 T e^{i\pi/2} \quad (46)$$

$$K = C \sqrt{2\sigma T} e^{i\pi/4} \quad (47)$$

Considering that the coefficient of i in the imaginary component of K must be positive. We first defend the form of the phrases (17) that we initially picked as a starting point. Subsequently, we observe that an infinite number of potential atmospheric waves can correspond to a specific wave on the ground. The left is entirely random, as it is absent in (22), and the polarization state of the incident wave is also fully arbitrary. One is permitted to conceive many atmospheric events, and no specific condition mandates that the polarization state of the hitting wave remains entirely arbitrary. Therefore, acceptable to conceptualize several atmospheric phenomena without the necessity for the E_z component, which is at right angle to the surface of the magnetic field, to be nonexistent or insignificant (Cagniard, 1953).

CHAPTER 4

DATA ACQUISITION

4. Data Acquisition

Figure 4.1 shows the workflow sequence of the geophysical field work the Audio frequency Magnetotelluric AMT and Transient Electromagnetic or time Domain Electromagnetic.

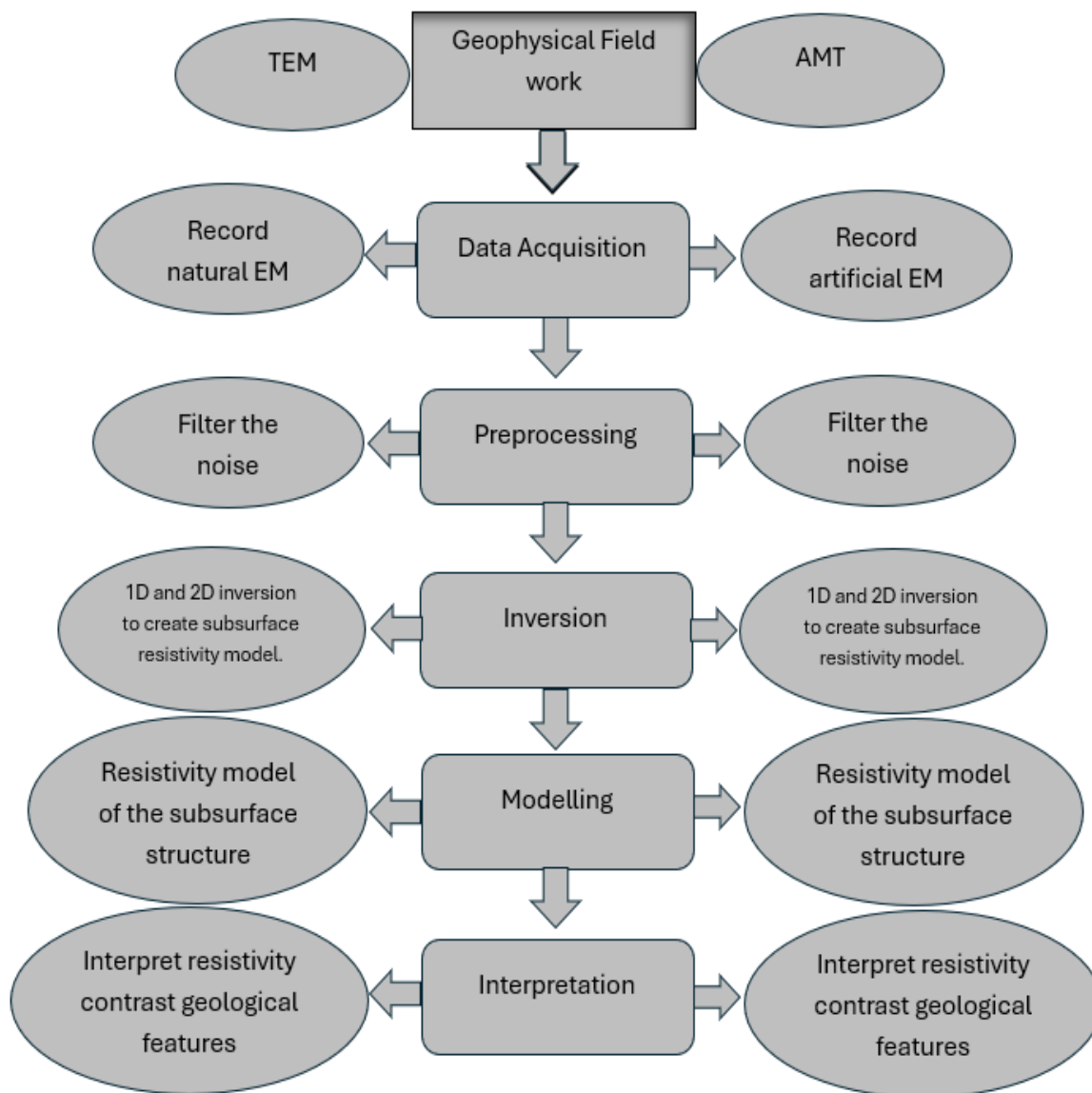


Figure 4.1 Show workflow for the geophysical methods, Transient Electromagnetic TEM and Audio Frequency Magnetotelluric AMT

4.1. Time Domain Electromagnetic Method

The area north of Riyadh and the TEM profile are employed to produce quasi-2D resistivity sections and depth slices that reconstruct the subsurface by data inversion. Figure 4.4 illustrates the SW-NE profile, with a ten-day duration from November 17 to November 26, 2023. This profile includes around three to four stations daily, spanning a total distance of 136 kilometers across thirty TEM stations, with a separation of five kilometers between each station. It is essential to augment the distance between station locations to facilitate the deeper targeting aquifer and the heightened importance of resolution in this context. Figure 4.2 illustrates the transient electromagnetic setup employed in the investigation. An increase in loop size enhances the depth of study for a 100×100 transmitter loop and a 10×10 receiver loop.

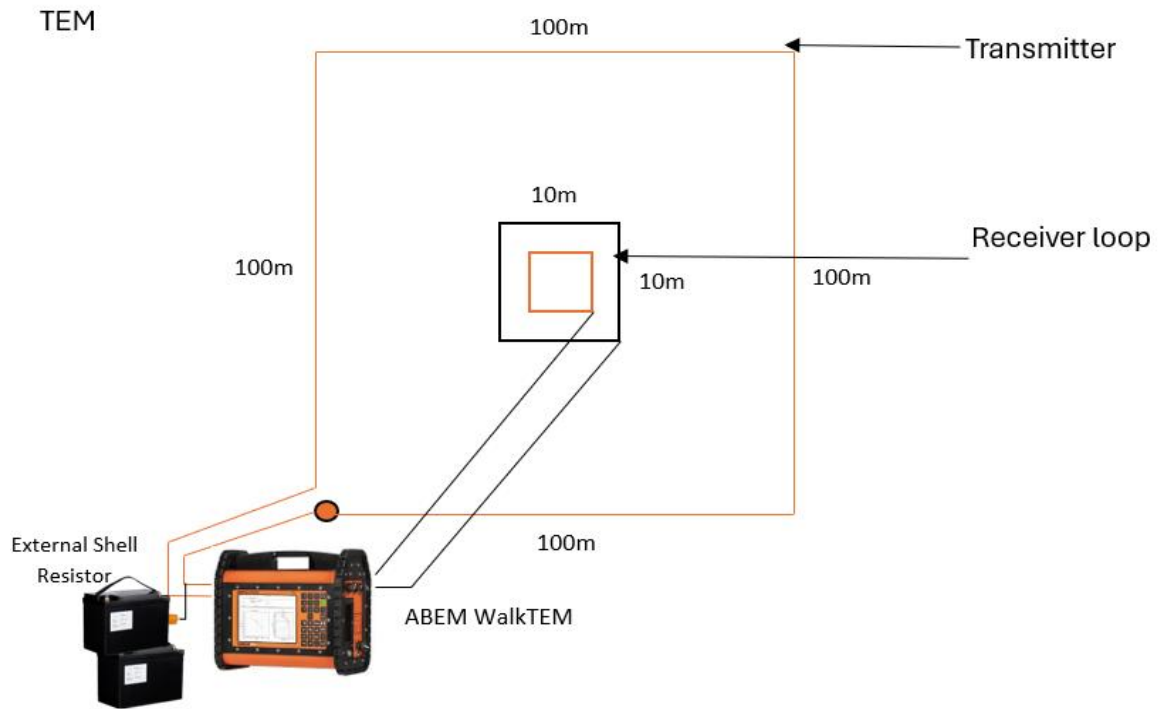


Figure 4.2 Standard TEM field configuration and measurement.

Utilizing both TEM and AMT methods, which are sensitive to resistive or conductive layers, is the optimal approach for the Minjur aquifer, addressing both the upper freshwater and lower saline sections, while offering a more thorough understanding of the subsurface at shallower (TEM) and deeper (AMT) depths.



Figure 4.3 Showing TEM device that use the conducting the measurement

The profile intersects significant geological features, and accessibility within the study area influences the profile's orientation.

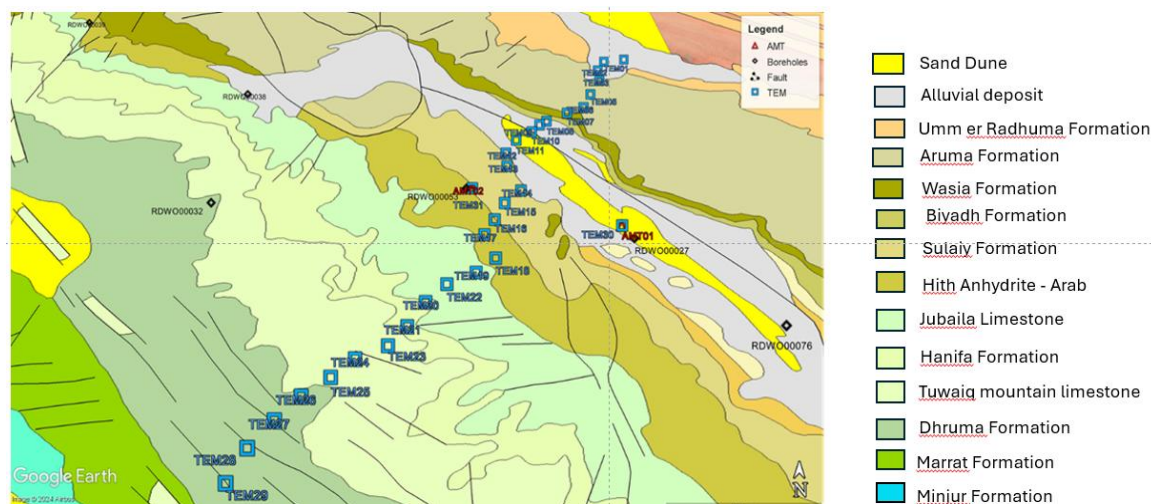


Figure 4.4 A profile of 29 TEM geophysical soundings incorporated to the different geological formations and tectonic zones.

4.2. Audio Frequency Magnetotelluric

The two AMT “Audio frequency Magnetotelluric” in the NE eastern part of the profile one on the SE of the profile and other in NW of the profile, stations adjacent to the borehole facilitate the calibration and correlation of geophysical data interpretation with the lithology and hydrogeology of the borehole. AMT measurements were conducted for

roughly 25 minutes with three distinct sampling frequencies: 4 kHz, 20 kHz, and 80 kHz[18]. Figure 4.5 shows Standard field setup and measurement configuration.

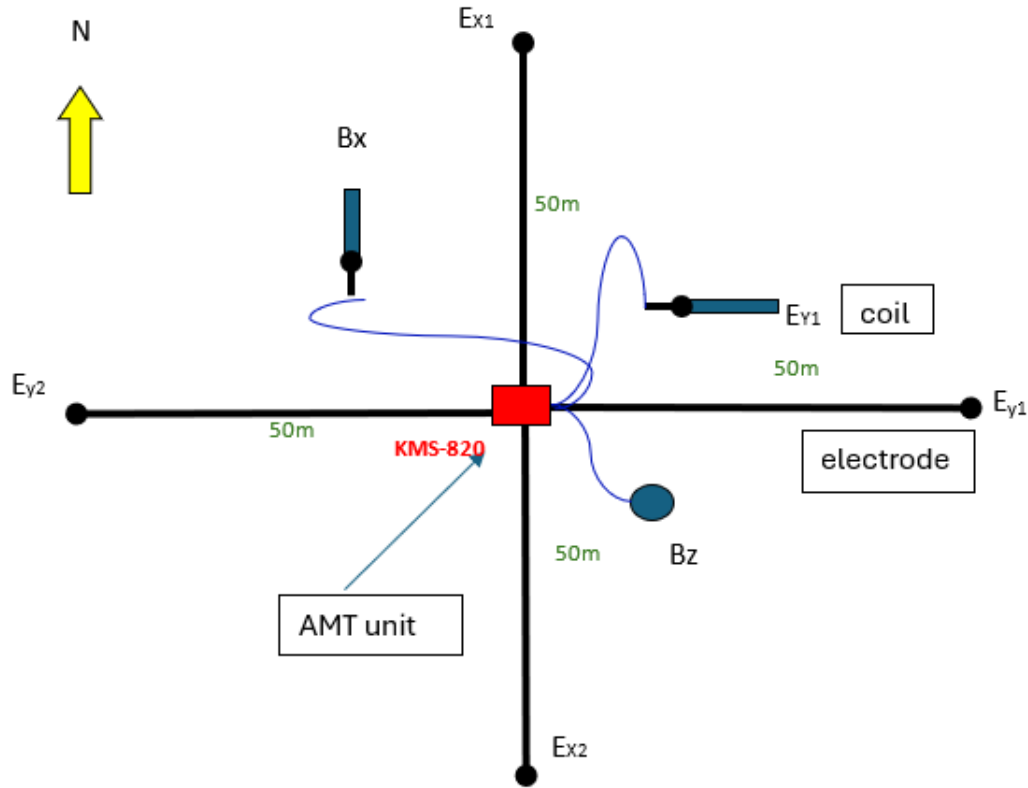


Figure 4.5 Standard field setup and measurement for AMT]

Each and every survey site is equipped with electrode pairs for the purpose of measuring the electric field (E field), and magnetometers are utilized for the purpose of measuring the magnetic field (H field). The electrical conductivity of the subsurface has an effect on the amplitude, phase, and directional relationships of the electric and magnetic fields that are present at the surface of the Earth. The designations "Ex" and "Ey" signify that the measured electric field comprises two different elements. Letters "Hx" and "Hy" represent the measured components of the magnetic field [22].

An AMT survey station comprises the burial of three magnetic sensors oriented in the X, Y, and vertical axes, along with four porous pot electrodes positioned in four orthogonal directions. At each station, the magnetic and electric fields are recorded over a duration ranging from hours to days to generate a one-dimensional time series measurement [23].



Figure 4.6 The unit of the AMT setup and measurement.



Figure 4.7 The Whole unit of the AMT four electrode, three coils, cables and PC to run the unit.

The coil is positioned in order to capture the electromagnetic field that is present in nature, and the leveller is employed to guarantee that the coils are properly orientated in order to prevent measurement mistakes that are caused by tilting. In order to determine the electric field (E), electrodes Ex1, Ex2, Ey1, and Ey2 are utilized to measure the field along the N-

S and E-W directions. The magnetic field, denoted by the letter H, is measured in the same horizontal direction, Bx, as well as in the same directions, Bz.



Figure 4.8 Leveling and fixing the cable.

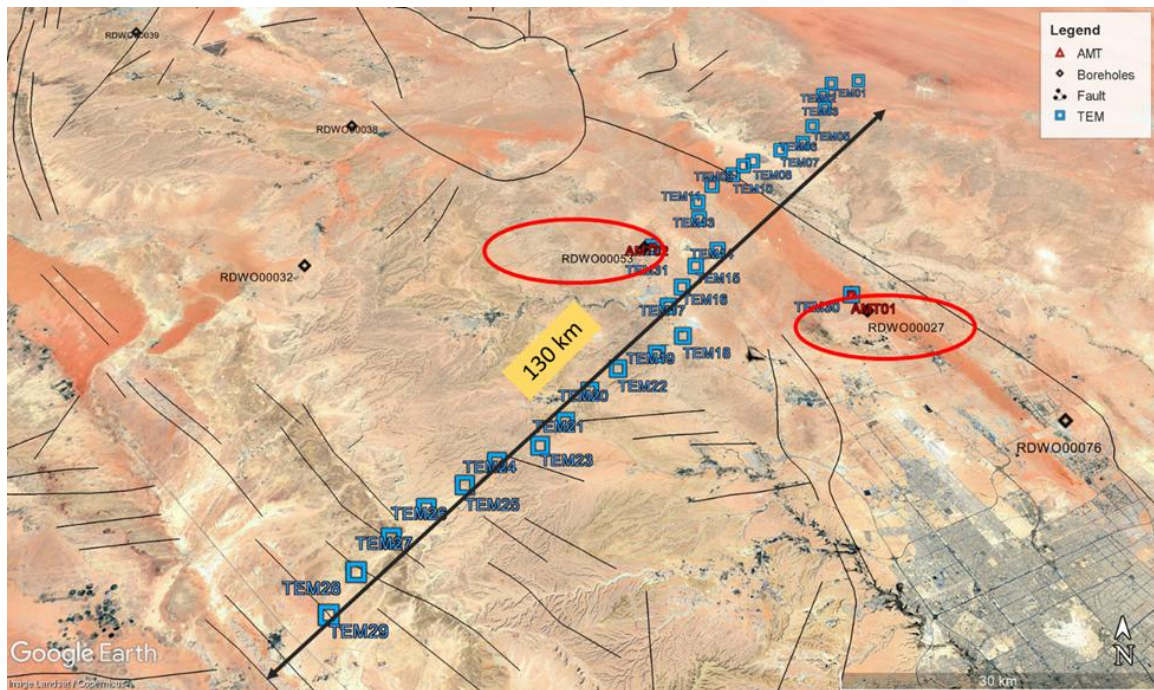


Figure 4.9 NE – SW Profile of 31 TEM and 2 AMT sounding of 136 Km.

There are many criteria for electromagnetic measurement selection based on accessibility, proximity to targets, and minimum noise interference such as way from power lines fences, and urban areas flat topography for uniform measurements.

At least 1-2 km away from high noise sources such as airports or industrial zones. Cagniard in 1953 mentioned that electromagnetic phenomena inside the planet are the same regardless of whether the currents originate from the ionospheric or crust of the earth, from natural sources (real telluric currents) or manufactured ones (vagrant currents). The justification relies solely on the telluric current sheet's need to be sufficiently uniform. However, this homogeneity depends on personal experience. Telluric prospecting demonstrates that in large sedimentary basins, this homogeneity roughly covers a sizable area, frequently ten kilometers across. If one merely takes into account the extremely limited field that comes into a magnetotelluric comparison, then such uniformity should be expected even more. Vagrant currents Telluric prospectors fear vagrant currents because of the proximity of the sources that generate them and the low level of homogeneity of the sheets associated with such artificial currents. On the contrary, magneto-telluric prospectors view them as a boon as they provide enough homogeneity to satisfy the new method's requirements, and they effectively broaden the frequency band.

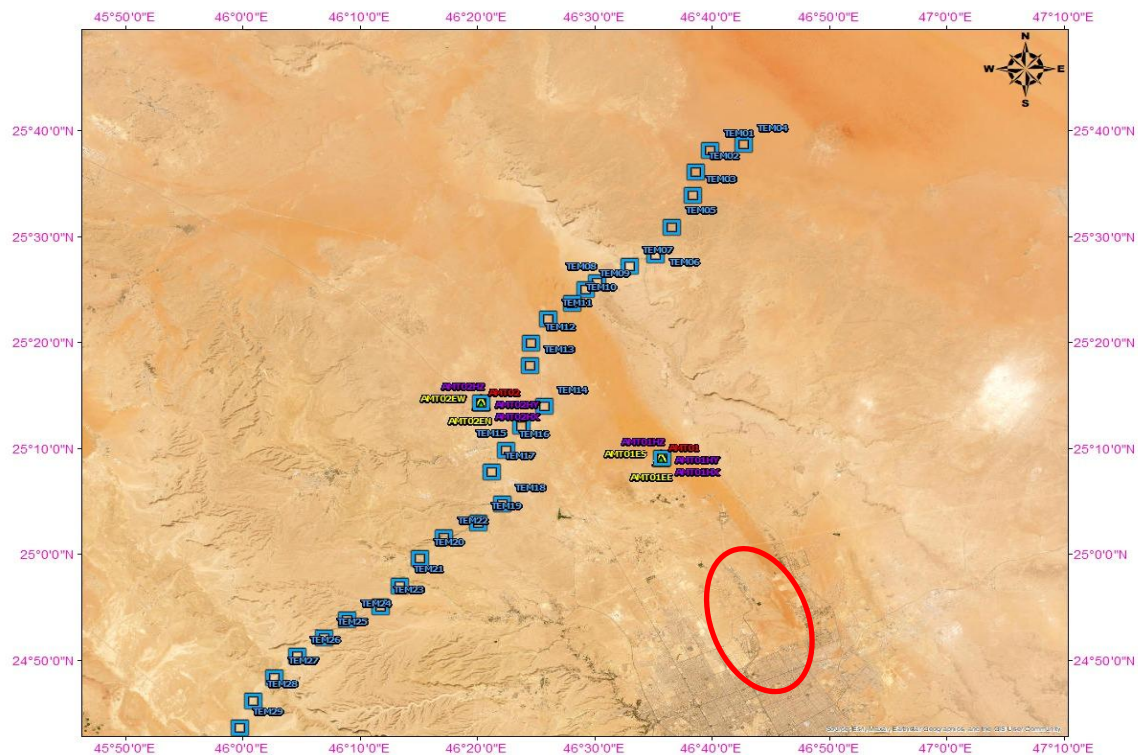


Figure 4.10 The King Khalid airport in the Riyadh area and the study area profile.

CHAPTER 5

RESULTS AND DISCUSSION

5. Results and Discussion

5.1. Transient Electromagnetic Result

The Aarhus SPIA program, which was developed by Foged et al. (2013), and SPIA (<https://hgg.au.dk/software/spia/>) were utilized in order to process and invert the TEM data after it had been collected. To perform an analysis on the filtered data, the efficient AarhusInv inversion method (Auken et al., 2015) was utilized, in addition to a number of different smoothing levels (low, normal, or high). The SPIA database stores the processed data as well as the inversion models. These models may be readily loaded into Aarhus Workbench (Vignoli et al., 2015) in order to present the findings in the form of depth slices or cross-sections [18].

5.1.1 1D Model of TEM

Figure 5.1 employs a logarithmic scale, with time in seconds represented on the x-axis and dB/dt on the y-axis. The left graph illustrates the raw data, A dual-moment setup was utilized to do each measurement simultaneously with low and high moments featuring a curve divided into two segments: the green line signifies the higher moment or initial phase of magnetic field decay, while the blue segment indicates the lower moment or later stage of decay, characterized by a decrease in signal and amplitude. The data on the right graph corresponds to the one-dimensional model following the inversion.

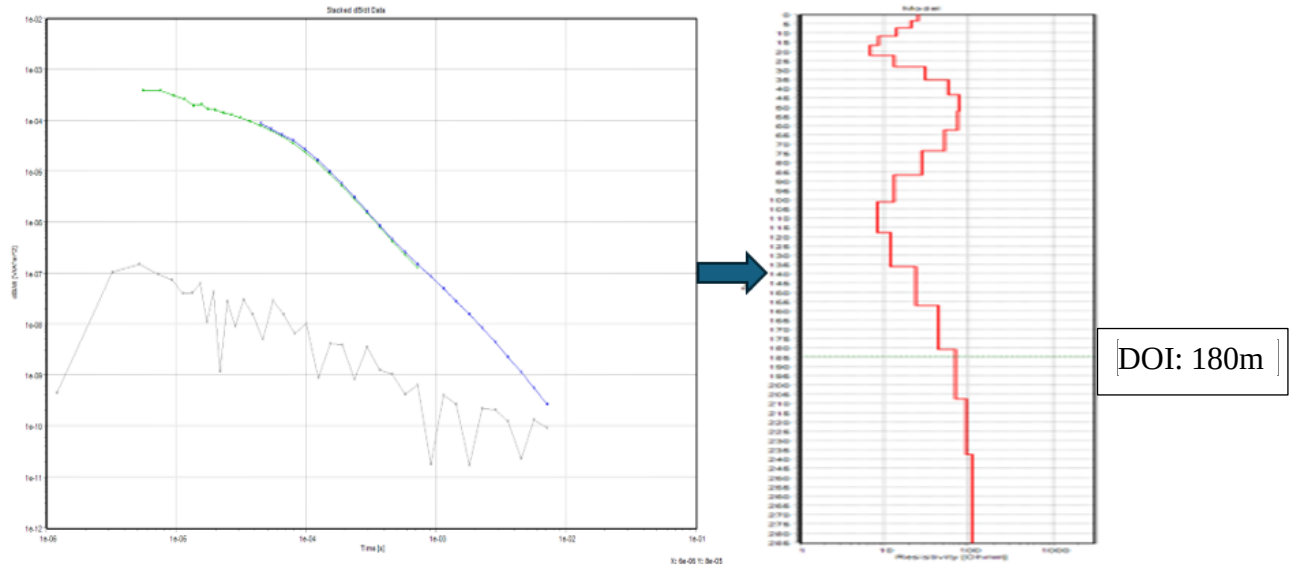


Figure 5.1 The Raw data of the TEM field Shallow moment and Deep moment and the noise (TEM 01) and the 1D model of the TEM field resistivity and depth (TEM 01).

5.1.2 2D Model of TEM

The 2D geoelectric section of the subsurface, extending 136 km in a NNE-WWS direction with 5 km intervals, is depicted in the image, where the red arrows indicates the station points in the field position, while black dashed lines is sharped boundaries of resistivity contrast and the question marks is expected to be tectonic features (faults or Fracture) with saline water.

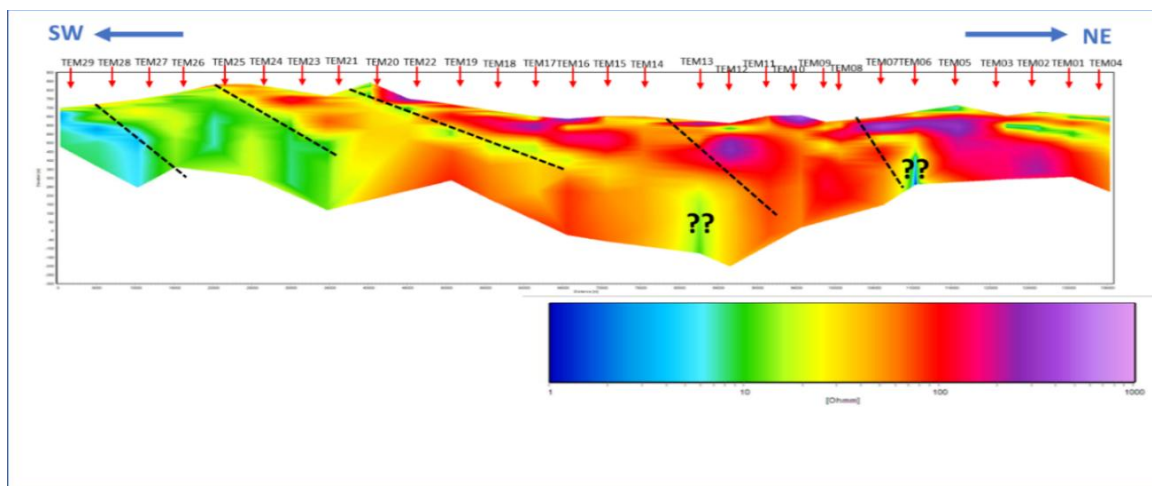


Figure 5.2 The 2D inversion result profile of the TEM field resulted from 30 stations with 136 km length targeting deferent formations and geological features. North of Riyadh area.

5.1.3 2D Geoelectric Section with Related to Geology of Study Area

The initial five TEM stations, 25, 26, 27, 28, and 29, located in the southwest over the Dhurma formation, exhibit the lowest resistivity values in the 2D section. There are two distinct zones: the first zone has strong conductivity (low resistivity) of less than 5 Ωm consider to be caving or karstic zone from dissolution of one of the chemical rocks (Anhydrite), while the second zone has a resistivity of approximately 13 Ωm . The Dhurma formation comprises lower shale with gypsum, a middle limestone interspersed with clean calcarenite, and a higher shale having limestone in its lower half (Hisyan Member). The Marrat formation, underlying the area of Dhurma formation, comprises a soft red shale surrounded by resilient limestones.

The Tuwaiq, Hanifa, Jubaila, and Sulaiy Formations are carbonate composition in general, while it exhibiting resistivity values of 100 Ωm , the areas of both low and high resistivity as indicated by TEM station 17, 18, 19, 20, 21, 22, 23, and 24. The Arab Formation is mostly composed of carbonate, with some dolomite and anhydrite, while the Hith Formation predominantly consists of substantial anhydrite. TEM 16, 17, and 18 exhibit high resistance over 100 Ωm . The Biyadh and Wasia (Sakaka) Formations consist of siliciclastic rocks, specifically sandstone and shale. Conglomeratic strata are located beneath TEM stations 7 and 8 in Biyadh. The Aruma Formation predominantly comprises limestone, partially replaced by significant dolomite. Subordinate shale and impure dolomite are predominant, particularly throughout the upper 25 to 35 meters. Is represented by the low conductivity or high resistivity zones over TEM 3, 5, and 6. The Umm er Radhuma formation comprises a recurring sequence of limestones, silicified limestones, and sporadic chert, overlain by superficial deposits. It exhibits zones of low resistivity at 10 Ωm within the upper 200 m, interbedded with 30 Ωm in TEM 1, 2, 3, and 4 in the far northeastern of the 2D profile section.

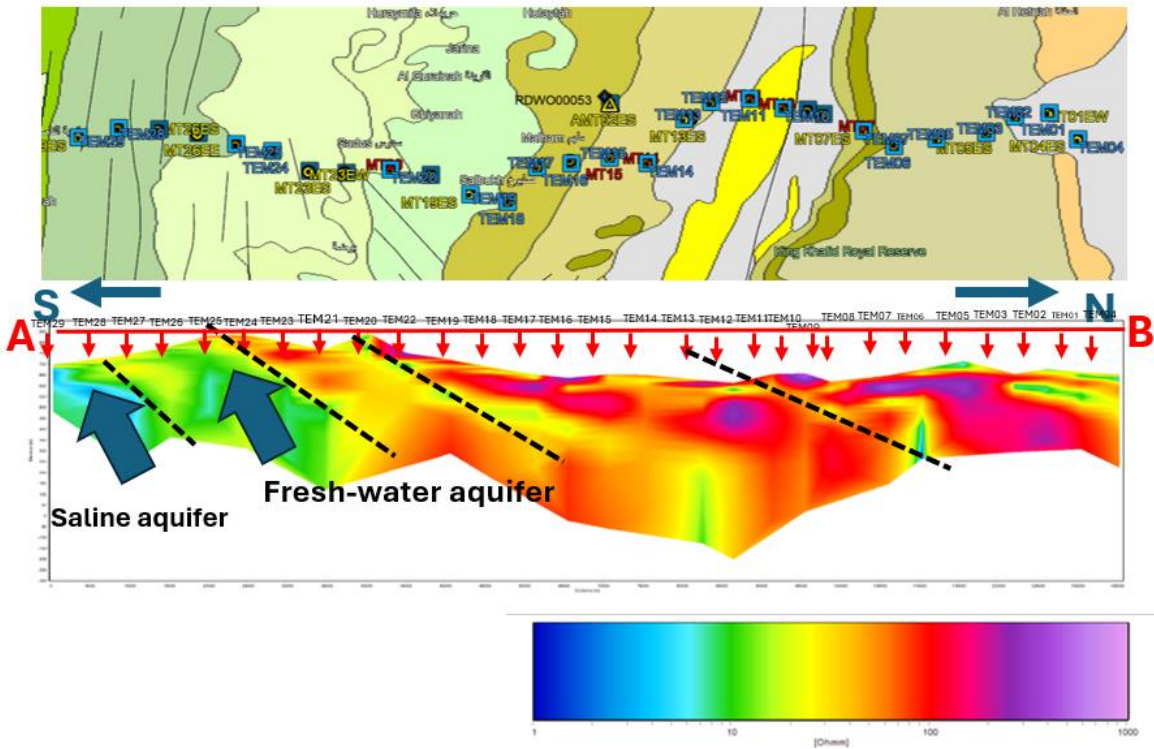


Figure 5.3 The 2D inversion result profile of the TEM with related to the geology of the study area.

5.1.4 3D Model of TEM

The segment illustrated in figure 5.2 is utilized to create the five depth slices depicted in figure 5.5. The slices are as follows: A: 0-100 meters, B: 100-200 meters, C: 200-300 meters, D: 300-400 meters, E: 400-500 meters. Figure 5.4 illustrates the distribution of resistivity at different depths.

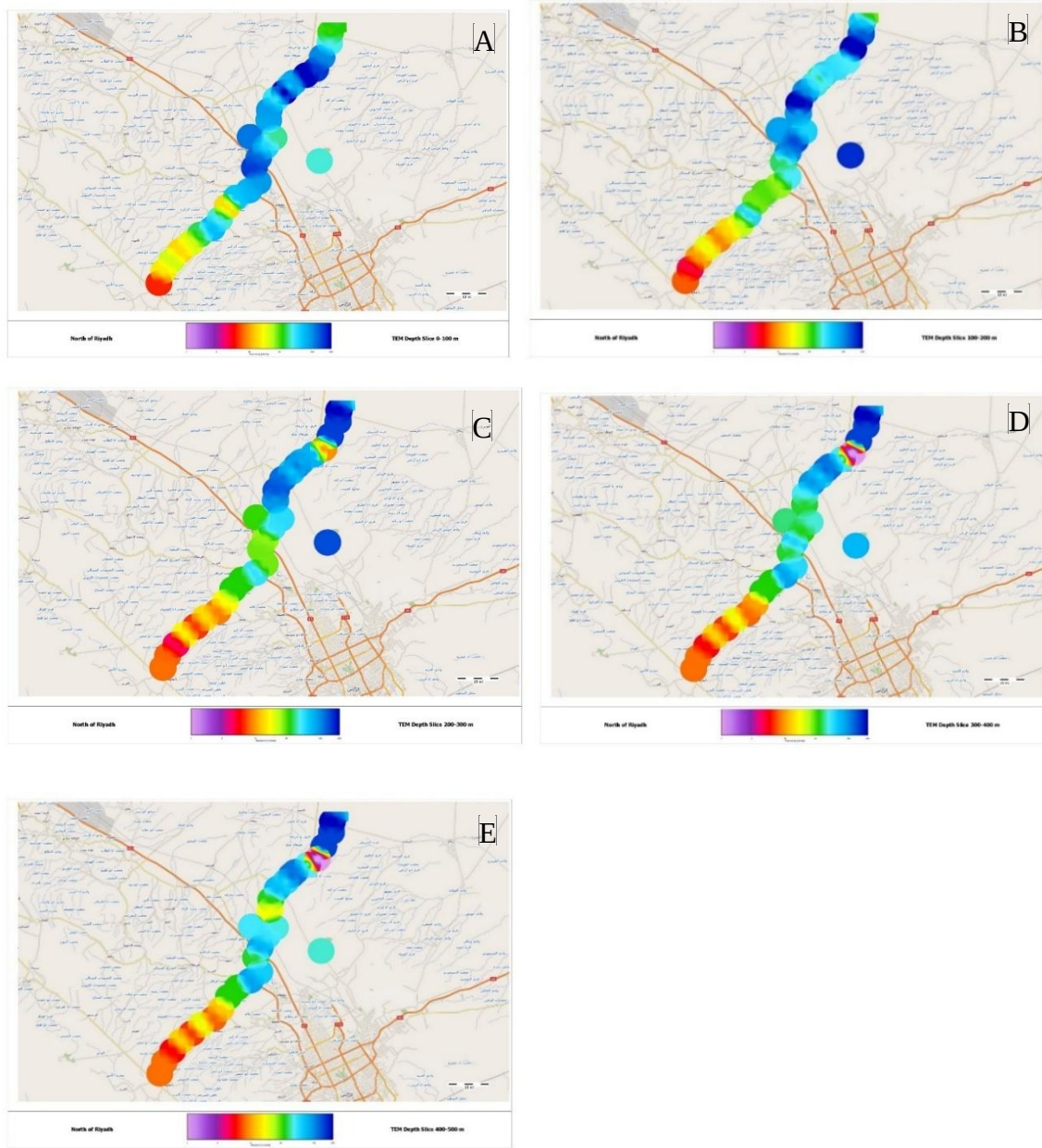


Figure 5.4 The results of the quasi-2D TEM inversion performed using the time-domain electromagnetic (TEM) data belonging to the research region are shown in Parts A–E. The 2D resistivity model is composed of X- and Y-sections that are spaced exactly 100 meters apart. You will notice an increase in depth as you move from left to right and from top to bottom.

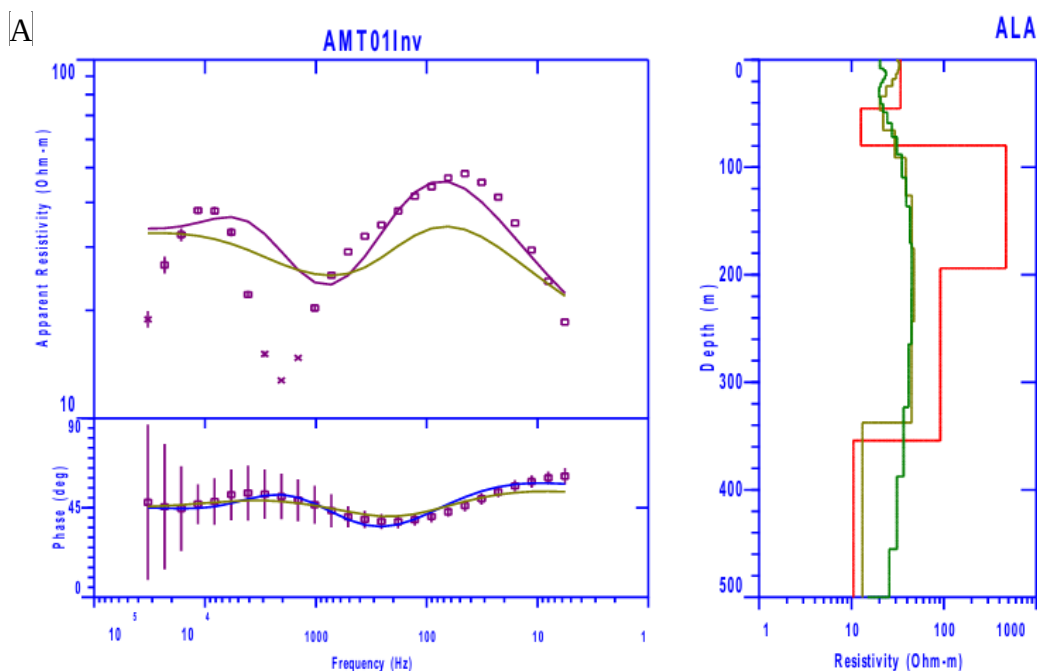
5.2. Audio-Frequency Magnetotelluric Result

The frequency range covered by the AMT readings is around 1 Hz to 80 kHz. During a period of about 25 minutes, AMT measurements were conducted using three distinct sampling frequencies: 4 kHz, 20 kHz, and 80 kHz. According to Smirnov (2003), a

rigorous statistical technique was used to examine the time series AMT operations in KMSPro. For data processing at a sampling rate of 40 Hz, low-frequency filter parameters were chosen with short FFT windows of 16, 32, and 64 samples; for data processing at higher sampling rates of 1 kHz, 4 kHz, 20 kHz, and 80 kHz, high-frequency parameters with an FFT window of 65k samples were used. The data filtering process made use of the notch filter to remove 60 Hz interference from power lines and other limited frequency bands while maintaining the integrity of the remaining spectrum.

1D Model of ATM

Two panels make up Figures 5.5 A and B. The left panel depicts the apparent resistivity and phase as a function of frequency, whereas the right panel shows the opposite. The upper section of the graph illustrates the apparent resistivity in ($\Omega \cdot m$) as a function of frequency in hertz (Hz), while the lower section illustrates the phase of the impedance as a function of frequency. Resistivity is plotted against depth in meters in the right panel, with the horizontal axis representing resistivity and the vertical axis representing depth. Figure 5.5 A displays the resistivity versus depth up to 500 meters, and figure 5.5 B shows the resistivity against depth up to 400 meters.



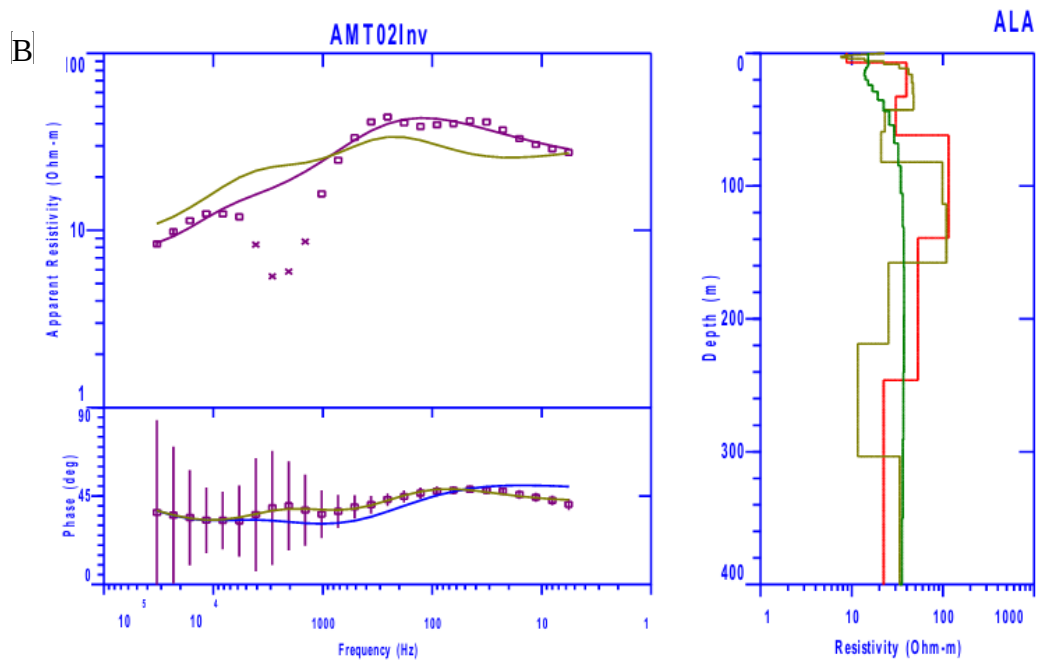


Figure 5.5 The Audio-magnetotelluric sounding curves and inversion 1D model for A and B.

5.3. AMT Method and CO2 Storage

The AMT method, an advanced geophysical technology that aids in identifying conductive or resistive "upper freshwater and lower saline Minjur aquifer" subsurface rock formations, can be used to reach further research depths. The shallow subsurface structures can be found and identified more successfully using the TEM and AMT techniques. In the studied area, the TEM and AMT techniques were quite successful in revealing details about the subsurface geology. When the two approaches were used together, one outcome was obtained. By utilizing the effective TEM and AMT surveys, the stratigraphic succession of the study area and the overall geological succession, as well as structural trends, were established. The changes encompass thumping patterns, and they spread across regions. The conductivity characteristics of the subsurface layers were easily characterized using both methods. TEM and AMT data yielded excellent images of 2D electrical profiles. Integrating TEM and AMT with the study site enabled a thorough understanding of subsurface layers. However, no additional observations were observed. Consequently, the models provided were both informative of the geological structure and beneficial as a

means of forecasting hydrogeology in the area being examined. This study highlights problems related to obtaining or processing primary datasets as the importance of methodological integration in geophysical surveys.

5.4. Conclusion:

The methodological approach of TEM and AMT successfully characterized the geological with resistivity variation of the study area. The result of TEM method in 1D, 2D and 3D inversion models gave a comprehensive understanding of subsurface geoelectric properties, bringing to view the most relevant geological features and stratigraphic units. The TEM result outlined the resistivity contrast of several geological units such as the Dhurma, Tuwaiq, Hanifa, Jubaila, and Sulaiy formations, Umm er-Radhuma, and Aruma Formations. Ones with low resistivities in the SW part of the profile indicated saline aquifers, while the relatively higher resistivity in comparison to the first one, is overly the previous one is carbonate formations or dolomites, were indicative of potential freshwater aquifers. The result is further confirmed by the AMT data, which is applied to get more deeper information but it still with the same depth of TEM methods also it provides additional information of resistivity for interpretation. The thickness and lateral discontinuities of the lithological units compose the study area are depicted. The different quality of water in the local aquifers is also presented. Finally, some fracture zones are detected. The study has shown that integrated data of TEM and AMT provide higher resolutions and reliable subsurface models to identify the lithological and tectonic features accurately. These results are beneficial for groundwater exploration and regional geology. Future research might utilize more geophysical methods to enhance resolution and depth of examination or to optimize inversion models. Concerning CO₂ storage by the AMT method, we could not outline the deeper geology and structure of the study region; however, we deem the results of the TEM and AMT enough for comprehending the subsurface. We possess extensive geoelectric data in both 2D and 3D regarding the subsurface of the study area, revealing a resistive zone with resistivity exceeding 500 ohm.m, a very low resistivity zone around 4 ohm.m indicative of a weak zone (caving or karstic zone), and relatively low resistivity zones of approximately 11 and 13 ohm.m, this information is now suitable for the geomodeler to develop future conceptual models.

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Vitae

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