

**THE USE OF GEOPHYSICAL METHODS IN
GEOTHERMAL EXPLORATION OF THE
WADI AL LITH FIELD IN WESTERN SAUDI
ARABIA**

BY

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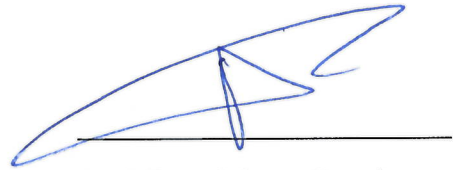
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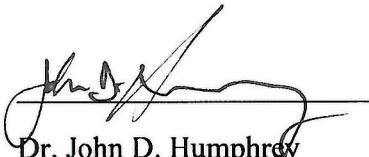
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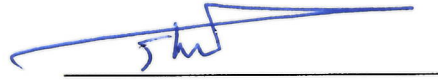
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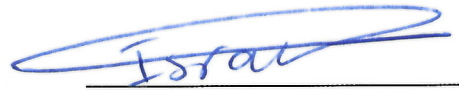
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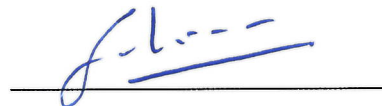


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2024

*This PhD thesis is dedicated to my parents, whose unwavering support and inspiration
have helped me to achieve my dreams.*

To my deceased relatives, your memory lives on through these pages.

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LIST OF ABBREVIATIONS

1D	:	One-dimensional
2D	:	Two-dimensional
3D	:	Three-dimensional
AMT	:	Audio Magnetotelluric
AS	:	Analytic Signal
CBA	:	Complete Bouguer Anomaly
CCUS	:	Carbon Capture, Usage, and Storage
CE	:	Common Era
CET	:	Centre for Exploration Targeting
CO₂	:	Carbon Dioxide
CORS	:	Continuously Operating Reference Station
CSAMT	:	Controlled-Source Audio Magnetotelluric
CSEM	:	Controlled-Source Electromagnetic
DEM	:	Digital Elevation Model
EGS	:	Enhanced Geothermal System
ERT	:	Electric Resistivity Tomography

EM	:	Electromagnetic
FFT	:	Fast Fourier Transform
GIS	:	Geographic Information System
GNSS	:	Global Navigation Satellite System
HGM	:	Horizontal Gradient Magnitude
IAGBN	:	International Absolute Gravity Basestation Network
IGRF	:	International Geomagnetic Reference Field
KFUPM	:	King Fahd University of Petroleum & Minerals
KSA	:	Kingdom of Saudi Arabia
LAB	:	Lithosphere-Asthenosphere Boundary
LOTEm	:	Long-Offset Transient Electromagnetic
MMN	:	Makkah-Madinah-Nafud
MT	:	Magnetotelluric
O&G	:	Oil and Gas
RMS	:	Root Mean Square
RSGP	:	Red Sea Geothermal Provinces
RTP	:	Reduction to the Pole

SGS	:	Saudi Geological Survey
SPI	:	Source Parameter Imaging
SRTM	:	Shuttle Radar Topography Mapping
SURE	:	Scale, Uncertainty, Resolution, Environment
TDEM	:	Time-Domain Electromagnetic
TDR	:	Tilt Derivative
TEM	:	Transient Electromagnetic
THDR	:	Total Horizontal Derivative
TMI	:	Total Magnetic Intensity
USGS	:	United States Geological Survey

ABSTRACT

Full Name : Konstantinos Chavanidis

Thesis Title : The use of geophysical methods in geothermal exploration of the Wadi Al Lith field in Western Saudi Arabia

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Western Saudi Arabia is a promising area for geothermal energy exploration since it has many prospective areas related to the ongoing evolution of the Red Sea Rift. This study focuses on the area of Wadi Al Lith, where several hot springs indicate the presence of potential geothermal resources. Land gravity and magnetic geophysical data were acquired, analyzed, and integrated with electromagnetic and airborne magnetic data to characterize the subsurface structures of the area surrounding the most promising hot spring, Ain Al Harrah, in both 2D and 3D. The study also suggests and evaluates a workflow for geophysical data processing and integration that can be used for natural resources exploration and any application that requires subsurface characterization. The results imaged the features of the potential geothermal field of the study area, such as the heat source and the reservoir, as well as the tectonic structures (fracture zones and dikes) that assist the thermal fluids circulation and bring them to the surface. The airborne magnetic dataset of the wider area was analyzed to delineate regional structures of interest, to estimate the depth of the Curie isotherm, and to construct the geotherm that was used in the prediction of the surface heat flow at the area of the hot spring. Deep electromagnetic soundings confirmed the calculated geotherm. This study constructs a

3D subsurface model of the geothermally prospective study area by integrating potential field and electromagnetic geophysical data. The model can be further enhanced with additional data from geological, geochemical, and geophysical surveys to gather more information about the geothermal setting of the area and develop a drilling program that will verify and assess the geothermal resources and put the reservoir into production, in line with the worldwide need to reduce carbon emissions by increasing renewable energy production.

ملخص الرسالة

الاسم الكامل	:	كونستانتينوس شافانيديس
عنوان الرسالة	:	استخدام الطرق الجيوفيزيائية في التنقيب عن الطاقة الحرارية الأرضية في حقل وادي الليث غرب المملكة العربية السعودية
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يعد غرب المملكة العربية السعودية منطقة واعدة لاستكشاف الطاقة الحرارية الأرضية نظرًا لوجود العديد من المناطق المحتملة المرتبطة بالتطور المستمر لصدع البحر الأحمر. تركز هذه الدراسة على منطقة وادي الليث، حيث تشير العديد من الينابيع الساخنة إلى وجود موارد الطاقة الحرارية الأرضية المحتملة. تم جمع بيانات الجاذبية الأرضية والجيوفيزيائية المغناطيسية وتحليلها ودمجها مع البيانات المغناطيسية الكهرومغناطيسية وبيانات ملتقطة جواً لتوصيف التراكيب تحت السطحية للمنطقة المحيطة بالينابيع الساخنة الواعدة، عين الحارة، في كل من البعدين الثنائي والثلاثي الأبعاد. تقترح الدراسة أيضاً وتقيم سير العمل لمعالجة البيانات الجيوفيزيائية وتكاملها والتي يمكن استخدامها لاستكشاف الموارد الطبيعية وأي إجراء يتطلب توصيفاً تحت سطحيًا. بينت النتائج ملامح المجال الحراري الأرضي المحتمل لمنطقة الدراسة، مثل مصدر الحرارة والخزان الحراري الجوفي، وكذلك التراكيب التكتونية (مناطق الصدع والقواطع النارية) التي تساعد على حركة السوائل الساخنة وإيصالها إلى السطح. تم تحليل مجموعة البيانات المغناطيسية التي تم جمعها من الجو لكامل المنطقة لتحديد التراكيب الرئيسية ذات الأهمية، ولتقدير عمق درجة كوري متساوية الحرارة، ولبناء صورة الحرارة الأرضية التي تم استخدامها في التنبؤ بتدفق الحرارة السطحية في منطقة الينابيع الساخن. وأكدت أيضاً السبر الكهرومغناطيسي العميقة الحرارة الأرضية المحسوبة. تقوم هذه الدراسة ببناء نموذج ثلاثي الأبعاد تحت سطحي لمنطقة الدراسة للطاقة الحرارية الأرضية من خلال دمج البيانات الجيوفيزيائية الميدانية والكهرومغناطيسية المحتملة. يمكن تعزيز النموذج بشكل أكبر ببيانات إضافية من المسوحات الجيولوجية والجيوكيميائية والجيوفيزيائية لجمع المزيد من المعلومات حول بيئة الطاقة الحرارية الأرضية للمنطقة وتطوير برنامج الحفر الذي بإمكانه أن يتحقق من موارد الطاقة الحرارية الأرضية وقيمتها و الذي قد يدخل الخزان الحراري في مرحلة الإنتاج، بما يتماشى مع الحاجة العالمية للحد من انبعاثات الكربون عن طريق زيادة إنتاج الطاقة المتجددة.

CHAPTER 1

Introduction

The global need for lower carbon dioxide emissions, sustainable economic development, and the increasing energy demands of modern society have outlined a clear path toward alternative energy production techniques that are distinct from fossil fuel resources (such as hydrocarbons and coal). One of these energy sources is geothermal energy, which is environment-friendly and renewable since it is continuously replenished in the interior of the Earth due to the upward heat flow. The capacity of the planet concerning heat storage is enormous, and geothermal energy has the potential to replace fossil fuels as the main source of energy for electricity generation. Furthermore, geothermal energy includes fewer operational and technological hazards than fossil fuel energy and may deliver continuous and reliable electricity at a relatively low cost.

In Saudi Arabia, the electricity demand is satisfied by hydrocarbon usage at a percentage of 99% (67% from natural gas and 33% from oil in 2022) [1]. A percentage of approximately 80% of the produced electricity is consumed for space cooling purposes, which are linked to significant carbon dioxide emissions [2]. Therefore, there is an urgent requirement to prioritize alternative sources of energy. The country's ambitious Vision 2030 aims, among others, to diversify the Saudi economy from the excessive hydrocarbon exploitation for energy production and, instead, largely utilize renewable sources of energy that allow for sustainable development, in line with the world's effort

to reduce carbon dioxide emissions. The use of renewable resources can facilitate and importantly cover different energy needs, and Saudi Arabia plans on reducing hydrocarbon consumption by using different forms of renewable energy (e.g., solid waste, solar, geothermal, wind) instead [3], contributing to the global efforts to reduce carbon dioxide emissions and combat climate change.

Apart from electricity production, geothermal energy can be largely utilized in household, industrial, and district heating, in the agriculture, aquaculture, and livestock farming industries, as well as for touristic purposes (e.g., heating/cooling for recreational and curative activities) [4]. Furthermore, it might play a significant role in hydrogen production. Studies have shown that hydrogen has the potential to substitute fossil fuels as a source of energy. Hydrogen can be produced from renewable and non-renewable sources, creating two main types: green and blue hydrogen [5]. Blue hydrogen is produced by fossil-fuel-based techniques, such as oil/naphtha reforming and coal gasification [6]. On the other hand, green hydrogen is the product of the transformation of the surplus electricity produced by renewable sources (e.g., geothermal energy) into an energy carrier (hydrogen) for multiple uses [5] through the method of electrolysis.

1.1 Problem Statement

Before stating the problem and the objectives of the study, it should be noted that a factor that is used for the classification of geothermal resources is the temperature of the geothermal reservoir. So, the resources can be classified as low, medium (or intermediate), and high temperature or enthalpy resources. Several publications use

slightly different temperature ranges (e.g., [7, 8, 9]); however, the most commonly applied division is that of Muffler & Cataldi (1978) [10], which is also used by the United States Geological Survey (USGS). According to this division, the geothermal resources are divided into three categories; the low enthalpy resources that are found at temperatures less than 90 °C, the medium enthalpy between 90 °C and 150 °C, while the resources above 150 °C are referred to as high enthalpy.

Geothermal studies in Saudi Arabia have recently started to become of interest due to the global trend of energy transition from fossil fuels to renewable forms of energy. The geothermal resources of the country can be generally classified into all of the three above-mentioned categories. The low enthalpy resources are found in deep aquifers within the sedimentary basins of the eastern part. The medium enthalpy resources, in which faults and fractures control the fluid movement and create surface manifestations in the form of shallow hot springs, and the high enthalpy resources that are represented by (mainly basaltic) lava explosions and create the so-called Harrats [11], are encountered in the western part of Saudi Arabia.

Geothermal energy has the potential to become the source that Saudi Arabia can rely on; however, the geothermal resources of the country have yet to be characterized in detail in terms of conceptualization and geophysical properties. Concerning the geothermal fields related to the Harrats, several publications discuss their geographic expansion, geotectonic history, and potential use as electrical energy providers [12, 13]. However, there are still knowledge gaps in the study of the medium enthalpy resources that need to be fully understood. The most important questions that need further study are the relation

of these resources with known geothermal fields related to the Red Sea tectonic rift and the energy potential of these resources.

This study focuses on the geothermal field of the wider Wadi (Valley) Al Lith area. The existence of the field is verified by the presence of surficial manifestations in the form of hot springs, and there are previous studies that examined the thermal waters of the springs for their relation to a deeper geothermal reservoir. The published subsurface information for the Wadi Al Lith area until now mostly comes from small-scale and shallow geophysical surveys carried out in the vicinity of the most known and geothermally promising hot spring, the Ain Al Harrah. However, not much information is known concerning the geometry of the geothermal reservoir and the tectonic structures that determine the flow of thermal waters in the subsurface and to the surface. A detailed and expanded study of the wider area has yet to be published.

1.2 Research Objectives

The objective of the study is to utilize geophysical data mainly from potential field methods (airborne and land magnetic and gravity) to characterize the prospective geothermal field of Wadi Al Lith in western Saudi Arabia and highlight the importance of these methods in geothermal exploration. Other geophysical data (electromagnetic - EM, most specifically magnetotelluric - MT, audio (frequency) magnetotelluric - AMT, and transient electromagnetic - TEM), and all available information including boreholes and legacy geophysical data (seismic refraction, time-domain electromagnetic - TDEM, etc.) acquired from field reports are used to constrain the final resulting geophysical model.

The characterization of the geothermal reservoir is achieved through the combination of the geophysical data for the shallower and the deeper parts, and two- and three-dimensional (2D and 3D) models of the complex subsurface are constructed. Based on the distribution of the measured stations, the gravity, TEM, and land magnetic data represent the shallower structures compared to the airborne magnetic and MT data which provide information on the deeper structures.

The analysis of the airborne magnetic dataset provided the depth of the Curie isotherm, where magnetic rocks lose their magnetic properties. The knowledge of this depth and the type of geothermal field can be used for the estimation of the surface heat flow and the relationship of temperature with depth (geotherm curve) within the study area. This information is necessary to assess the geothermal energy potential of a field for electricity production as well as for its further development (e.g., drilling program, plant construction).

Moreover, the most important target of this study is the development of a workflow to characterize a geothermal field during the exploration stage by integrating information from multi-geophysical and geoscientific datasets. Finally, suitable sites for the drilling of exploratory wells are indicated based on the results of the data integration; these wells will confirm the potential of the geothermal resources to be used for energy production or other uses.

1.2.1 Research Questions

This study aims to answer the following research questions:

- What information and insights can be acquired for the geotectonic regime of a prospective area in geothermal exploration using potential field data? What are the results for the study area of Wadi Al Lith?
- Which tectonic elements are responsible for the subsurface circulation of the thermal fluids in the study area and how do they reach the surface, where they manifest in the form of hot springs?
- How do surface geologic features (e.g., dikes) impact the circulation of geothermal fluids in the research area? What additional insights can be gained from analyzing these dikes with geophysical data that may be beneficial in industries beyond geothermal energy, such as mineral exploration?
- What locations can be identified as potential sites for drilling exploratory wells to expand geothermal exploration in Wadi Al Lith?
- What other information can be extracted from the analysis of potential field data concerning the thermal characteristics and parameters of a geothermal field?
- What workflow can be followed for the analysis and integration of diverse geoscientific datasets in order to visualize the subsurface of the region under exploration? How can this workflow be applied to geothermal exploration, and how can it be adapted for alternate research objectives, such as Oil and Gas (O&G) exploration or natural gas storage?

1.3 Thesis Structure

The present PhD Dissertation report is divided into five (5) chapters as follows:

Chapter 1 introduces the topic of the Dissertation and presents the research objectives by outlining the significance of the study.

In Chapter 2, a review of the published information related to the geologic and tectonic regime of the study area of Wadi Al Lith is made. The chapter also discusses the geothermal potential of both Wadi Al Lith and wider Western Saudi Arabia areas, along with the relevant exploratory studies that have been carried out to gain insights into the geothermal resources.

Chapter 3 introduces a proposed workflow for geoscientific data analysis and integration in order to characterize the subsurface. The application of this workflow in two case studies of O&G exploration is described, along with the corresponding results, that validate its robustness to any activity that requires subsurface characterization (e.g., O&G, geothermal, mineral exploration, natural gas storage, CO₂ sequestration). Moreover, the chapter describes the processing and analysis of the acquired geophysical data of the Wadi Al Lith area (gravity and magnetic), together with the additional geoscientific datasets (electromagnetic data, surface geology, etc.) that were used to constrain and complete the modeling of the geothermally prospective study area.

In Chapter 4, the results of the gravity data analysis are presented. More specifically, the maps of the gravity field and the 2D and 3D subsurface models of the area around the most promising hot spring of Wadi Al Lith are shown in detail. The circulation of the geothermal fluids within the subsurface is also discussed in relation to the modeled tectonic regime. Similarly, the results of the magnetic data analysis are also presented in this chapter. Important parameters of the Wadi Al Lith prospective geothermal field, such

as the depth of the Curie isotherm and the surface heat flow, are estimated using an airborne magnetic dataset, while a preliminary geotherm curve (the relationship of temperature with depth) for the study area is shown. Moreover, the influence of the numerous surface and shallow-subsurface dikes present in the study area on the circulation of geothermal fluids is also studied using land magnetic data.

Chapter 5 summarizes the main findings of the study, in line with the objectives and the importance of the research. It also recommends activities for future studies to extend the knowledge on the subsurface of the study area concerning geothermal resources, and, based on the results, proposes suitable sites for the first exploratory boreholes that will verify and assess the potential of the area for geothermal energy production.

CHAPTER 2

The Wadi Al Lith Geothermal Field

The Arabian Shield, in the western part of Saudi Arabia, offers a strong potential for geothermal energy [14]. More specifically, there are three known areas belonging to two distinct geothermal provinces, on which most of the relative studies focus. They are generally classified into two categories according to their reservoir temperature. These are the high enthalpy resources created by lava flows in the areas known as Harrats in the northwestern part, which are related to the Makkah-Madinah-Nafud (MMN) active volcanism (i.e., volcanic geothermal system), and the medium enthalpy resources, which create hot springs at the surface and are located in the Al Lith area in the western, and the Jizan area in the southwestern part, near the borders with Yemen.

The present research focuses on the Wadi Al Lith area (Figure 1), which is part of the southern Arabian Shield structural terrane. The Wadi Al Lith is constrained by the Jabal Afaf basin on the east and the Wadi Sadiyah basin on the north and extends until the Red Sea shoreline. It covers approximately 3100 km², between latitudes 20°00' and 21°31' and longitudes 40°15' and 40°30'. This area is considered very promising for the existence of a medium-to-high-enthalpy geothermal system allowing power generation since four major hot springs exist [15]. The most promising is the Ain Al Harrah (Figure 2) in the Ghomygah area, next to the village Al Ma'a Al Har, with a surface temperature of up to 96 °C [15]. Other important springs in the Wadi are the Al Sader-Bani Hilal, Markoub, and Al Darakah.



Figure 1: Google Earth map where the study area near the city of Al Lith in Western Saudi Arabia is shown. The location of the Ain Al Harrah hot spring is also indicated.



Figure 2: Field photographs of the Ain Al Harrah hot spring (a) in 2012 (archive image), and (b) in 2023.

In the following sections, the geology and the geotectonic evolution of the Wadi Al Lith area are summarized, as well as the current knowledge of the prospective geothermal field is described. Also, previous geothermal exploration surveys that were carried out in Saudi Arabia are reviewed.

2.1 Geology and Geotectonic Evolution of the Wadi Al Lith Area

During its initial stages of evolution in the Precambrian (900-631 Ma), the Arabian Shield broke up into five micro-plates (terranes), separated by paleo-suture zones with ophiolite occurrence, related to NW-SE to E-W compressive island arc tectonics [2, 16]. Wadi Al Lith area was part of the Asir terrane [17]. The collision-related deformation continued in the Late Precambrian (between 630 and 550 Ma) and created the Najd Fault Zone, a sinistral fault system that, in combination with several NW-trending faults, displaced the northern part of the Arabian Shield approximately 250 km to the northwest [18]. Between 660 and 610 Ma, four magmatic and tectonic events acted on these terranes, in an orogenic tectonic regime, creating radiogenic felsic plutonic rocks (granites, granodiorites, tonalites, diorites, syenites) with high concentrations of uranium, thorium, and potassium [19].

The Tertiary (started at 31 Ma) Red Sea rifting was initiated by a plume (Afar plume) related volcanism in the southern part of the Red Sea area that migrated to the northern part [19] and rotated the Arabian Shield anti-clockwise [2], creating an extensional environment of NE-SW direction [11]. Due to the continental breakup and the seafloor spreading along the Red Sea rift, dike swarms parallel to the rift axis and lava

outpourings created volcanic centers (the Harrats) along the western margin of the Arabian Shield [19]. These volcanic centers are mainly dominated by mafic rocks created by basaltic flows and dikes [17]. The following mantle upwelling (after 12 Ma) caused further magmatic and tectonic activity in the Harrat areas, as well as the creation of the wide topographic feature of the West Arabian Swell feature [14]. The historic eruption of the Harrat Rahat in 1256 CE is the most intensely studied eruption of the MMN volcanic complex [14, 20], while the most recent eruption was that of the Jabal Yar in 1810 CE [14]. The continuing volcanic and tectonic activities within the Arabian Shield and the areas surrounding the Red Sea [19] provide a significant advantage for creating geothermal energy resources [14].

Several geothermal provinces in all the continents that surround the Red Sea (thus known as the Red Sea Geothermal Provinces – RSGP), located in Saudi Arabia, Yemen, Egypt, Ethiopia, Djibouti, and Eritrea, were created due to the aforementioned tectono-magmatic events [19]. Active basaltic volcanoes and dike swarm activity created high geothermal gradient and heat flow in the northwestern margin of the Arabian Shield, in areas such as the Harrat Lunayyir, the Harrat Khaybar, and the Rahat Volcanic Field [14, 20]. Water vapors from the magma chambers and the overlying boiling aquifers emerge to the surface as fumaroles [13].

The rock formations within Wadi Al Lith mainly include metamorphic volcanic and sedimentary rock, as well as Late Proterozoic plutonic rocks, which are divided into four units [11]. The older unit dates to Precambrian, it is made of rocks of the Baish and Baha groups and is found in the eastern part of the area as basaltic, andesitic, and rhyolitic flows metamorphosed to the greenschist facies, as well as dacites, schists, and

amphibolites. The next unit contains mafic to intermediate plutonites that are encountered in the western part of the area. These rocks are part of the Al Lith suite and the Khasrah complex, consisting of gabbro and diorite [11]. The younger unit consists of granitic and other plutonic (e.g., serpentinite, syenite) intrusive rocks, belonging to the Proterozoic Hurqufah and Jumah suites. Other rock formations that are found in the Wadi include monzogabbro and gabbro dikes of the Ghomygah suite, conglomerates, and sandstones of the Miocene Bathan formation. The Quaternary sediments of the Wadi (alluvial sands, gravels, sabkha deposits, and silts) are deposited along the river valleys or create sand-dune and silt deposits of NW-SE direction in the coastal plain area [11]. A simplified geologic map of the study area is shown in Figure 3 (modified from the corresponding geologic maps of the Saudi Geological Survey - SGS [21, 22]).

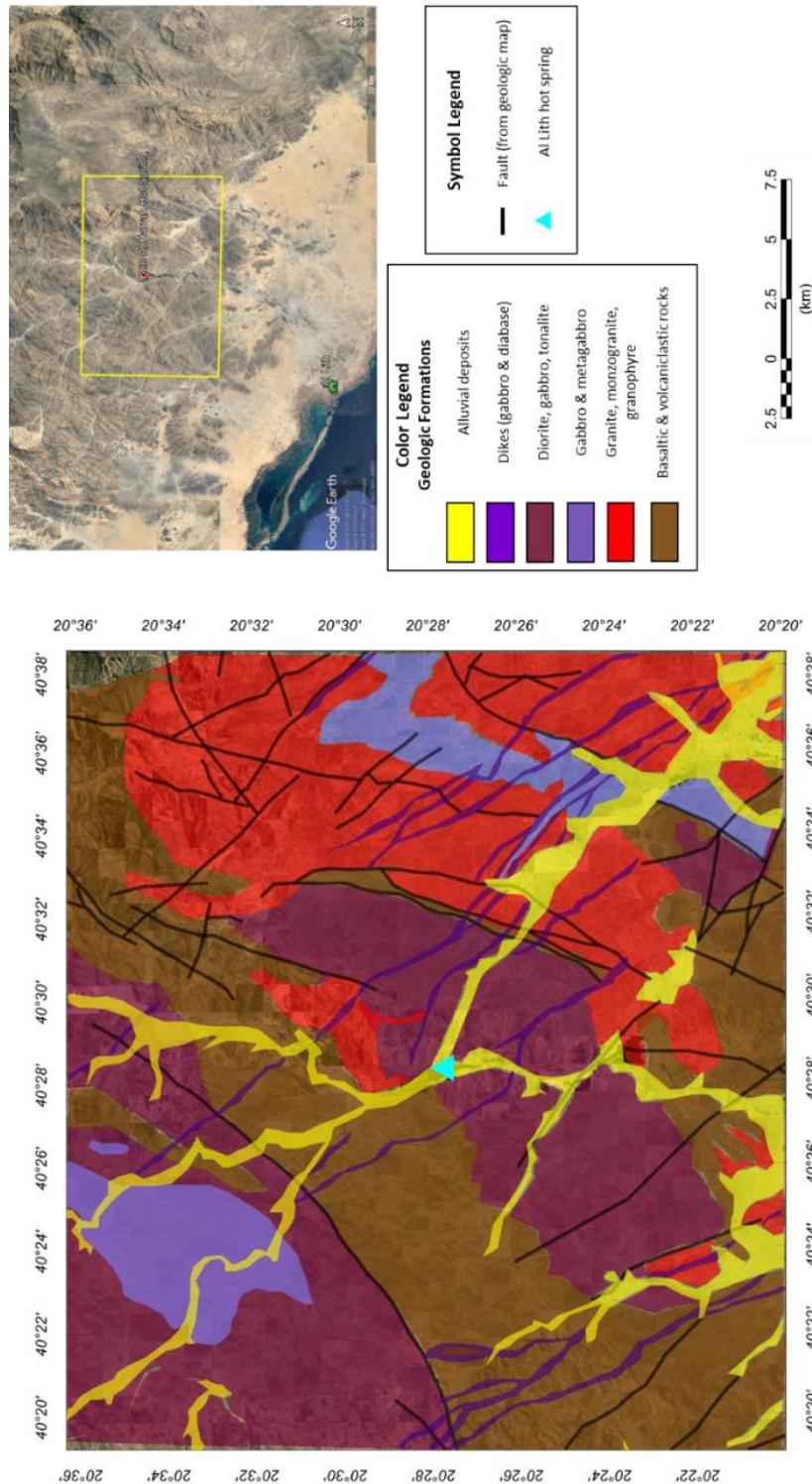


Figure 3: Geologic map of the area close to the Ain Al Harrah hot spring (indicated with a light blue triangle).

2.2 The Prospective Geothermal Field of Wadi Al Lith

The Wadi Al Lith geothermal system is associated mainly with the Precambrian radiogenic felsic intrusions [2]. Water circulates and gets heated in the granitic rocks for long periods, as the tritium concentration suggests (greater than 75 years) before reaching the surface in the form of hot springs, enriched in radiogenic elements, such as uranium, thorium, and potassium [17]. Because of this, heat mining or Enhanced Geothermal System (EGS) technology can be applied to the granitic rocks of the area to produce radiogenic heat [2].

Based on lineament analysis of previous studies (e.g., [11]) and the results of an electric resistivity survey that was conducted on the Wadi Al Lith area [11, 15], the surface structural elements do not affect the circulation of deep-seated thermal fluids; instead, subsurface faults and dikes that are related to the Precambrian and Tertiary tectonic events act as the main fluid conduits to the surface. The prevailing direction of the lineaments is NE-SW, with few lineaments near the Ain Al Harrah trending NW-SE, in agreement with the Red Sea Rift, which is the main prevailing tectonic structure of the wider area [11, 15].

Studies of the geochemistry of the Ain Al Harrah waters indicated an average reservoir temperature of 136 °C and a heat flow of around 183 mW/m² at the area of the hot spring using silica and Na-K-Ca geo-thermometers (e.g., [11, 15]). However, there is considerable uncertainty in the heat flow estimations from geo-thermometer calculations [23]. The calibration of the measured heat flow using geo-thermometers requires known heat flow values in the region; for the Wadi Al Lith area, such measurements have not

been carried out until now. Giggenbach ternary diagrams showed differences in the composition of waters from the hot spring and nearby wells; the geothermal parameters are higher in the hot spring water, which is characterized as a mature mixed water type, while the water from the wells is of volcanic unmixed type [11, 17]. The salinity of the hot spring water is, also, increased due to mixing with the Red Sea's water and the long-circulating time in the granites [2]. The chloride content is increased, as well, due to the prolonged water-rock interaction [11, 17]. Radioactive trace elements, such as strontium, rubidium, barium, and lithium, are abundant in the felsic host rocks, thus the thermal waters are enriched in such elements [17].

The presence of high heat-generating granites resulting in high heat flow value in the Wadi Al Lith area is also enhanced by the presence of the Moho discontinuity at a shallow depth, approximately 20 km below the Asir terrane [24] and 27 km near the study area of the Ain Al Harrah hot spring [25].

Aboud et al. [26] gathered previous geological (faults, rock types, presence of volcanoes) and geophysical (aeromagnetic, seismicity) data acquired during different geothermal exploration surveys and constructed a unified Geographic Information System (GIS) database and a geothermal favorability map for the country. Based on the results of this study, the wider Wadi Al Lith area is characterized by high geothermal gradient and heat flow values, more than 19 °C/km and between 47.7 and 87.8 mW/m² respectively, and a depth of the Curie isotherm shallower than 29.6 km.

Based on the analysis of magnetotelluric geophysical data that have been acquired close to the Ain Al Harrah hot spring [27, 28], the heat source of the prospective geothermal field is located at an approximate depth of 5-6 km.

2.3 Geothermal Exploration Surveys in Saudi Arabia

The geothermal exploration surveys in Saudi Arabia started in 1966, with preliminary works of the Deputy Ministry for Mineral Resources (currently, SGS) [26]. The works of Stieltjes [29] and Berthier et al. [30] focused on chemical analyses of the waters of the Al Lith and Jizan areas, while the first geophysical surveys for geothermal exploration were carried out in the 80s. Demange [31] was the first to work on geophysical data for the volcanic field of the Harrat Khaybar in the central-western part of the country. More detailed studies of the Harrats were made by Berthier et al. [30] and Demange [32], while Al Dayel [33] conducted the first broad geothermal research in Saudi Arabia, by studying the hydrochemistry of many areas of geothermal significance. Until recently, all the published research for potentially favorable areas for geothermal energy was limited only to the use of geological and geochemical methods. The power generation from geothermal energy in Saudi Arabia was first mentioned by Rehman and Shash [12], while Grímur and Guðmundur (2009) (as informed by [26]) evaluated the geothermal potential of the Harrat volcanic fields. Hussein and Loni [34], Khiyami et al. [35], and Hussein et al. [11] studied the geochemistry of the thermal waters of the Al Lith and Jizan areas by analyzing water samples and measuring the concentration of metallic and non-metallic elements. Lashin and Al Arifi [36] integrated LANDSAT images with chemical analyses

from different thermal springs in the Jizan area, while Hussein et al. [11] applied a similar methodology to the Al Lith area. Lashin et al. [15, 17] described the potential of Wadi Al Lith in terms of geothermal energy using geological, geochemical, and isotope data. Lashin et al. [13, 37] reviewed the geothermal resources and relevant activity in Saudi Arabia. From the geophysical point of view, Edigbue et al. [38] carried out Electric Resistivity Tomography (ERT) and TEM measurements for engineering purposes (dam construction) in a site close to the Ain Al Harrah hot spring and validated the presence of thermal waters and fractured zones that act as pathways for the fluids, while Lashin et al. [15], Hussein et al. [11], and Al-Douri et al. [39] integrated the results of a 2D resistivity survey in their studies of the Wadi Al Lith geothermal reservoir. Lashin and Al Arifi [40] and Chandrasekharam et al. [41] carried out ERT and seismic reflection surveys in the Jizan area. Due to their large areal extension and their high heat content, the Harrat areas are under detailed exploration using different geophysical methods, mainly non-seismic (e.g., [20, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51]). Arrofi and Abu-Mahfouz [52] delineated the geothermal reservoir area in Jizan using a comprehensive geologic remote sensing analysis. Abdelrahman et al. [53] and Melouah et al. [54] used airborne magnetic data to delineate the geothermal potential of the western part of the country, while Ashadi et al. [28], and Barajas-Olalde et al. [55] integrated controlled-source electromagnetic (CSEM) and MT data to characterize the subsurface and model the geothermal prospective reservoir of Wadi Al Lith.

CHAPTER 3

Geophysical Data and Methodology

In general, for the characterization of a natural resource reservoir or deposit (oil, gas, geothermal, mineral, etc.), information from every available dataset (geological, geophysical, petrophysical, and others) at different scales, resolutions, and degree of uncertainty should be optimally used, integrated, and studied. These essential factors constitute what is known as the SURE (Scale, Uncertainty, Resolution, Environment) challenge, and a successful reservoir characterization should take each factor into account [56]. Geophysical methods can provide preliminary subsurface insights into an area of interest and map the geometry of geologic and tectonic structures. They are usually applied during the first stage of a potential geothermal field exploration, to characterize and differentiate between shallow- and deep-seated sources of anomalies connected with different geologic structures of interest, and they allow the fast coverage of the study area.

To conduct the initial geophysical surveys during the first stage of a potential geothermal field exploration, the applied methods are usually non-destructive, passive methods. Potential field (gravity and magnetic) (e.g., [57, 58, 59, 60, 61, 62, 63, 64, 65, 66]), passive seismic such as ambient noise tomographic studies and/or microseismic (e.g., [67, 68, 69]) and electromagnetic methods such as the AMT, TEM and MT methods (e.g., [70, 71, 72, 73, 74, 75, 76]) are typically employed [77]. More detailed studies that

also include other methods, such as the reflection seismic method (e.g., [78]), usually follow for the most promising areas.

Developing an accurate geologic model that characterizes the rock types, their alterations, and the general tectonic structure is a critical component of geothermal exploration, as it enables the identification of potential reservoir rocks and fluid pathways [79]. However, in many cases, constructing precise 2D and 3D models is challenging due to limited data availability or other constraints (e.g. limited number of boreholes, inadequate data coverage). To objectively create a geologic model, geophysical inversion modeling of potential field and/or electromagnetic data can be used, supplemented by other data from geological and geophysical methods. However, it is essential to test and refine these models before drilling to mitigate risks and ensure accuracy [79].

3.1 General Information on Geophysical Methods

The gravity (or gravimetric) method measures the lateral rock density distribution at depth [80]. In geothermal exploration, the method is widely applied as a technique that can provide preliminary insights over an expanded area indicating large-scale tectonic elements that control the geothermal fluid circulation and targets for more detailed exploration using other geophysical and geochemical techniques. It provides the subsurface tectonic regime of the study area and the boundaries of different geologic formations, either due to lithology variation or due to the presence of structural features (e.g., faults, salt domes, magmatic intrusions). However, the method cannot provide

information on high temperature or heat flow anomalies, which are decisive for estimating the actual size and exact location of the geothermal reservoir.

Gravity data processing requires several corrections before the results are obtained [81]. The resolution of the results decreases with the depth of the anomaly sources [82], thus a more extensive survey is necessary in most cases. The gravity method has another drawback, the non-uniqueness of the interpreted models [80], i.e., the possibility that various structures, geometries, and spatial arrangements could produce the same gravity anomaly. The non-uniqueness could be overcome by incorporating other geological and geophysical methods, and previous studies on the area of interest, to constrain the resulting model.

The magnetic method measures the variations in the magnetic field intensity and indicates areas with either positive or negative anomalies [80]. The existence of anomalies depends on differences in the magnetic susceptibility of the geological formations and the tectonic structures of the study area, which can be very helpful in mapping contacts between rocks/structures with different content in magnetic minerals (commonly magnetite, pyrrhotite, and maghemite). The method can provide rapid results for a broader study area, especially in the cases of airborne and satellite data acquisition, with a much lower cost than the other common methods [80, 81]. Moreover, the time for data processing is much less in comparison to the timely seismic data processing [81]. However, the imaging resolution is not comparable to seismic results since the magnetic method aims to provide a preliminary model of structures that produce anomalous fields and the expected subsurface regime in a generally unexplored area. Another disadvantage is the non-uniqueness of the results provided [81] since a variety of structures,

geometries, and spatial arrangements can produce the same measured anomalous field. Additionally, the method is susceptible to external factors (artificial structures, buried metallic objects, etc.) that can “contaminate” the measured data and produce “artifacts” in the results (magnetic signatures from objects not related to geology) that need to be dealt with [83].

Furthermore, the magnetic method is widely used to determine the depth to the basement, due to the different magnetic properties between the basement rocks and the overlying sediments and sedimentary rocks [84, 85]. This methodology can be further expanded to estimate the depth where the magnetic basement loses its magnetization due to heating. In most cases, this depth is linked to the Curie isotherm and is known as the Curie point depth. For magnetite, which is the most common magnetic mineral, this depth is encountered at the temperature of approximately 580 °C. In a geothermal field, the depth of the Curie isotherm can be shallower due to the overall heating of the area. At the same time, it may also be affected by the Curie temperature of the magnetic minerals (other than magnetite) present in the study area [86], thus reflecting mineralogical rather than temperature variations [87].

The EM methods are among the basic, widely used methods for geothermal exploration [88]. The operation of these methods mainly includes the propagation of electromagnetic waves (continuous or transient) in the subsurface; waves produced by a natural or an artificial source. In a geothermal field, the high temperature creates a high resistivity contrast between hydrothermal fluids, their overlying cap rocks, and the host rock environment [89]. The presence of subsurface conductive zones produced by the brines and clays capping a geothermal system provides a feature that can be easily detected by

various EM techniques, such as long-offset TEM (LOTEM), short-offset TEM, controlled-source AMT (CSAMT), and MT [90, 91]. Another advantage of the EM methods is that the depth resolution varies according to the transmission frequency used, making them the main geophysical methods for studying deep-seated geothermal reservoirs [92]. Because of its cost-effectiveness and deep penetration into the subsurface, MT is the EM method usually applied for geothermal exploration.

MT is a frequency-domain passive EM method that measures naturally occurring variations in the magnetic and electric fields caused by the electromagnetic induction of the Earth [93], to infer the electrical conductivity structure of the subsurface from several tens of meters to several hundreds of kilometers according to the frequency and the time period used (the lower frequencies can image greater depths if operating for a long period) [20, 93, 94, 95, 96]. In addition, MT techniques can image both shallow and deep complex subsurface targets with a very good resolution, depending on the electromagnetic sounding period and the conductivity of the target structure [20]. By measuring the electrical properties of the subsurface at multiple frequencies, MT surveys can provide information on the distribution of electrically conductive and resistive zones, which can be related to the distribution of geothermal fluids and heat sources (e.g., [97, 98]). In addition, the presence of faults, fractures, and other structural features and discontinuities can also affect the electrical conductivity of the subsurface, providing additional information on the geometry and orientation of geothermal reservoirs [91, 99]. However, the complexity of MT data interpretation, its sensitivity to noise interference, and its limited lateral resolution can be drawbacks in certain geothermal exploration scenarios.

Similarly, the TEM method measures the electric resistivity of the subsurface structures. It uses an artificial source that transmits electric current on the surface, which produces a magnetic field around a wire loop or a receiver coil. When the current is turned off, the magnetic field slowly decays with time, and this time is measured relative to the induced voltage [100]. TEM can provide high-resolution results for the shallow parts of the exploration area, usually for the first hundreds of meters.

Seismic methods are generally divided into active and passive methods, based on the usage of a natural or an artificial source to produce acoustic (or seismic) waves. The active methods (e.g., reflection seismic method) measure the arrival time of the produced acoustic wave from an artificial source (vibroiseis, sledgehammer, explosives) to a receiver at the surface (or within a well). These methods can map the subsurface in detail, locating reservoirs, trap formations, or hazardous zones that should be avoided during drilling or can cause issues during the production stage [101]. Because of this, the active seismic methods are widely and most commonly applied during hydrocarbon exploration. However, the high logistic and data processing cost of the method usually makes its application necessary in geothermal exploration only in areas where prolific targets have already been located using other methods.

The passive seismic methods record the naturally produced earthquakes (from micro- to mega-scale) caused by rock fracturing or subsurface fluid flow. This makes them very useful in geothermal exploration, since geothermal areas are very tectonically active, with often micro-earthquakes related to the flow of thermal fluids in the subsurface. Seismic tomography is a passive geophysical technique that uses seismic records to construct a 2D or 3D model of the subsurface [102]. The technique records the differences in the

velocity of seismic waves when they propagate through different geologic formations. Generally, seismic waves travel more slowly in hotter and hydrated rocks [103] and this applies in geothermal exploration cases. The resolution of the results can vary, and the method can be equally applied to global and local scales. The data are gathered using sensors that record the seismic waves in every direction (horizontally and vertically); waves that contain geologic information of the formations they traveled through. After the collection, the data are processed and inverted to construct the subsurface models.

3.2 Data Integration Workflow

The optimum integration of geophysical with well and surface data is a crucial and necessary stage towards the completion of the SURE challenge with respect to natural resources exploration and production. All information regarding the subsurface regime of the research area should be studied and jointly interpreted in order to gain a thorough understanding of its complexity and reduce the uncertainty and risk that is involved in the first stages of every exploration survey. The existence of a detailed representation of the subsurface will also be crucial during the development and production stages, while information from different sources (e.g., logging, well pressure data) can significantly enhance the model by adding additional details.

In this study, a novel workflow for the integration of multi-geoscientific data is suggested, based on previous studies on interpreting separate datasets (e.g., [78, 80, 85, 104, 105, 106, 107]). The integrated workflow, presented in Figure 4, uses a variety of data (e.g., potential field, EM, seismic, well, surface geology, seismological) that provide

insights into the subsurface geological and tectonic regime. The steps include different procedures that analyze each dataset, both individually and constrained by the other datasets, to build a realistic conceptual model for the study area with minimum uncertainty.

The workflow can be easily modified according to the custom needs of different kinds of studies for natural resources exploration. Specifically, cases such as Carbon Capture, Usage, and Storage (CCUS), O&G, geothermal, and mining exploration and exploitation can use the same or a modified workflow to better understand the reservoir by integrating multi-geophysical and geological data.

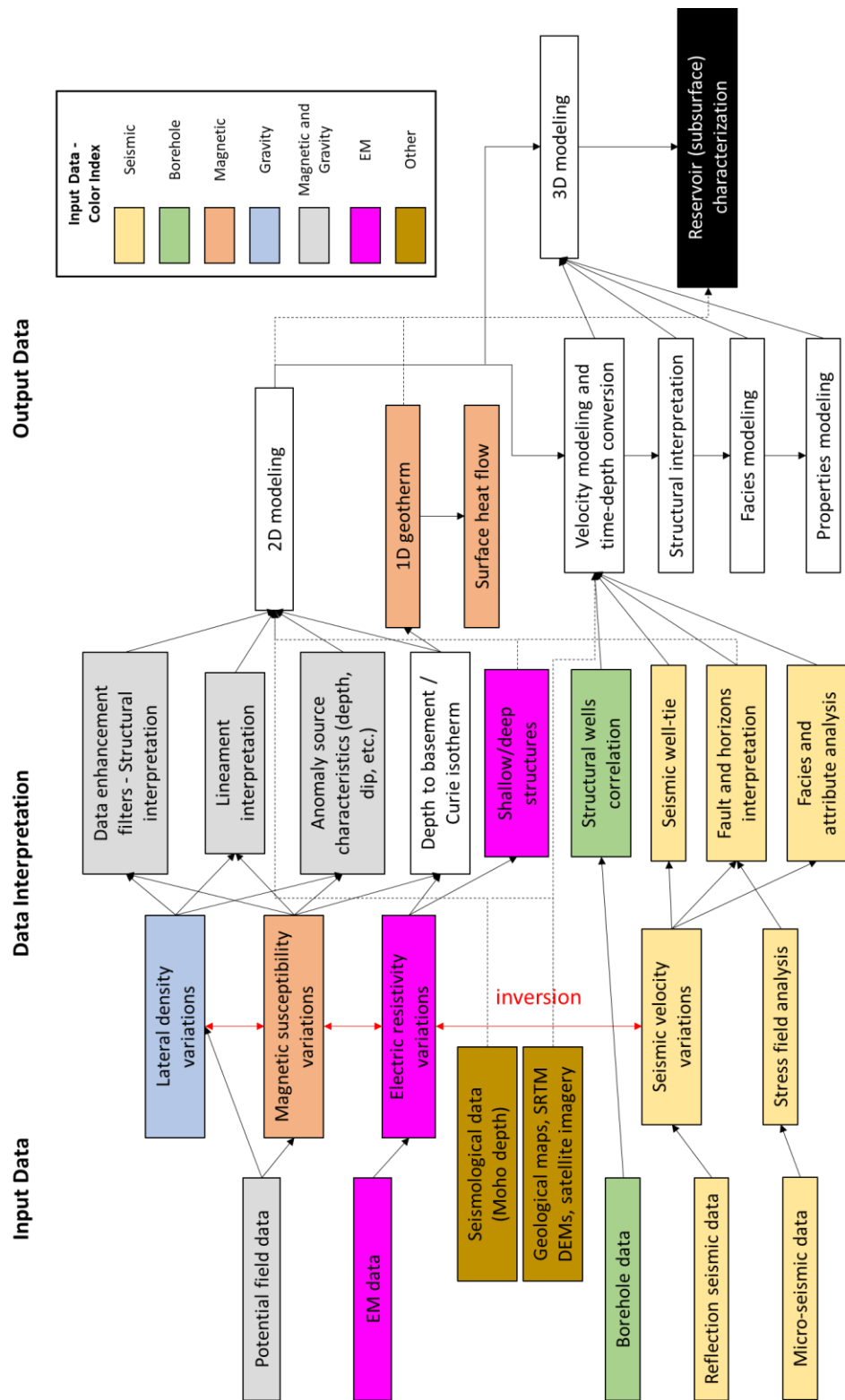


Figure 4: Geoscientific data analysis, interpretation, and modeling workflow.

3.2.1 General Description of the Workflow

The gravity and magnetic data can provide information on the lateral variations in density and magnetic susceptibility, respectively, which can be used to delineate the subsurface structures that cause detectable anomalies in the gravity and magnetic field. The conceptual subsurface model that represents the geometry of the area under study can be afterward enhanced by using the high-resolution seismic and well data, as well as constraints from the surface geology. Especially the velocity modeling and the formation boundaries resulting from the seismic reflection data analysis can be incorporated to revise the preliminary conceptual model until a good and reliable matching of all the datasets is achieved. Known information on the tectonic regime of the study area based on literature and satellite imagery can be added to the conceptual model for a close fit between the calculated and the measured gravity and magnetic anomalies.

Seismic data provide the seismic velocity variations in the subsurface and aid in the characterization of the different geologic formations; especially in the detection of the interface between the basement rocks and the overlying sediments. The knowledge of seismic velocities can be used to verify and calculate the densities of the geologic formations at depth through inversion, using different methodologies (e.g., [108, 109, 110, 111]), and update the conceptual model constructed from the gravity data.

The internal basin structure/stratigraphy can be delineated based on seismic data analysis and can be compared and/or verified by the lithostratigraphic changes acquired from the stratigraphy of wells. It should be afterward corrected using surface information from the geologic maps. Information from wells (e.g., sediments/basement interface) can also be utilized to constrain the estimated depth solutions from the potential field data analysis.

The lineament analysis of the derivatives of the potential field data provides the surface and subsurface tectonic regime of the basin, which can further support seismic interpretation and structural trends by detecting faults in the seismic images and correcting the interface between the basement and the sedimentary formations produced by the magnetic data processing. Moreover, the lineament maps can be compared with the known tectonic features from geologic maps, satellite imagery, and the literature for the detection of surface fractures and veins that might be of economic importance due to the minerals that can be encountered in them. The seismic sections can verify the presence and the trend of the structural features identified from the potential field data analysis. For a more robust re-interpretation of the seismic sections to match the potential field results more closely, the newly interpreted seismic sections can be added to the model again, and the interfaces of the geologic formations be modified so that a matching with the minimum possible difference among all the available datasets is achieved.

Land magnetic profiles can be used to compare the responses of the magnetic field at different heights (the heights of the instrument's sensor and the height of the flight of the aircraft) and to detect small anomalies in the magnetic field produced by small shallow sources not detected in the airborne data. Also, the resolution and consistency of the airborne data can be studied using the land profile as a guide for the existence of magnetic sources at the surface.

The EM (e.g., TEM and MT) data can be used to constrain the gravity data interpretation and the construction of the subsurface models. TEM soundings provide high-resolution results for the shallow parts of the exploration area, usually for the first hundreds of

meters, and constrain the deep geoelectrical models from the MT data. The TEM soundings can also be used to constrain the shallow part of the gravity model.

The depth of the Curie isotherm estimated from the aeromagnetic data analysis can be compared with the results of deep EM soundings. In this study, two MT soundings present a large resistivity contrast at a depth consistent with the estimated Curie isotherm depth, thus verifying the magnetic data analysis results. The depth of the Curie isotherm can be used to constrain the geotherm of the area, i.e., the temperature variations with depth. The geotherm can be used to estimate the surface heat flow; information that can define whether a geothermal field has the potential for further exploration and development. In addition to the rest of the results, this information aids in the indication of more favorable areas for the drilling of geothermal wells for production and/or re-injection.

The depth to the basement can be estimated using different methodologies (e.g., Werner deconvolution, analytic signal, Euler deconvolution) applied to the magnetic data. Using seismological data from the literature, the depth of the Moho interface can be added to adjust the model, allowing smaller calibrations based on the subsurface geology obtained from the seismic data.

3.2.2 Application of the Workflow in O&G Case Studies

The proposed workflow was applied to two case studies for O&G exploration, as described in the next sub-sections. The first study is relevant to a gas-prolific sedimentary basin in Northern Greece, where a variety of vintage geophysical and well data were available [112], while the second study refers to the area of Dammam Dome in Eastern

Saudi Arabia, where a gravity survey in an urban environment has been carried out [65]. Both cases validated the successful application and modification of the workflow based on the purpose of the study and the available datasets.

3.2.2.1 The Case Study of Axios-Thermaikos Basin

Axios-Thermaikos basin is an elongated depression that covers approximately 4000 km² within the central Northern Greece territory and extends up to the north Aegean offshore area. Numerous geological, geophysical, and drilling surveys have been carried out in the area, which has been proven to be a significant site for natural resources. Exploratory surveys for O&G proved the existence of a natural gas carbonate reservoir in the eastern offshore part [113]. Also, the strategic location of the basin in southeastern Europe and the existence of suitable geologic structures make it ideal for natural gas or CO₂ storage (unpublished report by Tsokas et al. [114]).

The application of the proposed workflow was based on the availability of vintage geophysical and well data for the onshore part of Axios-Thermaikos basin. More specifically, land gravity, airborne magnetic, and reflection seismic geophysical data, along with well lithostratigraphy data that were provided by the Greek Ministry of Environment & Energy, allowed a first “testing” of the workflow using real geoscientific datasets.

The lineament analysis of the potential field data provided the surface and subsurface tectonic regime of the basin, which was used to detect faults, mainly as lateral discontinuities, in the seismic images. The detected lineaments correspond to tectonic structures (fractures, faults, or dykes) and/or geologic boundaries.

An approximately 110 km SW-NE profile was drawn to cross the entire Axios-Thermaikos basin, and the basement depth was estimated from the magnetic data using the Werner deconvolution method [115, 116]. The gravity and magnetic data provided information on the lateral variations in density and magnetic susceptibility, respectively, which were used to delineate the subsurface structures that cause detectable anomalies in the gravity and magnetic field. Thus, the potential field data, constrained with surface geology and the wells that reached the bedrock, were used to construct the geometry of the study basin. The conceptual subsurface model for the internal part of the basin was enhanced by using high-resolution seismic and well data. Specifically, the velocity modeling and the formation boundaries as a result of the seismic reflection data analysis were incorporated to revise the preliminary conceptual model of the study area until a good and reliable matching of all the datasets was achieved. Surface data from geologic maps, satellite imagery, and digital elevation models were used to aid the interpretation of the different geophysical datasets and to add constraints in the geometric expansion of the geologic structures. The fault interpretation in the seismic data was constrained by the surface geology, the observed in satellite images faults at the surface, and the interpreted lineaments from the analysis of potential field data.

The depth to the Moho interface between the crust and the upper mantle was also added to the model using seismological data to account for the effect of this deeper interface on the observed gravity data. A density of 3300 kg/m^3 is a representative value that can be used for the upper mantle rocks [117]. The addition of information on the Moho interface depth correctly adjusts the model by matching the overall trend of the calculated gravity

anomaly with the measured data, allowing smaller calibrations to be made based on more detailed information about the local formation densities.

The final 2D model of the Axios-Thermaikos basin after the integration of all the available datasets is presented in Figure 5.

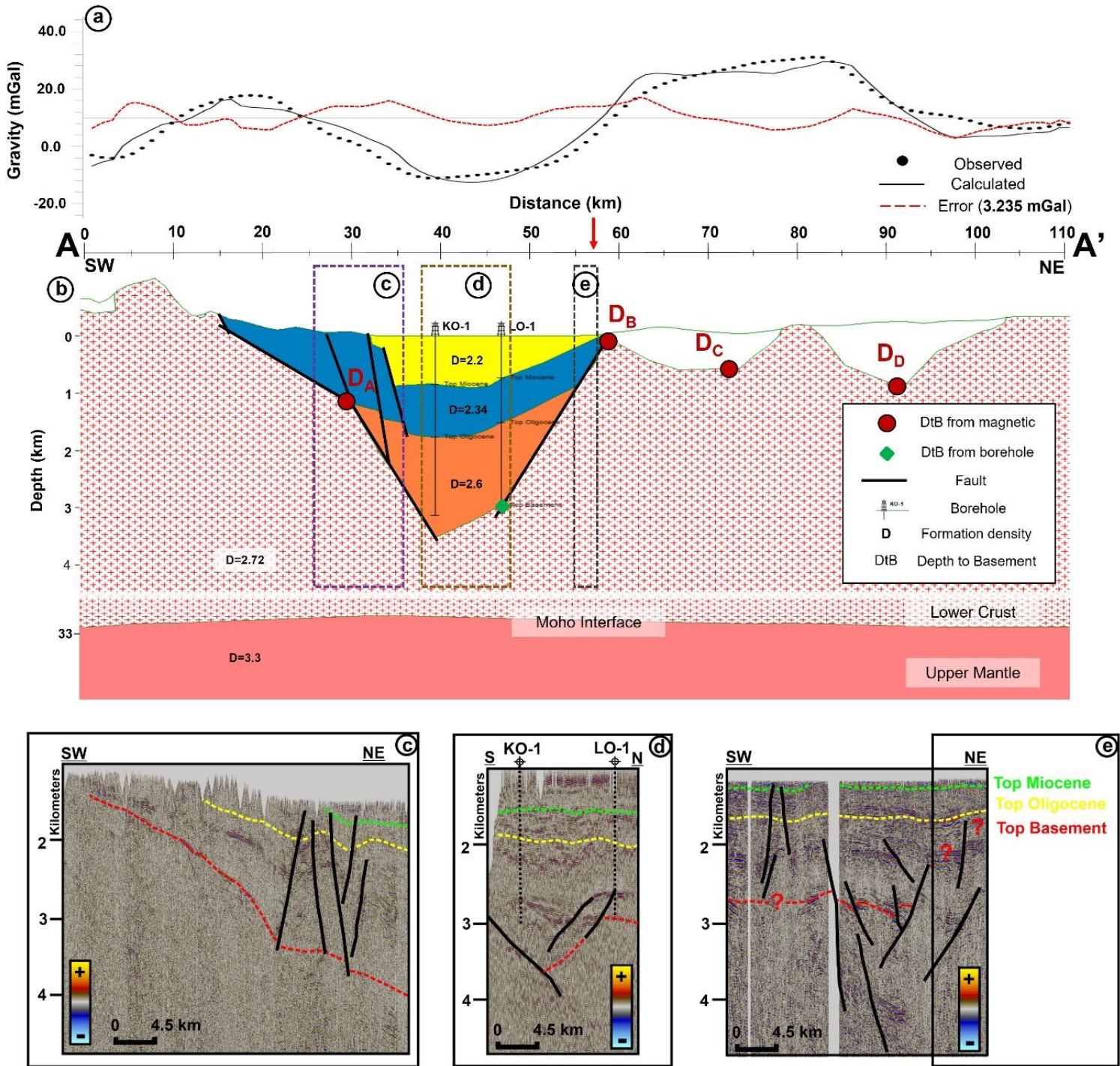


Figure 5: 2D model, constructed along a profile in the Axios-Thermaikos basin: (a) The observed and the calculated gravity anomalies; (b) The final gravity model, constrained by the surface geology, two boreholes (KO-1, LO-1), the depth to the basement as estimated from the magnetic data (points D_A-D_D), and three seismic lines. The depth of the Moho interface is also included. The seismic interpretation of the three seismic lines ((c) L105, (d) PEV203 (e) L9 [112]).

Seismic well-tie utilized the time-depth relationship provided by the wells. Specifically, for the time-depth conversion of seismic reflection data, the time-depth relationship from the well data (interval velocity, wells formation tops, and stratigraphic surfaces) were used. The reflectors that belonged to the formation stratigraphic marker at the wells were interpreted throughout all available 2D seismic reflection data using the horizon loop-tying method. The interpretation of faults in the seismic sections was achieved manually, while the surface geology and the interpreted lineaments from the analysis of the potential field data added additional constraints. Moreover, seismic facies and attributes analysis was performed to identify lithology, sedimentary processes, depositional environment, and fluid identification. The seismic facies analysis commonly follows the method of Mitchum et al. [118], whereas the instantaneous phase, Root Mean Square (RMS) amplitude, and variance are commonly utilized techniques for the seismic attribute analysis [119, 120, 121, 122, 123, 124, 125, 126].

The instantaneous phase ($\varphi(t)$) of a seismic trace is independent of the amplitude trace and is influenced by the propagation phase of the seismic wave-front detecting the lateral continuity. It can be calculated using Equation 3.1 [123]:

$$\varphi(t) = \arctan\left(\frac{\Im F(t)}{\Re F(t)}\right) \quad (3.1),$$

where $F(t)$ is the seismic trace, $\Re F(t)$ is the real part of the seismic data, and $\Im F(t)$ is the imaginary part of the complex trace.

The RMS amplitude is defined as a function of the square root of the sum of squared amplitudes (x) within the interval window, as described mathematically by Equation 3.2 [123]:

$$x_{RMS} = \sqrt{\frac{1}{n} \sum_{i=1}^n x_i^2} \quad (3.2) .$$

where n is the total number of amplitudes.

The variance measures the dissimilarity between seismic traces to produce a volume of discontinuity. Mathematically, it can be calculated by Equation 3.3 [123]:

$$var(t, p, q) = \frac{1}{J} \sum_{j=1}^J [u_j(t - px_j - qy_j) - \langle u(t, p, q) \rangle]^2 \quad (3.3) ,$$

where J is the number of seismic traces and t , p , and q are the different variables of the seismic trace. The mean $\langle u(t, p, q) \rangle$ is defined as shown in Equation 3.4:

$$\langle u(t, p, q) \rangle = \frac{1}{J} \sum_{j=1}^J u_j(t - px_j - qy_j) \quad (3.4) .$$

The application of the seismic attribute analysis is presented in Figure 6.

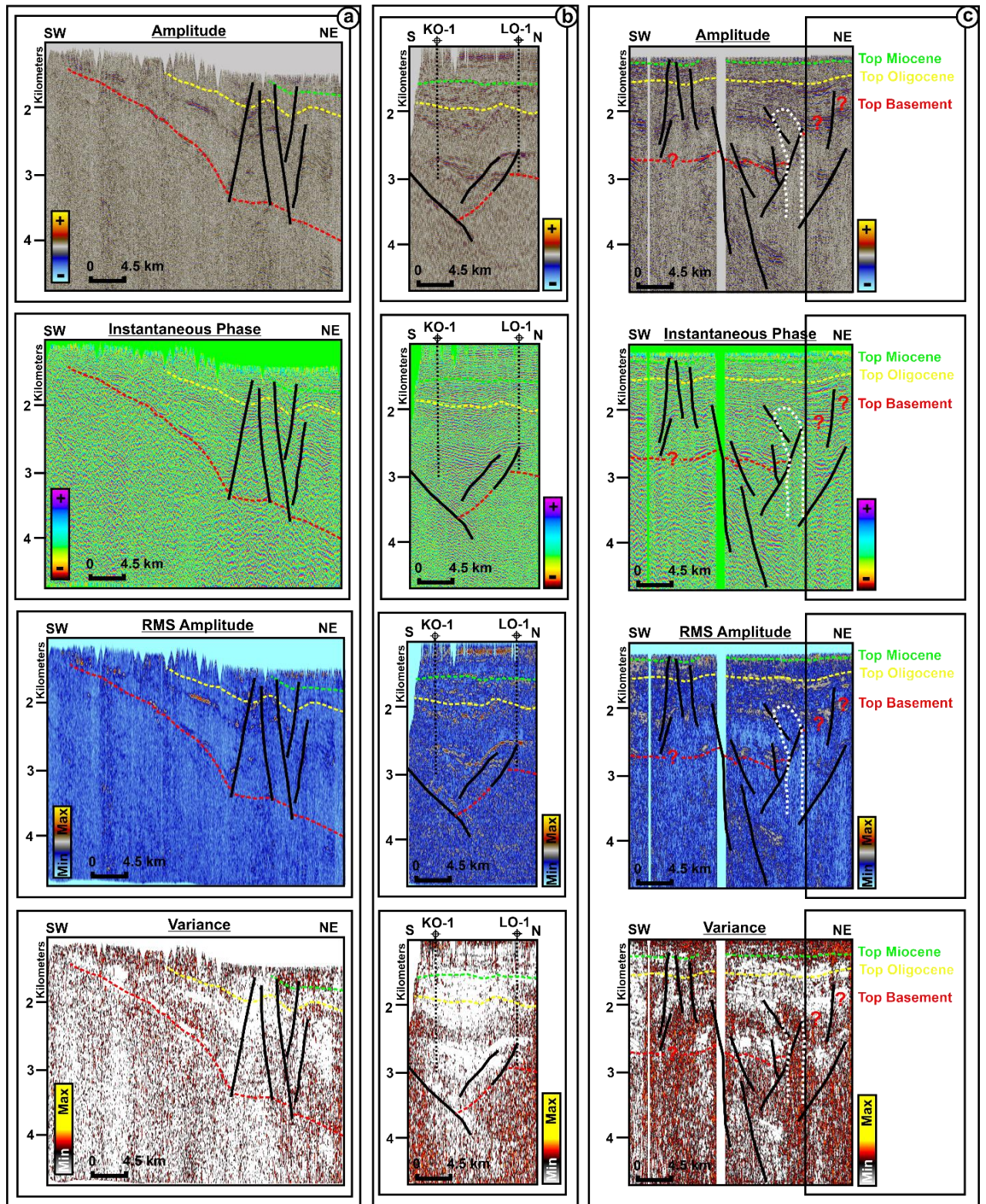


Figure 6: Seismic interpretation of three of the seismic lines ((a) L105, (b) PEV203, and (c) L9 [112]) using the instantaneous phase, RMS amplitude, and variance seismic attributes. Note that the white dashed line is a possible intrusive structure.

The correlation between the wells was achieved using the stratigraphy of the formations that each well penetrated. The structural correlation of the wells and faults seismic-surface interpretation provided the basis for the geomodeling (structural framework, gridding, and layering) by indicating the spatial distribution of the different lithologies and structures. However, there is an increased degree of uncertainty for the areas where no wells were present; the results for these areas can be extracted based on the results of the geophysical methods and the surface geology. The sequential indicators simulation is a geostatistical approach with regional geological controls and sedimentary processes, described in Equation 3.5 [127, 128]:

$$i(u; k) = \begin{cases} 1, & \text{if category } k \text{ prevails at location } u \\ 0, & \text{otherwise} \end{cases}, \quad k = 1, \dots, K \quad (3.5).$$

It can be utilized in facies modeling (Figure 7), which enables the distribution of the facies between the available wells into the 3D seismic subsurface model with no obvious geological body geometry [127, 128, 129].

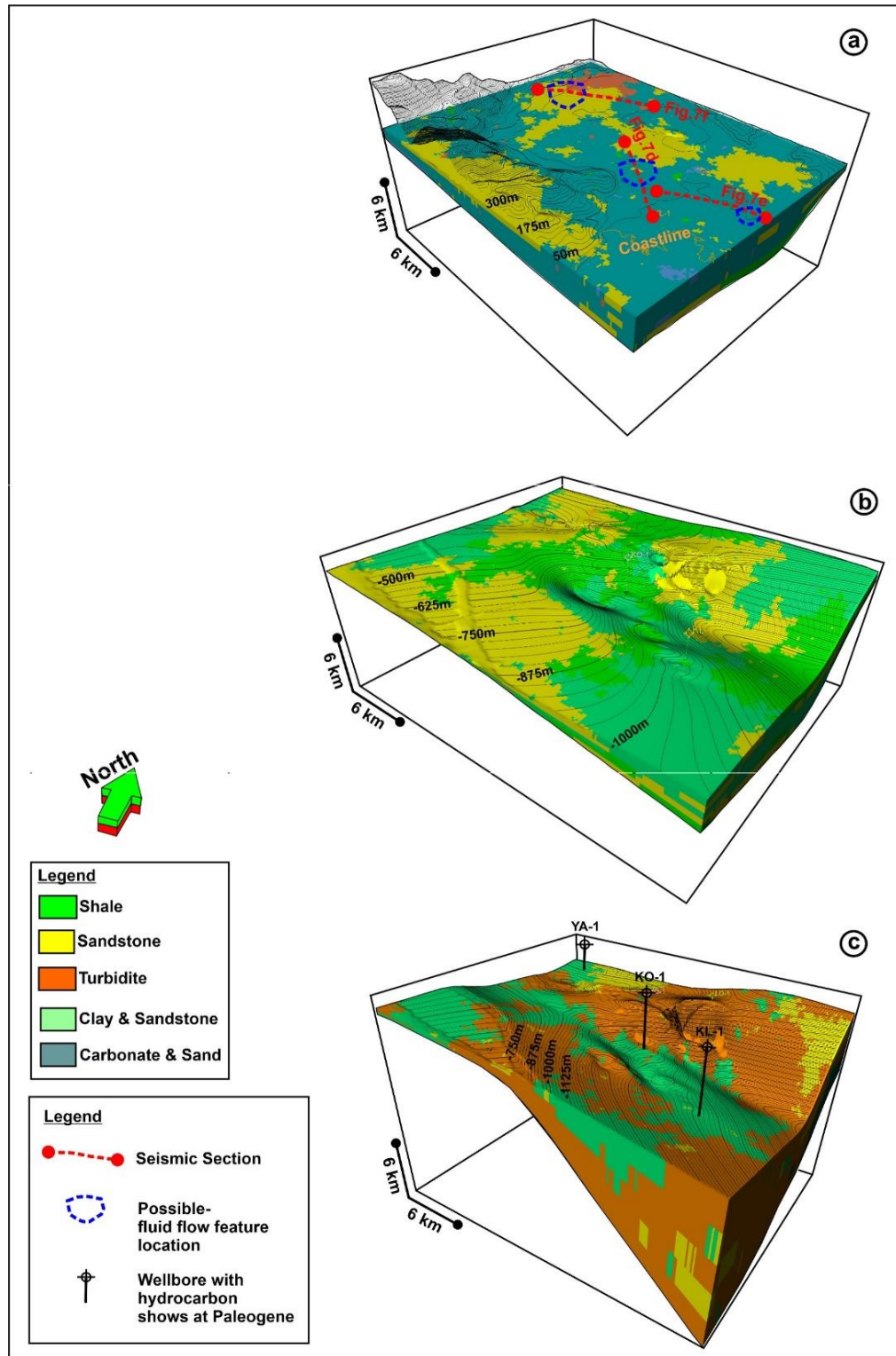


Figure 7: 3D facies models with the top structure of the different sedimentary rock groups in the Axios-Thermaikos basin ((a) Quaternary and Plio-Pleistocene, (b) Miocene, (c) Oligocene-Eocene [112]).

3.2.2.2 The Case Study of Dammam Dome

The presence of a salt dome creates impermeable barriers that stop the flow and migration of hydrocarbons, thus constituting a structural feature of crucial importance in O&G exploration. The Dammam Dome is located in the Eastern Province of Saudi Arabia, covering an area of about 150 km² along the coast of the Arabian Gulf [130], and holds historical importance as the site of the first successful oil well in the country, back in 1938 [131]. The exposure of the rocks constituting the Dammam Dome at the surface is limited due to weathering, sand cover, and construction. However, some of the best exposures of the dome's crest are encountered at the campus of the King Fahd University of Petroleum & Minerals (KFUPM). Thus, a dense gravity survey was carried out at the university campus to gain a better understanding of the subsurface geology and to provide new inferences about the geological setting of the Dammam Dome [65].

In this study of the Dammam Dome, the gravity method was implemented since the characteristics of the study area did not allow the application of magnetic or EM methods. The area is within an urban environment, with many buildings, electric cables, and places with concentrations of metals, e.g., roads and construction sites, as well as underground water circulation through sewers and buried pipes. At the same time, it was a good test of the robustness of the proposed workflow in cases where data from limited sources are available.

A total of 235 gravity measurements were collected covering an area of about 3.5 km², spatially distributed approximately every 100 m. During the measurements, special care was given to minimize errors resulting from noise and high air temperature, thus the data were collected during the night, eliminating noise from wind, traffic, machinery, and the

high day temperatures of the acquisition period (summer 2020). The gravitometer was set to automatically reject seismic noise and spikes, while it also calculated the Earth tide effect and applied the necessary tilt corrections. Three measuring cycles of 60 sec have been used at every gravity station. For better quality control on the data, if the gravity values of the three cycles differed more than 10 μGal , the measurement was repeated, with the application of more cycles. In cases of higher external noise levels, the cycle duration was increased. Furthermore, stations with tilt greater than 10 arcsec were rejected, and the gravity readings were repeated, resulting in an average standard deviation lower than 20 μGal [65]. To minimize the effect of the buildings on the acquired gravity data, the distance between the stations and buildings was no less than 30 m.

All the commonly applied corrections to the raw gravity data (tide, instrument's height and tilt, latitude, topographic, free-air, Bouguer) were made, before the production of the complete Bouguer anomaly map, which shows the effect of both long- (caused by deeper sources) and short- (caused by shallower sources) wavelength anomalies in the measured gravity field. To separate the regional and residual gravity field from the complete Bouguer anomaly map, the polynomial surface-fitting method by applying Fourier Transformation [132] was chosen, and the residual gravity field map was produced.

To delineate the boundaries of the anomalies' sources and to detect other tectonic elements and features, such as possible fault lines or fractures, the residual gridded data were processed with different edge detection algorithms, such as the Horizontal Gradient Magnitude (HGM) [133], the terracing transformation [134], and the tilt derivative [135, 136]. For a qualitative and quantitative approach to the anomalies' interpretation, the tilt-

depth method [84] technique was applied, which informs on the burial depth of the structures of interest by showing the upper part of the anomalies' sources. The results of the application of these methods are presented in Figure 8a.

Positive anomalies against negative ones indicate higher and lower density sources, respectively. These sources coincide mainly with two lines labeled A and B (Figure 8a), which trend ENE-WSW. The ENE-WSW trend is also defined by the maxima of the prevailing 25% of the HGM strikes (Figure 8b).

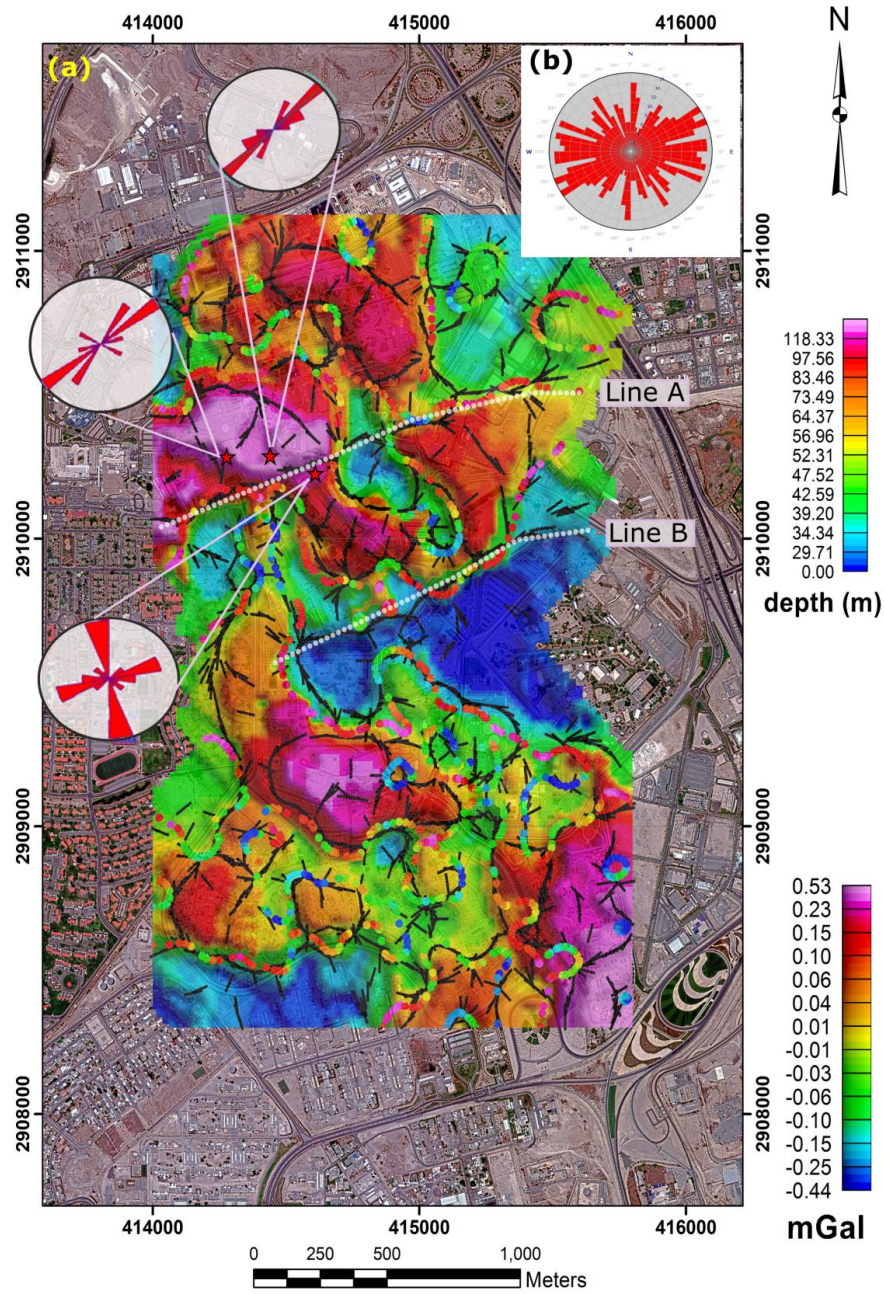


Figure 8: (a) The terracing map and the tilt-depth solutions are superimposed on the map of the KFUPM study area. The black line segments indicate the maxima of the HGM strikes, while the colored range symbols are the tilt-depth solutions calculated by the tilt derivative algorithm. Rose diagrams show the strike of the recorded joints [137]. The white dotted lines indicate lineaments A and B (Figure 9), which trend ENE-WSW and have a strong gravity imprint. (b) Rose diagram of the maxima of the strongest 25% of the HGM strikes.

3D unconstrained gravity inversion was carried out on the residual gravity field data, using a 3D mesh with blocks of 75x75x25 m dimensions. The results are shown in Figure 9. The inversion results show that lines A and B correspond to two tubular, almost vertical bodies of positive (greater than 0.05 gr/cm³) and negative (lower than -0.08 gr/cm³) density contrasts, respectively (the crustal reduction density used was equal to 2.67 gr/cm³). The thicknesses of the two bodies increase with depth and present a mean value of about 50 m. These bodies crosscut the substratum of the KFUPM campus at depths more than 100 m with an ENE-WSW trend, causing a strong gravity imprint [65]. Such trends have been defined by the exposed joints on the KFUPM campus, but they do not belong to the main exposed joint set since the latter strikes NNW-SSE [137] (Figure 8a). This is probably attributed to the regional stress regime, which reflects intraplate stresses originating within the Arabian and Eurasian tectonic plates due to their collision along the Zagros Orogen [138]. As a result, the interpretation of gravity data supports the conclusion that the Dammam Dome was affected by the intraplate stresses transferred from the convergence between the Arabian and Eurasian plates along the Zagros Orogeny [65].

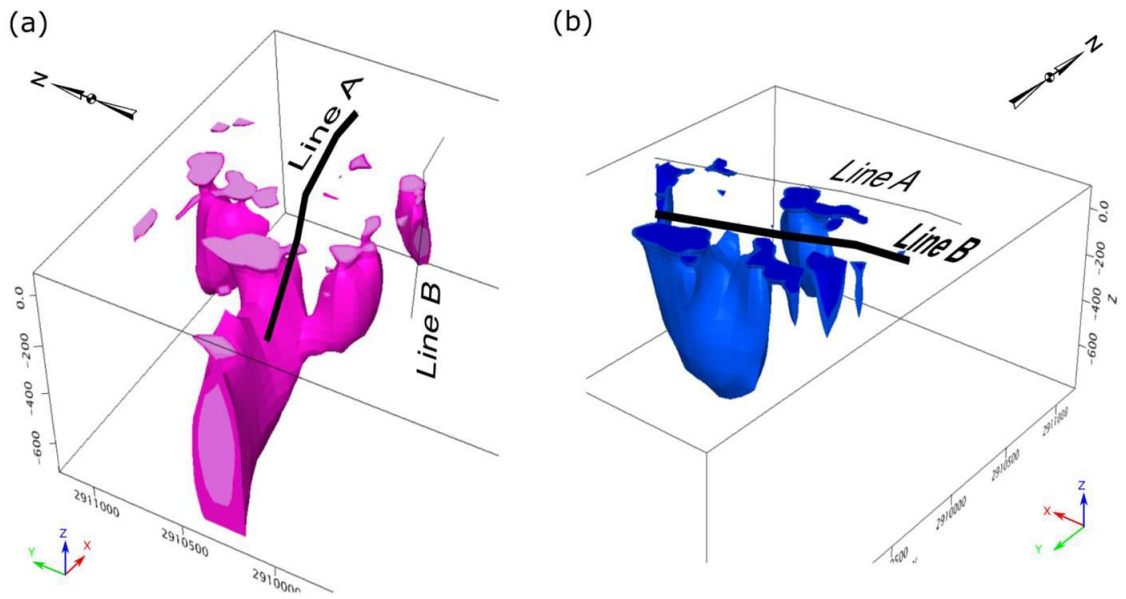


Figure 9: Results of the 3D gravity inversion. (a) Line A corresponds to a body with positive density contrast (purple color). (b) Line B corresponds to a body with negative density contrast (blue color).

3.3 Description of the Wadi Al Lith Datasets

In this section, the geophysical data that were used for this study are described. They include land gravity and magnetic data, as well as land MT and TEM measurements. All these data were collected by the geophysical laboratory of the KFUPM. Moreover, airborne magnetic data for a wider area of western Saudi Arabia, provided by the SGS, were also integrated into this study.

3.3.1 Gravity Data

A total of 206 relative gravity stations were measured in the Ain Al Harrah hot spring and the surrounding area in two field campaigns in May and December 2022. Due to the large extent of the study area, two data acquisition campaigns were conducted using two different base stations (A and B). The second base station was referred to the first by repeating measurements between them (A-B-A-B-A) at the end of the second survey. Since there was no information concerning an absolute gravity station in the area, that could be used as a reference for our measurements, the theoretical gravity value at the base station A was used as a reference and tied all the other relative measurements accordingly [65]. In case an absolute gravity point is known, the two base stations as well as all the other stations of this survey could be tied to the International Absolute Gravity Basestation Network (IAGBN). A gravity data profile of about 15 km in the North-South direction and grid-based data covering an area of approximately 16.5 km² in the Southern part of the study area were collected, with a spatial distribution varying between 150 and 300 m, following the local topography and the accessibility of the area. The distribution of the gravity stations is shown in Figure 10. Two CG-5 AUTOGRAVTM gravimeters

(Figure 11), manufactured by Scintrex Ltd, were used to acquire the gravity data. The instruments rejected seismic noise and spikes on the measured gravity data by default, while the Earth's tide effect on the local gravity field and the necessary tilt corrections on the data were also implemented. To minimize the effect of external noise and high air temperature on the measurements (especially during the May survey), three to five measuring cycles of 60 seconds were applied for each station, with additional repetitions in cases where the measurements differed more than 10 μGal or if the tilt values were higher than ± 10 arcsec.

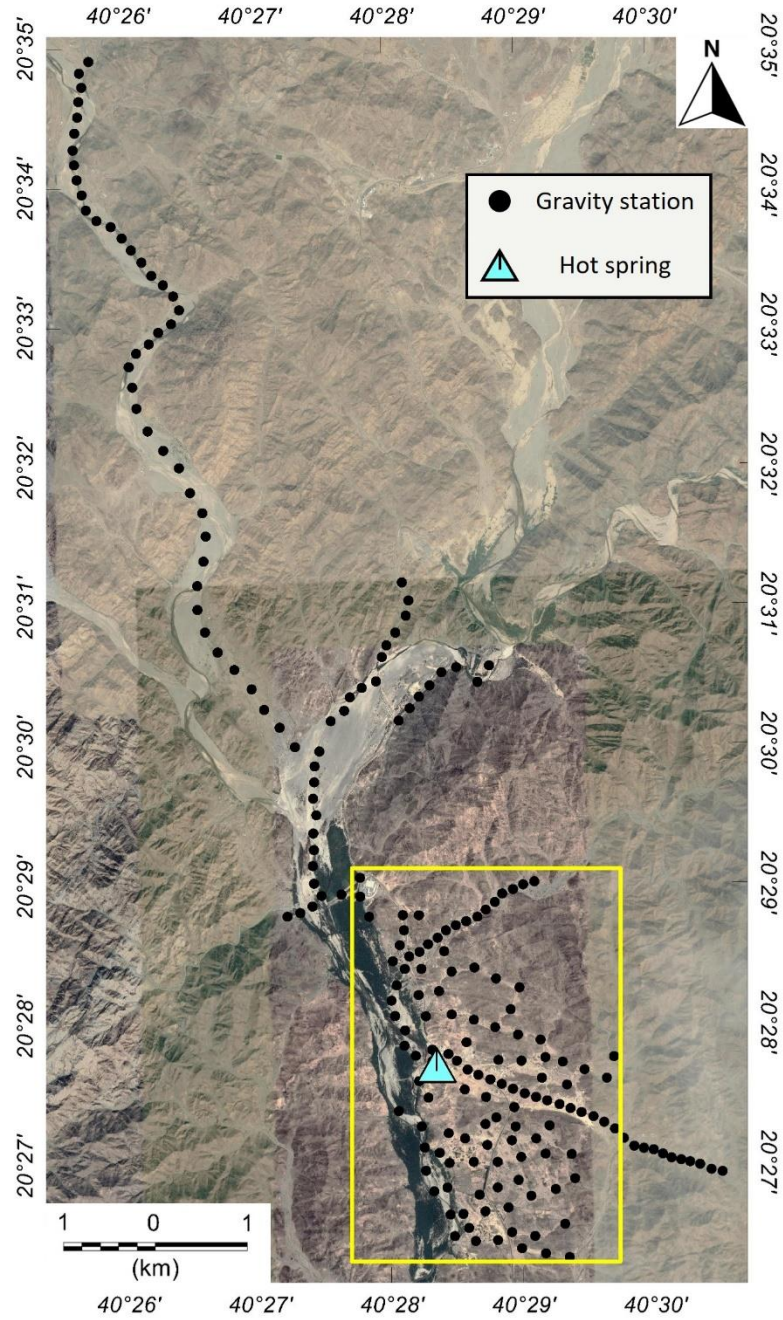


Figure 10: Measured gravity stations (black dots) in the Wadi Al Lith study area. The Ain Al Harrah is indicated with the light blue triangle. The yellow rectangle corresponds to the area used for the 3D model since the gravity measurements are dense.



Figure 11: Field photographs of the CG-5 gravimeter during the Wadi Al Lith surveys.

The Trimble Differential GPS R10 system was utilized to measure the accurate geographic coordinates (latitude and longitude) and elevation of the stations. The base station of the GPS was set according to the Kingdom of Saudi Arabia Continuously Operating Reference Station (KSA-CORS) network, which provides an accurate Global Navigation Satellite System (GNSS) positioning service for the entire country, making real-time corrections to increase the efficiency of the acquired location data.

3.3.2 Magnetic Data

The airborne magnetic data that are used in this study are part of a unified dataset covering the entire Western Province of Saudi Arabia, acquired between 1962 and 1983 by different geophysical companies (Aero Service Corp., Hunting Geology and Geophysics Ltd., Lockwood Survey Corp. Ltd., Arabian Geophysical and Surveying Co., Geosurvey International), on behalf of the SGS. The data covering the Wadi Al Lith area were acquired in 1966-1967, with a terrain clearance of 300 m and a distance between flight lines of 800 m [139]. The data were later digitized and after applying an upward continuation of 800 m above ground level, the total magnetic intensity (TMI) and the reduction to the Pole (RTP) maps were produced [140]. SGS provided the aeromagnetic data of this study in RTP format, and the area they cover is delineated in Figure 12.



Figure 12: The area covered by the airborne magnetic data (continuous black line). The study area close to the Ain Al Harrah hot spring is indicated with a red rectangle.

The land magnetic data were acquired during two field surveys, in January 2023 (data of Area A) and November 2023 (data of Area B), at two sites close to the Ain Al Harrah hot spring, as shown in Figure 13. The Geometrics G-858 MagMapper cesium magnetometer (Figure 14) was used as the data acquisition instrument. During the field acquisition, the instrument was used as a gradiometer collecting data with two sensors (with a distance of one meter between them) at vertical configuration. The continuous surveying, with a rate of up to ten readings per second, and the high sensitivity of the instrument make it ideal for several different applications of economic, geologic, military, and engineering purposes. In the Wadi Al Lith surveys, the gradiometer was set to make four measurements per second. The Geometrics MagMap software was used to download the data from the magnetometer and to convert them into a suitable format to be imported into the Oasis montaj software, which was used for data processing and interpretation.

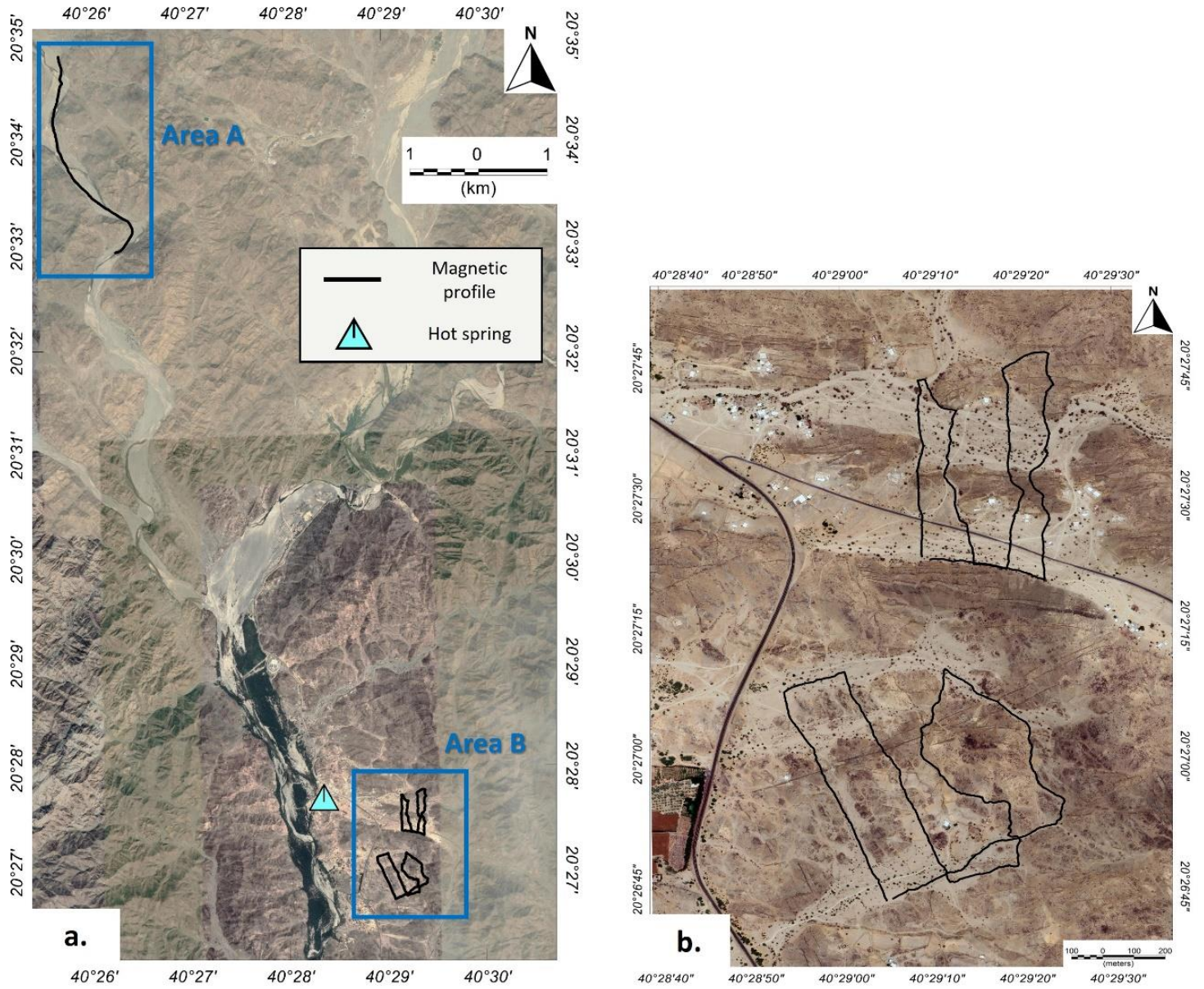


Figure 13: (a) The locations of the land magnetic profiles (black lines) acquired in the study area. They are located in two sites (Areas A and B, on the North and East of the Ain Al Harrah hot spring - light blue triangle, respectively), indicated with blue rectangles. (b) Zoom in Area B.



from <https://www.geometrics.com/product/g-858/>

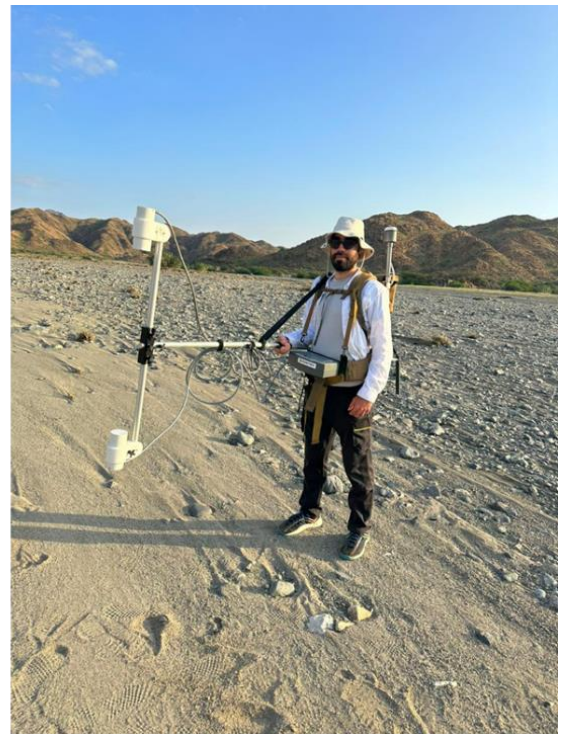


Figure 14: The G-858 MagMapper magnetometer.

In Area A, in the northern part of the study area, an approximately 4.3 km-long profile was acquired along a river valley (Area A in Figure 13a). Although this profile covers a small part of the area that is covered with the aeromagnetic data of SGS, it can be used to compare the resolution of the magnetic data at different heights (the heights of the two sensors of the gradiometer and the height of the flight of the aircraft), as well as to detect very small anomalies in the magnetic field produced by small shallow sources.

The data of Area B (Figure 13b) were acquired at sites where numerous dikes are present, to study in more detail the influence of these bodies in the circulation of thermal fluids. Also, to investigate the potential value of the dikes as carriers of precious minerals, such as gold and silver, owing to their geological relation to similar metalliferous structures in the western part of Saudi Arabia. These data were collected at continuous profiles of length between 550-850 m, with distance between profiles of 50-350 m (according to the local topography), that cross almost vertically the outcropping dikes. During the acquisition of these data, a Geometrics G-857 proton magnetometer was used as a base station to constantly record the secular and diurnal changes of the magnetic field [81] and apply the necessary corrections so that they are removed from the measured data.

3.3.3 Electromagnetic Data

The land EM (MT and TEM) data acquired over the study area are described in detail by Ashadi et al. [28]. The MT data that were used for this study are part of this dataset and were acquired during the first EM survey in the area, in May 2022. The broadband MT data were recorded using the KMS-820 system (Figure 15) and the KMS-5100-150 transmitter with different sampling frequencies (4 kHz, 1 kHz, 40 Hz). Good quality data were acquired in the period range of 0.001-300 seconds using the LEMI-120 induction

coils and the LEMI-701 electrodes. The induction coils were oriented, leveled, and buried, and the electrodes were also buried to avoid any disturbance to the measured signal. The TEM data were collected in December 2022-January 2023, using the ABEM WalkTEM system. The locations of the MT and TEM soundings used in this study are shown in Figure 16.



Figure 15: A deployed MT station during the Wadi Al Lith surveys.

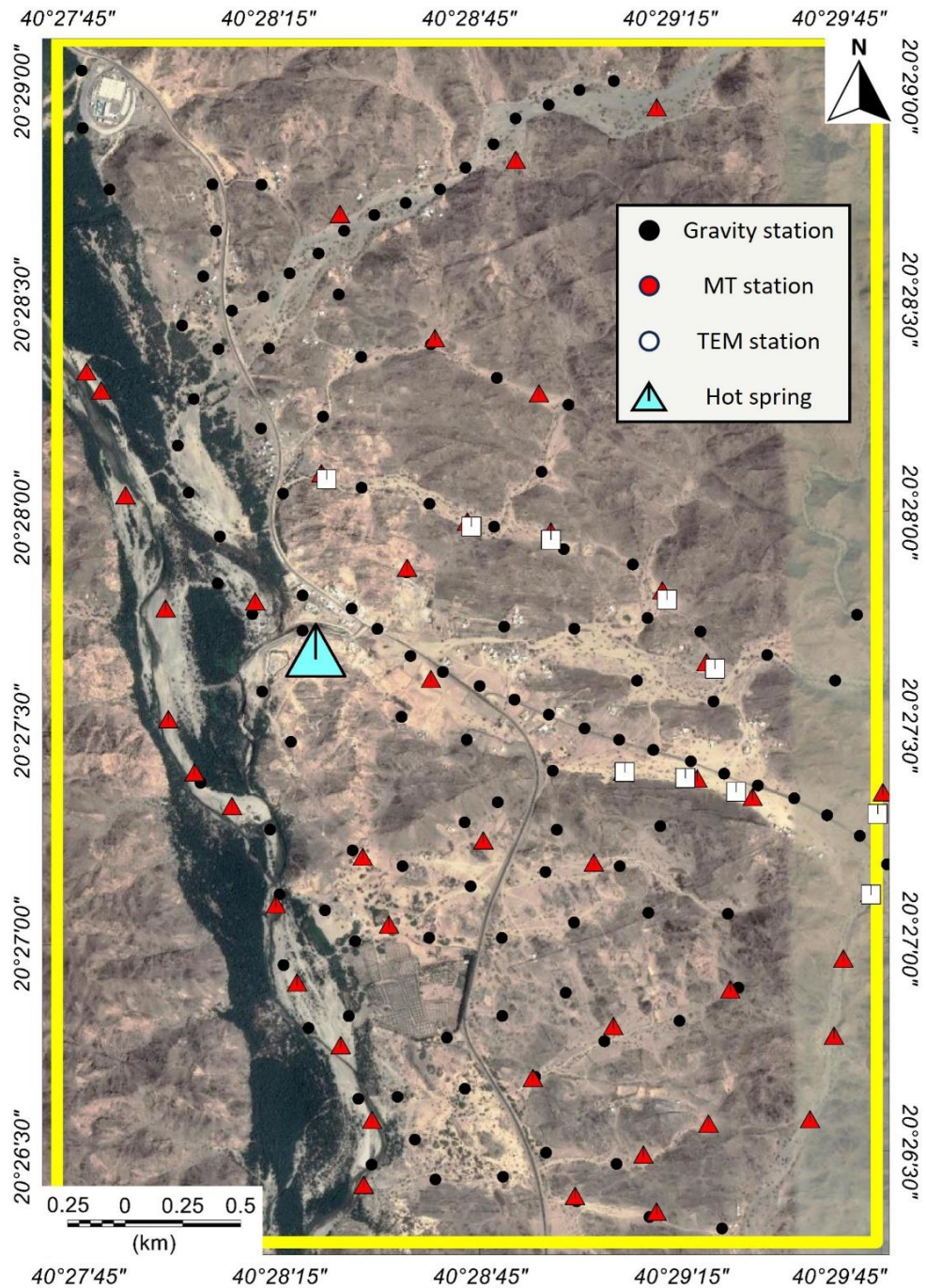


Figure 16: The area around the Ain Al Harrah hot spring (inside the yellow rectangle of Figure 4), with the locations of the MT (red triangles) and TEM (white rectangles) stations used for this study. The locations of the gravity stations (black dots) within the area are indicated, while the hot spring is also shown (light blue triangle).

3.3.4 Additional Data

Additional geologic and geophysical information was integrated from an existing water well and one refraction seismic profile to aid the interpretation of the different geophysical datasets and to add constraints in the geometric expansion of the geologic structures. Since the borehole was drilled for water acquisition, it reaches a depth of approximately 32 m; thus, it provides information only for the sediment layer thickness and its contact with the basement rock [141]. The seismic profile has a length of 750 m and crosses vertically the river valley. It also provides information only for shallow depths, around 50 m. It reveals the contacts between sediments and basement rock, due to the differences in seismic velocity (the basement rock presents high-velocity values) [142]. The locations of the water well and the seismic profile are shown in Figure 17.

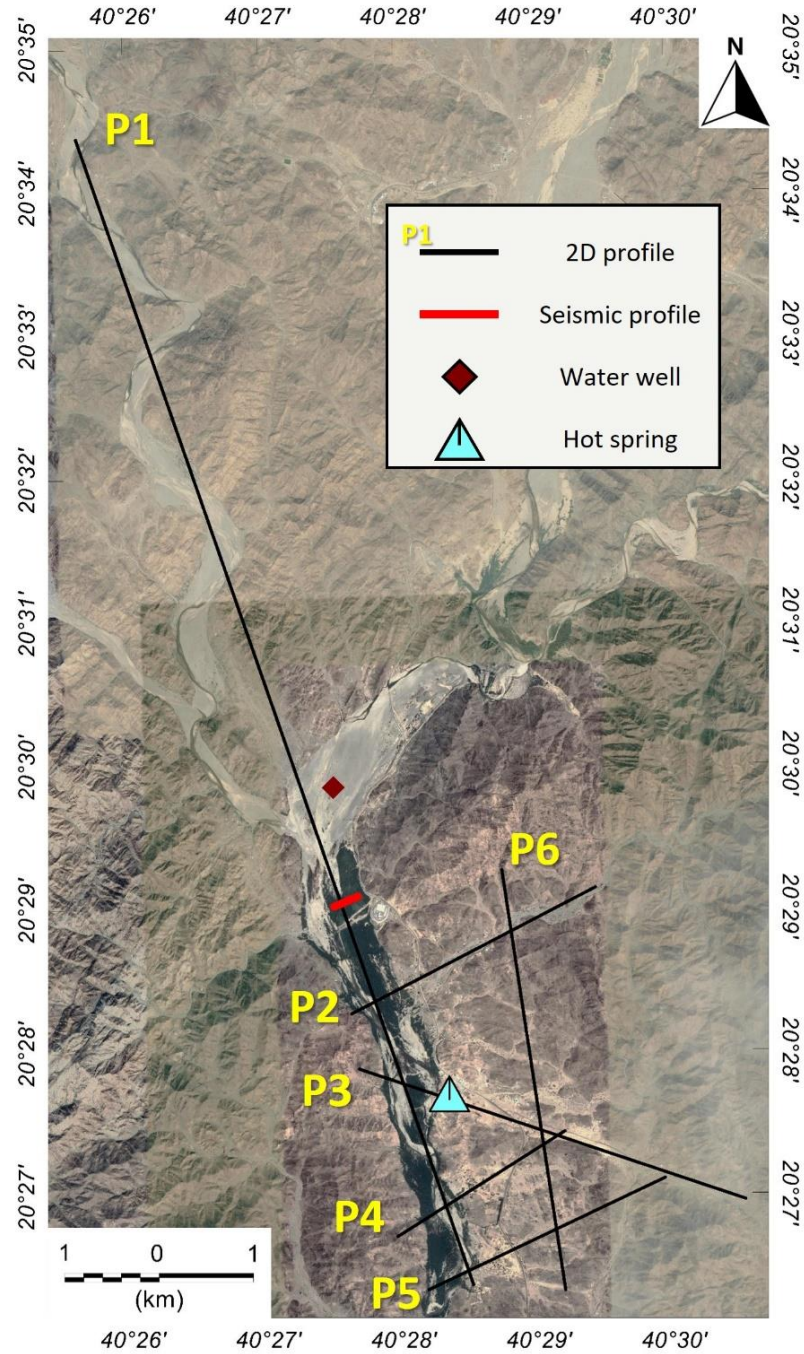


Figure 17: The locations of the water well (brown rhombus) and the seismic profile (red line), used as constraints for the gravity data modeling. The six profiles (P1-P6) locations used for the 2D modeling are also indicated (black lines).

Furthermore, surface data from geologic maps [21, 22] and digital elevation models were also used for geological interpretation and modeling.

3.4 Data Processing

This section describes the steps that were followed for the processing of the acquired land geophysical data.

3.4.1 Gravity Data

The gravity method is susceptible to several factors that can contaminate the measured data and produce noise that needs to be dealt with. Such factors can be related to external noise coming from artificial (passing vehicles, machinery working, man-made structures, etc.) and natural (wind, air temperature, earthquakes, etc.) sources, as well as the topography of the study area. To ensure accurate results, the effect of these factors should be minimized from the raw data by applying proper quality control during data acquisition and relevant corrections afterward. Concerning the corrections, the Earth tides and the instrument height corrections should be initially performed, followed by the instrument drift, the station latitude, the Free Air, and the Bouguer corrections. After applying the above corrections, the simple Bouguer anomaly is computed. To determine the complete Bouguer anomaly (CBA), it is crucial to correct for the terrain/topographic correction as well. Additional specific corrections might need to be applied according to the survey type (land, marine, airborne, or satellite) and the aim of the study (e.g., natural resources exploration, geotectonic studies, or civil engineering purposes) [65, 81]. The final CBA map includes both regional (large-scale) and residual (local) anomalies.

The gravity data were processed using Seequent Oasis montaj software and its Gravity and Terrain Correction extension. Oasis montaj allows for a detailed understanding of the subsurface owing to its advanced suite of processing, analyzing, and modeling tools, while the Gravity and Terrain Correction extension provides a complete solution for gravity data corrections and processing.

Initially, the tide, the instrument's height, and the instrument's drift corrections were applied. The 1980 International Gravity Formula [143] was used to calculate the theoretical Earth's gravity at the base station and to correct the raw values of all the measured gravity stations accordingly. Since there was no information on an absolute gravity station in the area of the measurements, that theoretical value at the first base station was used as the reference. Afterward, the latitude correction was applied to correct for the geographic latitude effect on the observed gravity values, followed by the topographic correction (or terrain effect correction), which accounts for the effect of the local topography.

Two SRTM (Shuttle Radar Topography Mapping) elevation grids were used as the regional and the local DEM (Digital Elevation Model) for the topographic correction. For the regional DEM, the SRTM 15+ dataset was used, which includes the topography at 15 arcsec with a spacing of 415 m. For the local DEM, the SRTM 90 dataset was used, which has a grid spacing of 90 m. The extent of the study area did not necessitate the use of bathymetry data.

The final step was the application of the free air and the Bouguer corrections. For the free air correction, a value of 0.3086 mGal/m [144] was added to the measurements to

account for the gravity field change with height above sea level. The Bouguer correction further adjusts for the elevation and the density of the geologic formations between the gravity stations and a reference level (usually the sea level). For the Wadi Al Lith dataset, a value of 2.67 g/cm^3 was used as the Bouguer reduction density.

3.4.2 Magnetic and Electromagnetic Data

The acquired land magnetic data were processed using the Oasis montaj software. Initially, the cultural noise caused by artificial magnetic sources was removed from the raw data and the rejected values were interpolated to follow the trend of the surrounding magnetic readings. The diurnal variations of the magnetic field recorded at the base station were later imported to the dataset and their influence was removed from the data. The International Geomagnetic Reference Field (IGRF) was also subtracted. Finally, the processed data were transformed to RTP format.

Two of the most widely applied magnetic data analysis techniques (Werner deconvolution and analytic signal) were employed to study the distribution and the characteristics (depth, dip) of the dikes along selected land magnetic profiles of Area B (Figure 13b), owing to the differences in magnetic susceptibility between the dikes and the surrounding rocks.

The MT dataset was processed using the KMSProMT software, based on an advanced robust processing technique [145] to estimate the MT transfer functions responses. This technique has been proven to eliminate the time domain outliers and large errors to produce a more stable result. The processing of the TEM data was done using the AGS (Aarhus GeoSoftware) Workbench software package.

To interpret the MT data individually, one-dimensional (1D) analysis was performed for each sounding with the help of IX1D software. The 1D inversions were carried out using the ridge regression technique in a manner described by Inman [146] and Occam's inversion method [147, 148], incorporating both apparent resistivity and phase data. The corresponding apparent resistivity and phase curves for MT11 and MT13 stations [28] that were used in this study are presented in Figure 18. The estimated transfer functions were smooth and consistent with high data quality. These two soundings were utilized in this study to verify the calculation of the Curie isotherm depth from the aeromagnetic data, as will be later discussed. The error at the short periods was slightly increased, due to the anthropogenic noise sources. The period dependence of apparent resistivity and phase indicates a good conductor for long periods (greater than 1 s). Finally, both polarizations show a rather consistent behavior with slight curve splitting for periods larger than 0.1 s, indicating a non-layered subsurface model. The ridge regression and Occam inversions were applied to trade off the size and the roughness of the model improvement.

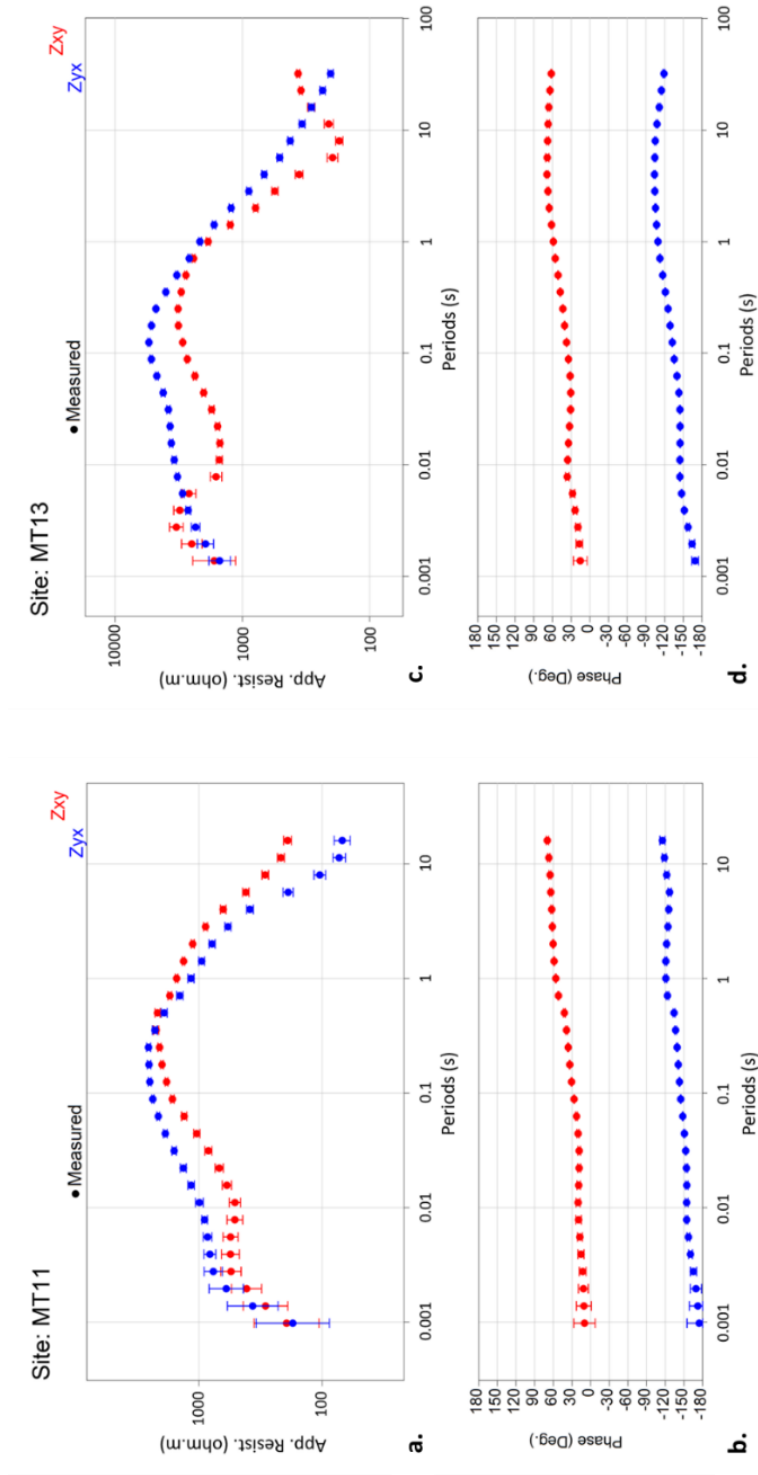


Figure 18: (a) Apparent resistivity and (b) phase curves of the MT11 sounding. (c) Apparent resistivity and (d) phase curves of the MT13 sounding. The red color curves show the XY components, while the blue colored curves represent the YX components.

3.5 Application of the Workflow to the Wadi Al Lith Case Study

The geotectonic complexity of the study area of Wadi Al Lith, in combination with the growing need for the identification of new geothermal reservoirs in Saudi Arabia and the availability of geoscientific information coming from different methods, creates an excellent case study for the application of the proposed workflow. The results of this study aim to support further and more detailed subsurface studies on an area with promising geothermal energy potential.

More details for each of the different processes of the workflow as applied to the Wadi Al Lith study area are provided in the following sub-sections.

3.5.1 Data Enhancement Filters

Different data enhancement filters can be applied to the processed potential field data to highlight or isolate features of interest [81]. The complete Bouguer anomaly map includes the effect of near-surface and deep-seated sources in the observed gravity field [81]. To separate the two, i.e., to distinguish between residual and regional gravity fields, the polynomial surface-fitting method [132] can be applied, by subtracting a first-order polynomial from the complete Bouguer field data. Generally, the residual gravity field can map different lithological units and structural lineaments (other than rock unit boundaries and faults) as lateral discontinuities.

Another common approach involves the calculation of the derivatives of the gravity or magnetic field, which can effectively delineate the boundaries of the anomaly sources and identify various tectonic and structural attributes [81]. The two categories that derivative methods are separated into are the amplitude- and the phase-sensitive

derivatives. The amplitude-sensitive derivatives are used to isolate and/or separate the anomalies that bodies of different sizes, burial depths, and densities/magnetic susceptibilities cause. The phase-sensitive derivatives are used to define subtle features more clearly [81].

The horizontal derivative (also known as HGM) is among the most commonly applied amplitude-sensitive derivatives and can be used as a good edge detector [85, 133]. The total horizontal derivative (THDR) is defined as the square root of the squared horizontal (x and y) derivatives, as shown in Equation 3.6:

$$THDR = \sqrt{\left(\frac{\partial F}{\partial x}\right)^2 + \left(\frac{\partial F}{\partial y}\right)^2} \quad (3.6),$$

where $\left(\frac{\partial F}{\partial x}\right)$ and $\left(\frac{\partial F}{\partial y}\right)$ are the horizontal derivatives of the gravity or magnetic field (F) in the x and y directions, respectively. The THDR presents maximum absolute values above strong density or magnetization contrasts, usually located at the edges of the geologic structures, and can map non-sloping contacts. A benefit is that it remains relatively stable regardless of the noise levels [149]. The lineaments interpreted from the residual gravity field data can refer both to the basement and the sedimentary formations within the river basin in the study area, according to differences in rock density.

One of the most useful phase-sensitive derivatives is the tilt (or tilt angle) derivative (TDR), which enhances anomalies with weak amplitudes due to either deep sources and/or low contrasts [135, 136, 150]. The tilt derivative is given by Equation 3.7:

$$TDR = \tan^{-1}\left(\frac{VDR}{THDR}\right) \quad (3.7),$$

where VDR is the vertical derivative given by Equation 3.8:

$$VDR = \frac{\partial F}{\partial z} \quad (3.8) .$$

When applied to magnetic data, the zero-value contour line of the tilt derivative outlines the regional signature of the basement rocks [85], since the difference in the magnetic susceptibility between the bedrock and the overlying sediments is usually large. The tilt derivative grid of the Wadi Al Lith area was produced from the RTP grid.

Another filter that can also be applied to the residual gravity field is the terracing transformation [134]. This filter produces areas of constant amplitude, known as terraces. Terraces are separated by distinct interfaces due to their difference in the field amplitude. Thirty (30) iterations of the terracing transformation algorithm were run to construct the terracing map of the Wadi Al Lith study area.

3.5.2 Subsurface Lineaments Detection

Special filters on the airborne magnetic data were applied to identify lineaments at the surface and the subsurface and, as a result, to reveal the density and direction of tectonic lineaments (mostly faults) in the study area, mainly as lateral discontinuities. These tectonic features describe and control the circulation of the geothermal fluids, forming a convection cell in the subsurface by primarily acting as conduits for their flow.

Due to mineral recrystallization or the filling with different materials, linear structures (most commonly faults, dikes, and fractures) present magnetic responses often in significant contrast with the corresponding responses of their host rock formations.

Therefore, the detection of these structures from magnetic data can indicate possible targets for further exploration using geological and other geophysical methods.

The SGS aeromagnetic data of the Wadi Al Lith area were used to detect the subsurface lineaments by applying the CET (Centre for Exploration Targeting) Grid Analysis. The CET Grid Analysis module is an extension of the Oasis montaj software developed by the University of Western Australia [151] and provides a valuable tool for texture enhancement, phase analysis, structural complexity analysis, and edge and threshold detection by estimation of the lineaments' trends from potential field geophysical data [152, 153]. It is widely used in the mining industry since it can identify promising areas of ore deposits and structural discontinuities [154, 155, 156, 157, 158] by outlining subsurface areas of intersections and/or changes in the strike direction of geologic structures and produce contact occurrence density maps [159].

After an upward continuation of 500 m, the RTP magnetic data grid was used as the starting grid of the CET grid analysis. The lineaments were extracted from a combination of texture analysis and phase-based ridge detection [160]. The lineaments can be interpreted mainly as faults and dikes within the study area of Wadi Al Lith. The CET algorithm achieves the lineament extraction through four main steps.

Initially, the Texture Analysis algorithm of the CET operation calculates the standard deviation of the data values within a local neighborhood for each grid point. Highly contrasting values, as compared to the background signal, indicate the possible presence of significant structural characteristics.

Next, Phase Symmetry identifies axes of symmetry using a frequency-based approach [154]. The 2D gridded data are split into 1D profiles, which were analyzed over multiple directions and scales to produce strong symmetry responses in every direction except for those parallel to the linear structures, thus enhancing their appearance and main trends. This was followed by the mapping of lithological boundaries and structures (faults and dikes). In our study, only the positive features were considered, i.e., the assumption that the magnetic anomaly sources of the area only caused high positive anomalies.

Afterward, the Amplitude Thresholding routine was applied, identifying ridges by extracting the desired information for the linear features from the processed data and removing the noise. The output is a binary grid where only the trend lines are presented.

The filtered grid was then vectorized through a line-fitting method included in the Skeleton-to-Vectors algorithm. The method divides the linear features into two groups on the points where the features deviate more than a user-assigned tolerance space. This method was repeated for the newly created segments until no feature deviated more than the tolerance value [161]. The outcome was a map showing thinned straight-linear features that can be further used for structural analyses.

The results of the lineament analysis were drawn on a lineament density map. This map was created by the open-source QGIS software using the Line Density plug-in. The plug-in calculates a density measure of linear features in a circular neighborhood within each raster cell. In the analysis of this study, a search radius of 10 km at a pixel size of 100 m was used. The automatically extracted lineaments from the aeromagnetic data using the CET Grid Analysis algorithm were verified and manually edited afterward using the tilt

derivative of the magnetic field to correct for lineaments that did not make sense or were incorrectly drawn.

3.5.3 Potential Field Anomaly Sources Characteristics Determination

Potential field data are widely used to estimate the depth of anomaly sources through a variety of methods [149]. The first methods were graphical [162, 163, 164] and they were applied assuming simple geometries (spheres, horizontal cylinders, dikes, etc.) These methods are rarely used nowadays but provide acceptable results in the study of isolated anomalies on limited datasets. Semi-automated methods, based on the study of the derivatives of the field were later developed and they are still used to accurately detect the boundaries and the location of the causative bodies [165]. Such methods include the horizontal and vertical derivative methods, the analytic signal (total derivative), and the tilt and theta derivatives. Next, automated methods made the processing and interpretation of potential field data easier. Examples of these methods are the statistical methods (e.g., [166, 167, 168]), the Werner deconvolution [115, 116], the 2D and 3D Euler deconvolution [169, 170], and the Source Parameter Imaging (SPI) method [171]. A specific category of statistical methods applied to magnetic data is the spectral analysis methods, which make use of the radial spectrum of the data (e.g., [172, 173]) and have been used in magnetic data analysis since the 1970s in many different applications [174]. Many publications discuss the enhancement and the combination of different methods to overcome some of the drawbacks of each and create a more robust and widely applied method (e.g., [165, 175, 176, 177]). The semi-automated and automated methods allow the rapid and easier handling of large datasets, however, the estimation of the source

location and characteristics (e.g., inclination, density, magnetic susceptibility) are still based on sets of assumptions [174].

The analytic signal approach makes use of the properties of the Hilbert transform [80, 178, 179, 180, 181]. The amplitude of the analytic signal (AS) is defined as the square root of the squared sum of the vertical and the two orthogonal horizontal derivatives of the magnetic field, where the horizontal and vertical derivatives of the magnetic field are Hilbert transform pairs [182] over 2D sources. It has been used successfully in the form of profile data to locate dike bodies [178, 179, 183, 184]. Moreover, the approach was further developed by Roest et al. [185] and MacLeod et al. [186] for the interpretation of aeromagnetic maps. The improvements in the approach to the interpretation of aeromagnetic data were presented by Hsu et al. [187, 188] and Debeglia and Corpeel [182]. The AS of magnetic anomalies can be easily computed. The horizontal derivatives can be calculated directly from a total field grid using a simple 3x3 difference filter. Also, both the horizontal and vertical gradients can be calculated in the frequency domain using the conventional Fast Fourier Transform (FFT) techniques. Another reason for the appeal of the method is that the locations and depths of the sources are found with only a few assumptions about the nature of the source bodies, which usually are assumed as 2D magnetic sources (for example, step, contact, horizontal cylinder, or dike). For these geological models, the shape of the amplitude of the analytic signal is a bell-shaped symmetric function located directly above the source body. In addition, depths can be obtained from the width of the AS.

The 2D expression of the amplitude of the AS is given by Nabighian [178] as shown in Equation 3.9:

$$|AS| = \sqrt{\left(\frac{\partial F}{\partial x}\right)^2 + \left(\frac{\partial F}{\partial z}\right)^2} \quad (3.9),$$

where $\partial F/\partial x$ and $\partial F/\partial z$ are the horizontal and vertical derivatives, respectively, of the total magnetic field F . The depth (z) of a 2D thin dike body located at location $x = 0$ is given by Salem and Ravat [165] as Equation 3.10 shows:

$$z = \frac{2 AS_0}{AS_1} \quad (3.10),$$

where AS_0 is the analytic signal of the magnetic field and AS_1 is the analytic signal of the vertical derivative of the magnetic field. Once the depth is calculated from Equation 3.10, the amplitude (S) of the magnetic anomaly of the dike body can be estimated as shown in Equation 3.11:

$$S = AS z^2 \quad (3.11).$$

The Werner deconvolution was first introduced as an automated magnetic interpretation tool to solve the thin-dike problem [115, 116]. Hartman et al. [189] extended the application of the method to other kinds of magnetic sources, while Stanley [190] proposed a manual approach to the Werner method. The method has been expanded to include different geometries and crustal structures (e.g., [191, 192, 193, 194]). The Werner method assumes that anomalies are produced by simple models (e.g., contacts or dikes), thus it is considered oversimplified, however, it can be applied in many situations to determine magnetic anomalies, while further refinements such as Marquardt's technique [195, 196, 197, 198] and the application of the K-means machine learning algorithm [199] can ameliorate interpretation and allow the inverse modeling of the

method's results. The Werner method can accurately estimate the depths of shallow thin sources and dikes, however, it has been observed that for deeper sources, other methods, such as the spectral, are considered more suitable [200]. Apart from the magnetic, the Werner method is also successfully applied in the case of gravity anomalies [201, 202]. The cloud-derived depth solutions can be plotted as histograms and an average solution for each cluster represents the estimated depth of the anomaly source at the selected location.

Considering a magnetic anomaly caused by an infinite-extend in y - and z -directions 2D vertical thin dike, with x -axis perpendicular to the dike's strike, y -axis parallel to the strike, and vertical z -axis, the produced vertical ($VMAG$), horizontal ($HMAG$), and total ($TMAG$) magnetic anomalies are given by Equations 3.12, 3.13, and 3.14 [203]:

$$VMAG(x, z) = 2 \int \int \left[J_x \frac{2(x' - x)(z' - z)}{R^4} + J_z \frac{2(z' - z)^2 - R^2}{R^4} \right] dx' dz' \quad (3.12),$$

$$HMAG(x, z) = 2 \int \int \left[J_x \frac{2(x' - x)^2 - R^2}{R^4} + J_z \frac{2(x' - x)(z' - z)}{R^4} \right] dx' dz' \quad (3.13),$$

$$TMAG(x, z) = HMAG(x, z) \cos I \sin \alpha + VMAG(x, z) \sin I \quad (3.14),$$

where I is the magnetic inclination of the main field F , α is the strike of the dike as measured from the magnetic north (positive counterclockwise),

$$R^2 = (x' - x)^2 + (z' - z)^2 \quad (3.15),$$

and $J = (J_x, J_z)$ is the polarization vector (the sum of induced and remanent magnetization).

For a magnetic dike of thickness $2\Delta T$ and its top at depth D where $\Delta T \ll D$, and the point of observation at location $(x, 0)$, Ku and Sharp [116] provide a straightforward integration of Equations 3.12 and 3.13 that leads to the simple approximations at the surface ($z = 0$):

$$VMAG(x, 0) \cong 2\Delta T \frac{J_z D - J_x x}{x^2 + D^2} \quad (3.15),$$

$$HMAG(x, 0) \cong -2\Delta T \frac{J_x D - J_z x}{x^2 + D^2} \quad (3.16),$$

$$TMAG(x, 0) \cong \frac{Ax + BD}{x^2 + D^2} \quad (3.17),$$

where

$$A = -2\Delta T(J_x \sin I + J_z \cos I \sin \alpha) \quad (3.18),$$

and

$$B = 2\Delta T(-J_x \cos I \sin \alpha + J_z \sin I) \quad (3.19).$$

Equations 3.15, 3.16, and 3.17 are the equations that are used in the Werner deconvolution for magnetic interpretation as expressed by Talwani and Heirtzler [203]. They refer to the vertical, horizontal, and total magnetic anomaly, respectfully.

For an arbitrary location at point (x_0, D) , the total magnetic anomaly is given by Equation 3.20:

$$TMAG(x_0, D) = \frac{A(x - x_0) + BD}{(x - x_0)^2 + D^2} \quad (3.20).$$

Rearranging Equation 3.20, Equation 3.21 is produced:

$$a_0 + a_1x + b_0TMAG(x_0, D) + b_1xTMAG(x_0, D) = x^2TMAG(x_0, D) \quad (3.21) ,$$

where

$$a_0 = -Ax_0 + BD \quad (3.22) ,$$

$$a_1 = A \quad (3.23) ,$$

$$b_0 = -x_0^2 - D^2 \quad (3.24) ,$$

$$b_1 = 2x_0 \quad (3.25) .$$

Terms A and B are given by Equations 3.18 and 3.19.

For instance, an equally spaced four-point Werner operator (or window) where the second point is selected as the reference, the measured field (TM) at each point will be given as shown below:

$$TM_1 = TMAG(x - \Delta x, 0) ,$$

$$TM_2 = TMAG(x, 0) ,$$

$$TM_3 = TMAG(x + \Delta x, 0) ,$$

$$TM_4 = TMAG(x + 2\Delta x, 0) ,$$

where Δx is the spacing between two consecutive points, while x is the coordinate of the reference point in the x -direction. The Equation 3.21 can be rewritten in matrix form; thus, using matrix inversion or the linear Werner operator, Ku and Sharp [116] showed that the following Equations 3.26-3.29 are produced:

$$\text{Horizontal position} = 0.5 b_1 \Delta x + x \quad (3.26) ,$$

$$\text{Depth} = \sqrt{-b_0 - 0.25 b_1^2 \Delta x} \quad (3.27) ,$$

$$\text{Magnetic susceptibility} = \frac{\sqrt{J_x^2 + J_z^2}}{|F|} \Delta x \quad (3.28) ,$$

$$\text{Dip angle} = \tan^{-1} \left(\frac{J_x}{J_z} \right) + I \quad (3.29) .$$

Equations 3.26-3.29 calculate the parameters of the anomaly source using a four-point Werner window for the thin dike model.

The size of the Werner operator should be relative to the size of the anomaly itself. If the operator is small relative to the anomaly size, it will detect a small part of the anomaly and will yield an overestimated depth value. In contrast, if the operator is larger than the anomaly size, it will create several peaks from nearby anomalies, resulting in errors in the calculations.

The original Euler deconvolution [169, 170] is a very popular, semi-automated method used in the interpretation of gravity and magnetic data in many applications (e.g., [204, 205, 206, 207]). It integrates the total field anomaly, its derivatives, and the type of the causative source (as expressed in the predicted structural index, which defines the nature of the source) and makes use of the Euler homogeneity equation to estimate the characteristics of the source (location, depth, and type). It is based on Euler's homogeneity equation, which relates the derivatives of a potential field to the depth and location of the sources:

$$(x - x_0) \frac{dF}{dx} + (y - y_0) \frac{dF}{dy} + (z - z_0) \frac{dF}{dz} = N(B - F) \quad (3.30),$$

where (x_0, y_0, z_0) is the position of the anomaly source whose total field F is detected at the point (x, y, z) . The total field has a regional value of B and N is the structural index.

The similarity between the predicted structural index and the real geometry of the causative source defines the precision of the Euler method [208, 209, 210, 211]. In contrast to other similar methods, the Euler method does not make any assumptions about the geologic model so it can not only be applied in specific situations like other similar methods do [169]. Yet, in many cases, the results of the method are unambiguous, and knowledge of the local geological and tectonic regime from other geoscientific datasets or a different method of potential field data interpretation is necessary.

The Werner and Euler deconvolution methods can be combined to provide clusters that importantly constrain the produced depth solution in 2D data [212], while the extended Euler deconvolution algorithm is considered a generalized unification of the two methods in the three dimensions [213, 214, 215].

The Bouguer anomaly data is affected by density variations within the geologic formations of the crust, as well as sources in deeper depths that reach up to the earth's mantle. On the contrary, the local magnetic field data is affected by the sediments and the basement rocks. The contrast in the magnetic response between the sedimentary pile and the crystalline basement is high; thus, in cases where there are limited other constraints, magnetic data can map directly the depth to the basement.

3.5.4 2D and 3D Gravity Modeling

To model the subsurface structure of the study area, six profiles of different directions were drawn, shown in Figure 17 as black lines (P1-P6). The 2D models were created by forward-modeling the Bouguer anomaly data using the Oasis montaj GM-SYS Advanced Profile Modeling extension. This software integrates gravity and magnetic data with other geoscientific information (e.g., seismic and non-seismic, well, geologic) to construct realistic subsurface models, thus reducing the uncertainty and risk during exploration and production/development projects. Using an iterative approach, the objective is to minimize the error between the observed and calculated gravity (and/or magnetic) field by manually changing the input model parameters and the geologic interfaces. The calculated field changes dynamically with every change in the model.

Considering the geology of the study area and the outcropping formations along each profile, the basement rocks were divided into two units, i.e., the dioritic/gabbroic rocks and the metamorphic volcaniclastic formations, and the corresponding weathered (affected by near-surface phenomena, such as erosion and groundwater flow) and fractured zones. The metamorphic volcaniclastic formations include greenstones derived from basaltic and andesitic lava flows, as well as greenschists subjected to intense foliation and shearing [38]. Since the formation density depends on many variables (mineralization, alterations, joints, etc.), a range of densities for the basement rocks was selected according to the extent of the surrounding fracture zone. It was assumed that geothermal water flows within the fracture zones before it reaches the surface, thus reducing the overall rock density of the latter.

Using only the gravity data as input, the 2D models were initially created assuming layered geology and no lateral change to the rock densities. The only changes were due to horizontal changes in the layered rocks. The RMS errors of these models were significant. Moreover, the models did not accurately depict the subsurface regime according to the outcropping geologic units.

To construct realistic conceptual models and to minimize the RMS errors, the gravity data were constrained using 2D MT cross-sections as *a priori* information, which indicated the contacts between resistive and conductive formations [28]. The cross-sections were selected, and slices were cut from the 3D model constructed by the MT data. The interfaces between the different rock formations were drawn following the geologic interfaces interpreted by the cross-sections. To translate to gravity results, the more resistive formations correspond to the fresh basement (metamorphic volcanoclastic and dioritic/gabbroic rocks). In contrast, the more conductive formations indicate the fractured basement, as well as the high heat-generating granitic rocks at the geothermal reservoir depths. The surface geology was used to differentiate between the basement rock formations at depth.

Since there was no information available concerning the densities of the geologic formations in the study area, these were assigned based on a study by Langenheim et al. [216] for the Rahat volcanic field area in Western Saudi Arabia and the general literature (e.g., [217, 218, 219]) and are shown in Table 1. Density values are higher in the fresh basement, and they decrease in the fractured and the weathered basement, while a homogeneous distribution of the density within each formation was assumed. An exception to this is in profile P1, in which the fractured basement was assigned different

values according to the surface distribution of the two main basement units (diorite/gabbro and metamorphic volcaniclastic rocks). The value of 2.67 g/cm³ was used as the crustal reduction density for all six profiles. To further constrain the 2D model of the P1 profile, additional geologic and geophysical information was integrated from a nearby water well and one refraction seismic profile to constrain the depth of the basement, as discussed in sub-section 3.3.4.

Table 1: Densities (in g/cm³) that were used for the 2D model construction.

Rock/Formation	Density (g/cm³)
Diorite/Gabbro	2.73 - 2.8
Metamorphic volcaniclastics	2.79 - 2.82
Fractured Basement	2.51 - 2.73
Weathered Basement	2.30 - 2.40
Granitic Rocks	2.67 - 2.71
Sediments	1.60 - 1.85

The 3D model of the study area was constructed by applying inversion of the gravity data. Oasis montaj VOXI Earth Modeling extension was used for this procedure. The forward modeling algorithm of the software predicts the distribution of the geologic and tectonic structures and produces a 3D model of the subsurface based on the physical property under study (e.g., density, magnetic susceptibility, electric resistivity). It mainly uses the Cartesian cut cell method [220, 221] for the inversion process. This approach utilizes a Cartesian voxel comprising prismatic elements, which diminishes

computational complexity and saves computation time, while also enabling highly accurate geometric depiction of geological surfaces. By integrating the method into inversion and forward calculations, well-known artifacts that arise from representing topography with prisms of fixed vertical extent are eliminated. The inversion was carried out in the southern part of the study area, where the gravity measurements were dense, in a 3D mesh discretized in blocks of 37x53x24 (cell size of 100x100x50 m) (the area in the yellow rectangle of Figure 10). The lower and upper boundaries of the model were set at -1 g/cm³ and 1 g/cm³, respectively. This means that differences in density (from the crustal reduction density of 2.67 g/cm³) exceeding these limits were not considered for the construction of the model.

3.5.5 Curie Isotherm Depth Estimation

Magnetic rocks often lose their magnetization when the temperature rises to the Curie temperature [80], which is approximately 580 °C for magnetite. The depth of the Curie isotherm can be estimated using different methods (e.g., [166, 167, 172, 222, 223, 224, 225, 226, 227, 228, 229, 230]). They all use the azimuthally averaged Fourier spectrum of the magnetic anomalies. The spectrum of the observed magnetic field (Φ) can be calculated using Equation 3.31:

$$\Phi(k_x, k_y) = A(k_x, k_y) \Phi_M(k_x, k_y) (e^{-kz_t} - e^{-kz_b})^2 \quad (3.31),$$

where Φ_M is the power-density spectrum of magnetization, A is a function dependent on the magnetization and the ambient field [80], and z_t , z_b are the depths to the top and the bottom of the magnetic source, respectively. The radial wavenumber k is given by Equation 3.32:

$$k = \sqrt{k_x^2 + k_y^2} \quad (3.32),$$

in which k_x and k_y are the components in the x and y directions.

The slope of the logarithm of the azimuthally averaged Fourier power spectrum at mid to high wavenumbers can be used to estimate the depth to the top (z_t) of the magnetic layer [166], as shown in Equation 3.33:

$$\log[\Phi(|k|)] = B_1 - 2 |k| z_t \quad (3.33),$$

where B_1 is a constant.

For estimating the depth to the bottom of the magnetic layer, the centroid method [172, 222, 223] can be used to estimate the centroid depth (z_c). This depth can be calculated using the logarithm of an azimuthally averaged Fourier amplitude spectrum at low wavenumbers, as described in Equation 3.34:

$$\log \left[\Phi(|k|)^{1/2} / |k| \right] = B_2 - 2 |k| z_c \quad (3.34),$$

where B_2 is a constant.

The last step is to calculate the depth to the bottom of the magnetic source (z_b) using Equation 3.35:

$$z_b = 2z_c - z_t \quad (3.35).$$

This depth (z_b) can be assumed to correspond to the Curie isotherm depth. The estimation of the Curie isotherm depth can provide information on the variation of the temperature

with depth, allowing an estimate of the average surface heat flow and the verification of the geothermal resources' potential for power generation.

3.5.6 Geotherm Construction and Surface Heat Flow Estimation

The utilization of magnetic data as the sole basis for mapping the depth to Curie isotherm is a valuable approach to determining the temperature at a particular depth and predicting temperatures at various depths. However, the estimation of temperature within the range of the Curie isotherm depth and the surface necessitates assumptions concerning thermal properties and heat flow information. In cases where thermal conductivity remains consistent and there is no presence of radiogenic heat production, a linear interpolation curve can safely depict the temperature-depth correlation (geotherm). Nevertheless, when taking into account radiogenic heat production, the temperature-depth correlation becomes curved, with the curvature being proportional to the ratio of radiogenic heat production to thermal conductivity. To establish the geotherm of the Wadi Al Lith area, 1D steady-state heat conduction was assumed, thus the methodology described by Furlong and Chapman [231] was applied.

For a layer with constant radiogenic heat production (A) and thermal conductivity (λ), the temperature and heat flow at its bottom (T_b and Q_b , respectively) are described by Equations 3.36 and 3.37:

$$T_b = T_t - \left(\frac{A}{2\lambda}\right) \Delta z^2 + \left(\frac{Q_t}{\lambda}\right) \Delta z \quad (3.36),$$

$$Q_b = Q_t - A \Delta z \quad (3.37),$$

where T_t and Q_t are the temperature and heat flow at the top of the layer, respectively, and Δz is the thickness of the layer. The application of Equations 3.36 and 3.37 to successive layers using a 0.5 km depth increment created the geotherm that is presented in this study. For each new layer, the values for T_b and Q_b of the previous layer are considered as its T_t and Q_t .

For this study, a simple three-layered model was used, consisting of the upper crust, the lower crust, and the mantle. The rock composition of the upper crust was considered granitic to andesitic, the lower crust was considered to have a basic composition (silica content between 45% and 55%), while the upper mantle was considered ultramafic (silica content less than 45%). The values that were used for the thermal conductivity are 2.5 W/m·K for the crust and 4.5 W/m·K for the upper mantle, based on average values measured at the lab for different corresponding rock samples [231, 232, 233].

Heat flow is usually measured in boreholes, while factors such as groundwater flow and surface temperature variations, may affect these measurements [87]. Alternatively, the temperature at a given depth can be inferred from geochemical (helium isotope ratios [234] and silica concentrations in hot springs [235]) and geophysical (magnetic, MT, and seismic tomography) methods [87]. The average surface heat flow is generally partitioned as that coming from radiogenic sources in the upper crust and that produced by deeper sources [236]. Based on the assumed rock composition and the discussion of Furlong and Chapman [231], the heat production was considered equal to 2.02 mW/m² for the upper crust, 0.68 mW/m² for the lower crust, and 0.031 mW/m² for the lithospheric mantle.

Table 2 summarizes the parameters that were used for the construction of the geotherm. The value for the depth to the top of the lithospheric mantle comes from the study of Salem et al. [25] with the assumption that the top of the lower crust lies at the midpoint of the total depth, while the thermal conductivity and radiogenic heat production values come from Furlong and Chapman [231]. The strategy that was followed was to use a tentative value for the surface heat flow. Then, the 1D geotherm for this value was computed. The value that provided the temperatures of 580 °C and 1300 °C at the Curie isotherm and the Lithosphere-Asthenosphere Boundary (LAB) depths correspondingly, was the one finally selected.

Table 2: Parameters used in the geotherm construction.

	Depth to top (km)	Thermal conductivity (W/m·K)	Radiogenic heat production (mW/m³)
Upper crust	0	2.5	2.2
Lower crust	13.5	2.5	0.68
Lithospheric mantle	27	4.5	0.031

CHAPTER 4

Results and Discussion

In this chapter, the results from the analysis of the geophysical data of Wadi Al Lith are presented. Also, the implications for the geothermal potential of the study area of Wadi Al Lith that stem from these results are discussed and compared with results from published studies for the area.

4.1 Gravity Data Analysis Results

Figure 19 shows the complete Bouguer anomaly and the residual gravity field maps for the area of the Ain Al Harrah hot spring within Wadi Al Lith. The gravity measurements are denser in the southern part of the survey area, where the hot spring is located. For the northern part, the gravity points are situated along the river valley, and they construct one profile only. The complete Bouguer anomaly (Figure 19a) presents average to high values in the area of the hot spring. The residual gravity field (Figure 19b), which focuses on the near-surface inhomogeneities, presents low values over the hot spring and along the North-South direction for about 1.5 km.

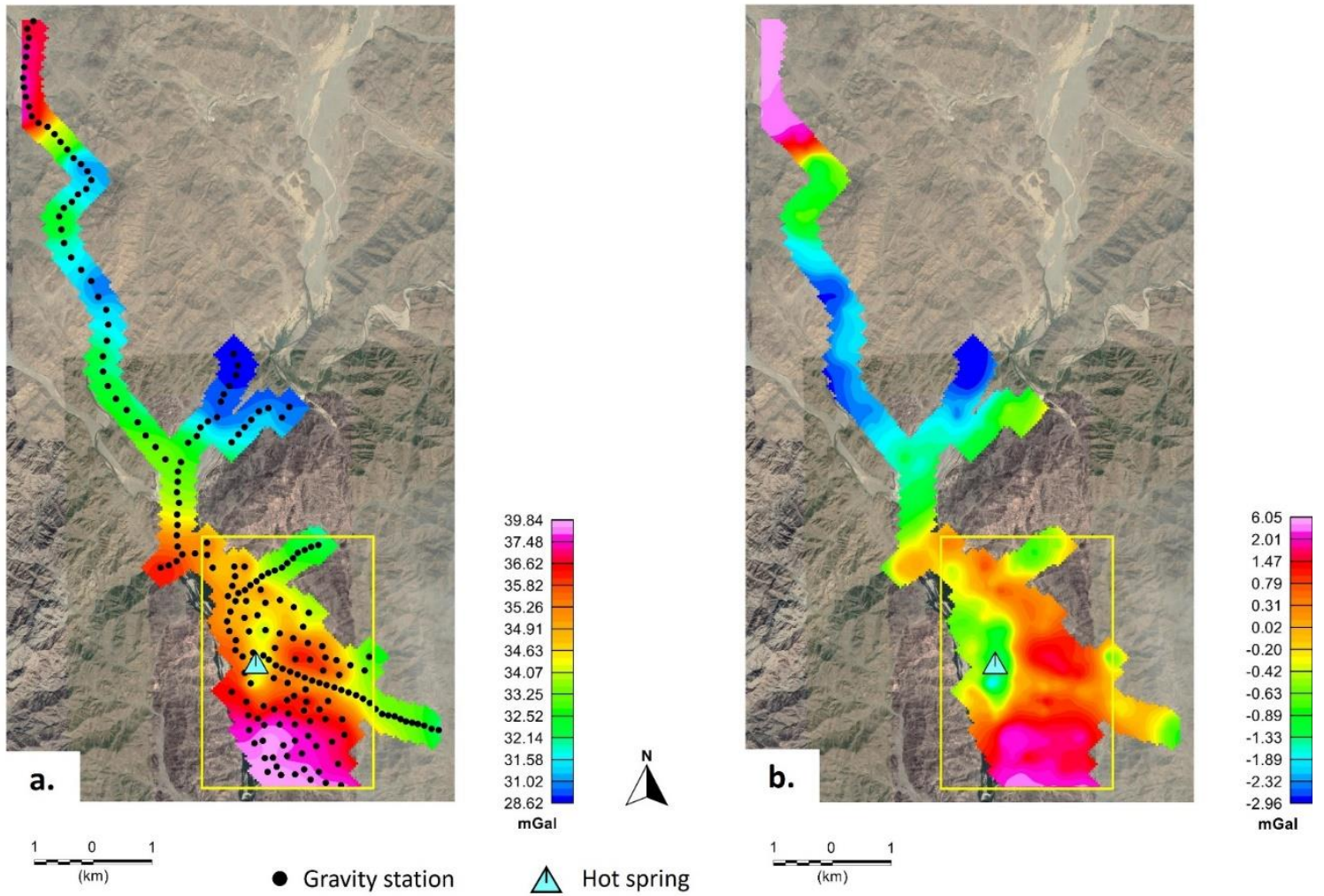


Figure 19: (a) Complete Bouguer anomaly map for the whole study area. The gravity stations are marked as black points. (b) Residual gravity field map for the whole study area. The yellow rectangle indicates the area where the 3D modeling was applied. The location of the hot spring is shown with the light blue triangle.

To study in detail the residual gravity field in the vicinity of the hot spring, the complete Bouguer anomaly only for the area indicated within the yellow rectangle (as shown in Figure 19a) is analyzed. The resulting residual field is presented in Figure 20a. By comparing the two Figures of the residual field (Figures 19b and 20a) it can be noticed that the gravity field presents low values above the hot spring, following an N-S direction but the same gravity responses are found and continued in an E-W trend. A similar N-S low residual gravity anomaly to the one located over the hot spring is detected on the eastern side (edges) of the area inside the yellow rectangle. This low residual gravity anomaly cannot be confirmed since, as mentioned, this anomaly is at the edges of the model, and more measurements in the eastern part of the study area are needed.

To analyze the signature of the fracture zones in the gravity field further, data enhancement filters were used. Figure 20b shows the terracing map overlaid by the peaks of the horizontal derivative; all constructed from the residual gravity field. The peaks (maxima) of the horizontal derivative grid were calculated using the curvature analysis method [237] and are indicated as black triangles above the edges of horizontal formations and vertical contacts. Similarly to the residual gravity field map of Figure 20a, the terracing map shows an area (terrace) of low gravity values along an E-W axis passing through the hot spring location, surrounded by terraces of higher gravity values. Within the river valley, a terrace of intermediate gravity amplitude is created. The horizontal gradient presents peaks at locations that mostly coincide with the boundaries of the different terraces.

The white numbered points in Figure 20b indicate the locations of the TEM stations used for this study. The five corresponding TEM soundings (TEM 1-5) are shown in Figure 20c.

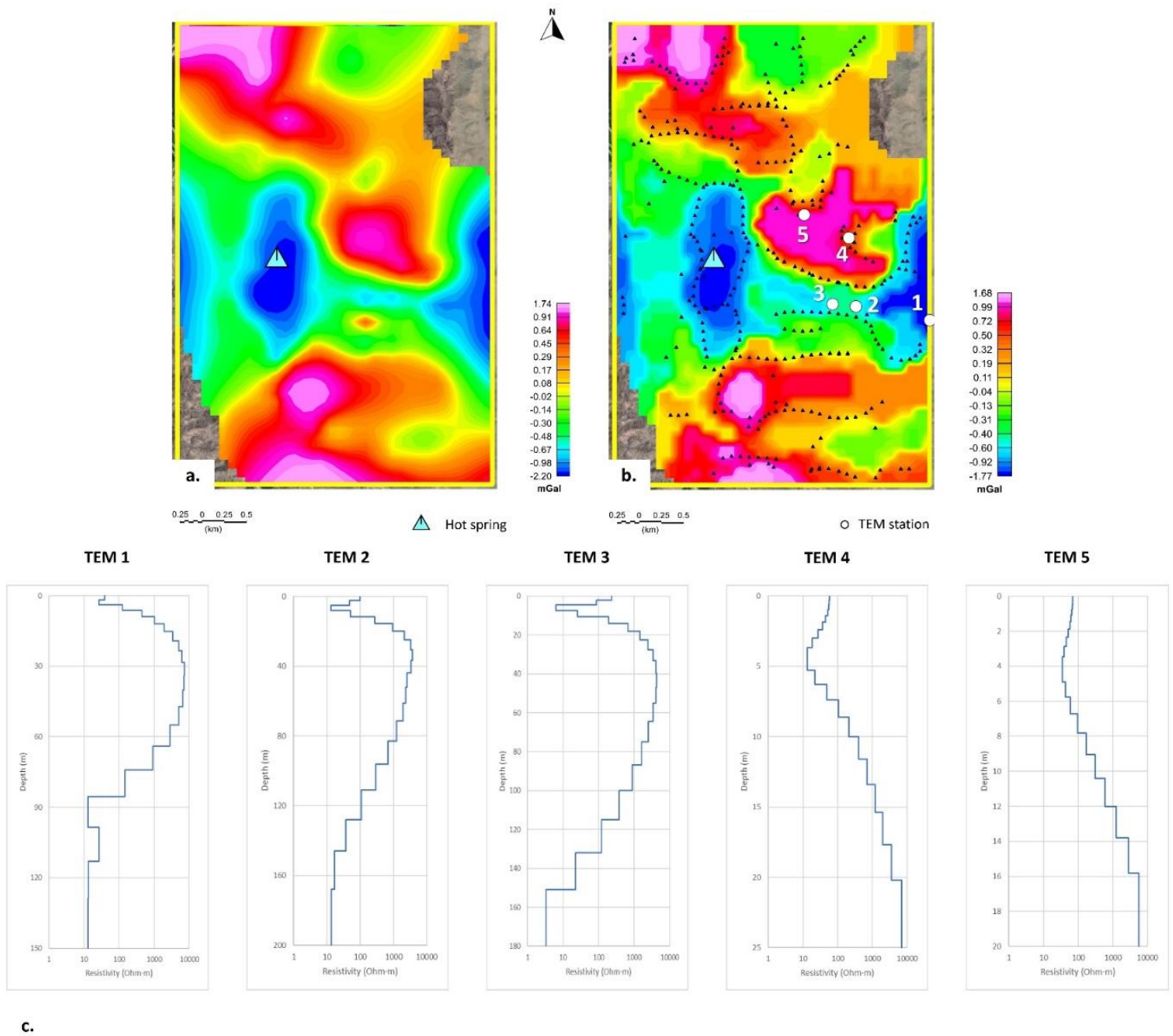
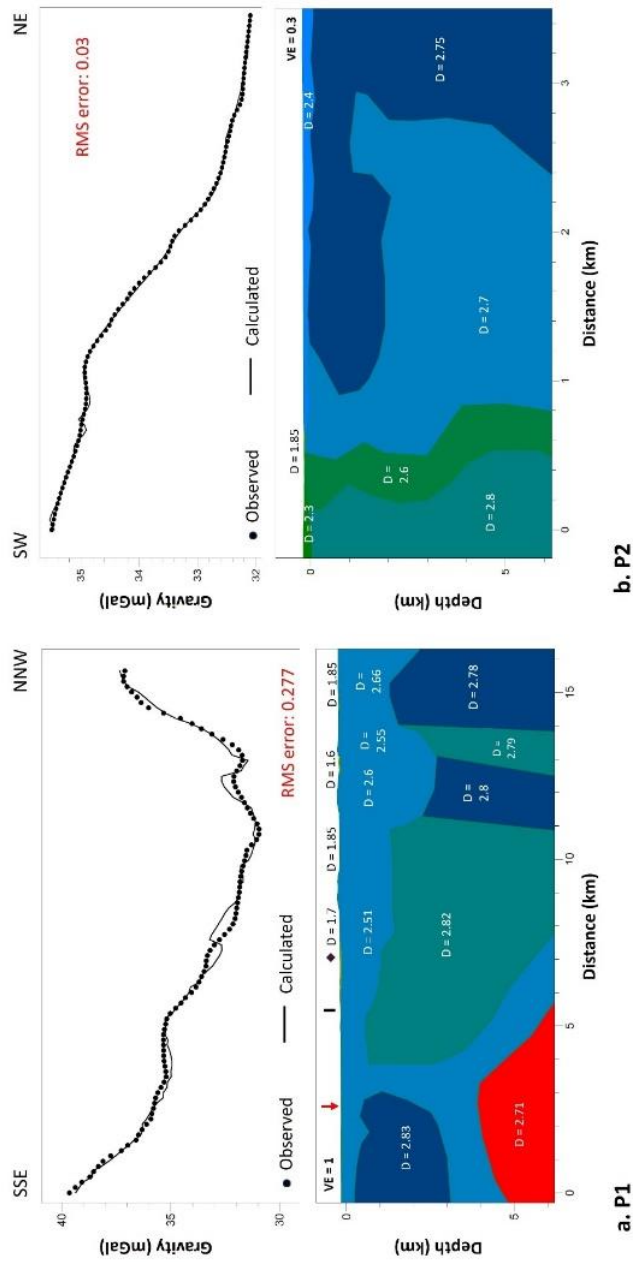
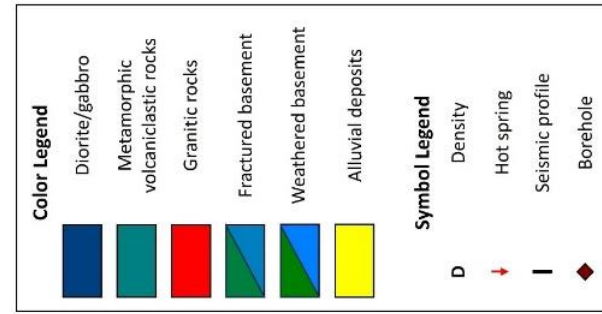
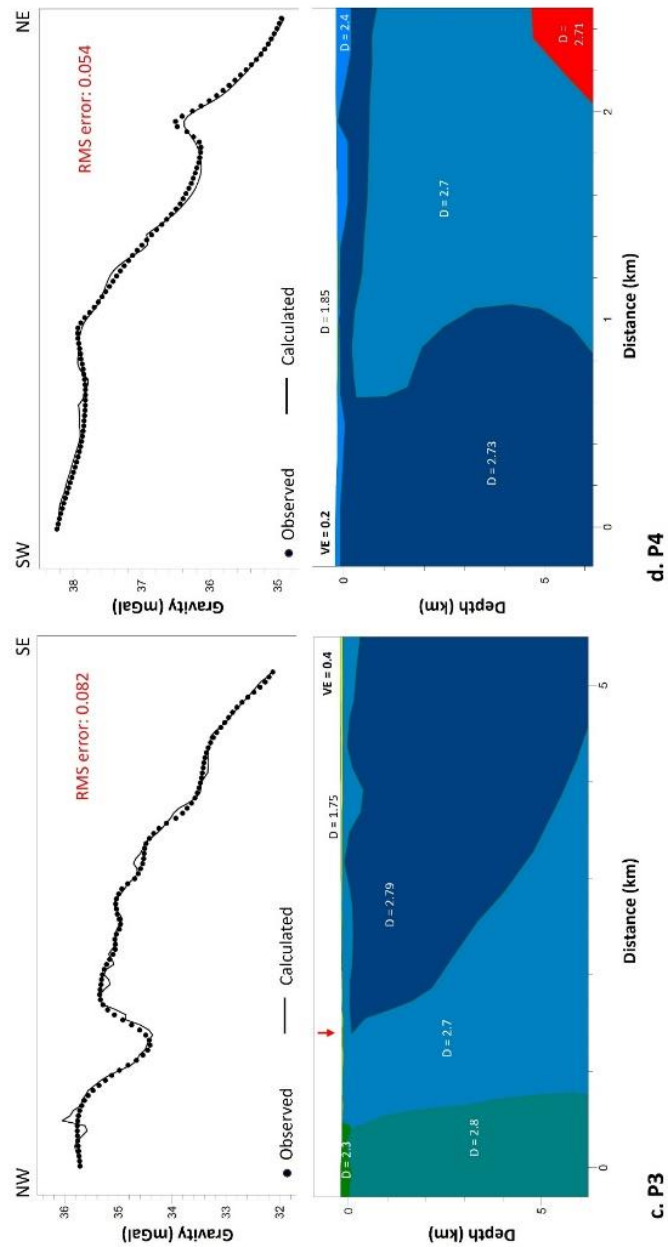


Figure 20: (a) Residual gravity field of the area inside the yellow rectangle shown in Figure 14a. (b) The terracing map of the area inside the yellow rectangle. The black triangles show the maxima of the horizontal gradient. The white points are the TEM stations that were used to verify the gravity results. (c) The results of the five TEM soundings (TEM 1 - TEM 5) that were used.

The 2D models constructed for the six profiles (P1-P6) presented in Figure 17 are shown in Figure 21. For each profile, the depth model is presented along with the corresponding gravity anomalies (observed and calculated). The observed gravity field is presented with the dotted line, while the continuous black line represents the calculated gravity field. The RMS error (the difference between the two fields) is also shown in the Figure. The depth models represent the structure/geometry of the study area in different directions, and they were constrained using the MT data that were acquired in the area around the hot spring [28]. The geologic maps [21, 22] were used to constrain the surface distribution of the different rocks and the sediment cover. The rock density values assigned for each formation are presented in Table 1 in sub-section 3.5.4. The lack of information on the exact density values of the geologic formations of the study area introduced some uncertainty to the models. However, the selected density ranges minimized the RMS error and corresponded well with the models created using the MT data [28].

Diorite/gabbro and metamorphic volcanoclastic formations are represented by the dark blue and green areas, respectively, indicating fresh basement rocks. The light blue and green colors illustrate the fractured and weathered basement formations. The thin, low-density sediment cover along the river valley is shown in yellow. It reaches a maximum thickness of around 30 m, using information from the water well and the seismic section located in the P1 profile (their locations are shown in Figure 17 and are marked with a black line and a brown rhombus in Figure 21a).





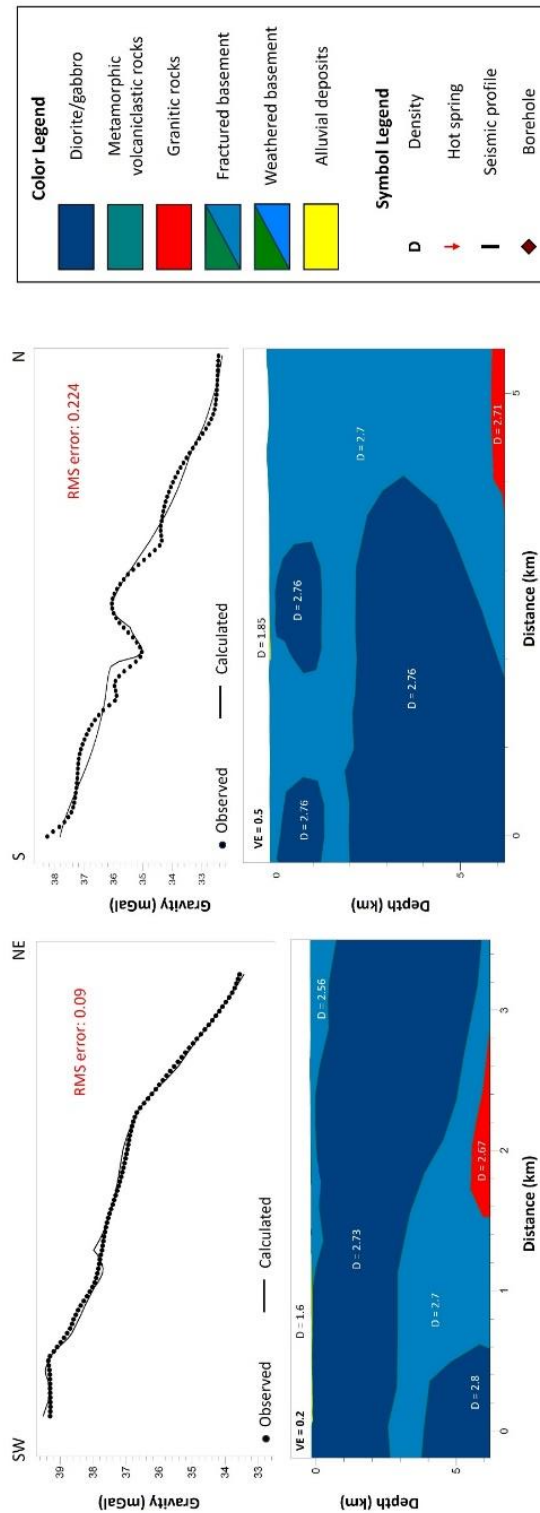


Figure 21: 2D gravity models. The locations of the profiles (P1-P6) are shown in Figure 11 (VE: Vertical Exaggeration). (a) P1. (b) P2. (c) P3. (d) P4. (e) P5. (f) P6.

The 3D gravity inversion results for the data within the yellow rectangle in Figure 10 for the upper 1 km are shown in Figure 22. The red and blue color bodies indicate positive (greater than 0.35 g/cm^3) and negative (lower than 0.1 g/cm^3) density contrast, correspondingly. Figure 22a shows a top view of the area overlaid by the residual gravity field map, along with the location of the hot spring. Lateral views of the 3D model are presented in Figure 22b, at viewing angles of 45° and 315° .

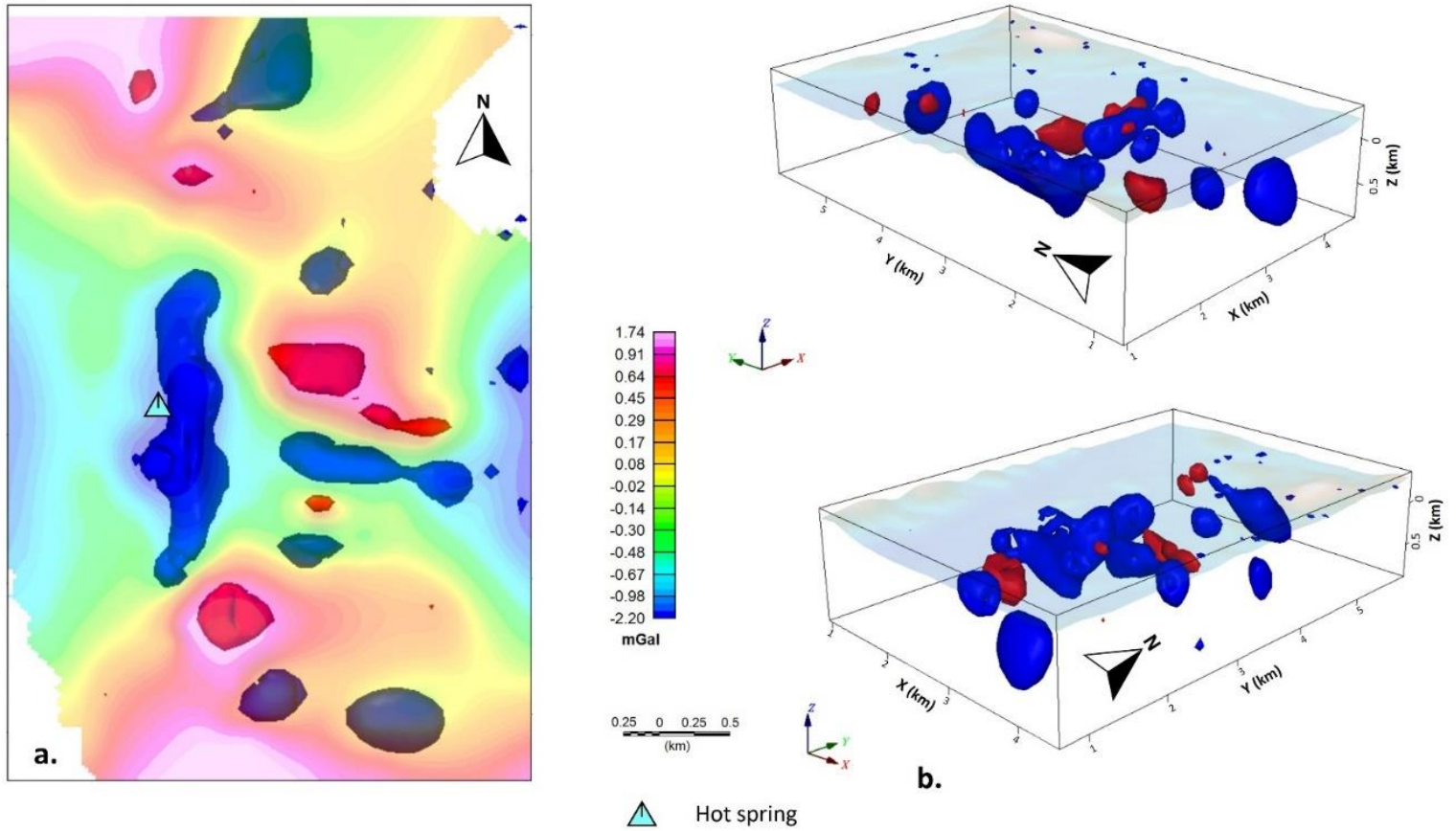


Figure 22: 3D model: (a) Top view of the model, overlaid by the residual gravity field map. The location of the hot spring is indicated with the light blue triangle. (b) Lateral views of the model, at viewing angles of 45° (top) and 315° (bottom).

4.2 Magnetic Data Analysis Results

The results of the CET Grid Analysis are presented as a lineament density map (Figure 23) that shows the existence of numerous structural features within the wider study area. Darker colors (blue-green colors in Figure 23) indicate areas with high lineament density (existence of more lineaments) in comparison to areas with brighter colors (yellow-red colors in Figure 23). Moreover, the tectonic features in the geologic map of the study area were also added, which include faults and dikes (mafic rocks, mostly metadiabases and basalts, and felsic rocks consisting of granites, aplites, rhyolites, and granophyres).

The subsurface lineament density map built using airborne magnetic data subdivides the area into three main parts. These are a very high-density area (NW part), a high-density area (central and central-east part), and a very low-density area (SE part). The map shows a concentration of lineaments in the central and NW parts of the study area which coincides with the most of existing surface dikes/fractures observed in the Wadi Al Lith. In contrast, the SE part of the area shows very low intensity of subsurface lineaments. The mapped subsurface lineaments in the study area display NNE-SSW and NW-SW major azimuth orientations (Figure 23), which is in agreement with the major trend of the lineaments/faults observed on the surface.

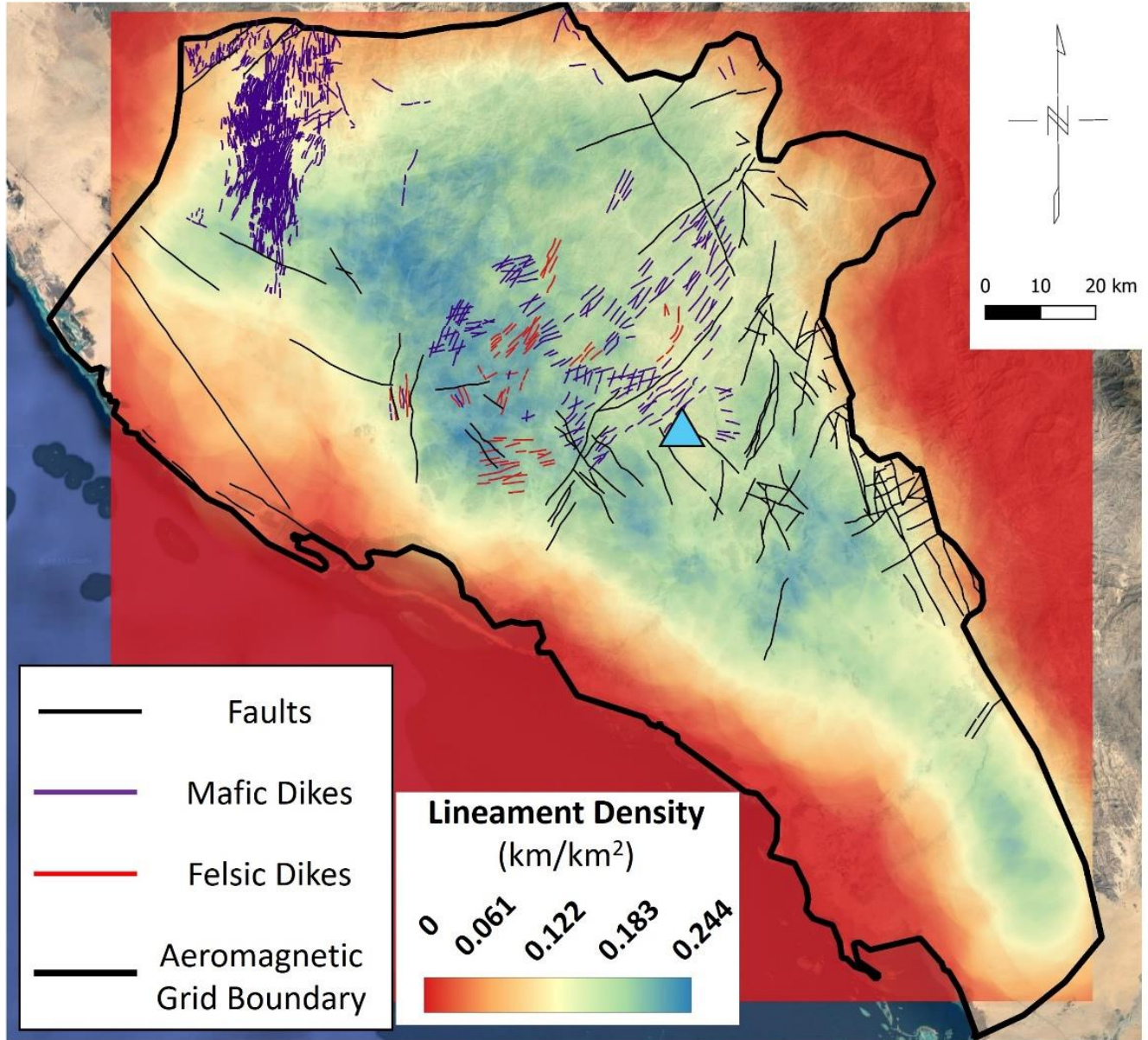


Figure 23: Subsurface lineament density map, produced from the automated and manual interpretation of tectonic lineaments from the airborne magnetic data. The black lines indicate faults at the surface based on geological maps, while the purple and red lines correspond to mafic and felsic dikes observed at the surface. The location of the hot spring is indicated with the light blue triangle.

In the wider Red Sea region, it is expected that the depth of the Curie isotherm is shallow. Due to the available aeromagnetic data dimensions (90 km x 70 km), it was not possible to split the magnetic data into overlapping windows to laterally map the depth to Curie isotherm. Blakely [80] showed that the grid dimension should be five times the expected depth to the bottom. Consequently, only one value for the depth of the Curie point isotherm is expected to be obtained by the application of spectral analysis of the magnetic data, representing the average for the entire area.

Specifically, the depths to the top and centroid of the magnetic sources estimated using the spectral peak [166] and the centroid [172] method correspondingly, are graphically presented in Figure 24. Figure 24a shows the scatterplot of the logarithm of the power spectrum in the region of mid- to high-wavenumbers. The regression equation of this graph corresponds to Equation 3.33, from which the depth to the top of the magnetic sources is calculated at 0.7 km. Similarly, Figure 24b shows the region of the low-wavenumbers, where the application of the centroid method (Equation 3.34) gives the depth of the centroid of the magnetic sources at 8.2 km.

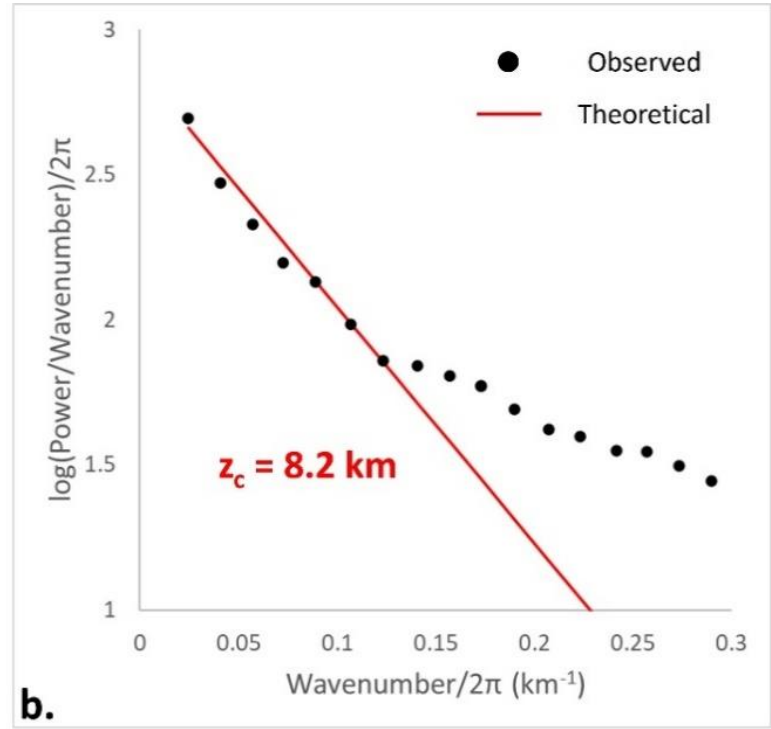
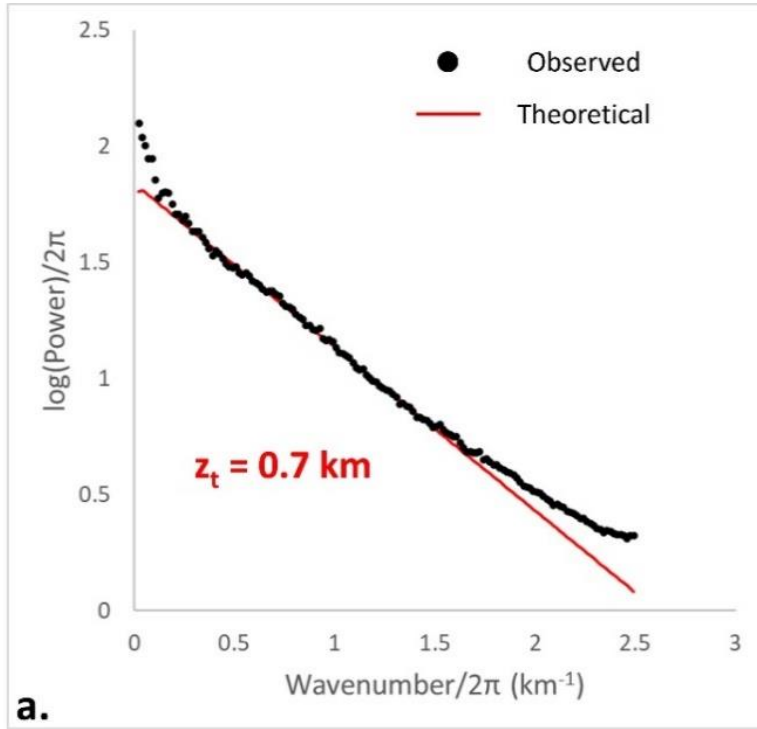


Figure 24: The power spectrum of the airborne magnetic data as produced from the (a) spectral peak [166], and (b) centroid [172] method. The red line indicates the theoretical curve, which corresponds to the depth of the shallow (low-wavenumber) anomalies in the spectral peak method and the depth of the centroid in the centroid method.

To estimate the bottom of the magnetic sources, Equation 3.35 was utilized; this depth was calculated at 14.8 km. Since the bottom of the magnetic sources was assumed to be related to the depth of the Curie isotherm, the value of 14.8 km also indicates a mean value for this depth for the study area of Wadi Al Lith. At this depth, the temperature is expected to be around 580 °C, if magnetite is assumed to be the prevailing magnetic mineral in the rocks.

A set of 1D geotherms was generated using different values of surface heat flow and the thermal parameters described in Table 2 in sub-section 3.5.6. It was found that a surface heat flow value of 109.8 mW/m² could provide a temperature of 580 °C at the estimated depth of 14.8 km obtained from the spectral analysis of the magnetic data. Figure 25 illustrates the 1D geotherm for the Wadi Al Lith study area. The depths of the Curie isotherm, Moho discontinuity (between crust and mantle), and LAB are indicated with green, gray, and light blue dashed lines, with their corresponding depths and temperatures. The MT sounding 13 [27, 28] is used to verify the depths that correspond to the Curie isotherm and the Moho discontinuity. Significant resistivity reduction occurs at similar depths, which can be attributed to an interface that causes changes in the natural properties of the geologic formations (more information on the MT interpretation is provided in section 4.3.2). Table 3 summarizes the estimated parameters.

Table 3: Estimated parameters from the analysis of the airborne magnetic data.

Centroid Depth (km)	Depth to Top (km)	Depth to Bottom (Curie Depth) (km)	Heat flow (mW/m ²)
8.2	0.7	14.82	109.8

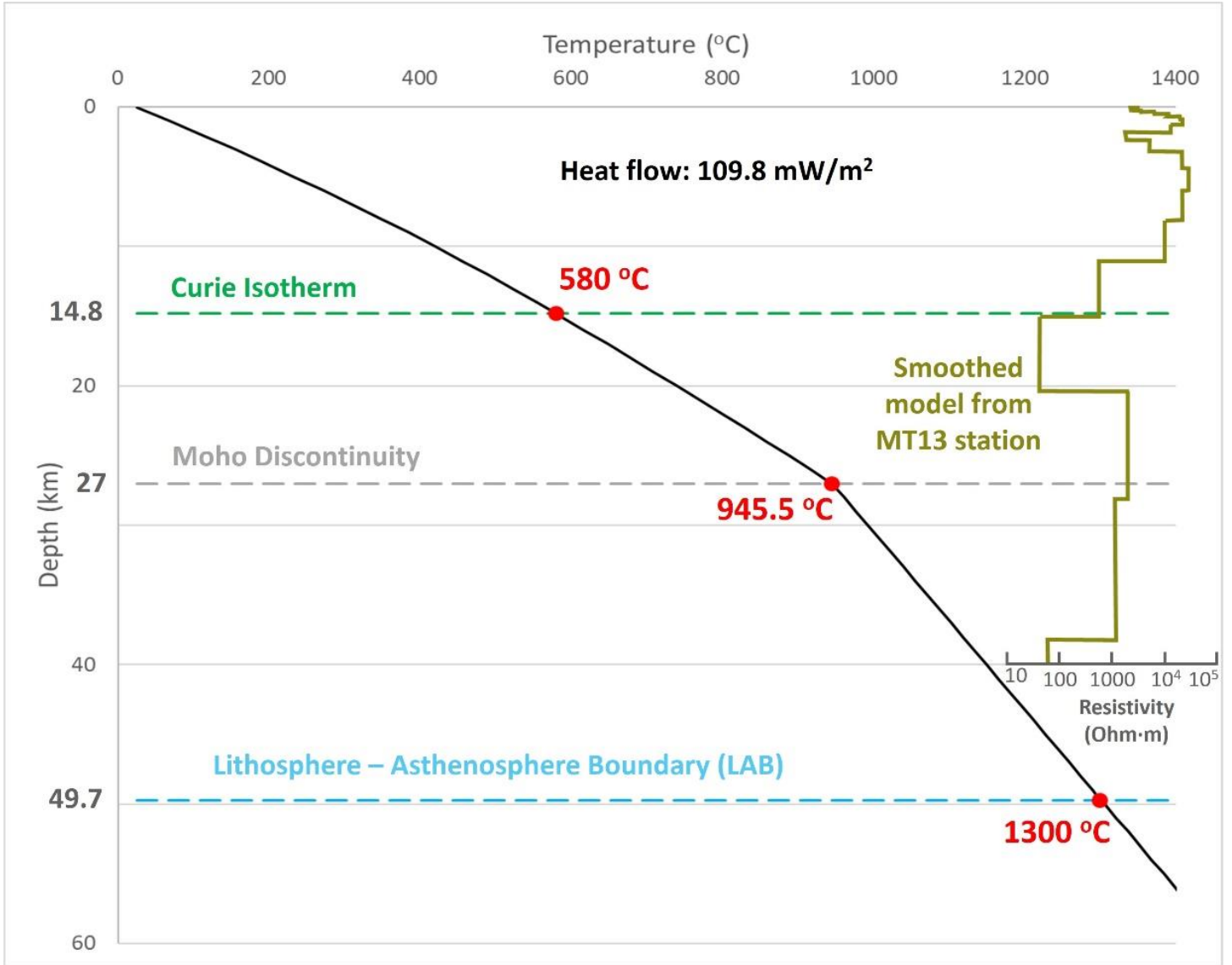


Figure 25: The 1D geotherm of the study area (black line). The dashed lines indicate the Curie isotherm at an average depth of 14.8 km (green color), the Moho discontinuity at a depth of 27 km (grey color), and the LAB at a depth of 49.7 km (light blue color). The temperatures at these depths are pointed out (red dots). The MT13 sounding is also displayed for depth comparison.

The use of airborne magnetic data minimizes the need to apply a low-pass filter since the short-wavelength anomalies related to shallow magnetic sources are already removed. As discussed by Ibrahim et al. [87], the removal of the short-wavelength anomalies may be appropriate for an area where volcanic rocks are present, such as the Wadi Al Lith area. The residual magnetic field calculated from the airborne and land magnetic data (after applying an upward continuation of 800 m to be at the same level as the airborne) for the northern profile of Figure 13a (in Area A) is shown in Figure 26. The two profiles show good correlation, providing a similar general magnetic response; thus verifying the good quality of the airborne data. The changes might be attributed to the difference in the orientation of the land profile in comparison with the flight lines.

Along the land magnetic profile of Area A (Figure 13a), shown in Figure 26, two major anomalies can be observed, indicated by the dashed circles as A1 and A2. A1 is located at the beginning of the profile and can be studied in the airborne data only, since the land data probably did not cover the entire anomaly area. A2 is a significant response seen very well in the airborne data, while it is smoother and of smaller amplitude in the land data. The A2 anomaly point coincides with the geologic contact of the diorite-gabbro with the basaltic rocks, as shown in the geologic background map of Figure 27, two formations with different mineralogical and magnetic properties. Thus, it is expected that it shows a more distinct anomaly in the airborne data, which can highlight deeper features. The starting and ending points of the profile are indicated as S (start) and E (end) in Figures 26 and 27.

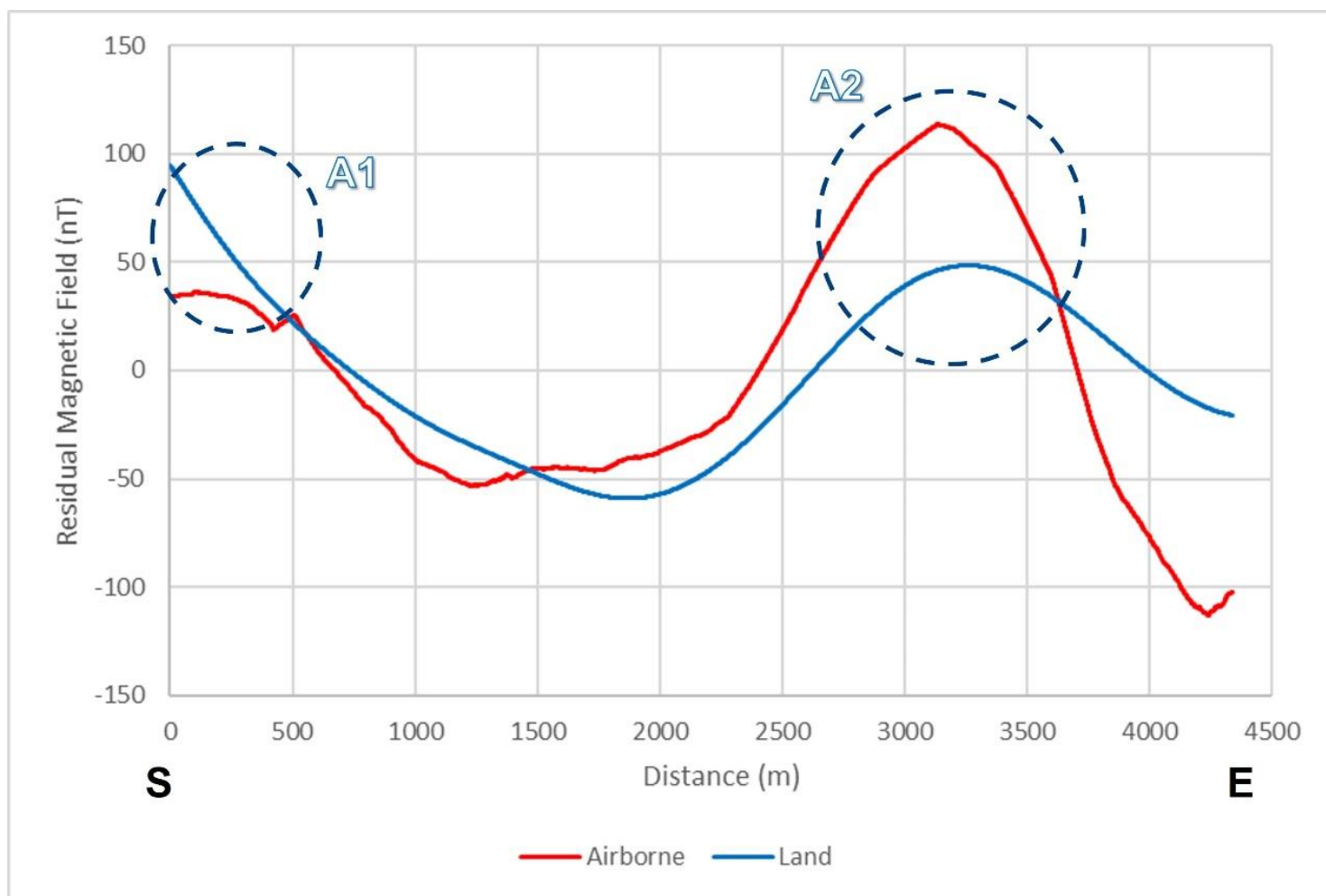


Figure 26: The comparison between the residual magnetic field produced from the airborne (red line) and the land (blue line) magnetic data along the North-South profile in Area A of Figure 13a (S: start, E: end).

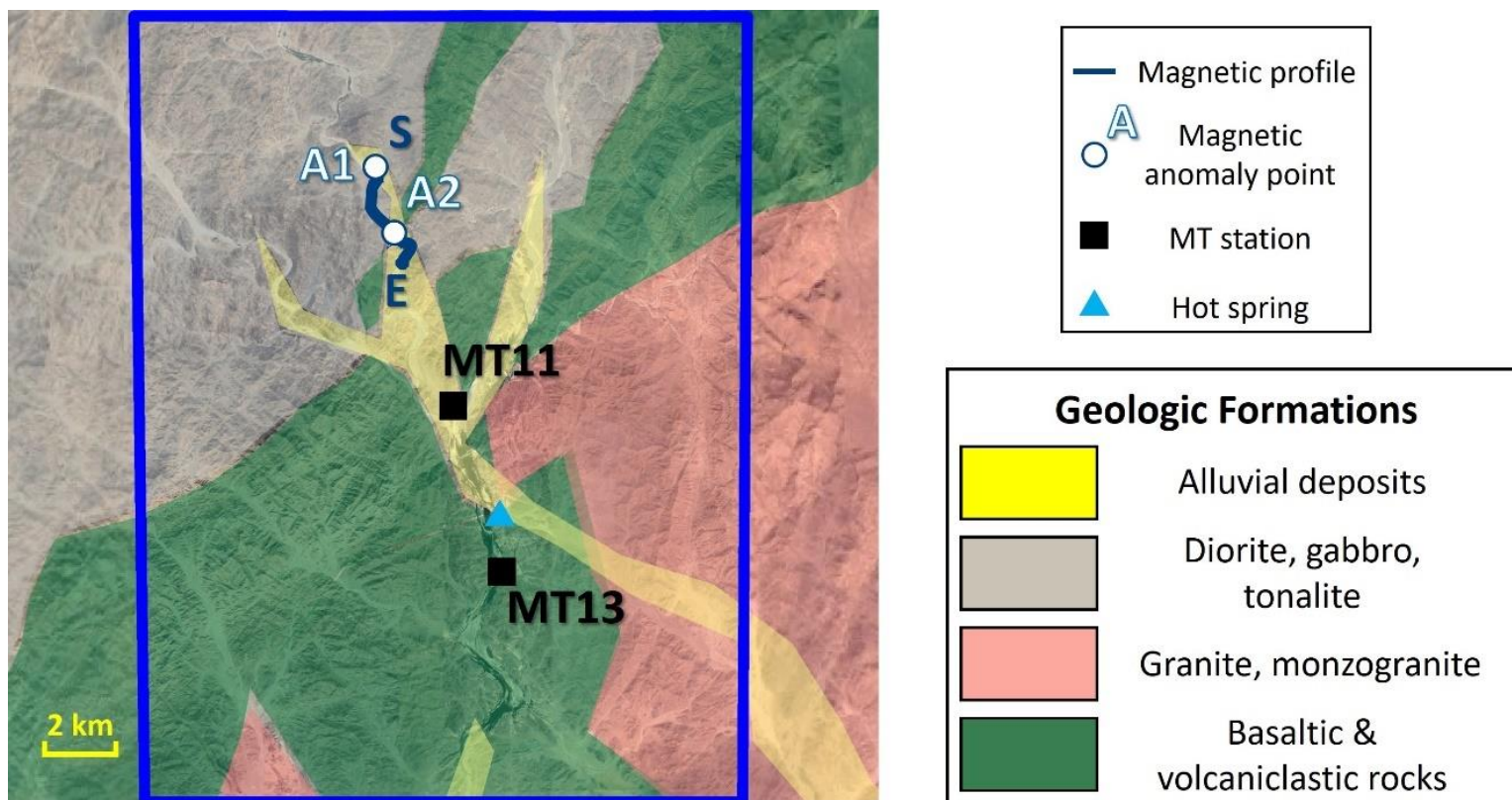


Figure 27: Map of the study area, which includes the land magnetic profile of Area A (Figure 13a) and the MT stations used for verifying the airborne magnetic data analysis results (as discussed in sub-section 4.3.2). The starting (S) and ending (E) points of the magnetic profile, as well as the two detected magnetic anomalies (A1 and A2) are also displayed.

The results of the land magnetic data analysis of Area B (Figure 13b) image the interactions of the modeled dikes with the tectonic structures identified by the gravity and EM techniques conducted in the study area and highlight their importance in the thermal fluid movement as secondary pathways. Figure 28 shows an example of one of the profiles in Area B (Figure 13b). The depth and dip of the dikes are modeled in the locations that the latter are encountered, while their magnetic susceptibility is depicted with different colors (black and red) according to its value (positive or negative). Note that the analytic signal can provide better results for the magnetic susceptibility variations, while the Werner deconvolution method is more adept in identifying the depth and dip angle of the body under study.

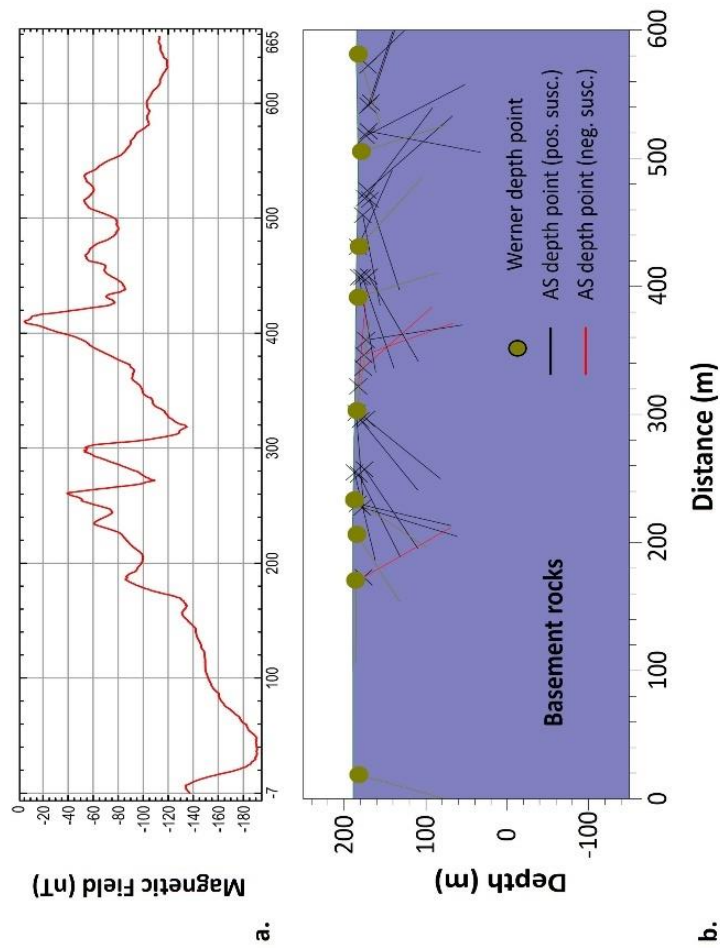


Figure 28: The results of the magnetic data analysis along one of the profiles shown in Figure 13b. (a) The measured magnetic field. (b) The depth section along the profile. The interpreted dikes' locations and depths are presented with black and red colors, for positive and negative magnetic susceptibility correspondingly (analytic signal method), and gold color (Werner method), together with their dipping angle. (c) Field photograph of the dikes in the study area, at a site close to the Ain Al Harrah hot spring.

The results of the land magnetic data analysis of Area B (Figure 13b) image the interactions of the modeled dikes with the tectonic structures identified by the gravity and EM techniques

4.3 Discussion

4.3.1 Insights from the Gravity Data Analysis

The study of the gravity data analysis results provides valuable information concerning the Wadi Al Lith geothermal prospect. The presence of the basement outcrops in the study area [38] is indicated by lower Bouguer anomaly values in the NE part. High values of the residual gravity field close to the spring indicate the presence of dioritic and gabbroic rock units, while ESE of the spring a discontinuity along the river basin is detected. Very low residual field values in the middle of the N-S profile P1 are probably related to the effect of the metamorphic volcanoclastic rocks in the area, as shown in the geologic map of Figure 3. The low-value anomalies in the residual field of Figure 20a could be attributed to fracture zones within the basement rocks. Thermal fluids can use these fracture zones as pathways for their subsurface circulation, penetrate shallow depths in the areas east of the hot spring and along the zones, and reach the surface through the hot spring. However, the fracture zones might also act as barriers to the fluids' movement.

The horizontal gradient indicates very well the boundaries of the low-gravity area of the hot spring that continues in the E-W direction, showing the existence of an abrupt change in the field because of the change in the rock formation density (solid basement rocks vs.

fractured basement rocks where thermal fluids circulate). This is translated into the existence of peaks in the corresponding locations, as shown in Figure 20b.

The interpretation of the TEM soundings indicates the depth of the shallow high- and low-resistivity formations. High resistivity values indicate unweathered rock units where the formations present fewer fractures and lower secondary porosity and are less affected by tectonic activity, thus having a higher density. Low resistivity values are caused by more tectonically affected rocks in which the circulation of thermal fluids along their fractures is possible. These formations also present lower density values. The three soundings (TEM 1-3) that were acquired along the interpreted fracture zone, validated the presence of the fracture zone and the geothermal fluids within it below the depth of 120 m (resistivity of around or less than 10 Ohm·m, as shown in Figure 20c). The other two TEM soundings (TEM 4 and 5) that were collected in similar terrain, about 700 m away from TEM 2 and 3, detected only the bedrock of the study area with an average resistivity of 1000 Ohm·m (Figure 20c), 15 m below the ground surface.

The 3D model identified positive and negative anomaly bodies corresponding to solid and fractured basement areas, respectively. The distribution of these bodies aligned with the general geologic regime of the study area as described by the magnetotelluric data analysis of Ashadi et al. [28] and geologic studies of the outcropping rock formations in the northern [38] and southern parts of the area. The negative density contrast bodies are mainly situated within the area of low gravity values close to the hot spring, starting from a depth of around 150 m, which agrees with the results from the TEM soundings (Figure 20c, TEM 1-3). They largely coincide with the primary N-S trending fracture zone over and close to the hot spring and continue to the east following an E-W trend. Previous

geological studies also indicated that E-W faulting and NW-SE-trending fractures created permeable zones favorable for fluid circulation deeper within the basement rocks (e.g., [38, 238]). This is verified by the gravity data analysis, which identified the existence of an E-W-trending fracture zone below and in the vicinity of the Ain Al Harrah hot spring.

4.3.2 Insights from the Magnetic Data Analysis

The Curie isotherm depth calculation of 14.8 km agrees with the results of Aboud et al. [26, 239], who proposed a depth for the Curie isotherm shallower than 29.6 km. However, the heat flow value estimated from the aeromagnetic data is higher than that proposed by Aboud et al. [26], who estimated a range from 47.7 to 87.8 mW/m² for the largest extent of the Wadi Al Lith area. The area is characterized as a high to very high favorable area for geothermal energy [26]. Using geothermometers, a heat flow value of approximately 183 mW/m² for the area close to the Ain Al Harrah was indicated [11, 15]. This high heat flow could correspond to the maximum that can be reached in the Wadi.

Concerning the interpretation of the MT data, both 1D and 2D inversion results [27, 28] show three geoelectrical units. The first is a very low to low-resistivity unit, with resistivities varying from 50 to 200 $\Omega \cdot m$, which is the top layer in the models. It corresponds to the fully- or partly-saturated Quaternary deposits and the upper weathered and fractured part of the resistive basement. A medium to high resistivity unit follows, with resistivities between 200 and 3000 $\Omega \cdot m$. It represents the saturated with geothermal fluids fractured/faulted zone. The last unit presents very high resistivities and is associated with the basement of the study area. The resistivity values of this unit lie between 3000 and 10000 $\Omega \cdot m$. A very conductive zone (less than 50 $\Omega \cdot m$) below 6 km depth indicates the upper surface of the magma chamber. Finally, a very low resistivity

response is shown at a depth of around 15 km at the edge of MT11 sounding. The same response is observed at a similar depth at MT13 sounding, which reached a depth of approximately 40 km due to a higher signal-to-noise ratio and longer recording time. This change could be related to the existence of the Curie isotherm at around this depth and is indicated with a black dashed line in Figure 29. The locations of these two MT soundings are included in the map of Figure 27 since MT11 is outside the boundaries of the area shown in Figure 16. MT13 is the southernmost MT station, at the western side of Figure 16.

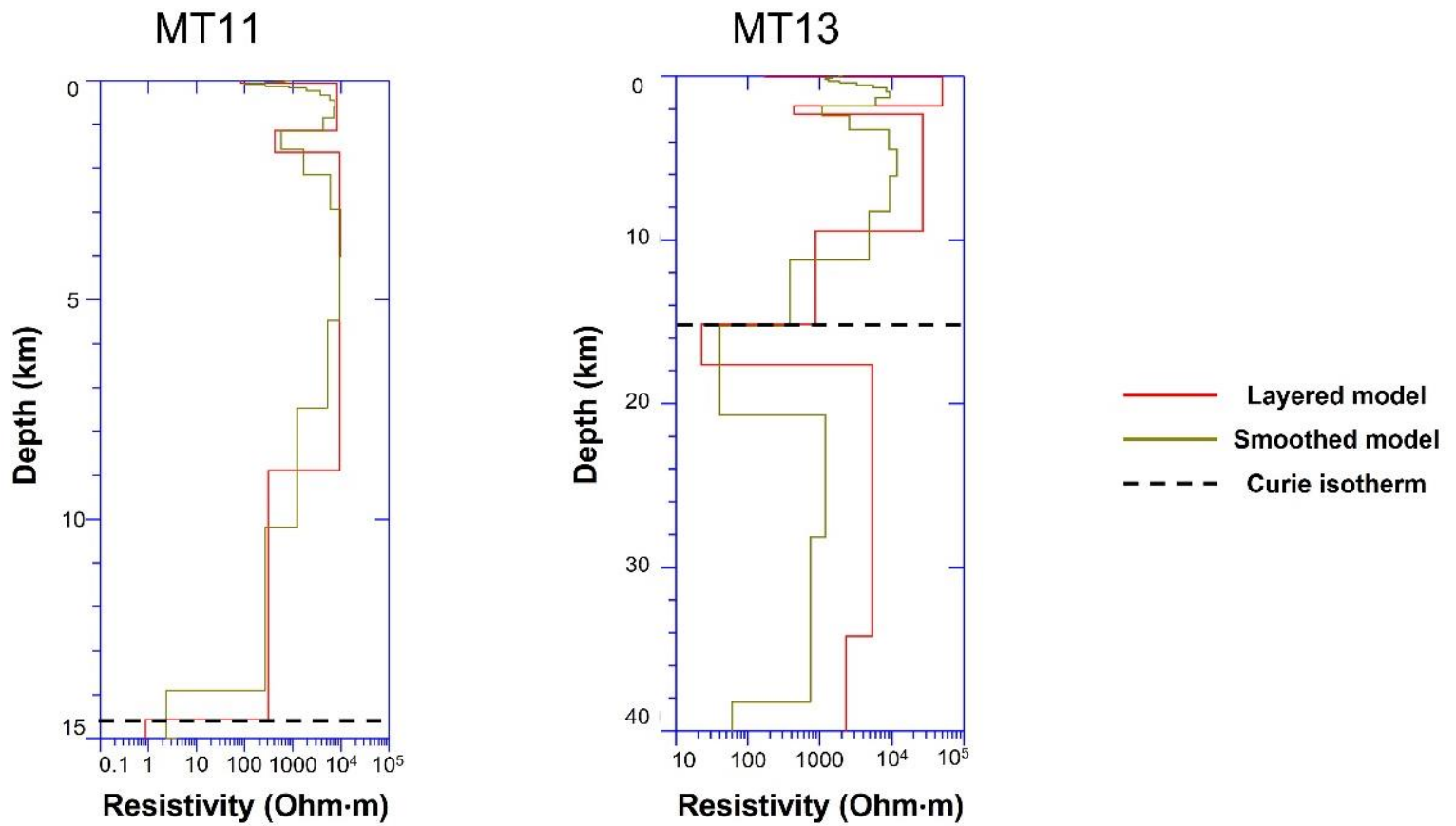


Figure 29: The MT soundings in the area near the hot spring that were used to verify the aeromagnetic data analysis results. The black dashed lines correspond to the depth of the Curie isotherm, based on the abrupt reduction in resistivity.

Based on geochemical measurements in the Ain Al-Harrah hot spring, Lashin et al. [15] estimated a geothermal reservoir temperature of 136 °C. Based on the updated geophysical interpretation (airborne magnetic, 1D/2D MT [28]) and the geotherm of Figure 25, for the depth of 6 km where the heat source bodies are located [27, 28], a temperature of around 270 °C is expected. Concerning the potential geothermal reservoir, it should be located at a depth of 1-4 km, with an average expected temperature of 150 °C.

The subsurface lineament analysis applied to the airborne magnetic data for the Wadi Al Lith area showed the existence of numerous tectonic elements, including major faults and dikes. The major trends of the surface tectonic structures in the Wadi are NE-SW and NNE-SSW, while few lineaments close to the Ain Al Harra hot spring trend NW-SE [11]. The mapped subsurface lineaments also display NNE-SSW and NW-SE major azimuth orientations, which agrees with the major trend of the surface lineaments/faults observed in the field, and, more importantly, parallel to the Red Sea rift axis. In the Wadi Al Lith potential geothermal reservoir, the surface features do not control the circulation of the geothermal fluids [11, 15]; instead, the fluid circulation in the subsurface is mainly controlled by tectonic features that are expressed at the surface only in some areas, such as the area of Ain Al Harrah and its surrounding area.

The dikes in the study area of Wadi Al Lith are related to the extension and the relevant tectonic events associated with the Red Sea Rift opening and the uplift of the Red Sea escarpment (Miocene-Pliocene) [240]. It is documented in the literature that they might possibly act as pathways for groundwater and geothermal fluids, bringing thermal water to sites different than the known location of the Ain Al Harrah hot spring (e.g., in a site to

the central north part of the area) [38]. The locations of the identified from the magnetic data dikes correspond to an area where the rock formations present low density and high conductivity, as the joint gravity and EM data analysis showed. Thus, they influence the circulation of the geothermal fluids by acting as secondary pathways within the main conduit of the interpreted fracture zone, bringing the fluids to shallow depths close to the surface. Besides geothermal, the dikes in the study area are also prolific for mineral exploration, due to the existence of negative susceptibility responses, which indicate formations of remanent magnetization and/or containing precious metals (e.g., gold, silver).

CHAPTER 5

Conclusions and Recommendations

5.1 Conclusions

The geophysical investigations conducted near the Ain Al Harrah hot spring have provided valuable insights into the subsurface structure and the complex tectonic regime of the Wadi Al Lith region through 2D and 3D modeling. The collected gravity data were analyzed, and their modeling was constrained using electromagnetic methods (MT and TEM). The 3D modeling revealed the presence of a low-density zone with an E-W trend in the southern part of the study area, crossing the location of the hot spring. This could be attributed to the existence of a fracture zone of such direction, created due to tectonic processes associated with the opening of the Red Sea. This fracture zone is connected with the Wadi Al Lith prospective geothermal field and the surficial streaming of thermal fluids through the Ain Al Harrah hot spring. The dikes in the study area act as secondary fluid pathways that bring the thermal waters to depths where it is more feasible and economically viable to be drawn and put into potential production. Moreover, they could serve as an example for the rest of the dikes found within the hot spring areas of Wadi Al Lith, as a similar geotectonic regime is observed within the whole of Wadi.

The airborne magnetic data that were processed with the radially averaged spectral analysis method provided an estimate of the depth to the bottom of the magnetic source at the area of the Wadi. This depth is assumed to be related to the Curie isotherm depth, in

which magnetic rocks lose their magnetic properties, and was estimated to be located at 14.8 km; a depth that was also confirmed by the MT data. The depths to the top and the centroid of the magnetic source were estimated at the intervals of mid- to high-wavenumbers and low-wavenumbers using the spectral peak and centroid methods, respectively. Using the Curie isotherm depth information, the 1D geotherm for the area was constructed, which also provided a mean value of the surface heat flow for the study area at 109.8 mW/m².

Also, a workflow for the integration of different kinds of geoscientific data (geophysical, geological, and wellbore) is described, verified in two case studies of O&G exploration, and applied for the characterization of the geothermally prospective area of Wadi Al Lith. Based on the proposed workflow, gravity, magnetic, and electromagnetic data were jointly interpreted, with one dataset adding constraints to the other. The knowledge of the temperature variation with depth, the characteristics of the heat source (geometry and depth) as extracted from geophysical methods such as MT, gravity, and magnetic, and the geometry of the fracture and dike network which provide pathways for the circulation of the hot fluids, was used in the design of a conceptual subsurface model of the study area of Wadi Al Lith. This conceptual model can be utilized as a base for any future exploitation stage for the use of the potential geothermal resources of the area for energy production. According to the scope of the study, the workflow can be expanded to include seismic, wellbore, and geology data that will further simplify and constrain the interpretation of the available datasets both at depth and to the surface, allowing for better decision-making and reduced development risk.

The findings of this study demonstrate the potential of the Wadi Al Lith area for geothermal energy production and can guide future research and exploration efforts following Saudi Arabia's Vision 2030 for the transition to renewable energy production from alternative sources. The comprehensive conceptual model (hot body and fracture zones) constructed through this study serves as a starting point for planning an exploratory and production drilling program and underscores the importance of geophysical investigations in the sustainable utilization of geothermal resources.

5.2 Recommendations

The analysis of all geophysical data showed that the geothermal prospectivity of the Wadi Al Lith area needs to be considered. The outcomes of this study can be further used to study the potential of the area for energy production. However, the geothermal system is yet to be accurately defined since this study provides preliminary insights, limited to the results obtained using only some of the available methods and techniques for the exploration of a geothermally prospective area.

The full characterization of the potential geothermal system could be achieved by conducting more detailed high-resolution seismic and non-seismic geophysical surveys, probably by applying 3D seismic, surface CSEM, and micro-gravity methods, to enhance the data resolution over the sites of interest (e.g., along the fracture zones). This will provide a clearer and updated view of the subsurface geology and tectonic regime by reconstructing a high-accuracy 3D image of the reservoir, highlighting its internal structure. A joint inversion and interpretation of the MT, CSEM, gravity, magnetic, and

seismic data could provide important information about the reservoir and hot body characteristics and the role of the fracture zones, faults, and dikes in geothermal fluid circulation.

Detailed geological and updated geochemical studies of the surface and groundwater and the water of the hot spring, as well as of the geologic formations of the area are highly recommended, since they will provide insights into the expanse of the potential geothermal field and its potential for further development. All the newly acquired datasets can be used as the basis for a 3D modeling study. This study will significantly reduce the uncertainty on the interpretation of the subsurface and will provide a profound understanding of the study area.

Lastly, the drilling of exploratory boreholes conforming to the international geothermal industry standards can provide the ground truthing for the estimated surface heat flow for the studied area. The final step could be the design of a drilling program in specific sites based on the integrated geoscientific model of the study area, which will provide accurate information on the reservoir parameters and put the possible geothermal resources into production.

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Vitae

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Konstantinos Chavanidis is a geologist/geophysicist, with a Bachelor's degree in Geology from the Aristotle University of Thessaloniki (AUTH), Greece, in 2016, and a Master's degree in Hydrocarbon Exploration and Exploitation from four of the most esteemed Greek universities (Aristotle University of Thessaloniki, National Technical University of Athens, National and Kapodistrian University of Athens, and Democritus University of Thrace), in 2020. Currently (May 2024), he is a PhD candidate in Geophysics at the

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As an active member of the Geophysical Laboratories of KFUPM and AUTH, he has participated in several research projects related to the application of geophysical methods to natural resources (geothermal, O&G, groundwater) exploration, mining (VMS and clay minerals) studies, and archaeological research. Also, he has industrial working experience as an internship geoscientist at the Hellenic Petroleum Company (Athens, Greece), where he contributed to new projects of petroleum exploration and well design.

As a young researcher, Konstantinos focuses on serving the Geoscientific community by contributing to the advancement of geoscientific knowledge, while maintaining the highest standards of academic and industrial excellence. Simultaneously, the constant motivation of his research stems from the practical applications of the outcomes that could be utilized to satisfy the needs of society and preserve the natural environment.

Konstantinos' publications are a proven contribution to geoscientific research. During his PhD time only, he co-authored ten journal (four as first author) and fifteen conference/workshop (five as first author) papers. It should also be noted that Konstantinos was awarded a research grant of 50,000 SAR for his PhD research by the Renewable Energy Technical Incubator (RETI) funded by the National Industrial Development and Logistics Program (NIDLP) under the Interdisciplinary Research Center for Renewable Energy and Power Systems (IRC-REPS) at KFUPM (Project No. CREP2522). Details of Konstantinos' publications and submitted works as a PhD candidate at KFUPM are listed in chronological order below:

Journal Papers:

1. **Chavanidis K.**, Harishidayat D., Stampolidis A., Tsokas G. N., Salem A. & Soupios P. **2024**. An integrated workflow for characterizing gas potential: Axios-Thermaikos Basin (Greece). *Acta Geophysica*. <https://doi.org/10.1007/s11600-024-01358-8>.
2. Khogali A., **Chavanidis K.**, Kirmizakis P., Stampolidis A. & Soupios P. **2024**. Reconstruction of the subsurface of Al-Hassa Oasis using gravity geophysical data. *Applied Sciences*, 14, 9, 3707. <https://doi.org/10.3390/app14093707>.
3. Ashadi A L., Tezkan B., Yogeshwar P., Hanstein T., Kirmizakis P., Khogali A., **Chavanidis K.** & Soupios P. **2024**. Magnetotelluric case study from Ain Al-Harrah hot spring, Al-Lith, Saudi Arabia. *Arabian Journal for Science and Engineering*, 49, 899-912. <https://doi.org/10.1007/s13369-023-08293-8>.
4. **Chavanidis K.**, Stampolidis A., Kirmizakis P., Tranos M., Fedi M., Pasteka R., Al-Ramadan K., Kaka S., Tsokas G. N. & Soupios P. **2022**. Gravity Survey on the Oil-Bearing Dammam Dome (Eastern Saudi Arabia) and Its Implications. *Remote Sensing*, 14, 3, 735. <https://doi.org/10.3390/rs14030735>.
5. **Chavanidis K.**, Stampolidis A., Salem A., Ashadi A L., Khogali A., Kirmizakis P. & Soupios P. Gravity modeling of a hot spring geothermal prospect in Western Saudi Arabia (Geothermics, **in review**).
6. **Chavanidis K.**, Salem A., Stampolidis A., Ashadi A L., Abu-Mahfouz I. S., Kirmizakis P. & Soupios P. Geothermal energy potential of a hot spring area in Western Saudi Arabia, by analyzing magnetic data (Natural Resources Research, **in review**).

7. Khogali A., **Chavanidis K.**, Stampolidis A., Kirmizakis P., Yassin M., Abu-Mahfouz I. S., Al-Shaibani A. & Soupios P. Subsurface complexity controls the aquifer heterogeneity: a case study from the Al-Hassa oasis, Eastern Saudi Arabia (Groundwater for Sustainable Development, **in review**).
8. Khogali A., **Chavanidis K.**, Kirmizakis P., Stampolidis A., Ashadi A L., Hanstein T., Candansayar E. & Soupios P. Subsurface characterization of the Al-Hassa National Park, Eastern Saudi Arabia, using multi-geophysical methods (Arabian Journal for Science and Engineering, **in review**).
9. Rafiq J., **Chavanidis K.**, Abu-Mahfouz I. S. & Soupios P. Integrated structural analysis for geothermal exploration: A new protocol combining remote sensing and aeromagnetic geophysical data (MethodsX, **in review**).
10. Rafiq J., Abu-Mahfouz I. S., **Chavanidis K.**, Arrofi D., Soupios P. & Farooqui M. I. A. Spatial distribution analysis of structural lineaments in Al-Lith geothermal reservoir using remote sensing and aeromagnetic data, Western Arabia (Acta Geophysica, **in review**).

Conference Abstracts and Presentations / Extended Abstracts / Posters:

1. Ashadi A L., Tezkan B., Yogeshwar P., Hanstein T., Kirmizakis P., Khogali A., **Chavanidis K.** & Soupios P. **2024**. 3-D magnetotelluric (MT) modelling using transient electromagnetic (TEM) data as constraints for imaging the geothermal reservoir in Saudi Arabia. AAPG International Conference & Exhibition 2024, Muscat, Oman.
2. Khogali A., **Chavanidis K.**, Kirmizakis P., Stampolidis A., Candansayar E. & Soupios P. **2024**. Subsurface characterization of Al-Hassa National Park, Saudi

Arabia using gravity and electromagnetic methods. EAGE Annual 2024, Oslo, Norway.

3. **Chavanidis K.**, Stampolidis A., Kirmizakis P., Khogali A. & Soupios P. **2024**. Modeling of secondary geothermal fluid pathways using magnetic data: The case study of Wadi Al Lith (Western Saudi Arabia). SPWLA SAC 14th Workshop – Advances in Geothermal Energy Exploration and Development, Al Khobar, Saudi Arabia.
4. Khogali A., Kirmizakis P., **Chavanidis K.**, Ashadi A L., Hanstein T., Stampolidis A., Candansayar E. & Soupios P. **2024**. Electromagnetic insights: 3D subsurface modeling of Al-Hassa, Saudi Arabia. EGU General Assembly 2024, Vienna, Austria.
5. **Chavanidis K.**, Stampolidis A., Abu-Mahfouz I. S., Khogali A., AlShaibani A., Salem A. & Soupios P. **2024**. Gravity survey over a hot spring in Western Saudi Arabia. International Petroleum Technology Conference 2024, Dhahran, Saudi Arabia.
6. **Chavanidis K.**, Salem A., Stampolidis A., Ashadi A L., Abu-Mahfouz I. S., Kirmizakis P. & Soupios P. **2024**. Curie depth and heat flow estimation using magnetic data at a hot spring area in Western Saudi Arabia. International Petroleum Technology Conference 2024, Dhahran, Saudi Arabia.
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8. Rafiq J., **Chavanidis K.**, Abu-Mahfouz I. S., Soupios P. & Farooqui, M. I. **2024**. Integrated surface-subsurface analysis for high permeability zone delineation in a geothermal field: a case study from the Western Arabian Plate (Al-Lith, Saudi Arabia). International Petroleum Technology Conference 2024, Dhahran, Saudi Arabia.
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11. Khogali A., **Chavanidis K.**, Stampolidis A., Coles R., Hanafy S. & Soupios P. **2023**. Volcanic Massive Sulfide (VMS) ore deposit in Western Saudi Arabia: a geophysical study. Abstracts Book of the Eurasia Geoscience Congress and Exhibition 2023, Antalya, Turkey.
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remote sensing, geochemical, and hydrochemical approach. International Geomechanics Symposium 2023, Al Khobar, Saudi Arabia.

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15. **Chavanidis K.**, Stampolidis A., Harishidayat D., Tranos M., Tsokas G. N., Abu-Mahfouz I. S., Salem A. & Soupios P. **2023**. Reconstruction of a complex depth model for the onshore area of Axios-Thermaikos Basin in Greece by integrating seismic, borehole, and potential field data. Digital Abstracts of the Middle East Oil, Gas and Geosciences Show 2023, Manama, Bahrain.