

**Structural Characterization of a Geothermal
Field: Al-Lith, Western Saudi Arabia**

BY

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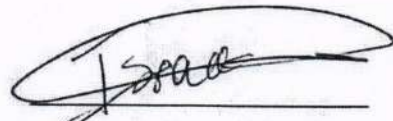
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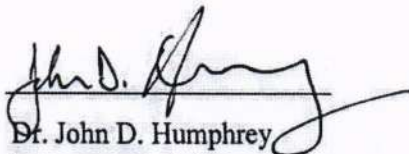
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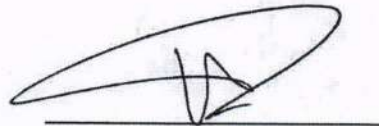
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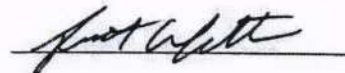
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Dedication

I DEDICATE MY THESIS TO MY FAMILY AND TEACHERS

ACKNOWLEDGMENTS

In the name of **ALLAH**, the most gracious and most merciful.

First of all, I want to thank **ALLAH** almighty who gives me the courage and strength to avail the opportunity to study at one of the most prestigious universities in the world.

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ABSTRACT

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Geothermal energy is a promising and sustainable alternative to fossil fuels that can help mitigate the negative impact of energy production on the environment. The Al-Lith geothermal field in western Saudi Arabia is one such resource with significant potential for exploration and development. However, understanding the structural characteristics of the geothermal system is crucial for the successful exploitation of resources. This research aims to characterize the surface and subsurface geological, and structural features, analyze their densities, and delineate high permeability zones of the Al-Lith geothermal field. Another aim of this study is to characterize the geochemical and hydrogeological properties of the rocks and fluids in the geothermal field. The present study utilizes an integrated approach that combines remote sensing, geophysical data, ground truthing/fracture mapping, rock and fracture geochemistry, and hydrogeochemistry. Surface lineament density analysis was performed using digital elevation models and Landsat-8 imagery supported by a series of fieldworks, whereas subsurface lineament density analysis was based on aeromagnetic data. Rock and fracture geochemistry were used to investigate the mineralogy and geochemistry of the rocks and fracture cement. Hydrogeochemistry was employed to assess reservoir temperature, fluid properties, and hydrological and geochemical processes controlling the geothermal system. The findings revealed that the Al-Lith geothermal field is influenced by a complex network of faults and fractures, which control the flow of water and heat.

Surface lineament density analysis subdivided the study area into ten zones (Zones A-J), with the highest lineament density zone located in the northern part of the study area (Zone A). Subsurface lineament density analysis shows five high-density zones, three of which show a very good correlation with those identified on the surface. The hydrogeochemistry results suggested that the thermal water is affected by a combination of several factors, including water-rock interactions, mixing, and dilution. The rock and fracture geochemistry results indicated that the rocks in the study area are mainly composed of granitic and felsic igneous and low-grade metamorphic rocks. The present study allowed the determination of the main high-permeability zones and associated high-potential geothermal areas in the Al-Lith geothermal field. Based on the analysis of all the data obtained from the integrated analyses conducted in this study, Al-Lith geothermal field has the potential to serve as a sustainable source of energy in Saudi Arabia, and can help accelerate the shift towards sustainable and renewable sources of energy. The study also generated a database that will assist decision-makers in the exploration of targeted resources such as geothermal and other mineral resources.

ملخص الرسالة

الاسم الكامل :[جواد رفیق]

عنوان الرسالة :[التوصيف الهيكلي لحقل حرارة جوفية: الليث، غرب المملكة العربية السعودية]

ال تخصص :[جيولوجيا]

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تعد الطاقة الحرارية الجوفية بديلاً واعدًا ومستدامًا للوقود الأحفوري الذي يمكن أن يساعد في التخفيف من التأثير السلبي لإنتاج الطاقة على البيئة. يعد حقل الليث الحراري الأرضي في غرب المملكة العربية السعودية أحد هذه الموارد التي تتمتع بإمكانيات كبيرة للاستكشاف والتطوير. ومع ذلك، فإن فهم الخصائص الهيكلية لنظام الطاقة الحرارية الأرضية أمر بالغ الأهمية لاستغلال الموارد بنجاح. يهدف هذا البحث إلى توصيف العناصر الجيولوجية والتراكيب السطحية وتحت السطحية، وتحليل كثافتها، وتحديد مناطق النفاذية العالية لحقل الليث الحراري الأرضي. الهدف الآخر لهذه الدراسة هو توصيف الخصائص البيوكيميائية والهيدرو جيولوجية للصخور والسوائل في مجال الطاقة الحرارية الأرضية. تستخدم الدراسة الحالية نهجًا متكاملًا يجمع بين الاستشعار عن بعد، والبيانات الجيوفيزيائية، ورسم خرائط الجيولوجية/التركيبية، وكيمياء الصخور والكسور، والكيمياء الهيدرو جيولوجية. تم إجراء تحليل كثافة الخط السطحي باستخدام نماذج الارتفاع الرقمية وصور Landsat-8 مدعومة بسلسلة من الأعمال الميدانية، في حين اعتمد تحليل كثافة التراكيب تحت السطحية على البيانات المغناطيسية. تم استخدام التحاليل البيوكيميائية لدراسة المعادن والخصائص البيوكيميائية للصخور المواد المائلة للكسور. تم استخدام الكيمياء الجيولوجية لتقييم درجة حرارة الخزان وخصائص السوائل والعمليات الهيدرو لوجية والبيوكيميائية التي تتحكم في نظام الطاقة الحرارية الأرضية. كشفت النتائج أن حقل الليث الحراري الأرضي يتأثر بشبكة معقدة من الصدوع والكسور التي تتحكم في تدفق الماء والحرارة. قسم تحليل كثافة التراكيب\الكسور السطحية منطقة الدراسة إلى عشر مناطق (مناطق A-J)، وكانت أعلى منطقة كثافة كسور تقع في الجزء الشمالي من منطقة الدراسة (المنطقة أ). يُظهر تحليل كثافة التراكيب تحت السطحية خمس مناطق عالية الكثافة، تظهر ثلاثة منها ارتباطًا جيدًا جدًا بتلك المحددة على السطح. اقترحت نتائج الكيمياء الجيولوجية المائية أن الماء الحراري يتأثر بمجموعة من عدة

عوامل، بما في ذلك تفاعلات الماء والصخور، والخلط، والتخفيف. أشارت نتائج الكيمياء الجيولوجية للصخور والكسور إلى أن الصخور في منطقة الدراسة تتكون أساسًا من صخور نارية جرانيتية وفلزية وصخور متحولة ذات درجة تحول منخفضة. سمحت الدراسة الحالية بتحديد المناطق الرئيسية عالية النفاذية والمناطق الحرارية الأرضية المرتبطة بها ذات الإمكانيات العالية في مجال الطاقة الحرارية الأرضية في منطقة الليث. بناءً على تحليل جميع البيانات التي تم الحصول عليها من التحليلات المتكاملة التي أجريت في هذه الدراسة، فإن مجال الطاقة الحرارية الأرضية في الليث لديه القدرة على العمل كمصدر مستدام للطاقة في المملكة العربية السعودية، ويمكن أن يساعد في تسريع التحول نحو المصادر المستدامة والمتجددة طاقة. كما أنشأت الدراسة قاعدة بيانات من شأنها أن تساعد صانعي القرار في استكشاف الموارد المستهدفة مثل الطاقة الحرارية الأرضية والموارد المعدنية الأخرى.

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Structural geology has numerous applications and developments in the energy resources sector, which have been closely linked to the industry over the years. It started with the use of restored and balanced cross-sections in hydrocarbon exploration and continued with fractures analysis for reservoir characterization and fluid flow modeling. With the current energy revolution, there has been a shift to renewable energies like geothermal energy, which requires a thorough understanding of the structural and geological architecture of a possible geothermal site. The regional tectonic regime and local structural context have a significant impact on geothermal plays, as fundamental variables such as fluid chemistry, hydrogeological controls, and heat flow are intimately connected to the geodynamic environment. The fracture aperture and connectivity are the key determinants of geothermal system permeability, making the understanding of fracture networks and fault zones essential for any acceptable, site-specific field development (Mazzoli, 2022). Using geothermal technology, heat from the earth's subsurface is extracted and transformed into energy, making it an important source of clean and renewable energy for several countries worldwide (IRENA, 2020). With the growing interest in renewable energy, many developed nations are now turning to geothermal energy, countries like Iceland, the United States, Indonesia, Turkey, Kenya, New Zealand,

and the Philippines actively exploring and drilling for geothermal energy sources (Figure 1.1). The potential for these active sites to produce clean electricity with minimal environmental restrictions is substantial (Think Geoenergy, 2020).

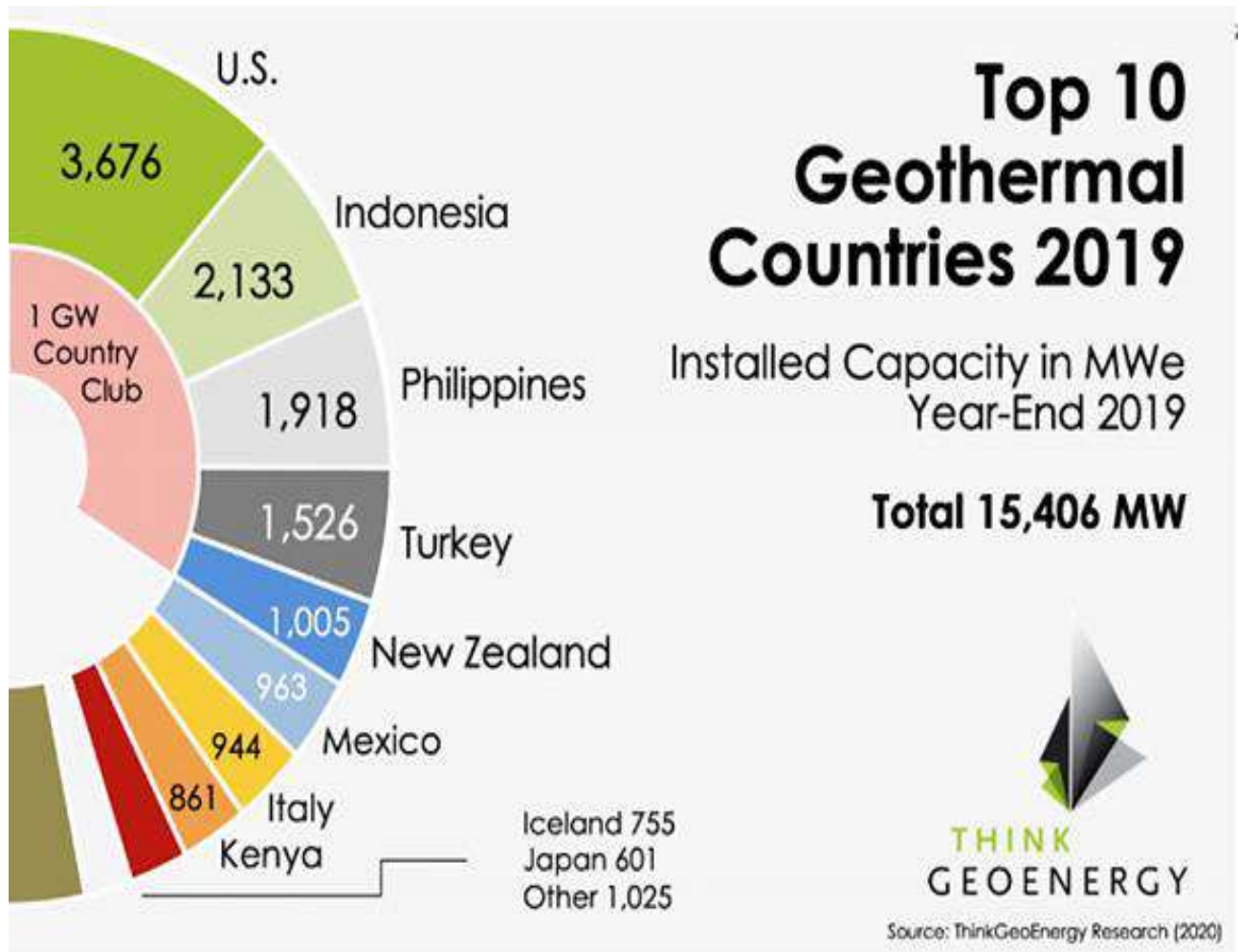


Figure 1. 1 Top 10 geothermal countries in the world (ThinkGeoenergy, 2020).

Saudi Arabia heavily relies on fossil fuels for energy production, but with a rapidly growing economy and increasing energy demand, the country cannot sustain future economic growth solely on this finite resource. Current data shows that Saudi Arabia used 240 terawatt hours of electricity in 2017, with 80% of it used for cooling and desalination facilities consuming 17 million Kwh to produce 2,35l B/day of drinking water per person. Oil and gas

are major contributors to the nation's CO₂ emissions from fuel burning, resulting in a rise from 0.012 Gg in 2000 to 0.016 Gg currently (IEA, 2012, WB 2009). As a result, the country is currently focusing on developing underutilized renewable energy resources, especially solar energy, and geothermal energy which has enormous economic potential and is one of the biggest, most environmentally friendly, and cleanest sources of energy in the world [(Ahmed, 1994); (Alnatheer, 2002)]. Geothermal energy can be utilized for various purposes, including electricity production, space heating, CO₂ and dry-ice manufacturing, greenhouse heating, home hot water supply, swimming pools, electricity generation, and different industrial activities, making it an attractive alternative to fossil fuels in Saudi Arabia's energy mix [(Aref and Nassir, 2012); (Lashin and Al Arifi, 2014)].

1.2 Background

Tectonically, Saudi Arabia covers up to 80 % of the Arabian plate. The Arabian shield covers most of the western portion of the country. This part of the Arabian plate comprises the crystalline basement rock (igneous and metamorphic) that ranges in thicknesses from 40 – 45 km and ages from 870-850 Ma. This is then overlaid by the younger and thick (0 – 10 km) sequence of the phanerozoic sedimentary rocks that ranges from Cambrian to Pliocene in age, followed by the Cenozoic age flood basalt. The Paleogene to Holocene intracontinental basin and as well as oceanic basins are present along the coastline of the Red Sea and the Gulf of Aden (Lashin, 2020). This exceptional situation of Saudi Arabia on tectonic plate boundaries along with the recent active tectonic and volcanic activities of the Red Sea makes the country a host of many geothermal resources. Since 27 Ma, when the Red Sea rift was activated, the Arabian continent began to drift away from the main African continent. This was the beginning of a sequence of

volcanic and tectonic events along Saudi Arabia's western continental boundary. Large-scale volcanic and plutonic activity near Saudi Arabia's western border followed this epoch. Volcanic centers containing significant amounts of basaltic and basaltic andesitic material (Harrats) characterize the volcanic activity. The Red Sea's western and southwestern coasts are where Saudi Arabia finds the majority of its geothermal resources. (Figure 1.2). It is represented by hydrothermal resources encountered mainly in the Jizan & Al-Lith areas and the hot dry rocks of the Harrats. Low, medium, and high enthalpy geothermal resources are available in Saudi Arabia, which are described as follows:

1.2.1 Low Enthalpy Resources:

Deep-seated aquifers found in substantial sedimentary basins in the eastern half of Saudi Arabia serve as a good representation of sedimentary aquifers. Low-enthalpy resources are constrained, and the typical geothermal gradient symbolizes their geothermal potential. They only have access to temperatures up to 70°C through deep oil wells.

1.2.2 Medium Enthalpy Resources:

The shallow hot springs of hot surface water that make up hydrothermal systems are found along the western and southwestern coast (Al-Lith and Jizan areas). Medium-enthalpy resources have direct access to hot sub-surface anomalies through the open network of active faults and fractures. Examples of these geothermal manifestations include thermal springs with surface temperatures ranging from 31°C to 96°C and a flow rate of 5 to 20 L/m, which may be found in the Al-Ardah, Al-Khouba, Ain Khulab, Bani Malik, and Al-Lith regions.



Figure 1. 2 Main geothermal features in Saudi Arabia. Hot springs (red triangles), volcanic fields (red polygons), and heat flow measurements (Aboud et al., 2021a).

1.2.3 High Enthalpy Resources:

There are roughly 80,000 km² of Harrats (lava fields), which are composed of granites, basaltic lavas, and other igneous rocks. They are a series of mostly basaltic volcanic eruptions that stretch along Saudi Arabia's western Red Sea coastline. These Harrats formed underneath hot aquifers because they covered a significant portion of the paleochannels along the west coast. Fumaroles appeared in several locations along the western margin of Harrats due to steam and condensate from the hot lavas and the host aquifers. A geothermal gradient of more than 90 °C/km has been seen in the Harrats (Coleman et al. 1983; Chandrasekharam et al. 2016a). The largest heat flux and enthalpy are found in the Harrats of Khayber and Rahat.

1.3 Literature Review

Geothermal resource exploration studies in Saudi Arabia began in 1980. Saudi Arabia is considered one of the Middle East's most geothermally active nations. [(Rehman and Shash, 2005); (Rehman, 2010)]. Based on the hydrogeological exploration of the country's southern hot springs and geological exploration of the western massive volcanic craters known as Harrats. Geothermal energy has great potential in Saudi Arabia's western region (Al-Lith), which is located along the Red Sea coast.

Al-Lith is one of the favorable potential geothermal systems for renewable energy development in Saudi Arabia as it encounters many hot springs (the closest one is the Ain Al Harrah hot spring), volcanoes, and hot spots along the coastal area (Aref and Nassir, 2012). The Al-Lith area has been previously studied for general geological surveys (HADLEY, 1980), mechanisms related to Red-Sea rift magmatism around Al-Lith (e.g., [(Brown et al., 1963); (Wier and Hadley, 1975); (Fleck and Hadley, 1985); (Pallister, 1986)]), geothermal power prospect studies (Lashin et al., 2015), geophysical investigations for construction purposes [e.g., (Edigbue

et al., 2021)] and geochemical studies of Al-Lith coastal sediments [e.g., (Al-Zubieri et al., 2020)]. However, a paucity of studies focuses on a comprehensive surface and subsurface geological, geochemical and geophysical analysis and its implications for geothermal exploration in the Al-Lith region. A significant knowledge and information gap exist about the potential of geothermal resources as well. Despite the work carried out by a group of researchers from King Saud University [(Hussein et al., 2013); (Lashin and Al Arifi, 2012, 2014) and (Lashin et al. 2012, 2014)], a more thorough and detailed study is required to evaluate the region's economic reserves from geothermal resources, for possible energy generation and other direct/domestic uses.

1.3.1 Previous Work:

El Dayel (1988) examined hot spring water samples to characterize the hydrochemical features of the hot springs in the Al-Lith region. Between 1992 and 2004, a more thorough investigation of the petrography, petrochemical makeup, and mineralogy of the Harrats was carried out by (Roobol and Camp, 1991a, b & Roobol et al., 1995 & 2002, Pint 2006 and Pint et al. 2004). The Harrats of Rahat, Ithnayn, and Khaybar, where multiple steam fumaroles were discovered, are considered to be excellent high-enthalpy locations that would be appropriate for geothermal power generation (Roobol et al., 2002). Rehman and Sash collated all the geothermal information and activity as reported in the World Geothermal Congress (WGS) proceedings in 2005 and 2010 (Rehman & Shash 2005 and Rehman 2010). A more detailed geophysical survey, including seismic reflection and MT methods, was done by Lashin et al. 2013 at the Wadi Al-Lith area. The first results are presented in the proceedings of the World Geothermal Congress (WGC) 2015. The analysis of seismic data indicated the Red Sea rift (NW-SE) and the transform faults (ENE-WSW) as the main structural players that control the movement of geothermal water. The

MT survey showed that the geothermal source is located deep at a depth of 2500 m (Lashin et al. 2015b). From 2010 to 2014, a new academic era of geothermal projects was launched by King Saud University (KSU) in order to research the geothermal resources found in the western and southern parts of Saudi Arabia (Lashin and Al Arifi 2010; 2012; Hussein et al. 2013). More detailed work was done by Chandrasekharam (Indian Institute of Earth Sciences-Bombay) with a group of scientists from KSU under the VPP program in the period from 2014-2019. Researchers looked into the different geothermal systems along the western coast of Saudi Arabia and the high-production granites, as well as how the geothermal systems along the Red Sea changed over time in relation to the systems in East Africa (Lashin et al. 2014; Chandrasekharam et al. 2015a, b, 2016a, b, and 2018). More recently, Aboud et al. (2018) carried out a more detailed geophysical survey on the Harrats area, with special emphasis on the volcanic field of Harrats Rahat, using the magnetotelluric (MT) method. To image the subsurface resistivity setting, the collected data were examined using a 3D inversion approach.

1.4 Location of Study Area

Wadi Al-Lith area is located around 250 kilometers southeast of Jeddah, with latitudes of 20°15' and 20°30'N and longitudes of 40°00' and 40°30'E. The Al-Lith region covers an area of approximately 2,897 km² along Saudi Arabia's western coastline. The research area is located on a tectonic plate boundary, has an elevation of 620 m and is extensively anatomized by wadis that flow toward the Red Sea. The northern part of the Al-Lith is underlain by Precambrian crystalline rocks, Tertiary sedimentary rocks, and mafic dikes. A variety of Quaternary deposits partially cover the southern portion of the area. Geomorphologically, the area is divided into three separate zones representing the nature of particular sedimentary processes: coastal zone, beach zone, and barrier reef island. A wide tidal plain bounds the

coastal zone with sabkha and mangrove swamps. Several wadis including Markub, Al-Fagha, Khudayr, Al Bir, Rahman, Hariq and Al-Lith cut across the Al-Lith coastal plains (Figure. 1.3) (Bantan et al., 2020).

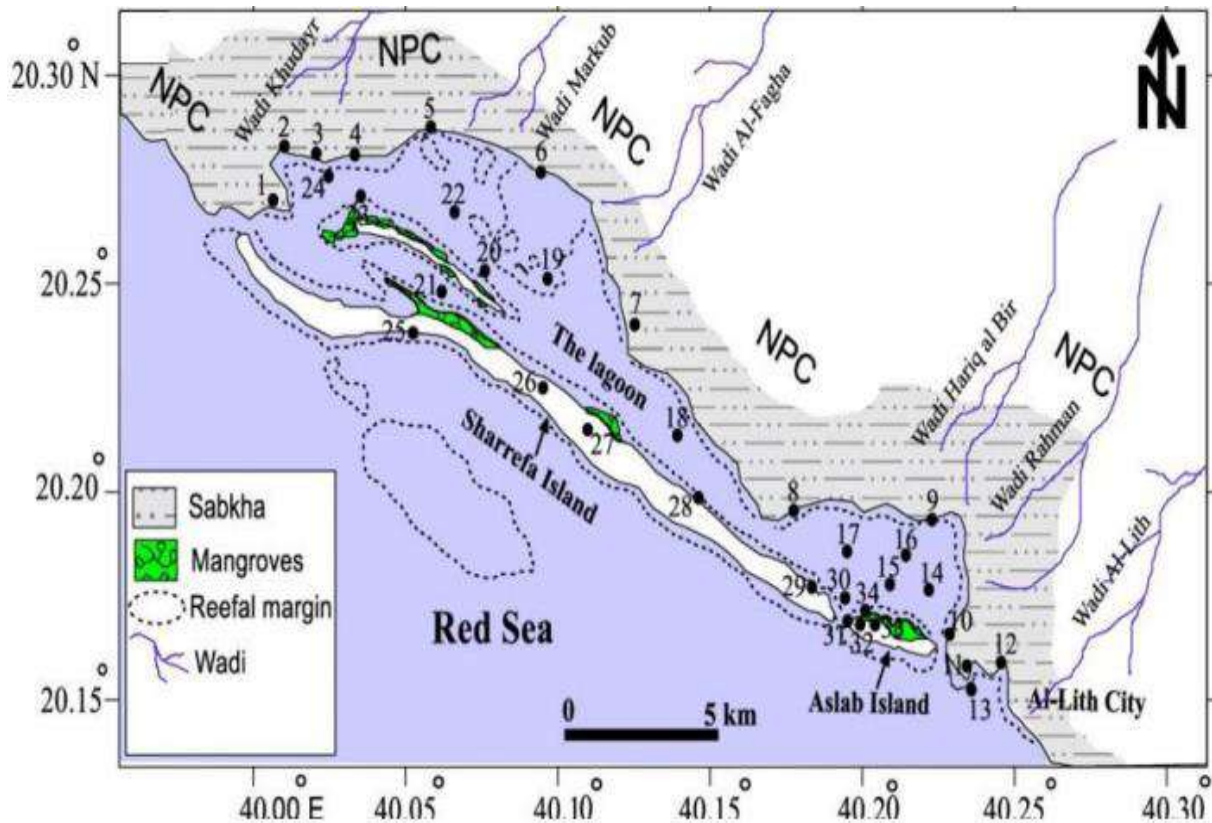


Figure 1. 3 Surface sedimentary features and geomorphological division of the study area (Bantan et al., 2020).

1.5 Problem Statement

The main focus of this research is the Al-Lith area which is classified as a prime interest of hydrothermal activities in Saudi Arabia's western part (Al-Douri et al., 2019). Al-Lith area is classified as medium-enthalpy geothermal resource (Lashin et al., 2015). Geothermal activity in the Al-Lith area has been well documented. In the east of the Al-Lith town, a significant portion of the Arabian Shield is exposed by four prominent geothermal sites (hot springs) namely: Wadi Al Sader, Bani-Hilal, Ain Al Harrah, and Wadi Markub. The Wadi Al-Lith region

in western Saudi Arabia is host to one of the most anticipated geothermal systems. (Aboud et al., 2021b). The Red Sea's tectonic activity and structural regimes have a significant impact on it because it is close to its coast. The Ain Al Harrah hot spring is the main geothermal target in the Wadi Al-Lith area because it has high surface temperatures of up to 95 °C and good Petro-thermal characteristics of 136 °C (reservoir temperature), 219 kJ/kg (discharge enthalpy), and 183 mW/m² (heat flow), as shown by the geo-thermometric analysis (Hussein et al., 2013). However, the geothermal activity of this area has not been studied in detail since the tectonic regime in the broader area and the fluid circulation through its fractured basement rocks and conceptualization of surface and sub-surface structural model is poorly understood.

This research investigates and explores more comprehensively the prospect of the geothermal resource in the Al-Lith (west of Saudi Arabia) by integrating remote sensing methods (such as Fault Fracture Density (FFD), and lineament analysis), geological, geochemical and geophysical data. The outcomes of this research will serve as the foundation for geothermal exploitation projects for either power generation or direct-use applications (e.g., heating and cooling of buildings).

1.6 Aims & Objectives:

This research will utilize the multi-disciplinary approach by integrating remote sensing, geological, geophysical, and geochemical data to better understand the fluid flow and permeability in the fractured, potential geothermal reservoir of Al-Lith, western Saudi Arabia. The primary goal of this research is to map the surficial and subsurface geological and structural elements and examine their implications on geothermal resource exploration. In addition, structural analysis of the surface geological features will help to enhance our understanding of the surface structure distribution and orientation in the study area and provide insights into the further structural interpretation of the area. Specifically, the current research aims to 1) perform a structural and geological mapping of the Al-Lith area and extract the main structural features and lineaments in the study area both manually and digitally, 2) identify the areas with high fracture densities using the fault fracture density (FFD) method and relate this to geothermal potential, and 3) characterize the geochemical and hydrogeological properties of the rocks and fluids in the Al-Lith geothermal field. Overall, this study will improve our conceptual model of the fracture system that holds the geothermal fluids in the study area and, in integration with geophysical measurements, will provide insight into the optimum modeling and exploitation of the geothermal field in Al-Lith.

The integration between surface (using remotely sensed data) and subsurface (using geophysical data) structural lineament analyses, particularly the combination of both, is novel and have previously not used. The main focus is to characterize the surface/subsurface structural architecture of the potential geothermal field. This research attempts to deliver substantial outcomes to potential stakeholders (Saudi government and international energy production companies) to qualify novel technology. The research questions this study attempts to address are listed as follows:

- i. What are the main characteristics of the structural features (surface and subsurface structural lineaments) in the study geothermal system: their densities, orientations and interactions?
- ii. Where are the high permeable zones distributed in the study area?
- iii. Can the direction of the geothermal fluids percolating through the fractures be identified by utilizing fracture density and orientation analysis and different geochemical and hydrochemical analyses?
- iv. What is the reservoir temperature of the geothermal resource in Al-Lith?

CHAPTER 2

Tectonic & Stratigraphic Framework

2.1 General Geology

The Al-Lith area is located in western Saudi Arabia and is part of the Arabian Shield. The geologic setting of the area is characterized by Precambrian rocks, including basement rocks of tonalite and granodiorite, overlain by volcanic and volcanoclastic rocks of the Neoproterozoic Arabian Shield. The stratigraphy of the area is dominated by the Al Lith Formation, which consists of metavolcanic rocks, metasedimentary rocks, and interbedded mafic and felsic volcanic rocks (Brown et al., 1963). This formation is overlain by the younger Jiddah Formation, which consists of a basal conglomerate, sandstone, and shale unit, followed by an upper limestone unit. The Jiddah Formation is unconformably overlain by the Tertiary sediments of the Red Sea coastal plain (Fleck and Hadley, 1985).

The majority of the northern section of the Al Lith quadrangle is covered by Precambrian layered and intrusive rocks, as well as Tertiary conglomerate and gabbro dikes, while unconsolidated Quaternary surficial deposits and coral reefs are the primary exposures in the southern half (Cater, 1977) (Figure 2.1). The Precambrian layered rocks are made up of volcanic and volcanoclastic materials from the Baish and Jiddah groups. These rocks are cut by a variety of plutonic rocks, like gabbro, diorite, and granite, which have different compositions. The volcanic rocks and many of the intrusive rocks change into greenschist.

The Precambrian structural grain has a northeast and northward orientation and resulted from one or more episodes of deformation. During the late Miocene period and continuing through the Pliocene, the Bathan formation was tilted towards the Red Sea escarpment due to antithetic faulting (Wier and Hadley, 1975).

2.2 Tectonic Settings:

The Al-Lith region is located in the western part of Saudi Arabia and is situated within the Red Sea Rift Zone. The tectonic setting of the region is complex, with multiple fault systems contributing to its geologic evolution. The region is bounded by two major fault systems, the Najd Fault System and the Red Sea Rift. The Najd Fault System is a major geological feature in the Arabian Shield, a large geologic formation in the Arabian Peninsula. The sinistral Najd Fault System is composed of three primary fault zones that run parallel to one another and are approximately 5 to 10km wide. These fault zones caused the much older Nabitah Suture (which is about 680-640 Ma) to be dislocated by about 250 to 300 km. The Najd fault system's width is about 300 km, and its length exposed above ground is 1,100 km (Johnson and Woldehaimanot, 2003). Felsic dikes that intruded the Najd faults between 577 and 529 Ma provide evidence of the Najd event's duration (Stoeser and Frost, 2006). The fault system is characterized by horizontal displacement, with the Arabian Shield moving to the west relative to the Arabian Platform. The fault is a result of the collision of the Arabian and African plates, caused the formation of the Zagros Mountains in Iran and the Alborz Mountains in Turkey (Johnson et al., 2011). The movement of the Arabian Plate has continued to the present day, resulting in ongoing tectonic activity in the region. The Najd Fault System has played a significant role in the geologic evolution of the Arabian Shield. The fault system has created numerous structural features, including major terranes, grabens, horsts, and uplifted blocks (Al-

Saleh, 2012) (Figure 2.2).

The Red Sea Rift is another major fault system that runs along the western coast of Saudi Arabia. It is an active divergent boundary that is slowly pulling the African Plate and the Arabian Plate apart. The Red Sea Rift is characterized by a complex system of faults, volcanic activity, and oceanic crust formation (Bosworth, 2015). The rift is composed of a series of grabens, horsts, and volcanoes that extend along the length of the rift. The Red Sea itself is a narrow, elongated body of water that occupies a central depression within the rift. The rift began forming approximately 30 million years ago during the Oligocene period (Augustin et al., 2014). The separation of the Arabian Plate from Africa started with the formation of a triple junction, where the Red Sea Rift intersects with the East African Rift to the south. As the rift widened, a new oceanic crust was formed and the Red Sea gradually formed. The Red Sea Rift is still actively spreading at a rate of approximately 1.5 cm per year. The Red Sea Rift is responsible for the formation of the Red Sea and has created a significant amount of volcanic and seismic activity in the region (Bohannon et al., 1989).

The tectonic setting of the Al-Lith region is further complicated by the presence of several minor faults that intersect with the Al-Lith Fault. These minor faults include the Zarghat Fault, the Wadi Rummah Fault, and the Al-Qatrah Fault. These faults have contributed to the formation of several graben and horst structures in the region (Dixon et al., 1987).

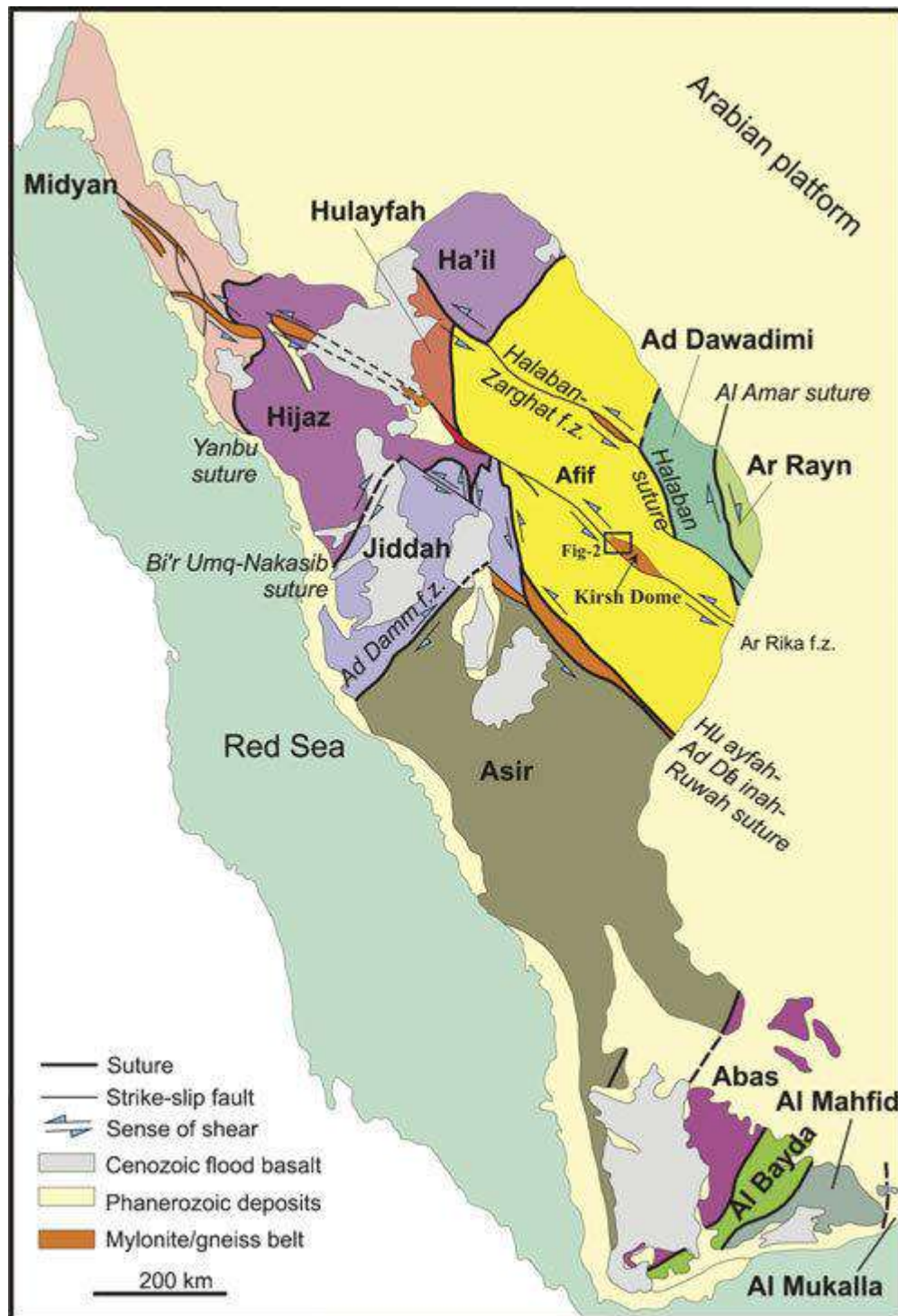


Figure 2.2 Map of the Arabian Shield's terrane that highlights the principal segments of the Najd fault system and the linked gneissic domains (adapted from Johnson, 2006).

2.3 Structure Architecture:

The Al Lith quadrangle is a structural component of the southern Arabian Shield. This region is well-known for its densely packed upright isoclinal folding, greenschist- to amphibolite-grade metamorphism, and extensive, steeply descending wrench faults. In this region, the Precambrian strata of the Al Lith area exhibit two major structural trends, namely north and northeast. The most prominent of these is the block of Baish volcanic rocks that extends from the northeastern extremity of the region to its center. The Baish rocks in this area are folded in a single direction, with dips ranging from 55° NW to vertical. There are also a number of steep wrench faults that run northeast and northwest, which help to balance out the rocks. In the east-central part of the quadrangle, there is another band of Baish rocks that goes northeast, but it is less continuous and has more quartz monzonite and granodiorite in it. Between these two belts of Baish rocks is the Jiddah group of volcanic rocks, which goes from Bir Mutaybah to Wadi Bathan. The Jiddah is younger than the Baish, and where it meets the Baish near Wadi al Faj, it is most likely turned over. It was not possible to determine the structural pattern of the Jiddah because it is composed of enormous andesite flows with no visible bedding plane contacts or other features. In the northwest of the Al Lith quadrangle, on either side of Wadi Khadrah, the Baish strikes north, descends 55° West to the vertical, is highly sheared, and is displaced by three wrench faults that strike north (Figure 2.2).

The Baish and Jiddah groups are the oldest rock formations in the Al Lith quadrangle area. These rocks have probably changed shape more than once. This is typical of the tectonic activity in the southern part of the Arabian Shield [(Schmidt and others, 1973); (Greenwood et al., 1976)]. Although the evidence for multiple folding is not entirely clear, small-scale folded schistosity and variably oriented linear elements suggest that the rocks

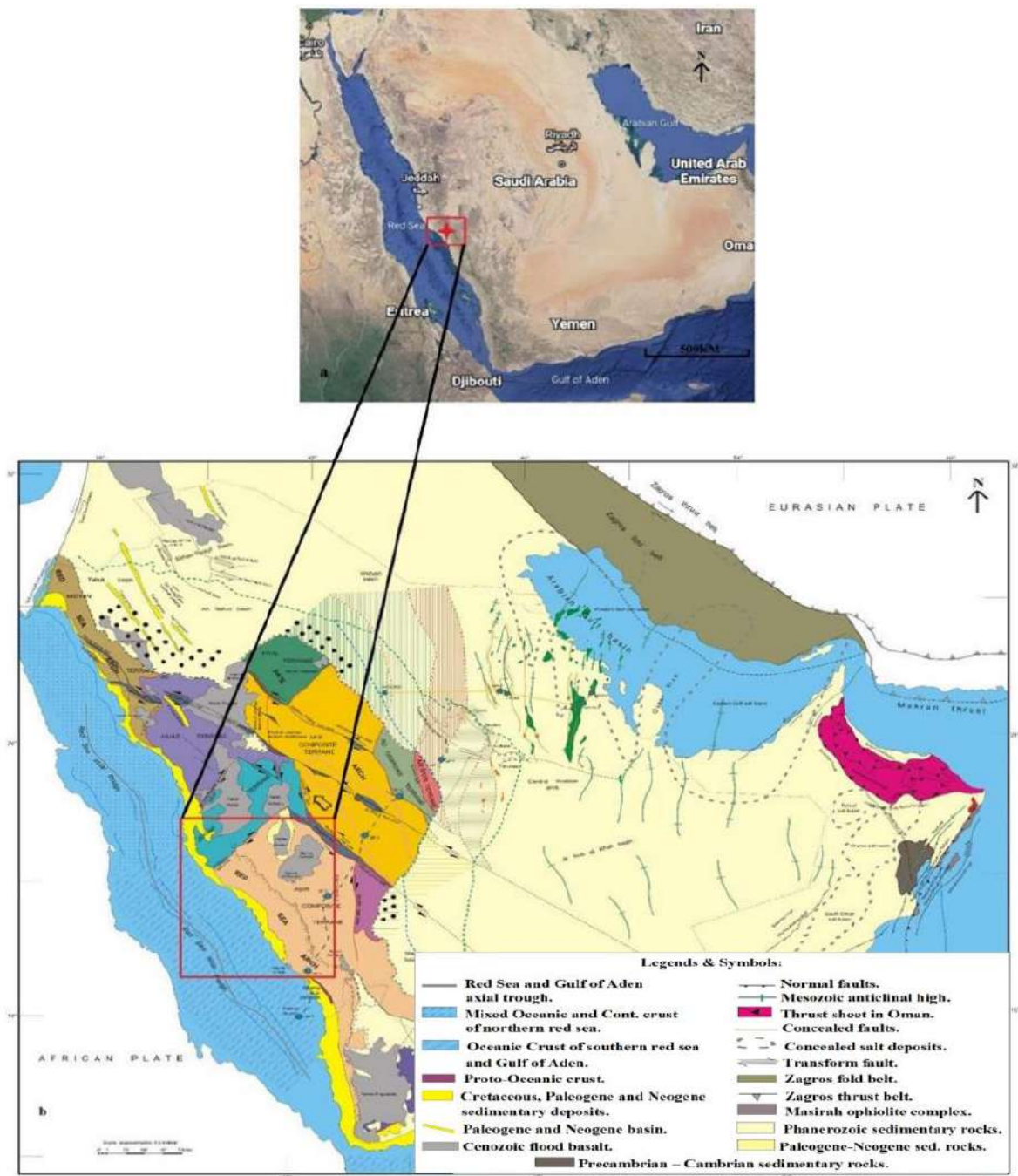


Figure 2.3 a) Map showing the location of the study area (red box) created using Google Earth. b) Simplified geological and tectonic map of Saudi Arabia showing the study area, Al-Lith (Modified from Johnson, 1998).

have experienced several rounds of deformation. Throughout the quadrangle, the Precambrian layered rocks have been intruded by pre-Phanerozoic plutonic rocks during three separate periods. The layered rocks in some areas, such as Jabal Basham and near Wadi Ghalah, have been completely engulfed by the intrusions, eroded away, or both. The quartz diorite complex is most likely the most ancient intrusive series. It is composed of four intrusive units that most likely formed concurrently during the first period of deformation. All intrusions are made of mafic to intermediate rock at this time. During the last two periods of intrusive activity, rocks with intermediate to granitic composition were most likely deposited during the late Precambrian syn- to post-Ablah orogenic or post-orogenic cycles (Fleck and others, 1979). Unfortunately, no radiometric dates for these intrusive rocks or sequences of layers younger than the Jiddah group exist to determine the age of the intrusions. The relative ages of most plutonic rocks can only be estimated based on the order in which they formed. As a result, these ages are only estimated. Overall, pre-Phanerozoic plutonic rocks deformed and changed the Precambrian rocks in the Al Lith quadrangle several times over three different time periods.

The Miocene gabbro dikes are a record of the Tertiary plutonic and tectonic events in the quadrangle. These dikes, which are approximately 22 million years old [(Brown, 1972); (Coleman, 1974)] were formed due to extension and tectonic activity associated with the initial opening of the Red Sea [(Coleman, 1974); (Coleman and others, 1979)]. On the other hand, the Bathan formation is the last stage of deformation, which took place during the Pliocene. The Bathan conglomerate leans 15 degrees to the northeast and runs parallel to the Red Sea. This shows that it was folded because of antithetic faulting caused by the Red Sea escarpment rising in the late Miocene and Pliocene [(HADLEY, 1980); (Ross and Schlee, 1973)]. The main antithetic fault is probably in the wadi on the northeast side of the Bathan outcrop. It could stretch from this wadi northwest across the Miocene gabbro dike, the Jiddah group, and Wadi

al Faj. However, the presence of several faults in the area cannot be determined without more extensive exposure of the Bathan formation.

2.4 Stratigraphy

Most of the northern part of the quadrangle is made up of Precambrian rocks, which include two volcanic series called the Baish and Jiddah groups, as well as a variety of intrusive rocks like batholithic diorite and quartz diorite. From the Wadi Sadiyah region, these intrusive rocks reach into the northern part of the quadrangle (Brown et al., 1963).

2.4.1 Baish Group:

The Baish volcanic group is made up of different types of volcanic flow rocks, like basaltic and rhyolitic, as well as stratified volcanoclastic rocks. It can be found in three different bands that are separated by zones of intrusive rocks. The group is divided into three units based on their rock types: volcanoclastic rocks and subordinate interbedded basalt and andesite; rhyolite minor interbedded siliceous pyroclastic rocks and basalt, andesite, and subordinate volcanoclastic rocks; and (Brown et al., 1963).

2.4.2 Jiddah group:

The Jiddah group is in the eastern part of the quadrangle. It is in a rectangular belt that goes from Bir Mutaybah to the Wadi Bathan fault and goes northeast. This group is made up of only andesite flow rocks, and there are no bedding planes or measurements of thickness in the area. People think that the flows are at least a few tens of meters thick. The rock is dark green and made up of many saussuritized plagioclase phenocrysts that are wrapped in a fine- to medium-grained felted intergranular groundmass. The presence of chlorite and epidote indicates the greenschist facies metamorphism of the group (Coleman, 1974).

2.4.3 Intrusive rocks:

Analysis of the ages of the intrusive rocks with respect to the Ablah group is done for the Al Lith quadrangle. Pre-Ablah, syn- to post-Ablah, and late Precambrian rocks are separated into these three groups. This classification is based on how the Ablah group is related to the intrusive rocks in the Jabal Afaf quadrangle, where they are well exposed (HADLEY, 1980).

2.4.3.1 Pre-Ablah intrusive rocks

The Pre-Ablah intrusive rocks present in the Al-Lith and Jabal Afaf quadrangles are composed of granodiorite, gabbro, quartz diorite, quartz diorite complex, and diorite intrusions. The quartz diorite complex is a medium-grained plutonic rock that varies in texture from fine to coarse and is usually greyish in color. The granodiorite intrusion is medium-grey in color, equigranular in texture, and hypidiomorphic in appearance. It is made of 25–35% quartz, 30–40% plagioclase, 10–15% potassium feldspar, 4–8% hornblende, 2–5% biotite, and other minerals like magnetite, chlorite, apatite, epidote, apatite, and sphene (FITCH, 1980). The intrusion of quartz diorite and gabbro in the Al-Lith and Jabal Afaf quadrangles has a gradual transition from one type to the other, and there are no clear contacts between them. The intrusion contains small, fine-grained mafic xenoliths scattered in various locations. The quartz diorite and diorite intrusions are coarse-grained and have a strong porphyritic texture, ranging from medium to dark gray. The phenocrysts of plagioclase are moderate to strongly saussuritized and as long as 1.5 cm. The quartz diorite complex has been radiometrically dated, and the result shows a whole-rock Rb-Sr age of 895 ± 173 m.y. with an initial $\text{Sr } 87/\text{Sr } 86$ ratio of $.7025 \pm .0003$ (AL-Harthi, 2009).

2.4.3.2 Syn - post Ablah intrusive rocks

The intrusive rocks found in the Al Lith quadrangle area, which are syn- to post-Ablah, include tonalite, granodiorite, and quartz monzonite. Granodiorite is a body that extends

longitudinally and intrudes into the quartz diorite complex and the quartz diorite and gabbro in the central-northern part of the quadrangle. The rock has a fine- to a medium-grained matrix with plagioclase and potassium feldspar phenocrysts, which are light pinkish-gray and leucocratic. It has less than 5% ferromagnetic minerals that have been changed into chlorite and between 2% and 5% of other minerals like sphene, magnetite, epidote, and apatite (Abu-Zied and Hariri, 2016).

In the northeast part of the quadrangle, a faulted body made up of tonalite and granodiorite is present. The rock has a strong porphyritic texture, with microcline phenocrysts measuring up to 3 cm in length. The medium-grained groundmass is strongly foliated and cataclastic in texture, with accessory minerals such as chloritized biotite, sphene, magnetite, epidote, and apatite. The rock is predominantly light pink in color (Al-Zubieri et al., 2020).

A large mass of quartz monzonite and granodiorite is exposed in the east-central part of the area. The intrusion has a medium-grained texture and is light pinkish orange in color, and is cataclastic and intensely schistose. The rock contains 2-5 percent ferromagnesian and accessory minerals, such as biotite (altered to chlorite), sphene, apatite, magnetite, and epidote. There are cobble-sized mafic inclusions distributed sparsely throughout the body (Bantan et al., 2020).

2.4.3.3 Late Pre-Cambrian Intrusive Rocks

Late Precambrian intrusive rocks represent a variety of igneous rocks that developed through the cooling and solidification of magma deep below the Earth's surface. These intrusive rocks are situated in the northwest portion of the study region. Various types of intrusive rocks, such as quartz monzonite, quartz diorite, tonalite, granite and monzonite, granite, and quartz monzodiorite, are present in this region (Fleck and Hadley, 1985).

The intrusion of quartz monzonite displays an abundance of tabular potassium feldspar grains and comes in a light gray to pink color. The intrusion of quartz diorite and tonalite, which consists of tonalite, quartz diorite, and gabbro, is fine to medium-grained. The quartz diorite intrusion, on the other hand, is coarse-grained, with a color range from light to medium gray, and consists of plagioclase phenocrysts. The intrusions of granite and monzonite are light reddish-gray and have sparse orthoclase phenocrysts. Lastly, the pluton of quartz monzodiorite is extremely light gray and exhibits a highly bleached character as a result of significant alterations. (Greenwood et al., 1976).

2.4.4 Dikes:

The study area exhibits the presence of discordant, tabular intrusions of igneous rocks, known as dikes. These dikes are classified into four sets, namely granodiorite dikes, late Precambrian granitic dikes, mafic dikes, and rhyolitic dikes (HADLEY, 1980).

The oldest dikes that cut through the pre-existing rocks in the study area are made up of granodiorite, which can be traced back to a parent pluton of similar composition. These dikes have a general trend towards the north and northwest and can have a width ranging from 10 cm to 1 m. They have a fine-grained texture, a light pinkish-gray color, and a higher relief than the surrounding rock. The late Precambrian granitic dikes at Jabal Basham are thought to be late-

stage offshoots of the pluton in that area. These dikes go west, and their widths range from 15 cm to 2 m. They have a fine-grained texture, are pink to orange in color, and have less than 1 percent mafic minerals (Husseini, 1989).

The middle unit of the Baish group, the quartz diorite complex, and the quartz diorite and diorite body are the three primary rock types that the mafic dikes, which are composed of basalt, andesite, and diabase, pass through. In the Baish rocks, these dikes go northeast, and in the intrusive bodies, they mostly go north and west. Their thickness ranges from a few centimeters to two meters. The edges have fine-grained textures that weather into positive relief, while the central parts are coarser-grained and may be porphyritic in some cases. Although the age of the mafic dikes is uncertain, evidence from one location suggests that they are primarily late Precambrian. However, they may also be associated with Phanerozoic volcanic events, including the Tertiary period (Pallister, 1986).

In the northwestern part of the area, rhyolitic dikes cut across the mafic dikes. Rhyolitic dikes only appear in the rhyolitic unit of the Baish group and in the quartz monzonite pluton that invades the Baish group. These dikes have a light orange color and contain quartz and potassium feldspar phenocrysts that measure 1-3 cm in diameter, arranged in a fine-grained groundmass. Based on their genetic characteristics, it seems that they are related to the quartz monzonite intrusion (Pallister, 1987).

2.4.5 Tertiary Rocks:

The tertiary rocks in the area comprise the Bathan Formation and Miocene gabbro:

The Bathan Formation is composed of terrigenous clastic rocks, such as boulder conglomerates, pebble conglomerates, and some coarse-grained sandstones. It encompasses various Precambrian rock types, is highly indurated, moderately inclined, and plunges towards the Red Sea escarpment. It formed during the Pliocene epoch, and its deposition and structural formation appear to be linked to the Pliocene tectonics of the Red Sea basin evolution, including simultaneous escarpment uplift and faulting, and the emergence of the Red Sea axial trough (Husseini, 1989).

The area's northwest section is crisscrossed by Miocene-era gabbro dikes that extend from Wadi Al Lith to the northern boundary and northwest corner. They tend to be parallel and range in width from 75 to 500 m, with a color that ranges from medium to dark gray and a texture that is fine to very coarse-grained. These dikes are part of a network of structures that extends from the Gulf of Aqaba to the Yemeni border, with ages ranging from 19 to 27 million years and averaging 22 million years. Their boundaries are fine-grained and weather more slowly than their coarse-grained centers, which can result in U-shaped troughs (HADLEY, 1980).

2.4.6 Quaternary Deposits:

The study area contains a diverse array of Quaternary deposits, including shallow bank and coral reef deposits, sand deposits from carbonate islands, alluvial sand and gravel deposits, silt deposits from wadi floodplains, sabkhah deposits, and eolian dune sand (FITCH, 1980).

There are a number of Quaternary deposits made of a combination of calcareous and terrigenous muds, such as shallow banks and coral reefs, which can be found along the coastal margins and in the vicinity of the islands. Fragmented coral and shell fragments can be found in the carbonate island sand deposits, which are present on small islands near the coast. Fine to coarse-grained, poorly sorted sand and gravel are prevalent in the pediment and plain deposits found in the coastal plain. The principal wadis are home to well-stratified, erratically sorted debris of sand, gravel, and cobble sizes known as alluvial sand and gravel deposits. Silt, fine-grained sand, and clay are found in Wadi flood-plain silt deposits that are located within and adjacent to the major wadis. The region's coastal length is home to the sabkhah deposits, which are made up of crusty silt that has been salt-impregnated. Last but not least, the coastal plain's eolian sand dune fields contain continuous sand hills and dunes with fine to medium-grained sand (Coleman, 1974).

CHAPTER 3

METHODOLOGY

3.1 Introduction

This research provides a comprehensive characterization of the geothermal potential of the study area. The main objective of this study is to characterize the structural features of the Al-Lith geothermal field located in western Saudi Arabia. To accomplish this, an integrated approach of remote sensing, geological and structural mapping, rock and fracture geochemistry, and hydrochemistry has been employed. The study area was mapped using satellite imagery and geospatial data, and the resulting geological map was used as a basis for fieldwork. Fieldwork included the collection of rock samples, structural measurements, and hydrochemical data from the main hot spring, Ain AL Harrah Spring, in the study area.

Both surface and subsurface structural measurements were used to characterize the fracture network of the geothermal reservoir, and the hydrochemical data were used to understand the fluid chemistry and potential recharge sources of the geothermal system. The integration of these techniques offers a unique opportunity to comprehensively understand the surface-to-subsurface structural architecture, geologic history, geochemistry, and hydrogeochemistry of the area, contributing to the development of a sustainable and efficient geothermal resource in western Saudi Arabia. The generalized methodology of the work is given in (Figure 3.1).

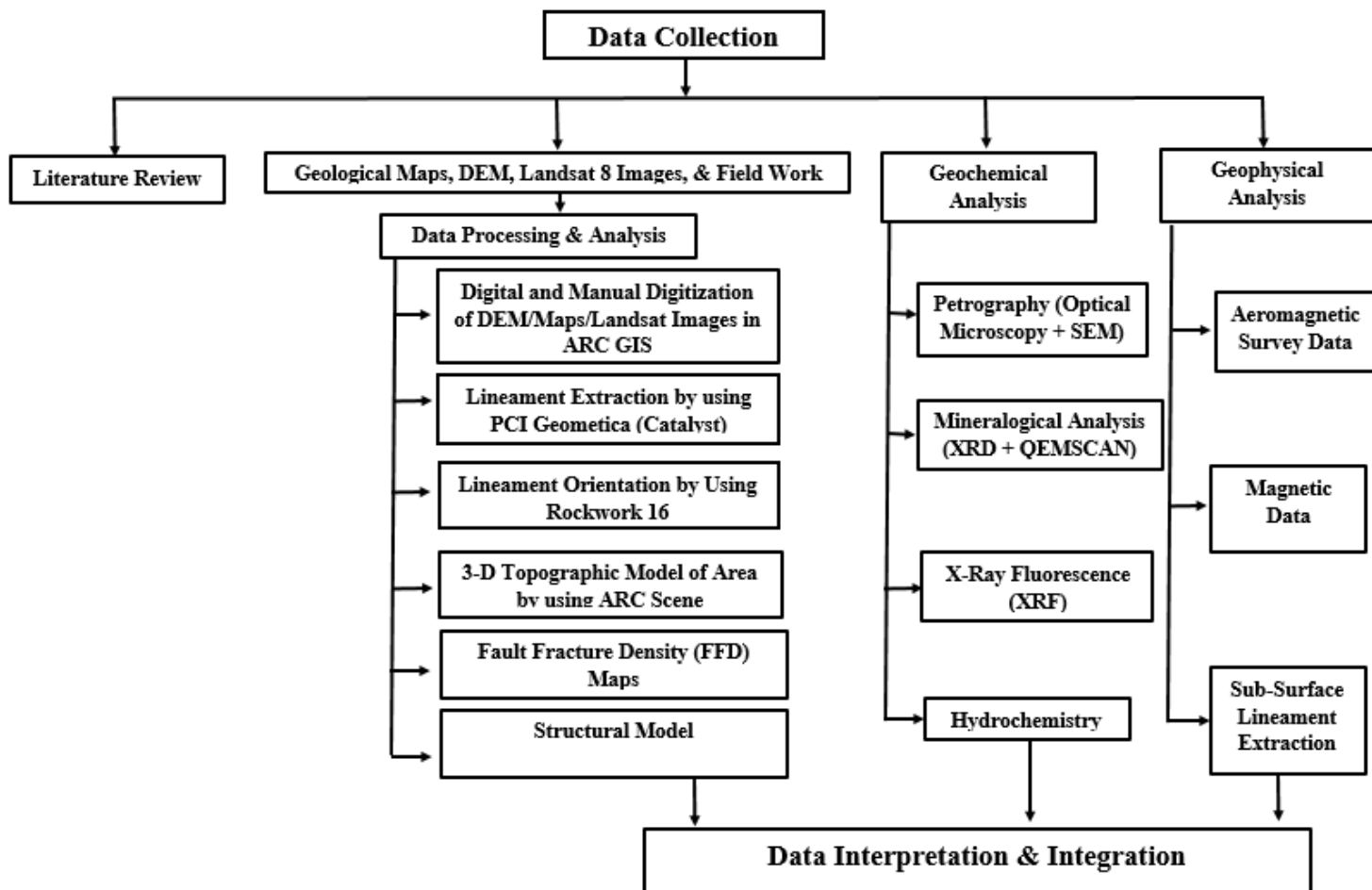


Figure 3.1: Flow chart of the methodology to be followed during research.

3.2 Materials

The materials used in this study includes geological maps and toposheet of the study area collected from the Saudi Geological Survey (SGS) that were manually used for structural lineament delineation. Landsat-8 Imagery of the study area obtained from the USGS GloVis website (<https://glovis.usgs.gov/app#>) was used for the digital lineament extraction. Remote sensing data was obtained from satellite imagery, aerial photography, and LiDAR data. A variety of samples were collected from the field. These include rock and water samples. Rock samples were collected using a geological hammer and a chisel for rock geochemistry and petrographic

analysis. The rock samples collected from outcrops were carefully labeled and packaged for analysis (Figure 3.2). The systematic method of sampling was adopted. Water samples were collected from the hot spring (Ain Al Harrah) using sterilized sampling bottles to avoid contamination. The samples were stored in coolers to maintain their chemical composition until analysis. The data was processed and analyzed using specialized software and tools to obtain accurate information about the study area. All the materials used in this study were carefully selected and handled to ensure the accuracy and reliability of the results obtained.

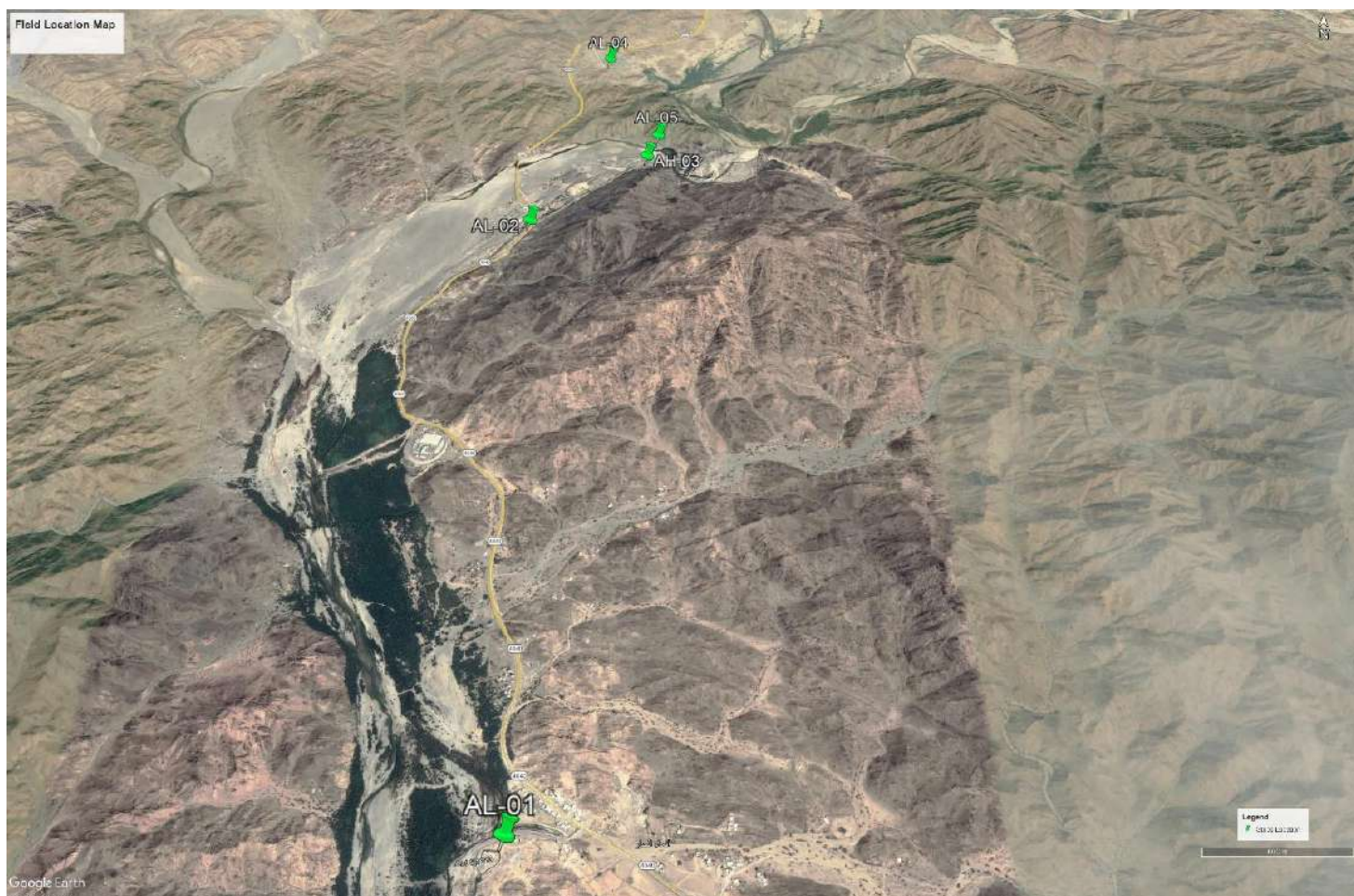


Figure 3.2 Google Earth map showing the ground truthing and sampling locations of the study area.

3.3 Methodology Applied

3.3.1 Surface Lineament Extraction

Landsat-8 Imagery and digital elevation model (DEM) data were used for lineament extractions. Extraction of surface structural lineaments was done using the latest version of PCI Geomatics software (Catalyst, <https://catalyst.earth/about/>). Digital lineament extraction is a valuable method for delineating lineaments for many objectives, such as describing geological formations over a regional extent. Directional filters were used to improve the lineaments detection. The convolution filter window three by three was utilized to get the shortest length lineament. Automatic extraction from the DEM and Landsat-8 was used to create the lineament map. The necessary and acceptable settings for the Line Module were utilized to extract discontinuities approximating geological lineaments in the research area. Lineament extraction process included edge detection, thresholding, and curve extraction (Table 3.1). The retrieved lineaments were used to create a synthetic lineament map. Because automated approaches generate many inconsequential lineaments, lineaments repeated more than once were removed to avoid repeating segments in the synthetic map. GIS technologies were used to remove lineaments resulting from human activities, hydrographic networks, and nonsensical lineaments. Other than the smaller and automated lineaments, the larger lineaments in the research area were also marked on the DEM. The lineament density maps were ultimately prepared. The fault fracture density (FFD) method was used to define the different structural lineament density zones in DEM [(Taucare et al., 2020), (Nahli et al., 2016), (Arrofi et al., 2022)]. This density of fractures in the area was calculated by dividing the length by the cell area; usually, the unit used is km/km². Detailed workflow of the fracture-fault density methodology (FFD) and how it can be applied after a detailed treatment of lineaments and fractures is explained in (Taucare et al., 2020).

Table 3.1 The parameters used in PCI Geomatics for automated (digital) lineament extraction.

Parameters	Values
RADI	10
DTHR	20
FTHR	3
GTHR	100
ATHR	30
LTHR	30

3.3.2 Subsurface Lineament Extraction

Subsurface structural lineaments were extracted based on the analysis of aeromagnetic data. The aeromagnetic data used in the present study were acquired by a consortium of different geophysical companies (Aero Service Corp., Hunting Geology and Geophysics Ltd., Lockwood Survey Corp. Ltd., Arabian Geophysical and Surveying Co.), at a terrain clearance of 300 m and a distance between flight lines of 800 m (Zahran et al., 2003). The data were processed by the Saudi Geological Survey (SGS) and a reduced to north magnetic pole (RTP) map was produced, along with other products. The wider Al-Lith area was selected within this map to detect the subsurface lineaments by applying the Centre for Exploration Targeting (CET) Grid Analysis. The CET Grid Analysis module is an extension of the Seequent Oasis montaj software (<https://www.seequent.com/>) that allows for the automatic detection of lineaments in gridded data, reducing the time needed for grid interpretation.

Analysis and interpretation of lineament orientation were made using rose diagrams in the Rockwork 16 software. The generalized split-window (GSW) algorithm was used to retrieve the land surface temperature (LST) from re-calibrated Landsat-8 data, and the operational land imager (OLI)

measurements were used to estimate the land surface emissivities (LSE) using a normalized difference vegetation index (NDVI)-based emissivity method.

3.3.3 Rock & fracture geochemistry

Two ground truthing field campaigns were undertaken in the study area in 5 localities (AL-01 – AL-05) to collect primary geological information and assist the analysis and interpretation of the remotely sensed imagery. Each campaign included geological mapping, collecting field observations and fracture measurements, photography, and sampling (Figure 3.2). Field observations included identifying lithology and stratigraphy, and measuring the geological structures in the study area. Ground truth measurements and sampling allowed the assessment of the accuracy of the results obtained from the imagery analysis. The collected rock samples were prepared for petrographic, mineralogical and geochemistry analysis. A multi-method approach has been utilized for the analysis of samples such as: Bulk X-ray Diffraction (XRD) and Quantitative Evaluation of Materials by Scanning Electron Microscopy (QEMSCAN) for mineralogical evaluation; X-Ray Fluorescence (XRF) for the major, minor, and some trace elements. Major oxides analysis was also carried out by (XRF). All of the samples are crushed and powdered for the (XRD) and (XRF) analysis. To ascertain the mineralogical composition of the samples, bulk (XRD) was utilized. Using a copper Cu target with a voltage of 45 kV and a current of 40 mA, bulk samples that had been manually ground were examined over a range of 0° to 70° 2θ angle. The percentage levels of main, minor, and trace elements were discovered via XRF analysis. The representative samples have been subjected to the QEMSCAN, and petrographic analysis (optical microscopy). The thin sections are prepared for the petrographic analysis, epoxies are prepared for the QEMSCAN and flat small samples are prepared for the SEM analysis. These samples are selected after analyzing the results of mineral compositions obtained by the XRD and are considered representative of all samples.

Optical microscopy revealed primary and secondary minerals under cross polarized light (XPL) and plane polarized light (PPL). Microscopy was also utilized to observe abundance, texture and degree of alterations of the minerals within the samples. The QEMSCAN analysis was carried out to further

comprehend the mineralogical variations within the samples at the micrometer scale. This technique also helps in accurate and precise mineral modalogy.

3.3.4 Hydrochemistry:

Hydrochemistry refers to the study of the chemical composition and behavior of water. In the context of geothermal exploration, hydrochemical analysis is essential to assess the thermal water characteristics and its interaction with surrounding rocks. The hydrochemical analysis typically involves the measurement of various ions, including cations (e.g., Na^+ , K^+ , Ca^{2+} , and Mg^{2+}) and anions (e.g., Cl^- , SO_4^{2-} , and HCO_3^-), as well as other parameters such as pH, temperature, and electrical conductivity. These measurements provide information about the source and origin of the thermal water, its mixing with other groundwater sources, and its subsurface flow path.

Additionally, isotopic analysis of water samples can provide valuable insights into the origin and age of the thermal water. Stable isotopes of hydrogen and oxygen (e.g., ^2H and ^{18}O) was used to determine the water source. The combination of hydrochemical and isotopic analyses helps to elucidate the hydrological and geological processes that control the occurrence and flow of thermal waters in the study area.

In the month of December 2022, fieldwork was conducted to gather samples and other data from the field. Pre-washed 0.5 L polyethylene bottles were used to collect five samples of water from the Ain Al Harrah hot spring (Figure 3.2). The water samples were sent to the Environmental Analysis Laboratory for hydrochemical investigation. Field measurements of temperature, pH, electrical conductivity, and total dissolved solids were taken using a portable multiparameter. The principal anions in the water were measured, including HCO_3^- , Cl^- , and SO_4^{2-} . Furthermore, NO_3^- , PO_4^{3-} , and SiO_4^{4-} concentrations were measured. A Microwave Plasma Atomic Emission Spectroscope was used to identify all of the main cations and anions (Agilent 4210 MP-AES). Water samples were analyzed using an inductively coupled plasma mass spectrometer for the presence of trace elements (Li, B, Al, Fe, Mn, Ni, Cu, Zn, As, U, Mo, W, Ga,

and Ge) (ICP-MS). The water samples were run through a Delta V Plus Isotope Ratio Mass Spectrometer to determine their relative amounts of deuterium (^2H) and oxygen (^{18}O) (IRMS). The isotope assays had a precision of 1 to within 1.0 for D and 0.1 for ^{18}O . (Jeelani et al., 2018). Hydrochemical data accuracy was measured by ionic balance inaccuracy (less than or equal to 10%). from the US Geological Survey to determine the saturation level (SI).

CHAPTER 4

RESULTS

4.1 Remote Sensing

The Al-Lith area is located in the western coastal part of Saudi Arabia. The southern part represents a flat area that dominantly comprises the quaternary alluvium deposits along the Red Sea coast. The area's updated surface geological and structural mapping has been carried out, identifying different formations in the area. The area dominantly consists of the late Proterozoic plutonic, metasedimentary, and metavolcanic rocks to Quaternary alluvium deposits. These rocks belong to different groups such as the Baish group, Jiddah group, Jumma suites, Khasrah group, and Lith suite. There is evidence that Pre-Cambrian layered rocks in the quadrangle were intruded by Pre-Phanerozoic plutonic rocks three times. The intrusions have either totally or partially engulfed Precambrian layered rocks in the vicinity of the Wadi Al-Lith. These igneous intrusions are oriented from the northeast (NE) to the northwest (NW). Tightly compressed vertical isoclinal folding, greenschist to amphibolite grade rocks, and steeply dipping faults characterize the structural features of the area. The map (Figure 2.1) shows formations that reflect the folding that is associated with small-scale folded schistosity and variably oriented linear structures. A steeply dipping anticline is present in the northwestern (NW) part of the area. Structures such as foliations and bedding planes also exhibit the steep dipping angles representing the late Miocene and Pliocene and the dominance of the compressional regime in the northern region of the project area (Figure 2.1). The majority of the Baish group is folded monoclinally, with dips from 45° NW to vertical, and is offset by multiple sharp strike-slip faults going northeast and northwest. The

primary antithetic left-lateral strike-slip faults are located in a wadi on the Baish group's northeastern (NE) edge, and the fault may continue from this wadi across the Miocene gabbro dike into the Jiddah group. The northern segment of the Al-Lith area which is away from the coast has a high elevation representing mountainous terrain that can be seen in the 3D topographic model of the area. This model also helped evaluate and manually extract the lineaments and their orientations in the area (Fig. 4.1).

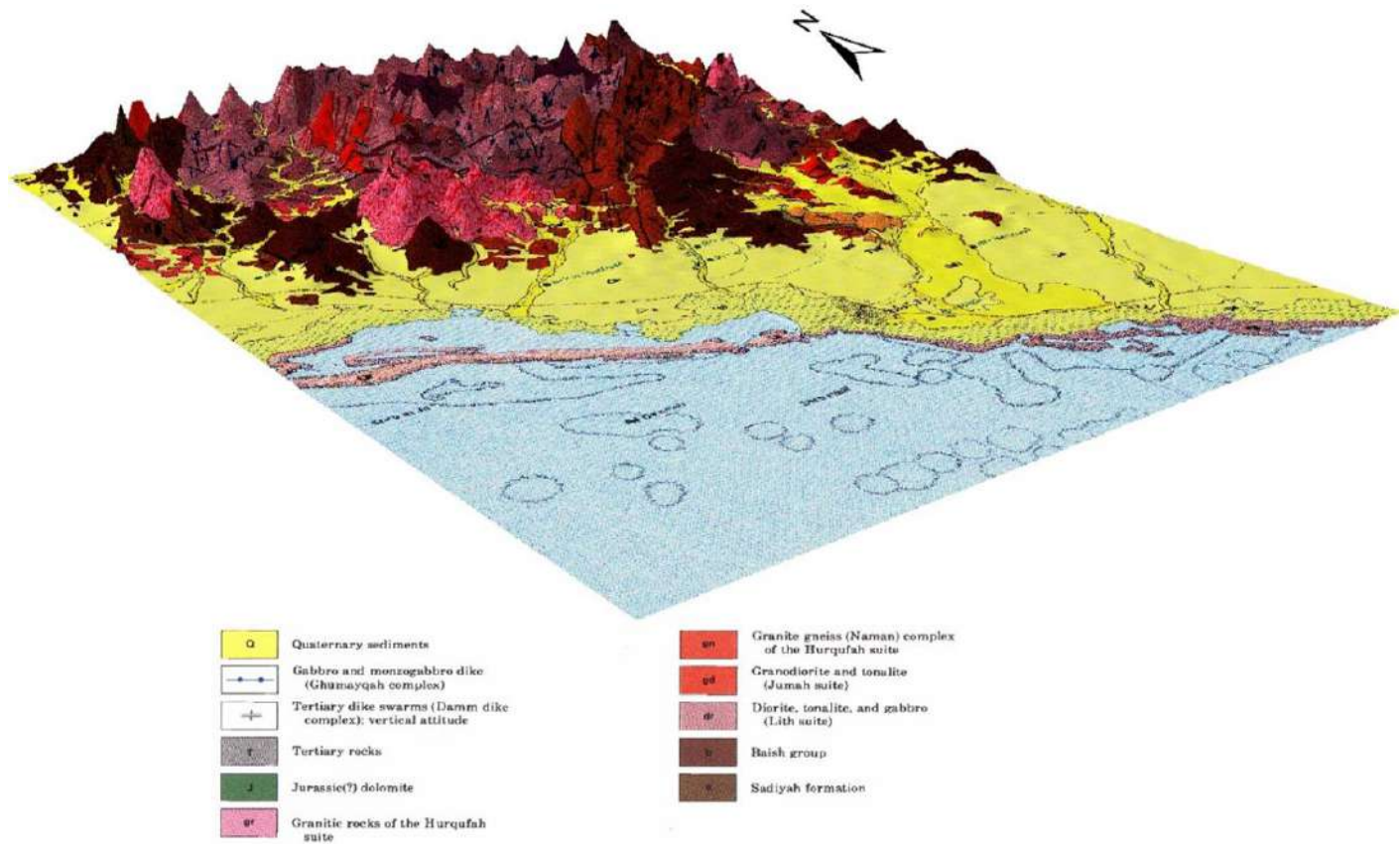


Figure 4.1 3D topographic model of the Al-Lith area representing the topography of the area constructed using Arc Scene (Rafiq et al., 2023; Under Review).

4.1.1 Surface Structural Lineaments

Hill shade analysis of the DEM data allowed the characterization of the topography in the study area. The more enhanced the resolution of the DEM data, the clearer the insight into the areal topography. In this research, two different resolutions of the digital elevation models (DEM) have been utilized, 12 m and 30 m, respectively. The 12 m DEM depicts the topography of the study area more clearly compared to the 30 m DEM data (Figure 4.2). The DEM data analysis of the area revealed that the northern part of the study area has much more varying topography compared to the southern part of the area close to the coast (Rafiq et al., 2023; Under Review).

4.1.2 Digitally- and Manually-Extracted Surface Lineaments

Automatic extraction from the DEM and Landsat-8 was used to create the lineament map [Figure 4.3 (a & b)]. Edge detection, thresholding and curve extraction were considered in the lineament extraction process (Table 1). The length of the smallest lineament extracted in the area is 23.5 m, while the largest lineament has a length of 1594 m (Rafiq et al., 2023; Under Review) (Figure 4.4a). A lineament density map and a rose diagram were used to evaluate the extracted lineaments to obtain information related to density and orientation analysis. Compared to the southern portion of the area, the frequency of automatically extracted lineaments is higher in the northern part. It is observed that the direction of the major lineaments is generally trending northeast-southwest (NE-SW) and northwest-southeast (NW-SE) (Figure 4.4b).

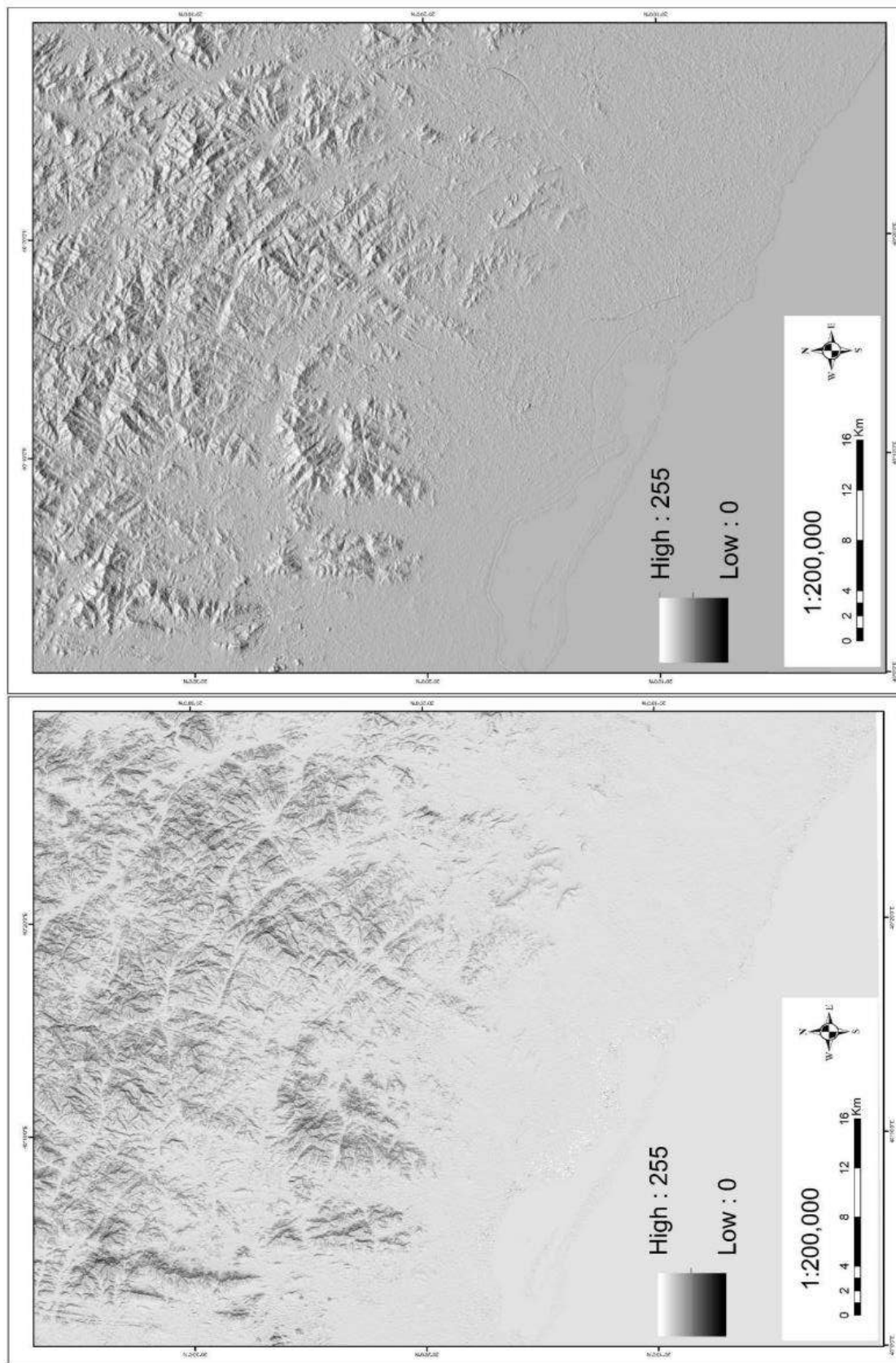


Figure 4.2 12 m (left) and 30 m (right) digital elevation models (DEMs) of the study area. Grayscale (low to high) shows the elevation in meters.

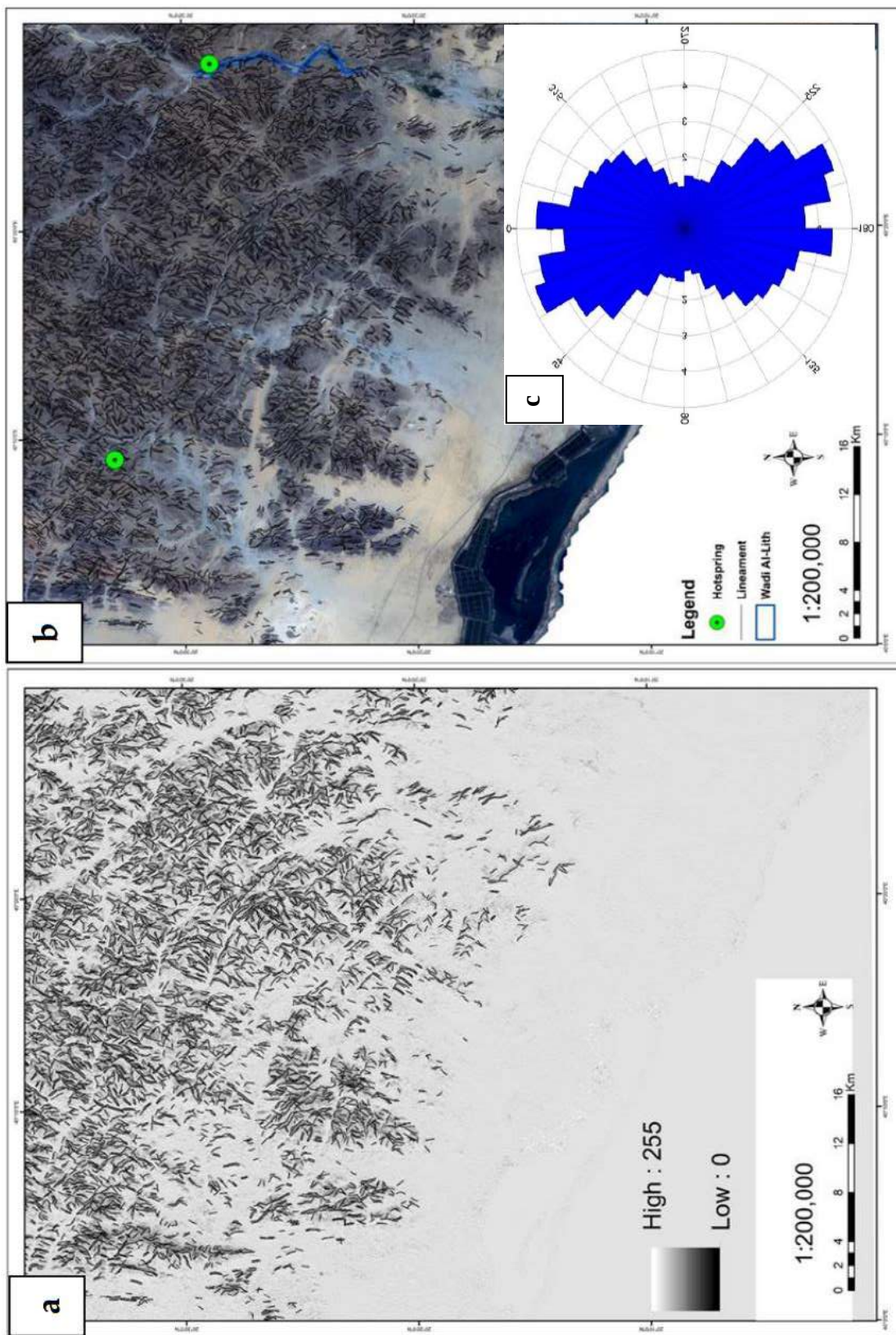


Figure 4.3: Lineaments extracted digitally using PCI Geomatics software from the 12 m DEM (a) and from the Landsat-8 imagery (b). Grayscale (low to high) shows the elevation in meters. c) Rose diagram showing the orientation of the digitally-extracted lineaments in the study area (N=14167).

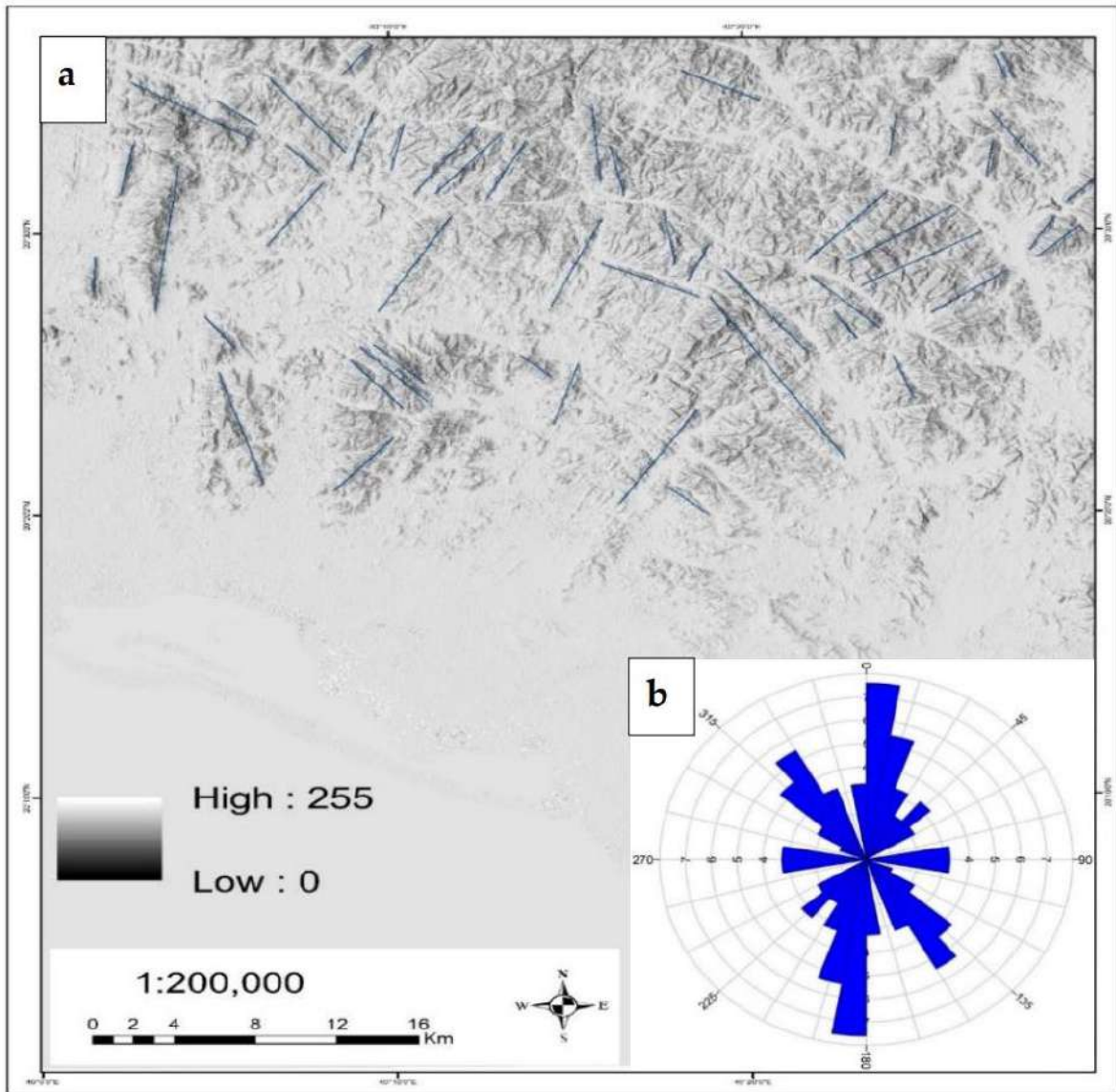


Figure 4.4 a) Major lineaments (blue lines) in the study area extracted from the 12 m DEM using the ARC GIS tool. b) Rose diagram showing the manually-extracted lineaments orientation in the study area (N=46) (Rafiq et al., 2023; Under Review).

4.1.3 Surface Lineament Density

The Lineament density analysis was performed using the Fault Fracture Density (FFD) method by calculating the frequency of lineaments per unit area and generating a map of lineament concentrations [(Ahmadi and Pekkan, 2021), (Liu et al., 2021), (Vanneschi et al., 2022), (Astolfi et al., 2014), (Bartuli et al., 2021), (Ceglia et al., 2020), & (Ceglia et al., 2022)]. The lineament density map in this research comprises the overall lineaments extracted from the study area. Lineament density analysis showed that the lineament density is substantially higher in the areas that show high topography (Figure 4.5a). The northern part of the area has the highest topography, as observed from the DEM data. The highest lineament density areas are mainly trending north-south (N-S) and northwest-southeast (NW-SE) (Figure 4.5a). Fracture/lineament density analysis identified ten high-density zones in the study area (labeled as Zone A to Zone J). Zone A covers an area of 57.22 km² with a total length of 120693.53 m, Zone B covers an area of 38.51 km² with a total length of 96777.19 m, Zone C covers an area of 24.80 km² with a total length of 57710.32 m, Zone D covers an area of 14.52 km² with a total length of 42014.61 m, Zone E covers an area of 12.29 km² with a total length of 30071.47 m, Zone F covers an area of 10.91 km² with a total length of 21357.37 m, Zone G covers an area of 10.85 km² with a total length of 32137.72 m, Zone H covers an area of 10.45 km² with a total length of 23042.07 m, zone I covers an area of 9.74 km² with a total length of 23835.12 m, Zone J covers an area of 8.63 km² with a total length of 23355.24 m (Figure 4.5b) (Rafiq et al., 2023; Under Review). Complete results of descriptive FFD measurements can be found in Table 4.1.

Table 4.1 Surface structural lineament/fracture measurements in five value categories in the study area (Rafiq et al., 2023; Under Review).

Category	FFD Value	Largest Area (km ²)	Least Area (Km ²)	Mean (Km ²)	Total Area (Km ²)	Percentage (%)
Very low	0 – 0.48	35.53	0.000068	1.14	91.44	5.65
Low	0.48 – 1.40	283.74	0.000064	2.84	403.77	24.98
Moderate	1.40 – 2.30	235.82	0.000068	1.24	402.42	24.90
High	2.30 – 3.19	333.08	0.000064	0.84	437.30	27.06
Very high	3.19 – 5.35	57.25	0.000064	1.17	280.77	17.37
Total area (Km ²)					1615.73	100

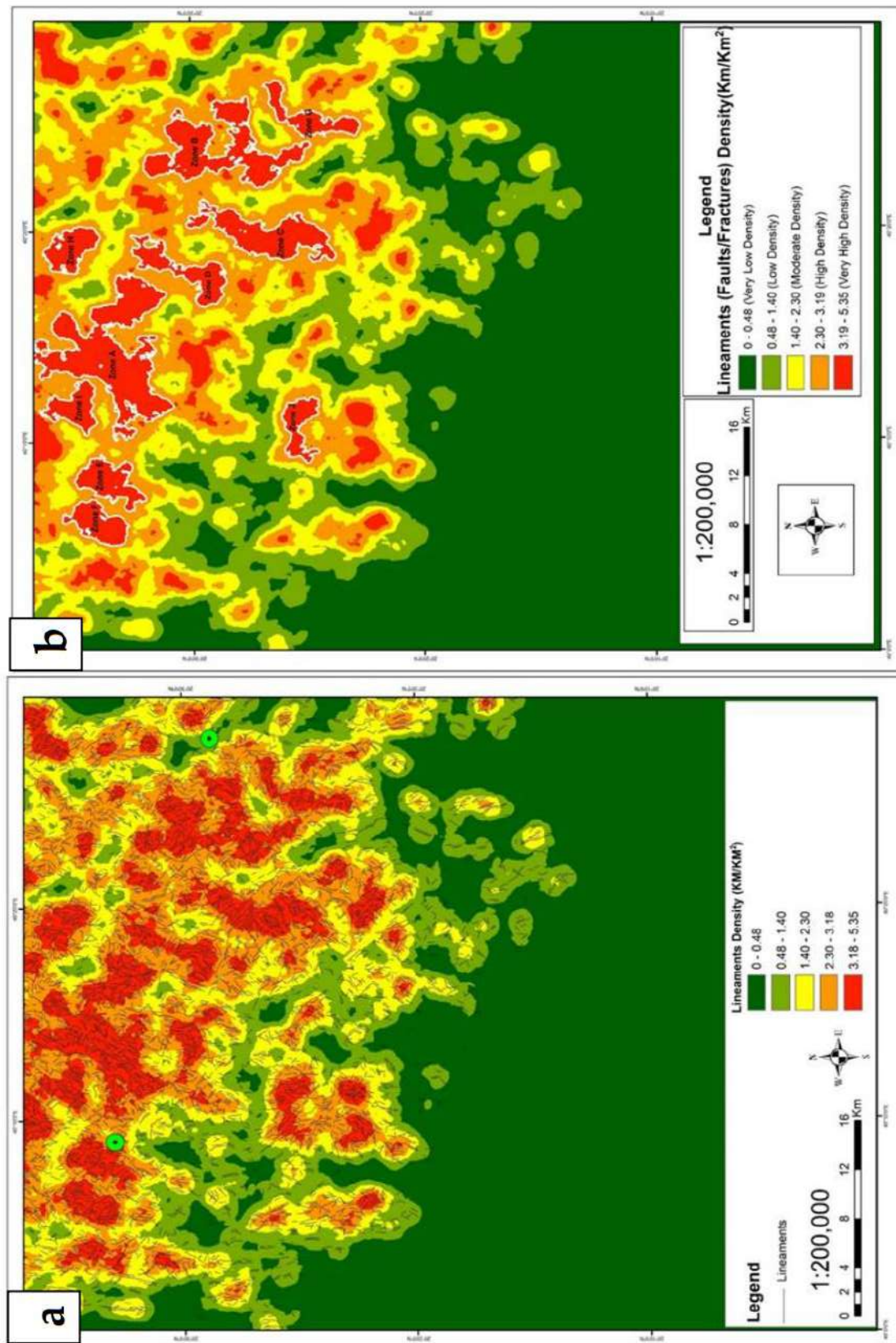


Figure 4.5 a) Surface lineament density map of the 12m DEM generated using ArcGIS. Green circles are the locations of the hot springs (Ain Al Harrah and Ain Mar-kub). b) Lineament density map highlighting the high-density zones identified in the study area.

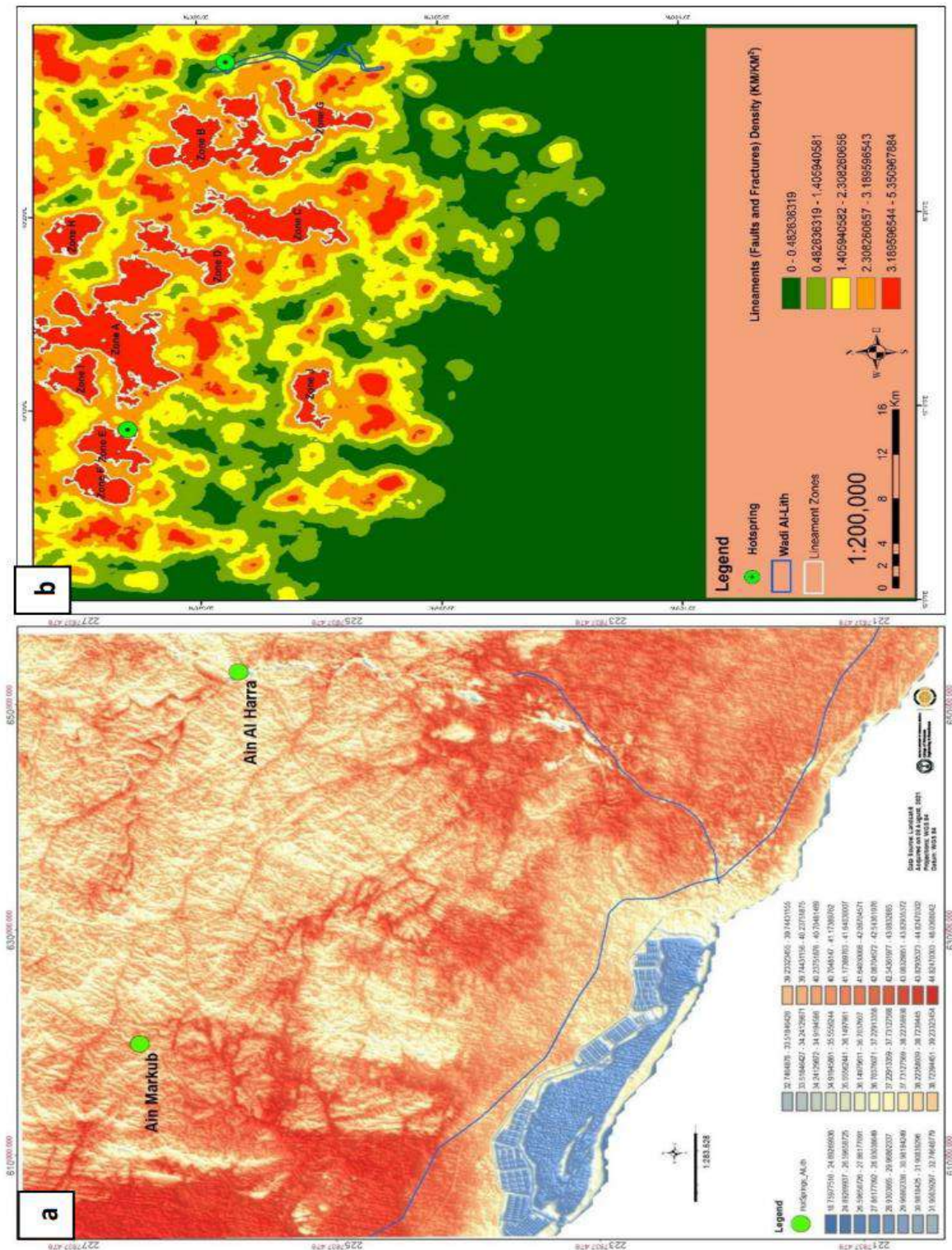
4.1.4 Surface Lineament Orientation

Lineament orientation was measured for both the digitally-extracted lineaments (automated analysis) and for the manually extracted major lineaments. As a result, for the automated/digital lineament analysis, the Northeast-Southwest direction has the most significant number of lineaments (10% of all lineaments). Lineament trends are N-S and NW-SE, which reflects the highest lineament density in the study area. EW-trending lineaments have the minimum lineament frequency of approximately 2%. The orientation analysis by the rose diagram showed that the lineament direction is more or less the same as interpreted in the DEM and LANDSAT-8 (Rafiq et al., 2023; Under Review). Moreover, as calculated by the rose diagram, a total of 14167 lineaments were extracted digitally in the area of study, with a total lineament length of 7254.897 m (Figure 4.3c). The orientation of the manually extracted major lineaments shows two major trends; NW-SE (northwest-southeast) and NE-SW (northeast-southwest). A total of 46 major lineaments have been mapped in the area with a cumulative lineament length of 43043.606 m (Figure 4.4b).

4.1.5 Land Surface Temperature (LST)

The Landsat-8 Satellite, Operational Land Imager (OLI) provides two Thermal Infrared Sensor (TIRS) bands (band 10 and band 11), at 10.9 micrometers and 12.0 micrometers, respectively. The TIRS bands are very suitable for Land surface temperature (LST) mapping.

LST data are presented in a surface temperature map in Figure 4.6a. The data show high land surface temperatures in the areas surrounding the two hot springs (Ain Al Harrah and Ain Al Markub) located in the study area along two main wadis (Fig. 4.6b).



4.1.6 Field Observations and Fracture Measurements

Rocks observed in the study area in the different ground-truthing locations mainly include different metamorphic rocks such as phyllite, schist, and gneiss, suggesting the metamorphism of igneous rocks. Igneous rocks such as granitoid have also been observed in the area very close to the thermal spring (Ain Al Harrah).

Fractures have been observed at various scales within the different rock units (Figures 4.7 and 4.8). Multiple fracture sets were identified, including open fractures (unmineralized joints), fissures, veins (mineralized fractures), and shear fractures. The average aperture size of open fractures is 2.88 cm while it is 1.30 cm for veins. The majority of the veins observed in the study area is silica filled veins. Multiple vertical intrusions (dykes) have been observed in the studied outcrops (Figures 4.7 and 4.8).

Crosscutting relationships have been observed between the different fracture sets (Figures 4.7a and 4.8a). A total of 199 fractures have been observed in the different study outcrops with different fracture intensities (Figure 4.9a). The azimuth orientation of the measured fractures ranges from NNE-NW to SSW-SE (Figure 4.9 b).

4.1.7 Subsurface Structural Lineaments

Subsurface lineaments extracted in the study area show a general NW-SE trend which is consistent with the major trend of the surface lineaments extracted manually and digitally and the fractures mapped in the field (Figs. 6c 4.5, 7b 4.6b and 10b 4.10b).

The subsurface fracture/lineament analysis identified five high-density zones in the study area (Zone A to Zone E). Based on the FFD method, Zone A covers an area of 87.82 km² with a total length of 116613 m, Zone B covers an area of 59.65 km² with a total length of 88227 m,

Zone C covers an area of 28.06 km² with a total length of 39601 m, Zone D covers an area of 16.21 with a total length of 25316 m, and Zone E covers an area of 11.63 km² with a total length of 19576 m.

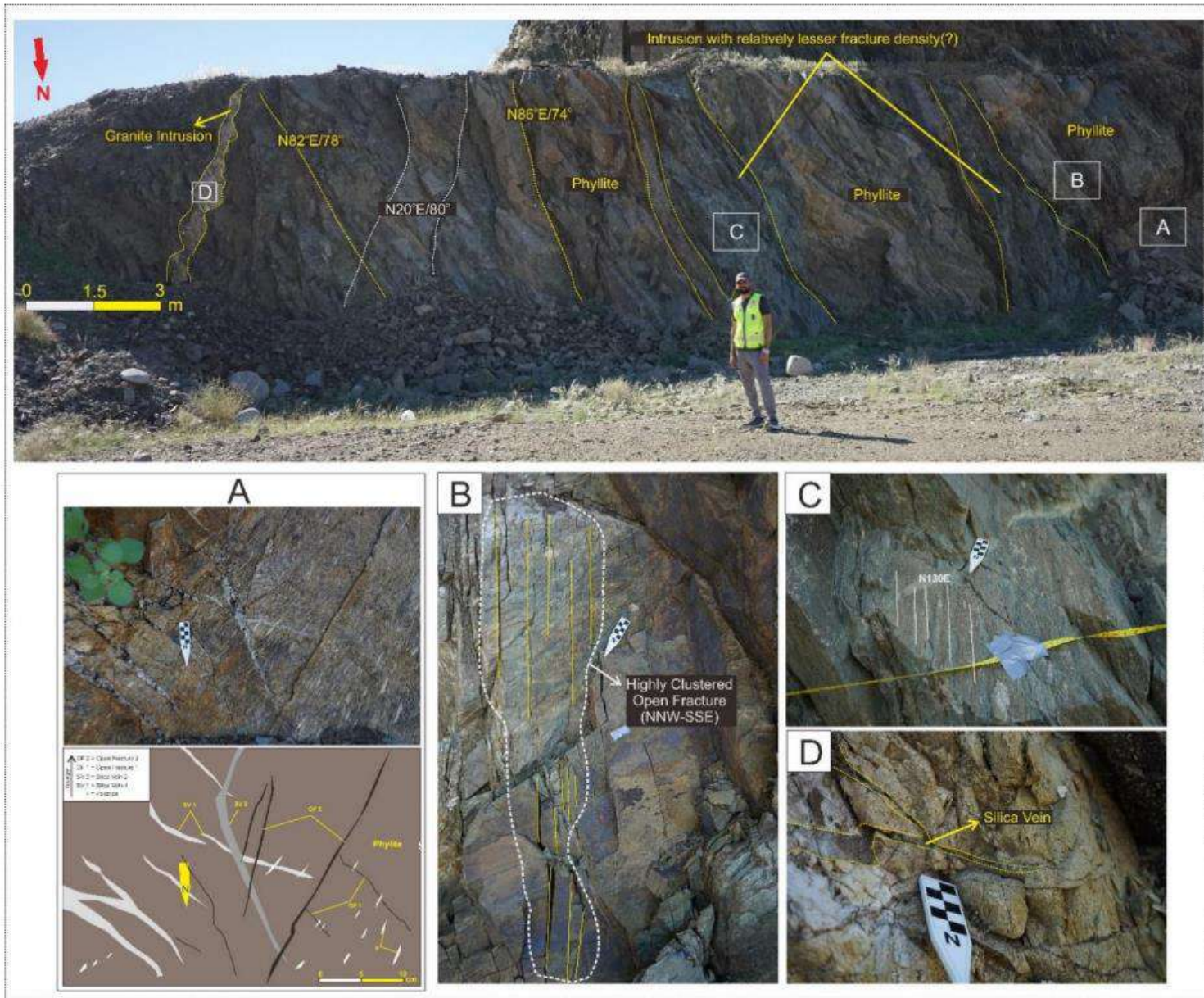


Figure 4.7 Field photographs of the rocks exposed at location 2 (AL-02) in the study area showing different rock units and granitic intrusions. a) field photograph and schematic drawing showing the cross-cutting relationships between the observed fractures (veins and open fractures); b) a cluster of open fractures (yellow lines) trending NNW-SSE; c) foliation in schist (white lines); d) thick silica veins trending EW. SV: Silica Vein; OF: Open Fracture; F: Foliation (Rafiq et al., 2023; Under Review).

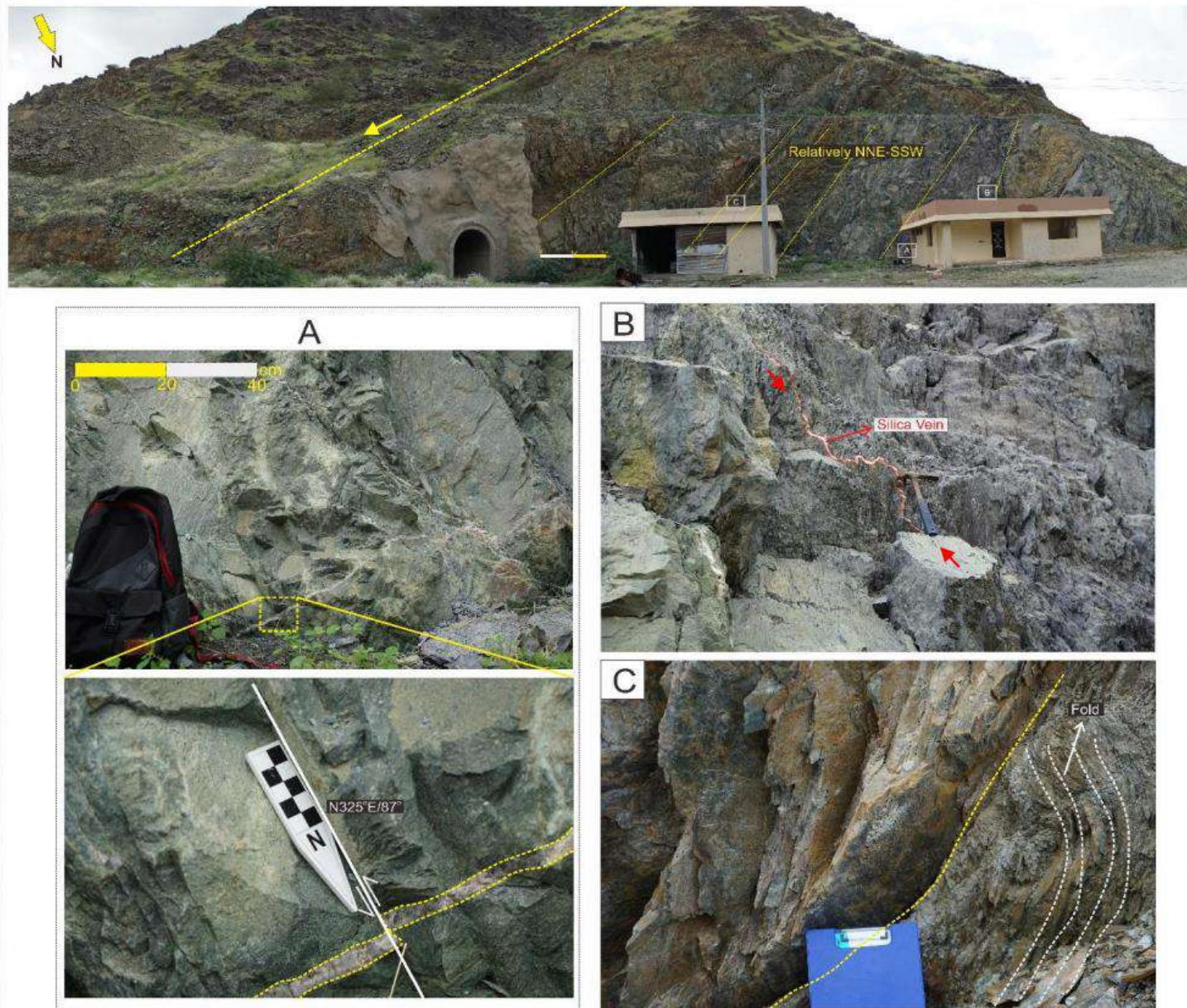


Figure 4.8 Outcrop photographs from location 3 (AL3) in the study area. a) shear fractures, filled with silica vein (aperture size: 1 cm) crosscut by a shear fracture; b) folded silica vein in a metamorphic rock unit (red arrows indicating the direction of compressive stresses); c) folded layers (Rafiq et al., 2023; Under Review).

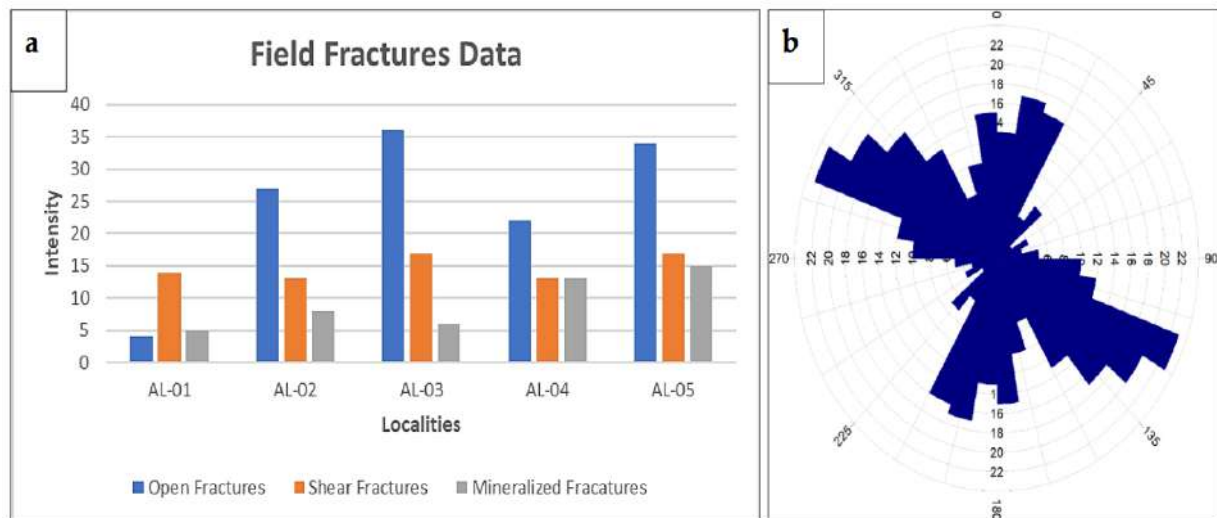


Figure 4.9 a) Histogram illustrating the intensities of fractures measured in the outcrops in the study area (locations AL-01 to AL-05). b) Rose diagram showing the orientation of all fractures mapped in the study area. N=199 (Rafiq et al., 2023; Under Review)

The largest area of high lineament density is very close to one of the hot springs in the study area (Ain Al Markub). The other hot spring (Ain Al Harrah) is also surrounded by a cluster of lineaments reflected by a smaller high permeable zone (Zone E). The other zones (B, C & D) also depict the highest permeable zone in the area (Figure 4.10). Complete results of descriptive FFD area measurements can be seen in Table 4.2.

Table 4.2 Subsurface lineament/fracture measurements in five value categories in the study area (Rafiq et al., 2023; Under Review).

Category	FFD Value	Largest Area (km ²)	Least Area (Km ²)	Mean (Km ²)	Total Area (Km ²)	Percentage (%)
Very low	0 – 0.08	987.22	0.029	25.83	1226.00	35.52
Low	0.08 – 0.23	48.60	0.029	3.93	480.67	13.48
Moderate	0.23 – 0.37	331.96	0.029	7.78	864.16	24.24
High	0.37 – 0.51	148.01	0.029	4.87	604.33	16.95
Very high	0.51 – 0.83	87.82	0.029	3.48	348.64	9.48
Total area (Km ²)					3563.80	100

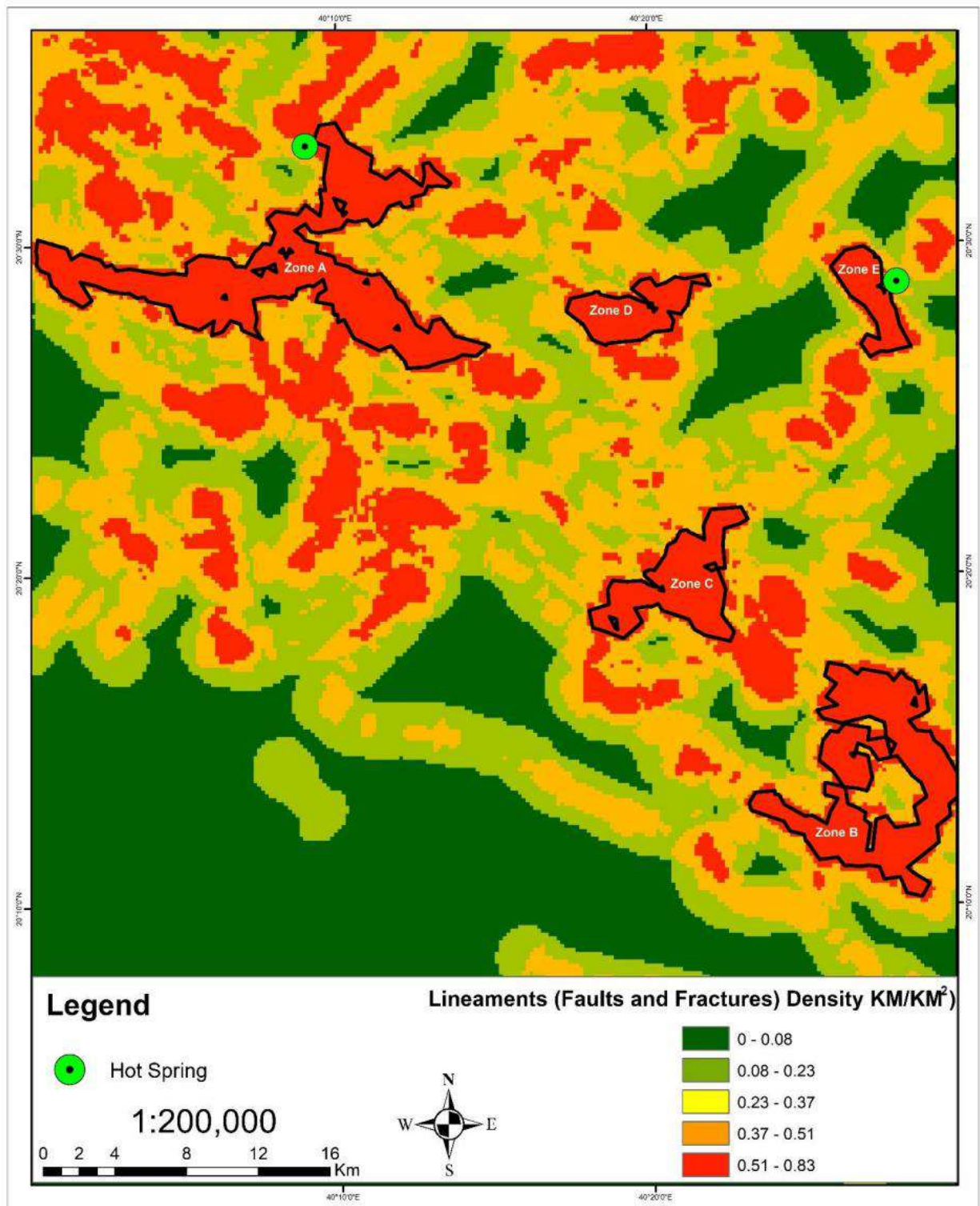


Figure 4.10 Subsurface lineament density (Fault Fracture Density (FFD)) map showing the different lineament density zones identified in the study area. Green circles are the locations of the hot springs (Ain Al Harrah and Ain Markub). High permeable zones are indicated by red color (Rafiq et al., 2023; Under Review).

4.2 Rock & fracture geochemistry

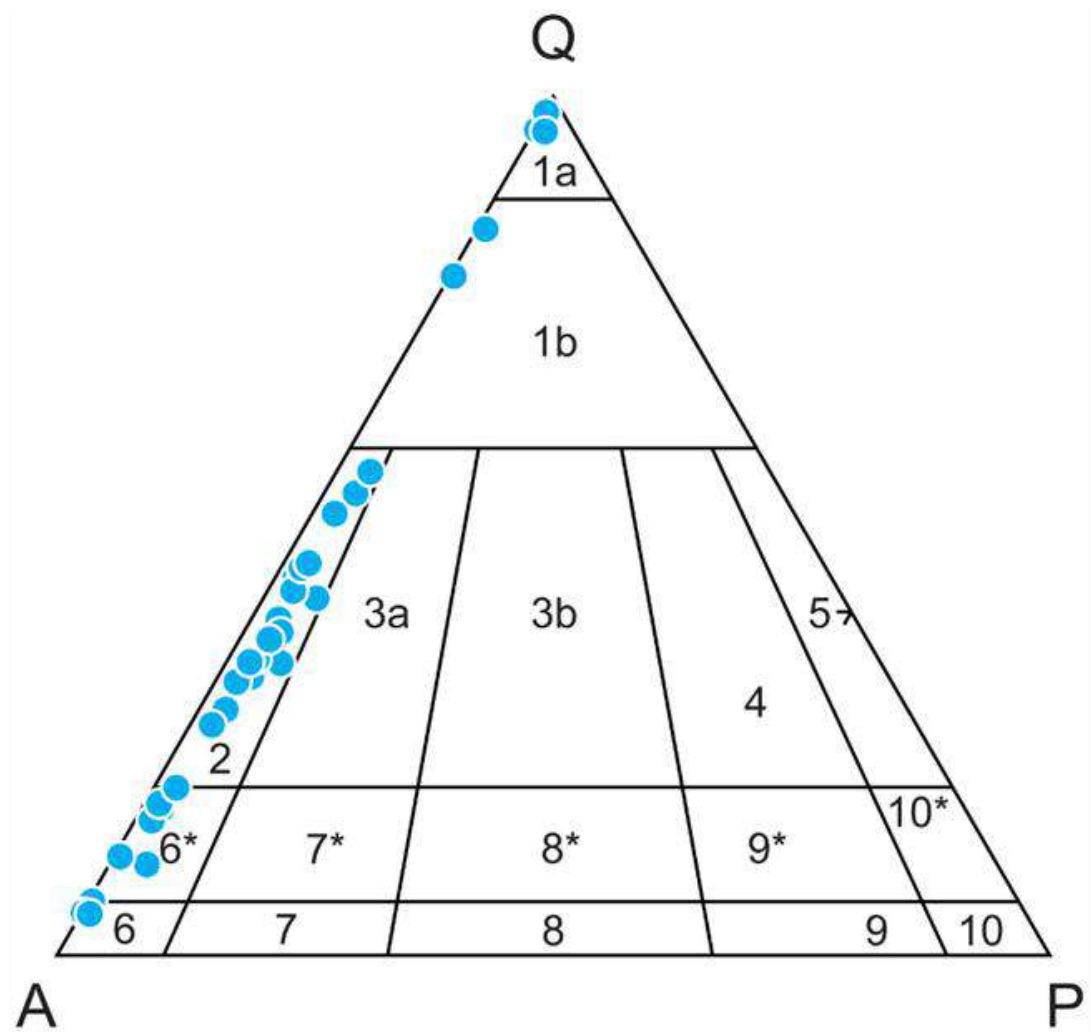
The Al-Lith geothermal field is a complex hydrothermal system characterized by a network of fractures and faults, which plays a significant role in the transport and circulation of fluids within the subsurface reservoir. Petrographic analysis of rock samples collected from various locations within the geothermal field was conducted to identify the mineralogical and textural features of the rocks. The results of the petrographic analysis revealed that the rocks in the study area are predominantly composed of volcanoclastic, granitoid and low-grade metamorphic rocks. The rocks show significant variations in their mineralogy and texture, with some exhibiting strong evidence of alteration due to hydrothermal activity.

In addition to petrographic analysis, the study also employed XRD, QEMSCAN, SEM, and XRF techniques to further investigate the geochemical characteristics of the rocks and fracture fill material. XRD and QEMSCAN analysis was used to identify the mineralogical composition of the rocks and to quantify the degree of alteration. SEM analysis was used to investigate the microstructure of the rocks and fractures via EDS mapping. XRF analysis was used to determine the chemical composition of the rocks and fractures, including major and trace elements. The results of the geochemical analysis showed that the rocks and fractures in the geothermal field are enriched in various elements, including silicon, aluminum, iron, and calcium, which are indicative of hydrothermal alteration. The results also showed that the rocks and fractures exhibit significant variations in their chemical composition, which may be attributed to variations in the degree of alteration and the intensity of fluid-rock interaction. The study findings suggest that the structural and geochemical features of the rocks and fractures in the Al-Lith geothermal field play a critical role in the hydrothermal circulation and the formation of the geothermal system.

4.2.1 General rock Classification

Generally, the AQP (Alkali feldspar - Quartz - Plagioclase) diagram is a classification diagram used to classify igneous rocks based on their mineral composition. The diagram plots the weight percent of the three minerals: alkali feldspar (A), quartz (Q), and plagioclase feldspar (P) in igneous rocks. In this study, all the samples are lying along the Alkali feldspar and quartz line, which indicates that they are all felsic rocks with high amounts of alkali feldspar and quartz. In a geothermal system, the presence of felsic rocks can create a favorable reservoir for heat storage and transfer. This is because the felsic rocks can act as a cap or seal over the geothermal reservoir, preventing the upward movement of hot water and steam. The rocks can also act as a thermal buffer, absorbing and releasing heat as needed to maintain a steady temperature in the reservoir. The specific rock samples can be classified as Quartzite, Quartz-rich granitoid, Alkali feldspar granite, Quartz-bearing alkali feldspar syenite, and Alkali feldspar syenite (Figure 4.11).

The similarity in mineral composition among the samples suggests that they are all part of a similar magmatic system. The high amounts of alkali feldspar and quartz suggest that there was a significant source of both silica and alkali metals in the magma. This could indicate that the area has a potential geothermal system. Additionally, the mineral composition of felsic rocks can provide information about the source of the geothermal fluids. For example, if the felsic rocks in the area are rich in potassium feldspar, this may indicate that the geothermal fluids are derived from a granitic source. The characterization of felsic igneous rocks would help in understanding the thermal and fluid characteristics of the geothermal system in the area, and can aid in the exploration and development of geothermal resources.



Legends

- | | |
|---|---|
| 1a Quartzolite | 7 Syenite |
| 1b Quartz-rich granitoid | 7a Quartz-bearing syenite |
| 2 Alkali feldspar granite | 7b Foid-bearing syenite |
| 3 Granite | 8 Monzonite |
| 4 Granodiorite | 8a Quartz monzonite |
| 5 Tonalite | 8b Foid monzonite |
| 6 Alkali feldspar syenite | 9 Monzodiorite/Monzogabbro |
| 6a quartz-bearing alkali feldspar syenite | 9a Quartz monzodiorite/Quartz Monzogabbro |
| 10 Diorite/Gabbro/Anorthosite | 10a quartz diorite/quartz gabbro |

Figure 4.11 AQP diagram showing the classification of igneous rocks in the study area (Blue circles), based on the relative proportions of alkali, quartz, and plagioclase (Rafiq et al., 2023; In Prep).

4.2.2 Petrographic Analysis

Petrographic analysis involves examining the mineralogical and textural characteristics of rocks to understand their geological history and formation processes. In the context of a geothermal system, a petrographic analysis can provide insights into the nature and distribution of the mineral assemblages, the degree of alteration and deformation, and the potential for geothermal fluid circulation.

For this purpose, a total of 21 representative samples are analyzed. One of the main observations from the petrographic analysis is the presence of quartz veins and pockets (Figure 4.12a & 4.12b). Quartz is a common mineral found in igneous, metamorphic, and sedimentary rocks, and its presence can indicate the presence of hydrothermal fluids that have been involved in the formation of the geothermal system (Figure 4.13a). Another important mineral identified in the petrographic analysis is orthoclase, a potassium feldspar that exhibits cross-hatched twinning (Figure 4.13b). This mineral is commonly associated with hydrothermal alteration and can indicate the presence of a high-temperature geothermal system. The differentiation of orthoclase and quartz using microscopy can be done under plane polarized light (PPL). Orthoclase appears dirty under PPL, while quartz appears clear (Rafiq et al., 2023; In Prep).

Chlorite is also observed in the rock samples under both plane-polarized light (PPL) and cross-polarized light (XPL). Chlorite is a common mineral found in hydrothermal alteration zones and can be indicative of the presence of geothermal activity (Figure 4.14a and 4.14b). Undulose quartz is also observed in the rock samples. Undulose quartz is a type of quartz that exhibits bending or distortion of the crystal lattice due to stress or deformation. This observation suggests that the rock has been subjected to high temperatures and pressure associated with hydrothermal activity. Furthermore, rocks are highly altered which indicates that rocks are

undergone hydrothermal alteration and metamorphism (Figure 4.15a). Secondary veins and fractures are also observed in the rock samples (Figure 4.15b). These features suggest that the rock has undergone deformation and has been subjected to stress, possibly from the movement of hydrothermal fluids.

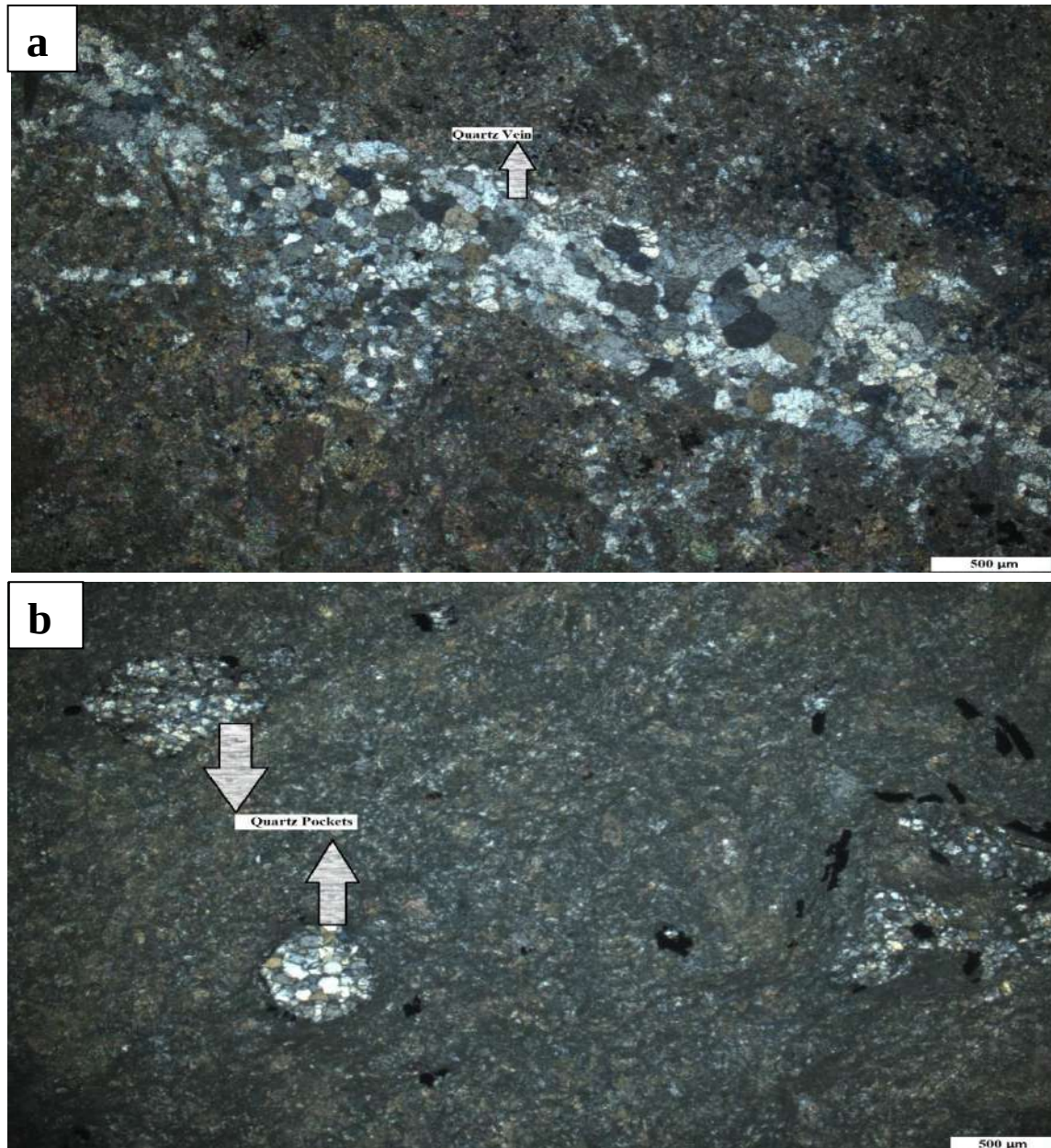


Figure 4.12 a) Microscopic analysis of quartz vein structure; b) Formation of quartz pockets within void spaces (Rafiq et al., 2023; In Prep).

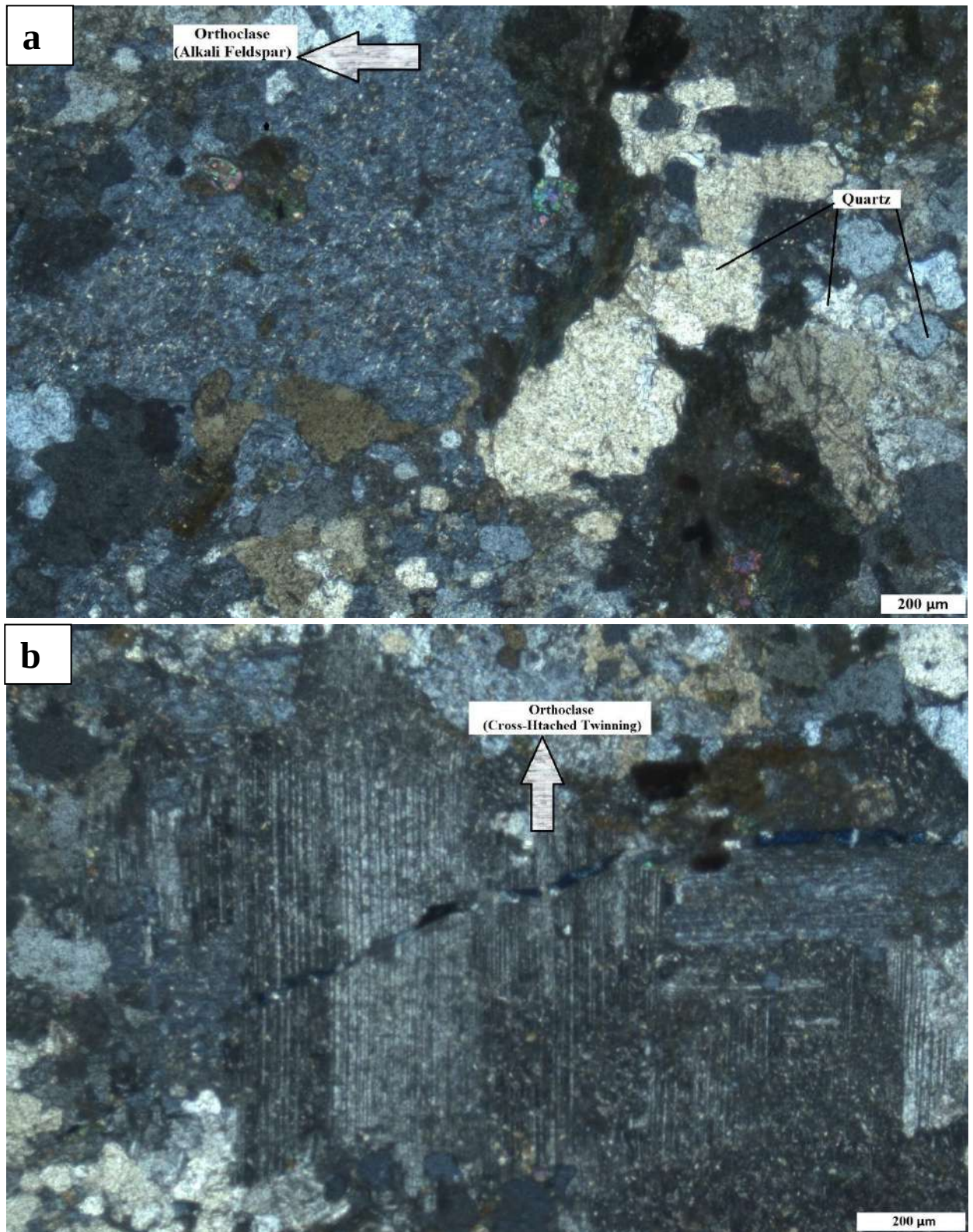


Figure 4.13 a) The quartz and orthoclase (Alkali feldspar) mineral association b) The cross-hatched twinning observed, a distinct feature of orthoclase (Rafiq et al., 2023; In Prep).

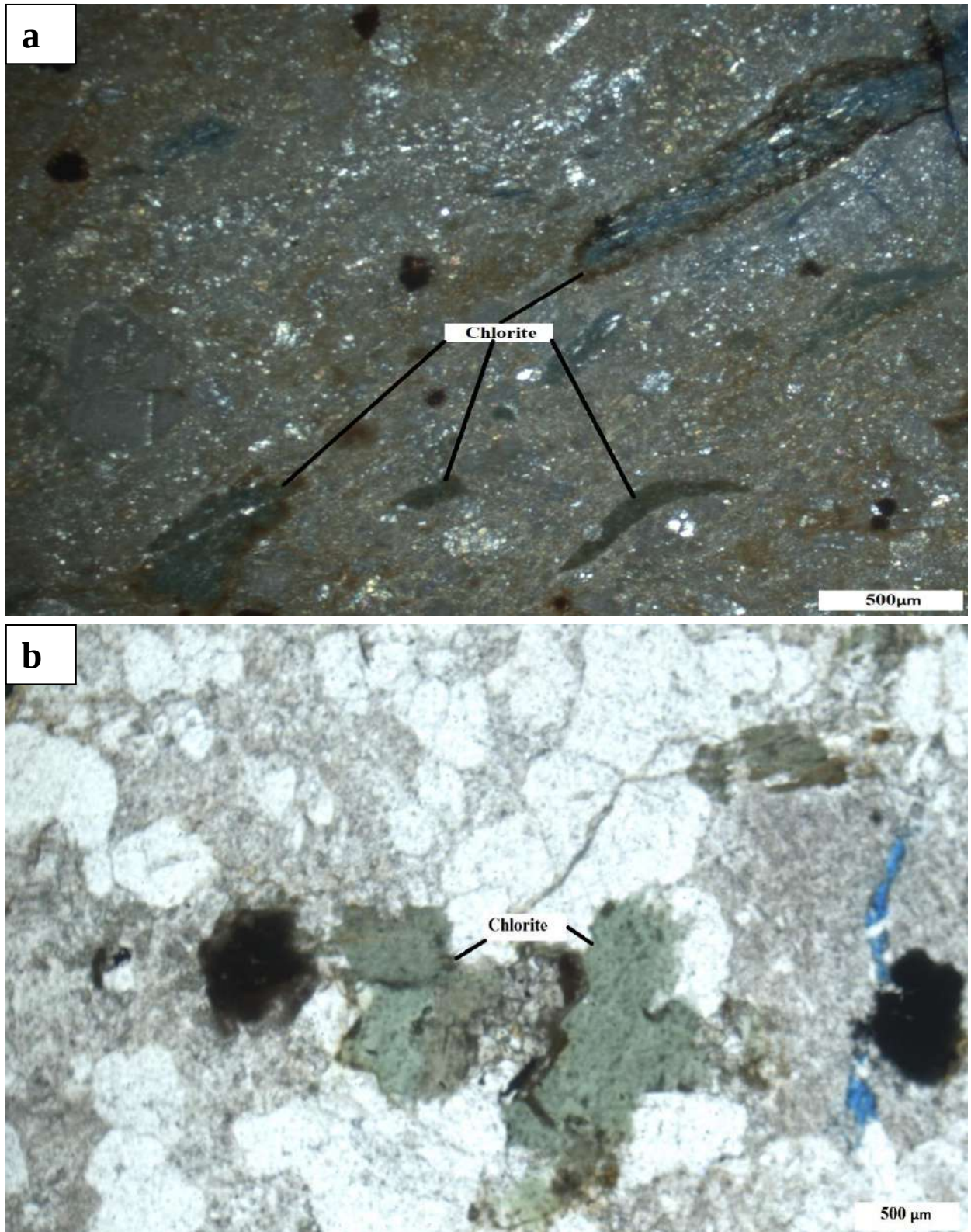


Figure 4.14 a) It shows the chlorite mineral under Cross polarized light (XPL) b) Chlorite under plane-polarized light (PPL) (Rafiq et al., 2023; In Prep).

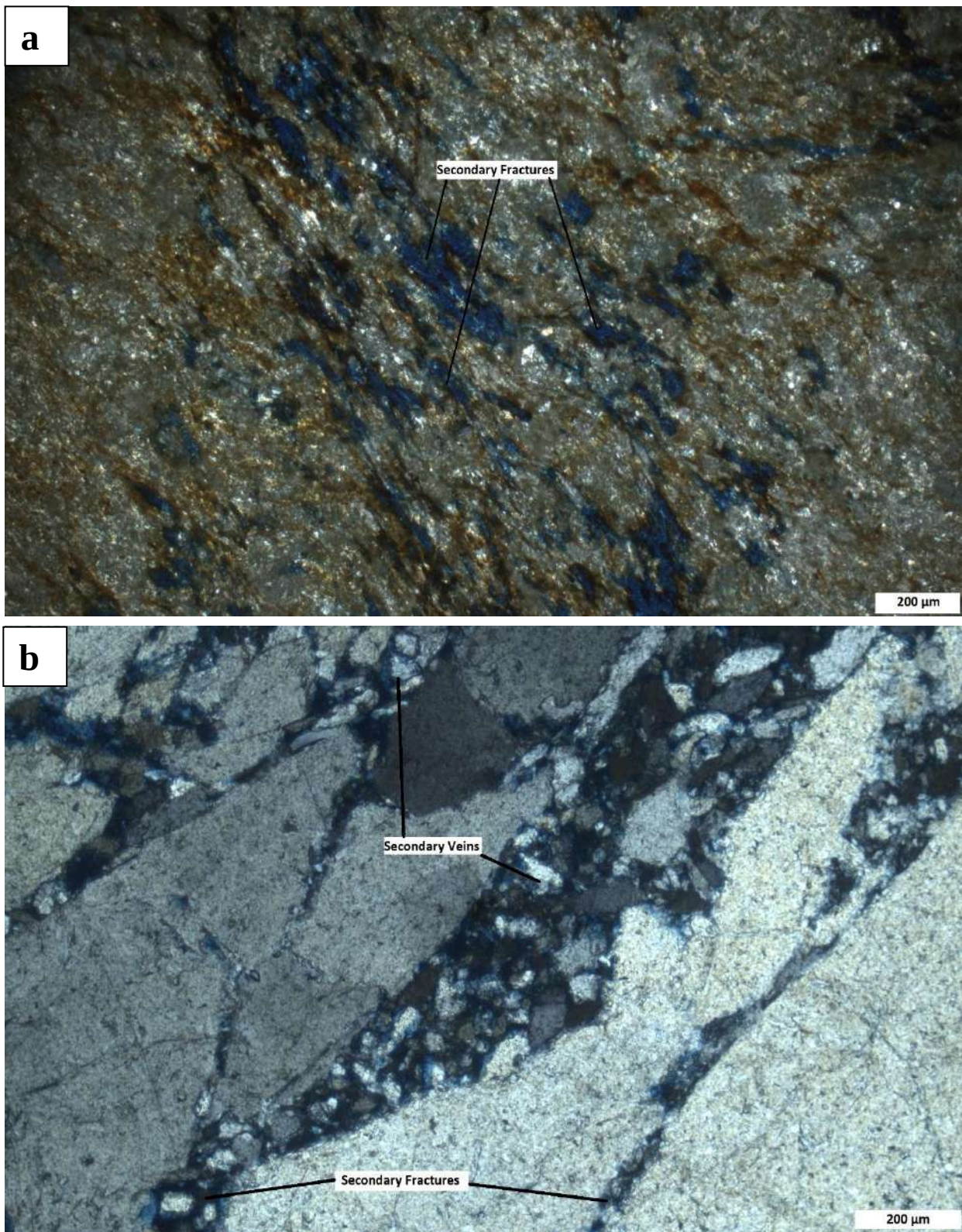


Figure 4.15 a) Highly altered rock minerals and development of secondary fractures b) It shows the secondary veins and fractures formed as a result of hydrothermal alteration (Rafiq et al., 2023; In Prep).

4.2.3 Mineralogical Analysis

The mineralogical analysis of the studied samples using XRD and QEMSCAN techniques has revealed the presence of several primary and secondary minerals. The dominant primary minerals in the sample are K-feldspar (Orthoclase), Quartz, and Muscovite. These minerals are commonly found in igneous rocks, particularly in granitic or granodioritic rocks. Amphibole, pyroxene, and biotite are present in minor amounts, which suggests that the rock may be a more mafic type of granite. The secondary or altered minerals in the sample are chlorite, epidote, and albite (Figures 4.16 and 4.17 & 4.18). Chlorite is a common alteration mineral that forms from the breakdown of mafic minerals such as amphiboles, pyroxenes, and biotite. Epidote forms from the breakdown of plagioclase feldspars. Albite is a minor secondary mineral that is an alteration product of the K-feldspar. The presence of chlorite and epidote as dominant secondary minerals suggests that there may have been some low-temperature hydrothermal alteration occurring in the area (Rafiq et al., 2023; In Prep). This is consistent with the geology of the area's geothermal system, where hot water circulates through the rocks, altering their mineralogy. Sulfide and carbonate minerals (calcite) are present in minor amounts. Sulfide minerals such as pyrite, chalcopyrite and calcite are commonly associated with hydrothermal systems, and their presence suggests that there may be some mineralization occurring in the area.

In a given geothermal system these minerals are known as hydrothermally altered ones and serve as a semi-quantitative geothermometer in any geothermal system (Lagat, 2009). According to this study, mineralogical analysis suggests that the medium to high temperature minerals are the major constituent of rocks within the study area. The presence of certain minerals suggests that there may be some hydrothermal alteration and mineralization occurring in the area, which could be of interest for further exploration and development of geothermal resources. Furthermore, cross over of the minerals temperatures lies in between 280 and 320°C (Figure 4.19).

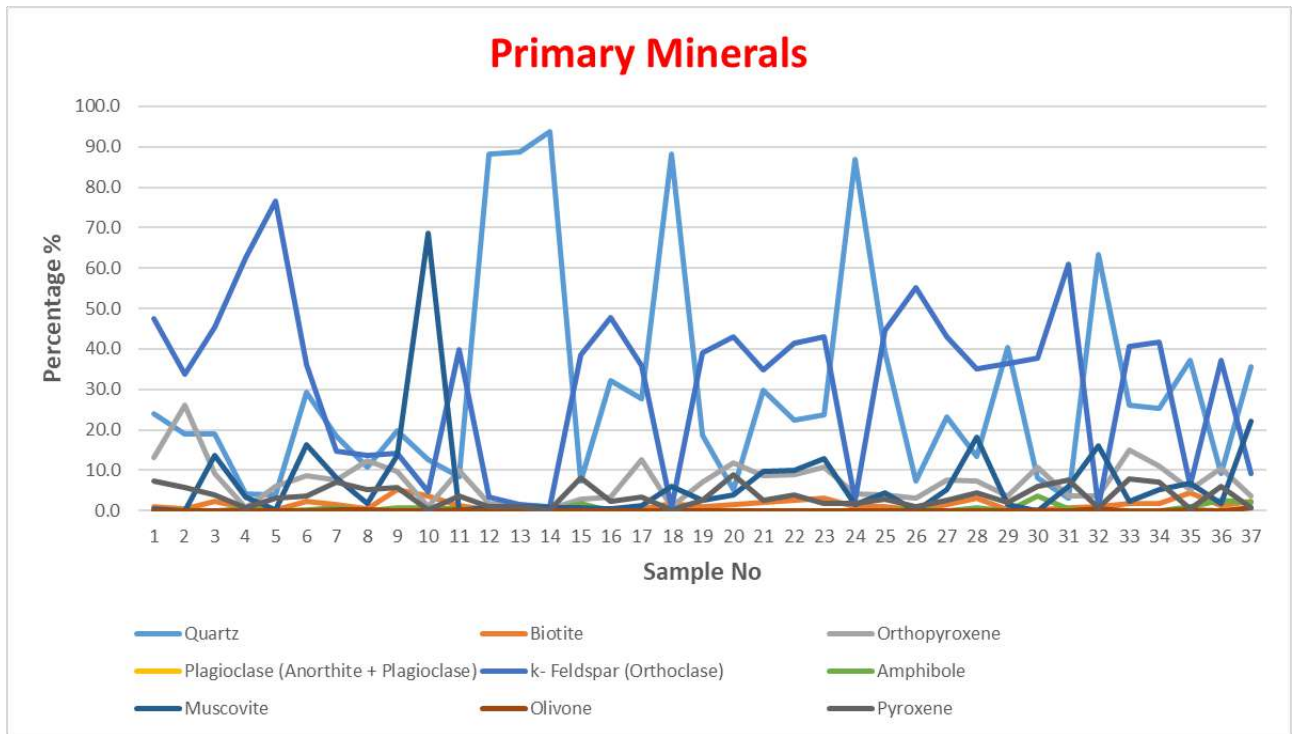


Figure 4.16 Graphical representation of the mineralogical composition (primary minerals) using X-ray diffraction (XRD) (Rafiq et al., 2023; In Prep).

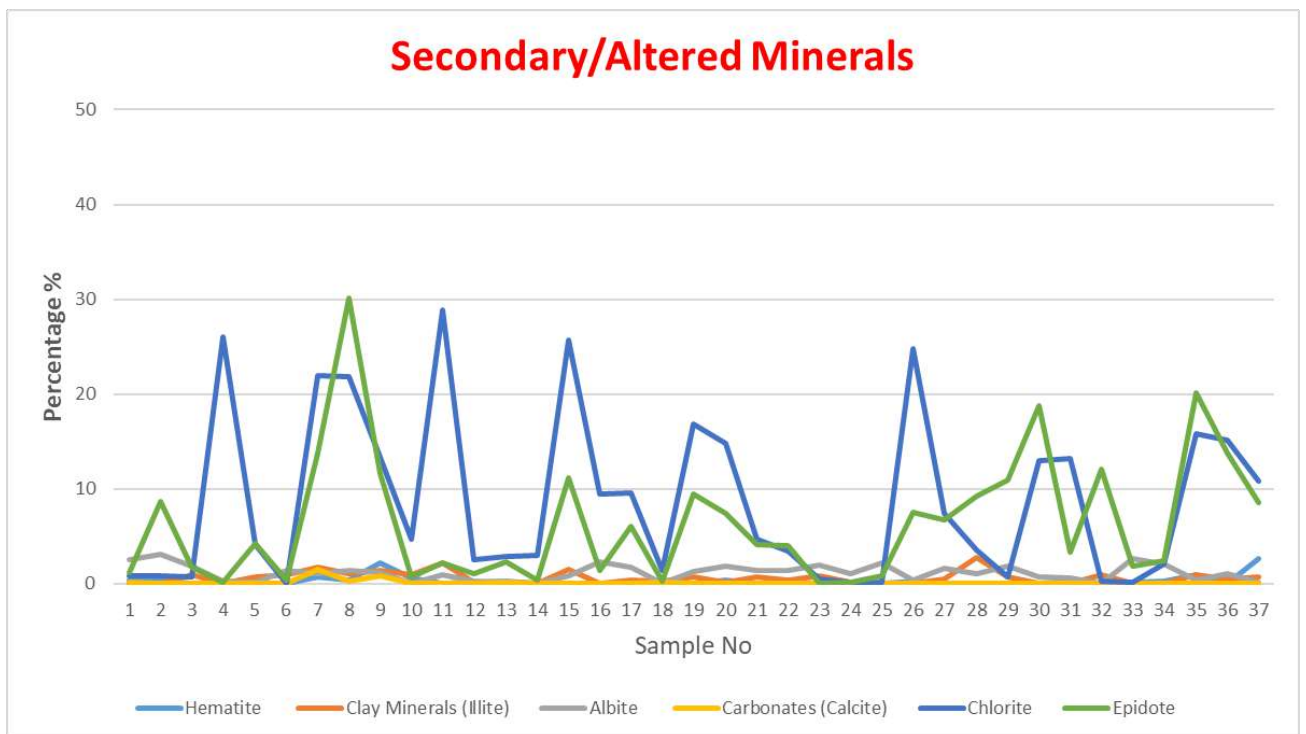


Figure 4.17 Graphical representation of the mineralogical composition (secondary/altered minerals) using X-ray diffraction (XRD) (Rafiq et al., 2023; In Prep).

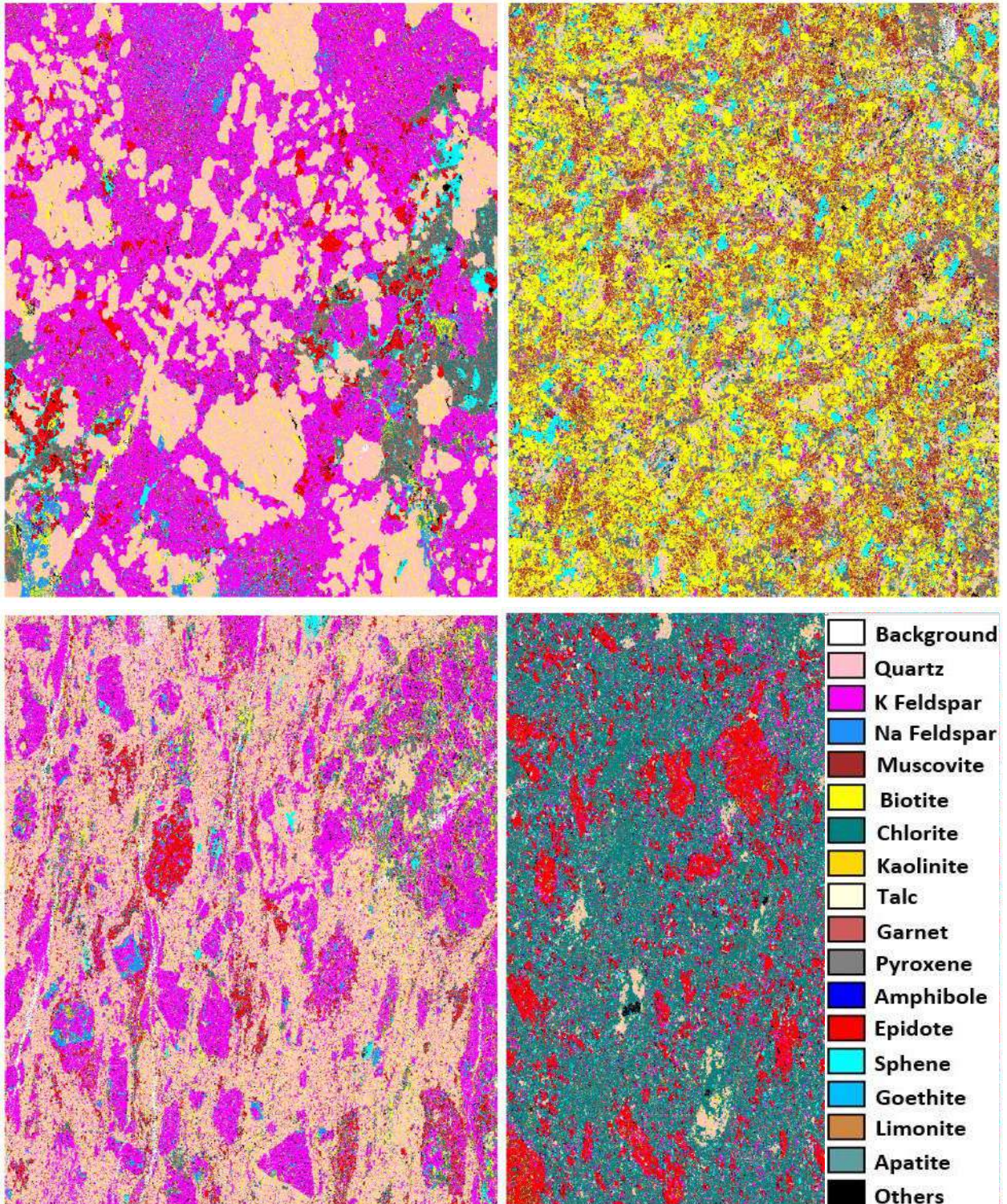


Figure 4.18 Mineralogical composition (primary and secondary/altered minerals) of the representative samples using the QEMSCAN technique (Rafiq et al., 2023; In Prep).

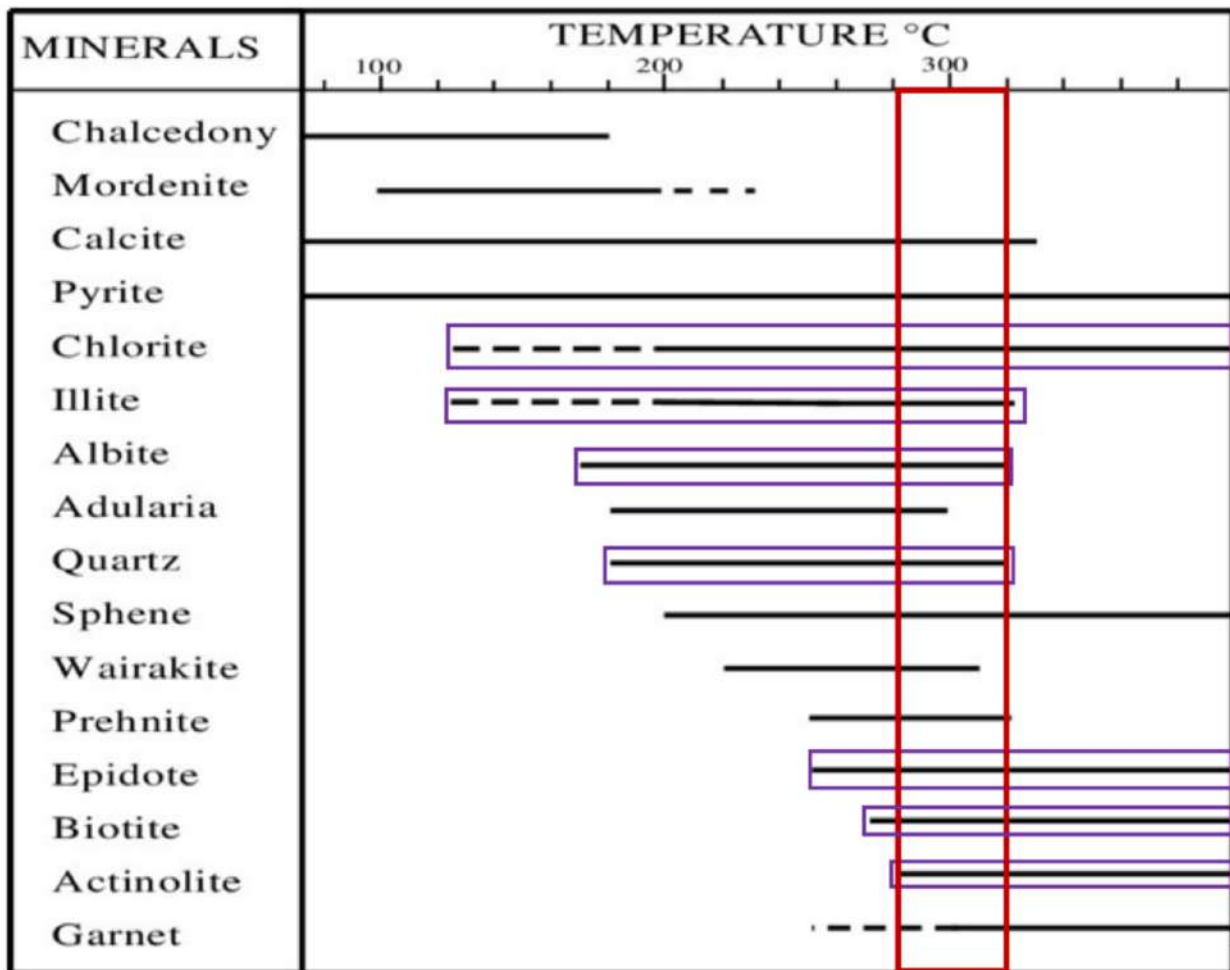


Figure 4.19 The typical hydrothermal alteration minerals used as geothermometers and their temperature stability ranges. Sections with dots show minerals outside their usual stability ranges (Lagat, 2009).

4.2.4 Geochemistry

4.2.4.1 X-Ray Fluorescence (XRF Analysis)

4.2.4.1.1 Major and Trace Element

X-ray fluorescence (XRF) analysis is a powerful analytical tool that provides valuable information about the chemical composition of samples. Major and trace elements analysis by XRF is particularly useful because it allows us to determine the types and relative abundances of elements that are present in the samples.

In this study, the dominant major elements found in the samples are Si, Mg, Al, and Fe (Figure 4.20). These elements are commonly found in geothermal systems and can provide

information about the mineralogy and chemistry of the system. Silicon (Si) is a major component of many minerals, including quartz and feldspar, and its abundance can indicate the presence of these minerals in the system. Magnesium (Mg) is commonly found in minerals such as olivine and pyroxene, and its abundance can provide information about the temperature and pressure conditions under which these minerals formed. Aluminum (Al) is also commonly found in minerals such as feldspar and mica. Iron (Fe) is an important component of many minerals, including magnetite and hematite, and its abundance can provide information about the oxidation state.

In addition to the major elements, trace elements such as Cl, K, Ca, and Na were also found in minor amounts (Figure 4.20). Chlorine (Cl) is an important indicator of fluid-rock interaction in geothermal systems, and its abundance can provide information about the salinity of the fluids in the system. Potassium (K) is commonly found in minerals such as feldspar and mica. Calcium (Ca) and sodium (Na) are important components of many minerals, including plagioclase feldspar and zeolites (Rafiq et al., 2023; In Prep). The abundance of these elements can provide further information about the mineralogy and chemistry of the system.

4.2.4.1.2 Major Oxides

In addition to major and trace element analysis, X-ray fluorescence (XRF) is a widely used analytical technique, that can be employed to analyze the major oxide components of rocks, which are crucial indicators of the rock's mineralogical and chemical properties. The major oxide components of the studied samples were found to be dominated by Silicon dioxide (SiO_2), Aluminum oxide (Al_2O_3), magnesium oxide (MgO), and Iron oxide (Fe_2O_3). These oxides are typically associated with volcanic and igneous rocks, which are commonly observed in geothermal systems due to the high temperatures and pressures found in such environments. Silica (SiO_2), in particular, is a crucial major oxide in geothermal systems as it significantly affects the solubility and transport of minerals and fluids (Figure 4.21). The

presence of higher SiO_2 concentrations suggests a more felsic (silica-rich) rock composition, which can impact the permeability and porosity of the rock and influence the fluid flow in the system. Aluminum oxide (Al_2O_3) is another important major oxide, which is a constituent of many common minerals in geothermal systems, such as feldspars and clay minerals. Its presence can indicate the degree of alteration and weathering that the rock has undergone, thereby affecting the chemical and physical properties of the geothermal system. Magnesium oxide (MgO) and iron oxide (Fe_2O_3) are also crucial major oxides associated with mafic (magnesium- and iron-rich) rocks such as basalts and gabbros, which are often related to volcanic activity. The presence of MgO and Fe_2O_3 can indicate the potential for the mineralization and fluid pathways in the geothermal system.

Furthermore, the analyzed samples showed minor amounts of potassium oxide (K_2O) and calcium oxide (CaO) (Figure 4.21). The presence of K_2O and CaO can indicate the potential for mineralization and fluid pathways in the geothermal system, as well as the degree of alteration and weathering. Potassium is often associated with feldspars and micas, while calcium is commonly found in carbonates and silicates. The minor amounts of these major oxides suggest a lesser contribution of these minerals to the overall rock composition, compared to the dominant major oxides. Nonetheless, the presence of K_2O and CaO can still provide important insights into the geothermal system of the Al-Lith area, which can inform future exploration and development efforts.

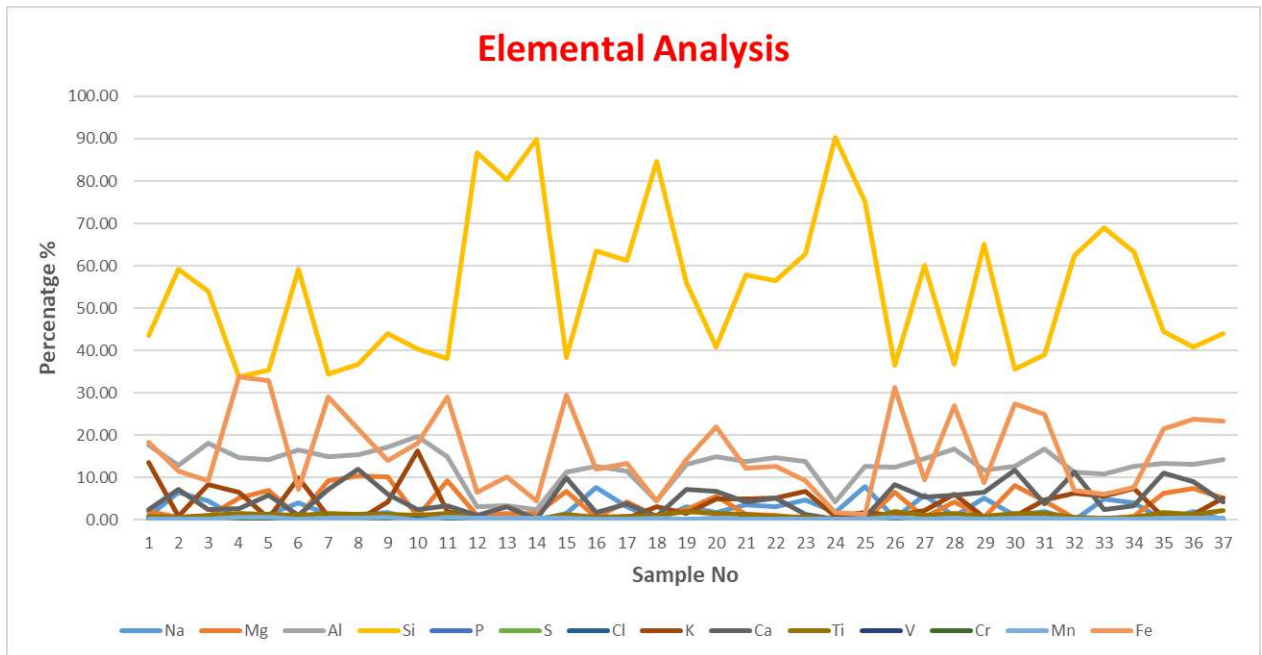


Figure 4.20 Graphical representation of the major and trace elements using X-ray Fluorescence (XRF) (Rafiq et al., 2023; In Prep).

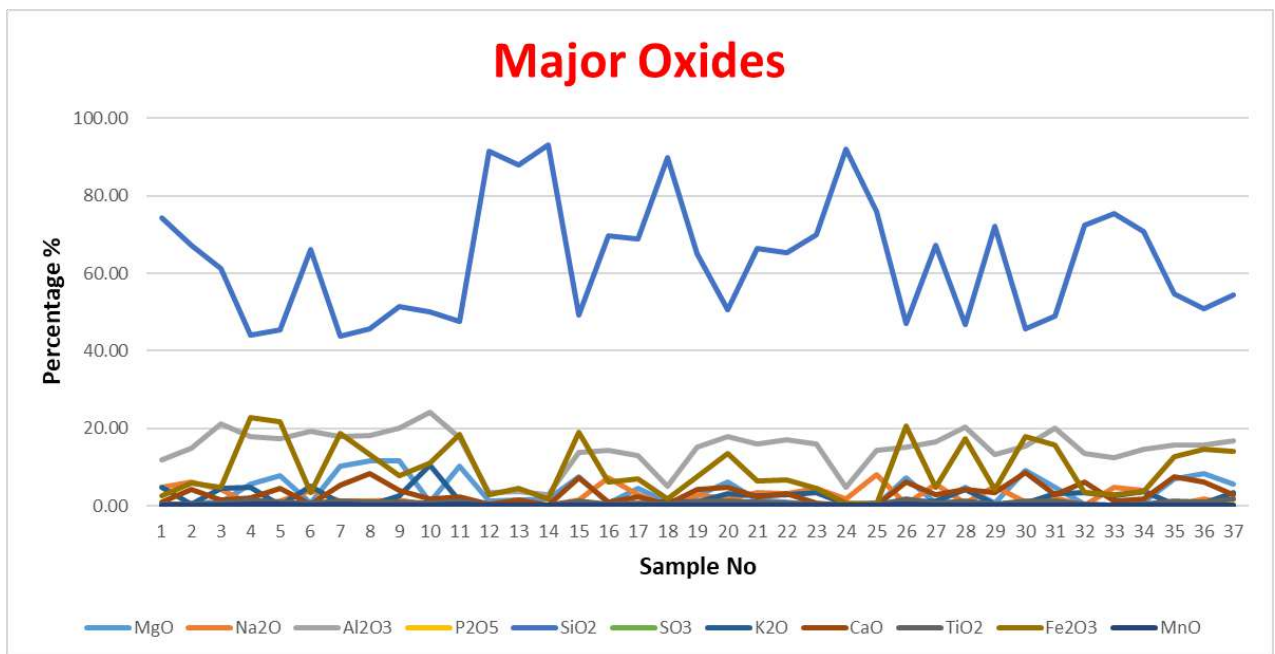


Figure 4.21 Graphical representation of the major oxides using X-ray Fluorescence (XRF) (Rafiq et al., 2023; In Prep).

4.3 Hydrogeochemistry

The findings from the in-situ parameter measurements are outlined in Table 4.3. The thermal waters of Ain Al-Harrah are nearly 60 °C (the hottest spring in the study area) (Rafiq et al., 2023; In Submission). The outlet temperature of the thermal spring is determined by local conditions such as water flow velocity, circulation time, and fracture characteristics (Saibi, 2009). Hence, the temperature of the thermal springs is a reflection of the water's penetration depth and velocity of ascent to the surface. (Grasby and Hutcheon, 2001). Ain Al-Harrah thermal spring was classified as a hyperthermal slightly alkaline water based on the pH values (7.9-8.2). The EC is proportional to the temperature of the water and is used to calculate the amount of salts dissolved in it (Haj-Amor et al., 2018). The values of measured electrical conductivity (EC) based on TDS and gravity method range between 2800 – 3161 $\mu\text{S cm}^{-1}$ and 1788 – 1920 $\mu\text{S cm}^{-1}$ respectively. These high values of EC reveal a high salinity of thermal waters (Table 4.3). This implies that the water was primarily circulated through a fault system affecting the rocks in the study area.

Table 4.3 Physical parameters of Ain Al-Harrah Hot spring (Rafiq et al., 2023; In Submission).

Sample ID	Temperature (°C)	pH (ATC)	EC ms/cm	TDS (EC) ppm	TDS (Gravity) ppm
AH-01	56	7.9	3161	2055	1920
AH-02	58	7.7	3131	2035	1900
AH-03	60	8.0	2864	1862	1868
AH-04	48	8.2	2869	1865	1840
AH-05	49	8.1	2816	1830	1788

The chemical parameters estimated for the thermal springs are listed in Table 4.4. A Schöeller (1964) diagram was used (Figure 4.22) to characterize and compare the concentrations of cations and anions. It was found that thermal waters generally had higher levels of K^+ , Na^+ , HCO_3^- , and Cl^- and lower levels of Mg^{2+} . The pattern also implies that there are more significant ions in the hot water. The majority of the hot spring water samples are of the Na- HCO_3 type, with

an alkaline pH (7.9–8.2). Na^+ and HCO_3^- levels in thermal waters range from 410 to 463 mg/L and 65 to 90 mg/L, respectively. Mg^{2+} was present, but only in very low levels (1.27–2.04 mg/L). The thermal spring water's total dissolved solids (TDS) concentration ranges between 1830 and 2055 mg/L. Chloride dominates the anions in almost all of the water samples, and their abundance is listed as follows: $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^-$. Sodium is the most abundant cation among the cations, followed by Ca^{2+} , K^+ , and Mg^{2+} in order of abundance. High concentrations of Na^+ , Cl^- , and SO_4^{2-} may indicate that the chloride and sulphate salts have dissolved, as shown in the equations below;



Table 4.4 Chemical parameters of Ain Al-Harrah hot spring (Rafiq et al., 2023; In Submission).

Sample ID	Na^+ (mg/l)	K^+ (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	HCO_3^- (mg/l)	Cl^- (mg/l)	SO_4^{2-} (mg/l)
AH-01	463	93	295	2.04	71.06	538.52	433.39
AH-02	450	74.9	293	1.27	64.48	472.76	376.71
AH-03	425	69.8	265	1.49	89.99	486.96	387.89
AH-04	411	56.4	267	1.48	89.04	557.76	436.70
AH-05	410	50.2	262	1.65	84.4	581.95	455.79

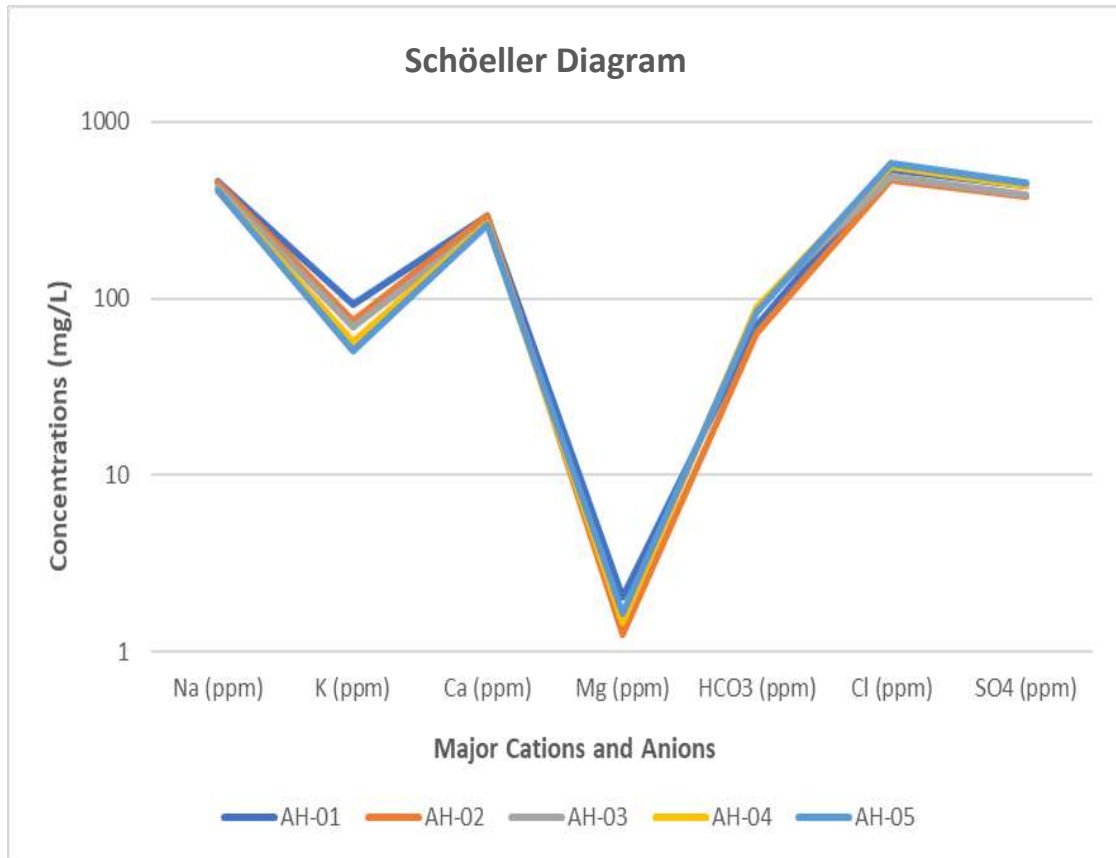


Figure 4.22 Schöeller diagram representing the data obtained from the study water samples (Rafiq et al., 2023; In Submission).

A Piper (1944) diagram is a graphical representation of water chemistry data that helps to visualize and interpret the geochemical composition of water samples. Additionally, it describes how different types of water facies are categorized based on how they interact with rock and soil minerals. The plot displays the relative proportions of cations ($\text{Na}^+ + \text{K}^+$, Ca^{2+} , and Mg^{2+}) and anions (HCO_3^- , Cl^- and SO_4^{2-}). Based on the Piper plot analysis of the thermal spring water samples, the dominant water facies is a mixture of sodium chloride and sodium bicarbonate water type facies, with a dominance of Na^+ and Ca^{2+} cations, and Cl^- and SO_4^{2-} anions (Figure 4.23). The increased concentration of main ions in thermal water leads to higher TDS values, indicating more intense water-rock interaction and ion dissolution from the host rocks due to the high sub-surface temperatures in the channels through which spring water flows.

The study of the hot spring water showed that Na^+ and Ca^{2+} were the most prevalent cations in the samples. Majority of the samples are located in the Na-Cl and Na- HCO_3 quadrants. The high concentration of Na^+ and Cl^- suggests a strong influence on marine evaporite deposits, while the high concentration of Na^+ and HCO_3^- could indicate the presence of volcanic activity. The dominant anion in the samples is Cl^- , which is consistent with the high chloride concentration range observed. The majority of the samples fall in the Na-Cl quadrant, indicating dominance of sodium chloride water type. The considerable concentration of sulfate (SO_4^{2-}) in the samples suggests the influence of sea water influx, which is known to release significant amounts of SO_4^{2-} into groundwater systems.

For a deeper insight into the hydrochemical processes taking place in thermal springs, the investigation of the geochemistry of trace elements in hot springs was also carried out. In this study, there is a wide range of trace element concentrations. Most elements were found in very low concentrations in the thermal water, such as < 1 ppb of Ni, Cd, and Cr; and < 10 ppb of As and Co; and elements such as Cu, Mn V, and Mo were found in intermediate concentrations ranging from 10 to 20 ppb. Conversely, some trace elements are present in very high concentrations such as Al (6000 – 7000 ppb), Sr (2900 – 3050 ppb), Fe (2000 – 2110 ppb), Li (370 - 400 ppb), B (120 – 145 ppb), and Ba (50 – 100 ppb) (Rafiq et al., 2023) (Table 4.5).

The high concentrations of Al, Fe, and Sr in the sample are indicative of hydrothermal alteration of rocks, which is a common characteristic of geothermal systems. High concentrations of Al suggested that the rocks contain minerals such as feldspars, which are rich in aluminum. Similarly, high concentrations of Fe indicate the presence of iron oxide minerals such as hematite or magnetite. The presence of Li, Sr and B at significant concentrations may suggest the abundance of felsic igneous rocks and presence of a high-temperature geothermal reservoir. The

presence of high concentrations of Sr can be related to the intrusions of igneous dykes. Moreover, Ba concentrations may indicate the presence of mineralization in the geothermal system.

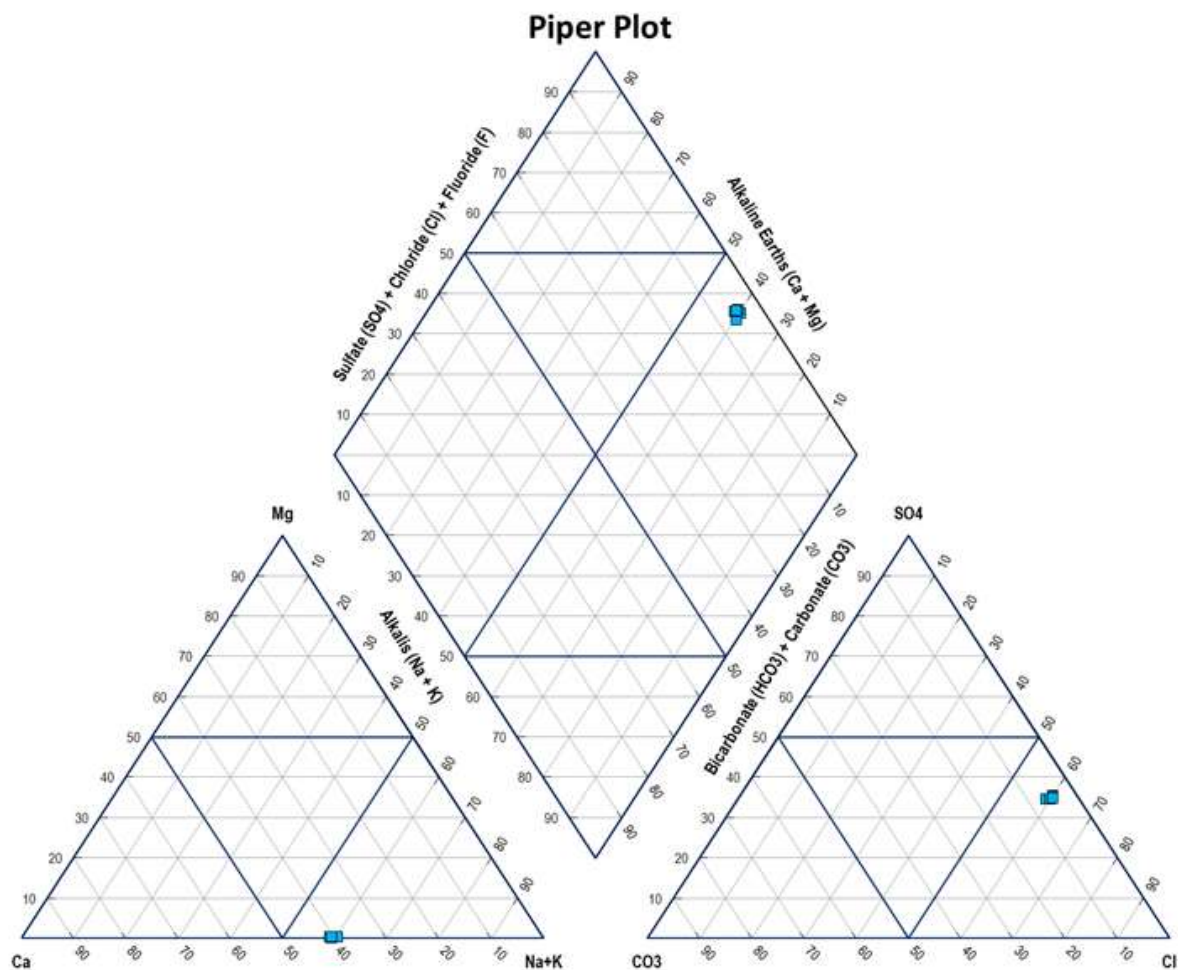


Figure 4.23 Piper (1994) diagram of analyzed water samples (Blue squares) for the hot spring (Rafiq et al., 2023; In Submission).

Table 4.5 Trace element concentration (ppb) of water samples from hot spring (Rafiq et al., 2023; In Submission).

Sample Id	Li	B	Ba	Al	Fe	Ni	Cd	Co	As	Cr	Cu	Mn	Sr	Mo	V
AH-01	401	123.12	94.86	7110	2100	0.46	0.06	1.20	3.90	0.06	12.27	11.48	2934.83	23.09	12.18
AH-02	390	120.11	96.98	6990	2010	0.52	0.06	1.20	4.08	0.10	14.78	18.47	2994.42	23.63	12.06
AH-03	370	143.56	55.37	6550	2010	0.28	0.04	0.98	3.04	0.28	16.45	22.69	2997.11	16.06	10.17
AH-04	400	143.91	54.85	6400	2105	1.10	0.04	1.04	3.02	0.30	18.36	35.69	2969.33	15.87	10.47
AH-05	390	136.49	55.59	6230	2118	0.26	0.03	0.96	2.93	0.31	20.64	4.82	3024.06	15.68	9.90

The low concentrations of certain trace elements in the hot spring water of Ain A l-Harrah can be explained by a combination of factors, including the abundance of these elements in the surrounding rocks, the solubility of these elements in water, and the pH and temperature of the hot spring water. For instance, nickel (Ni) is often associated with ultramafic rocks such as peridotite, but these types of rocks are not abundant in the area surrounding the hot spring. Similarly, cadmium (Cd) is often associated with sedimentary rocks, and they are not found in the area surrounding the hot spring. Furthermore, chromium (Cr) is often found in the mineral chromite, which is relatively insoluble in water. Arsenic (As) is often present in sulfide minerals, which can dissolve in acidic conditions. However, the hot spring water is relatively alkaline, the sulfide minerals may not dissolve, leading to low concentrations of As in the water (Figure 4.24).

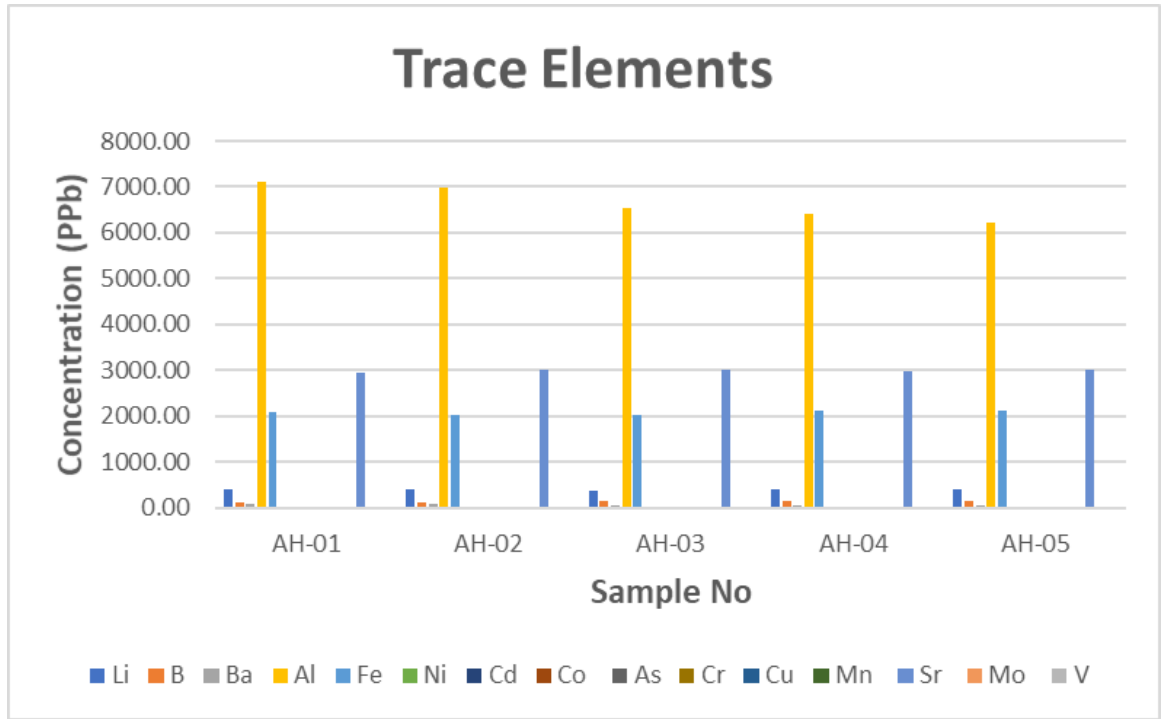


Figure 4.24 Concentrations of trace elements (ppb) in the thermal spring fluids for the hot spring (Rafiq et al., 2023; In Submission).

4.3.1 Geochemical characterization of water samples

4.3.1.1 Cl-SO₄-HCO₃ (TCHS) ternary diagram

The Cl-SO₄-HCO₃ ternary diagram is frequently utilized to classify diverse geothermal water types present in a specific locality. The TCSH diagram (Giggenbach and Gougel 1989; Giggenbach 1991a) is a valuable tool for assessing the distribution of major anions in a water sample. This ternary diagram allows for the classification of different geothermal water types, such as those originating from volcanic sources, steam heating, peripheral areas, and mature fluids. By using the Cl-SO₄-HCO₃ ternary diagram, the chemical information provided in Table 4.4 can be illustrated. All samples (AH-01 through AH-05) are located within the Cl-rich domain of mature geothermal water, which is close to the Cl-SO₄ and indicates a considerable sulphur concentration (Figure 4.25). The prevalence of Cl and SO₄ over HCO₃ suggests that the thermal water might have mixed with water that received only minimal steam heating or came into contact with a sulphur-rich environment during water-rock interaction. High Cl concentrations indicate

little to no conductive cooling or mixing, as the waters were fed directly from the deep reservoir. The presence of Cl-enriched water may indicate the influence of seawater mixing with thermal fluids (Rafiq et al., 2023; In Submission). Based on the Cl-SO₄-HCO₃ ternary diagram, it appears that the geothermal water under investigation is an alkali chloride type with a relatively high concentration of chloride, medium to high levels of sulfate, and a much lower concentration of bicarbonate than other geothermal waters with similar levels of chloride and sulfate. The high concentration of sulfate (SO₄²⁻) in the samples suggests the influence of geothermal activity, which is known to release significant amounts of SO₄²⁻ into groundwater systems.

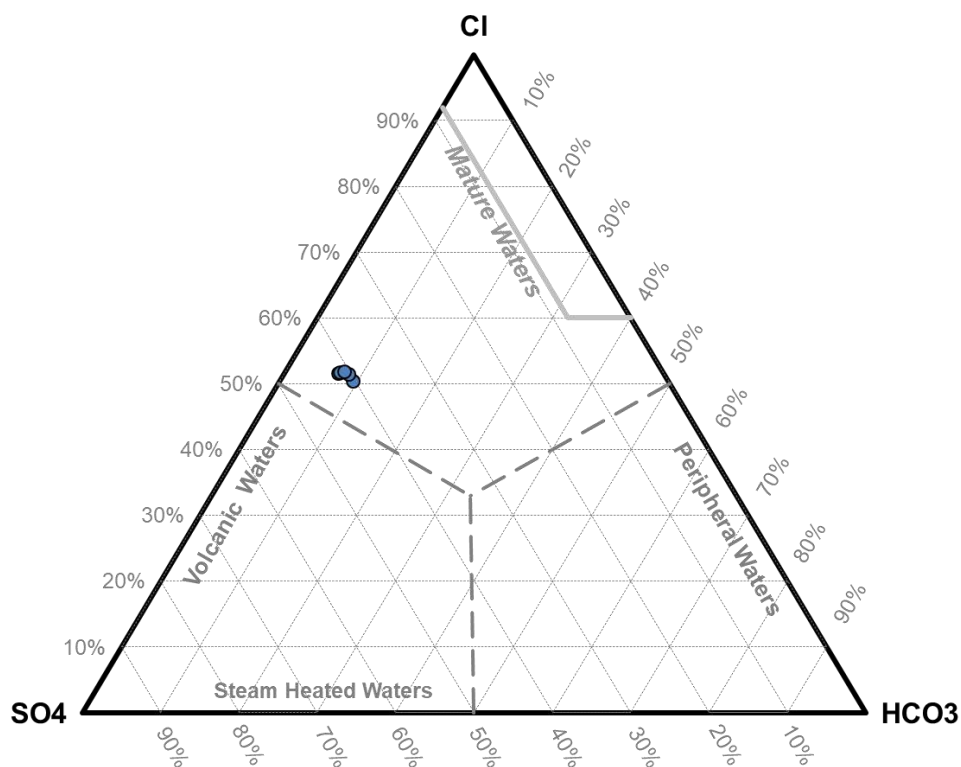


Figure 4.25 TCHS plot of water samples analyzed (Blue circles) for the hot spring water samples (Rafiq et al., 2023; In Submission).

4.3.1.2 Cl-Li-B (TCLB) ternary diagram

A ternary plot of Cl-Li-B, proposed by (Giggenbach, 1991a) was used to distinguish fluids from distinct origins and to indicate fractionation due to boiling, mixing with steam, or fluids produced by distinct steam sources.

The tracers for fluid from geothermal waters are boron, chloride, and lithium. Lithium suggests that thermal fluids are migrating from deeper geothermal sources, and boron may be leached from wall rocks. Based on the Ternary plot of Cl, Li, and Boron, it appears that the thermal spring water samples have relatively high levels of Chlorine (Cl^-) ranging from 450 - 590 ppm, while the levels of Lithium (Li) fall within a narrow range of 0.3-0.4 ppm. The Boron (B) content in the water samples is relatively low and falls within a narrow range of 0.12-0.14 ppm. The high levels of Chlorine in the water samples could indicate the presence of seawater or marine influence. The relatively low levels of Boron suggest that the water source may not be entirely geothermal in origin. Lithium is a relatively rare element, and its presence in the water samples could be an indication of geothermal activity in the area (Figure 4.26).

The Ternary plot suggests that the thermal spring water samples represent a mixture of geothermal and non-geothermal waters with some influence from seawater or marine sources. The analysis could be used to determine the source and potential use of the water, as well as the potential for resource development.

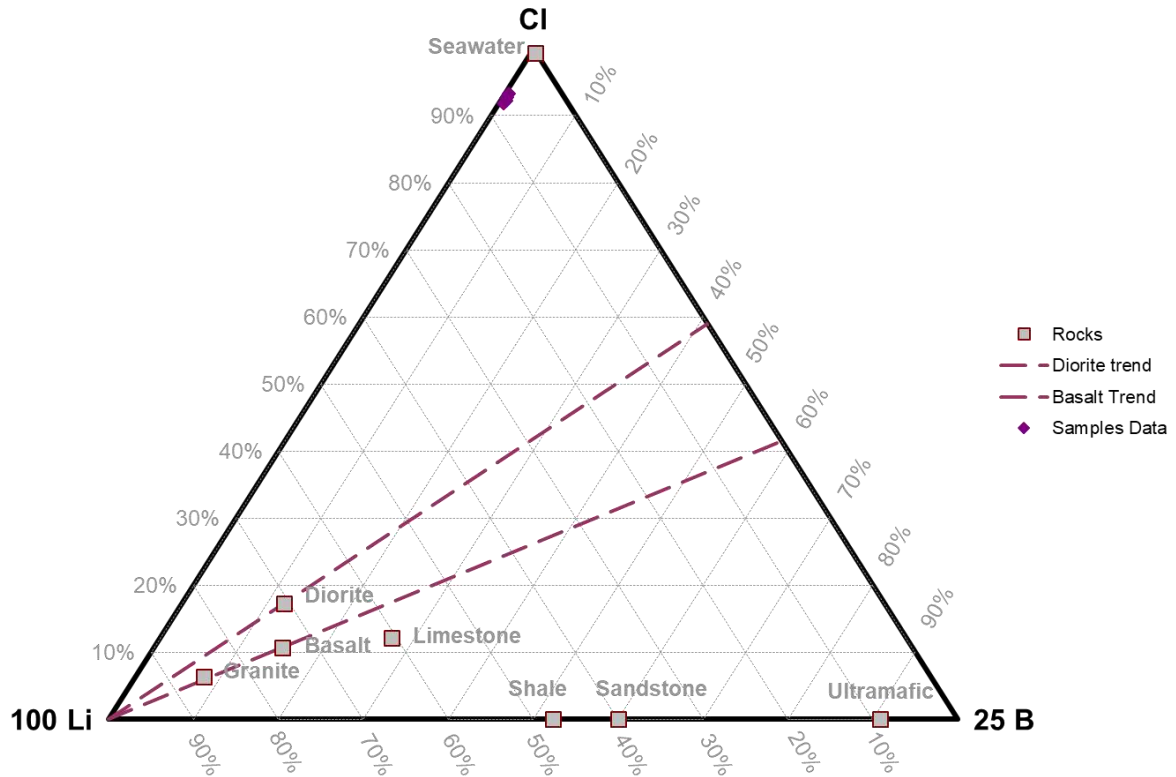


Figure 4.26 CI–Li–B (TCLB) ternary plot of water samples analyzed (purple circles) for the hot spring water samples; (Rafiq et., 2023; In Submission).

4.3.2 Geothermal reservoir temperatures

To determine the reservoir equilibrium temperature, chemical geothermometers are employed. This method forecasts the temperature of the subsurface by analyzing the distribution and relative concentrations of different chemical indicators (dissolved ions, gas, and isotopes) in the water. Chemical geothermometers often use ion-exchange processes (Na-K-Mg, Na-K, Na-K-Ca, etc.) and solubility reactions (silica, which is temperature dependent). Using both cation and silica geothermometers, the reservoir connected to the Ain Al-Harrah thermal spring's temperature was calculated.

4.3.2.1 Cation-based Geothermal temperature estimation (T1)

The Na-K-Ca geothermometer is a method used to estimate subsurface

temperatures in geothermal reservoirs. This geothermometer is based on the examination of the solubility of Na, K, and Ca ions during chemical reactions that affect the minerals of crystalline rocks, particularly feldspars. (Fournier and Truesdell, 1973). When using the relative solubility of ions to determine temperature, caution must be exercised as this relationship can vary in a similar way for both crystalline rocks and evaporites. (Lashin and Al Arifi, 2014), argued that the Al-Lith region is believed to have a geothermal gradient of 20°C - 35°C/km for the upper 4 km of the crust, with an average gradient of 35°C/km. This information is utilized to determine the source of the thermal waters.

4.3.2.1.1 TNKM (Na–K–Mg) ternary Plot

The Na-K-Mg ternary diagram (Giggenbach, 1988) is a widely used tool in geochemistry to estimate the temperature of geothermal fluids and to identify their source lithology. It combines the Na-K and K-Mg geothermometers in a single plot. The Na-K-Mg ternary diagram is utilized to estimate the temperature of the geothermal reservoir and to identify water samples that have reached equilibrium with the surrounding rock formations. The thermal waters of Ain Al-Harrah cluster near the Mg vertex and fall below the immature water curve, suggesting that they have undergone initial mineral dissolution but have not yet reached equilibrium with their host rocks. However, due to their immature nature, cation geothermometry cannot be used to estimate their temperature (Figure 4.27a).

4.3.2.1.1 XKMC (K–Mg) cross-plot

According to Giggenbach and Goguel (1989), a plot that matches potassium-magnesium geothermometers with CO₂ partial pressure measurement through the equilibrium between K-feldspar, calcite, and K-mica, and dissolved Ca⁺² and K⁺ is denoted as a "geoindicator" plot, not a geo-thermometers plot. The cross-plot aids in the determination of the partial pressure of CO₂ at the final temperature of the water-

rock equilibration as measured by the K-Mg geothermometers. The samples from the study area are positioned above the saturation line, leading to an insufficient partial pressure of CO₂ that could stimulate calcium-aluminum silicates to dissolve into calcite. The utilization of K-Mg geo-thermometry provides an accurate estimation of the partial pressure of CO₂ for water containing CO₂ or bicarbonates. Nonetheless, the plot in Figure 4.27b presents that all hot spring samples tested in the research exhibit temperatures ranging from 132 to 150 °C.

4.3.2.1.1 XMCKN (Na–K–Ca–Mg) cross-plot

Cations such as sodium, potassium, and magnesium can be used as temperature indicators in geothermal fluids. The underlying principle of cation geo-thermometers is that concentrations reflect the most recent equilibrium state of fluid and rock interaction. The temperature of the geothermal reservoir can be determined from the relative concentrations, which represent the temperature of the equilibrium state. The partial equilibrium state of rock and fluid interaction owing to dissolution is shown in Figure 4.27c, where the majority of samples are below but extremely close to the equilibrium line and one falls on equilibrium line. As the equilibration upon which cation geo-thermometry is based has not yet been attained, the accuracy of temperature estimates based on this method is questionable (Giggenbach and Goguel, 1989).

Inferring from the several ternary plots, the geothermal water likely originates from a system with a medium to high enthalpy, and has a temperature of between 150 and 280 °C.

4.3.2.2 Silica-based Geothermal temperature estimation (T2)

4.3.2.1.1 XKMS (K–Mg–SiO₂) cross-plot

The reservoir's temperature was estimated further with the help of a cross-plot of K-Mg and a quartz geothermometer (Giggenbach and Goguel, 1989). This method combines two low temperature geothermometers, making it preferable to use either a single quartz or K/Mg based

geothermometer to determine the source water's temperature. One typical sample has been analysed for this purpose (AH-01). The reservoir temperature was calculated to be around 150 °C based on a plot of K-Mg and the quartz geothermometers (Figure 4.28). These findings are consistent with the findings of the study conducted by Lashin et al. (2014) in the region; that have reported relatively the same silica contents in the thermal waters.

According to the analysis, the temperature range as estimated through the Na-K geothermometer is approximately 205 °C, and the Na-K-Ca geothermometer provides a temperature range of 130-280 °C. However, the quartz-based geothermometer produces a lower temperature range of around 150 °C. This might be because of a significant Na-K/silica disequilibrium, leading to much lower temperature estimates from quartz geothermometers as compared to Na-K and Na-K-Ca geothermometers. For various geothermometers to be useful, a temperature-dependent equilibrium between a certain solute and a mineral in the geothermal reservoir must be achieved. Hence, the use of a quartz-based geothermometer to determine a reservoir temperature of around 150 °C appears to be considerably more acceptable than using a cation-based geothermometer (Rafiq et al., 2023; In Submission).

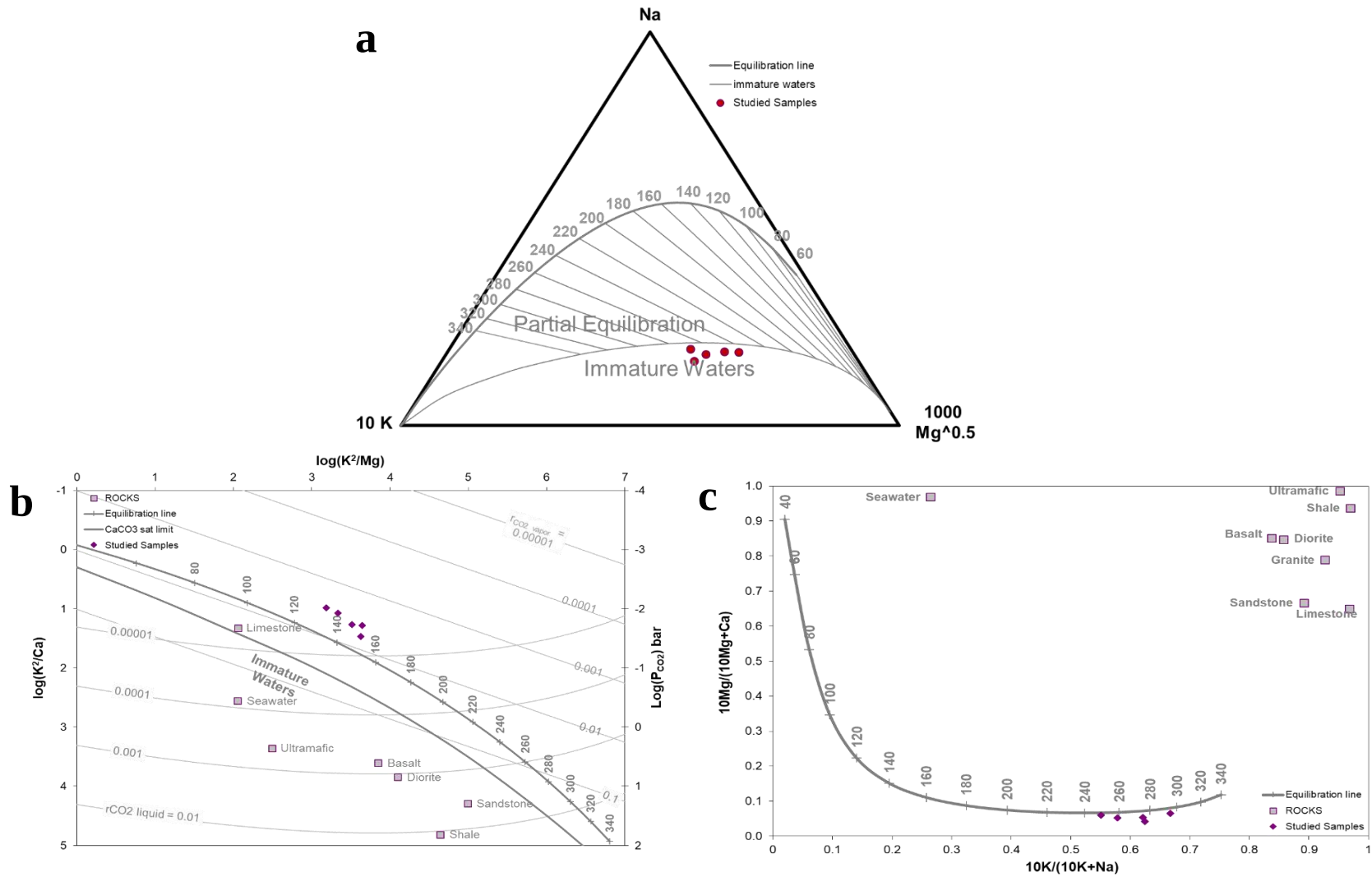


Figure 4.27 a) Comparison of Na, K, and Mg on a ternary diagram (Giggenbach, 1988); b) Cross-plots of K²/Ca and K²/Mg logarithms for evaluation of reservoir temperature (Giggenbach, 1988); c) Plots of 10 Mg/(10 Mg + Ca) vs 10 K/(10 K + Na) (mg/kg) for hot spring (Giggenbach and Goguel 1989).

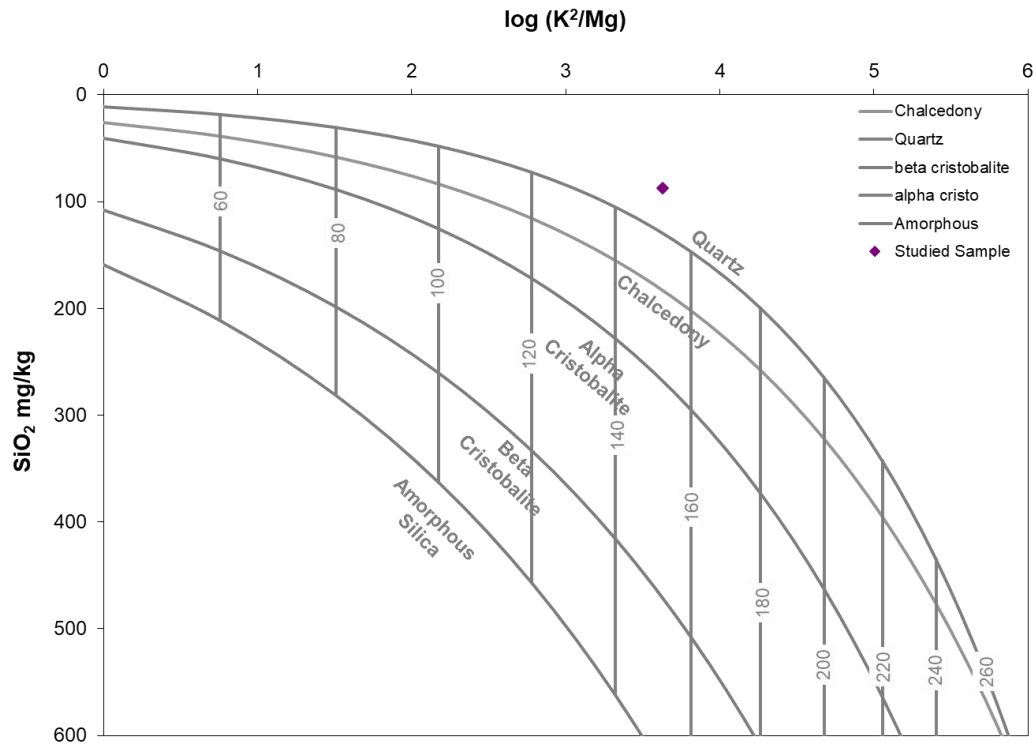


Figure 4.28 Geothermometer readings for the hot spring water samples, plotted as K^2/Mg versus Silica (Giggenbach, 1988).

4.3.3 Stable Isotope Geochemistry

The isotopic composition of hydrogen and oxygen in thermal springs is thought to be an efficient surrogate for determining the source of the water (Lambs et al., 2011). The three various types of origins of thermal water, namely magmatic, oceanic, and meteoric origins, can be distinguished by the δD and $\delta^{18}O$ values for waters. Table 4 illustrate the data for the δD and $\delta^{18}O$ isotopes in the thermal waters under investigation. The levels of $\delta^{18}O$ in the water samples have been recorded as spanning a range from -2.84 to -3.38. These values are expressed in per mil (‰) units relative to a standard reference material, and they represent the ratio of the heavy $\delta^{18}O$ isotope to the lighter $\delta^{16}O$ isotope in the water. The range of values suggests that the water samples have a relatively consistent isotopic composition, with only a small variation in $\delta^{18}O$ content. This could indicate that the water samples were sourced from a similar location, or that they have undergone similar isotopic fractionation processes. Conversely, the range of δD values in the water samples

is from -12.36 to 15.21. These values are also expressed in ‰ units relative to a standard reference material, and they represent the ratio of the heavy $\delta^2\text{H}$ isotope to the lighter ^1H isotope in the water. The large range of values indicates a greater degree of isotopic variability in the water samples compared to the $\delta^{18}\text{O}$ values. This variability could be due to several factors, such as differences in source water or variations in the isotopic fractionation that occurred during the water's movement through various systems.

Even though the range of results for the two isotopes varied, all of the geothermal water samples lie on the global meteoric trend line (GMWL), which suggests that meteoric water is the primary source of geothermal water recharge (Rafiq et al., In Submission) (Figure 4.29). This is a line that represents the relationship between δD and $\delta^{18}\text{O}$ in precipitation samples from around the world. There are a variety of factors that can affect the isotopic compositions of meteoric water, including the temperature and humidity levels that existed at the time of the precipitation, as well as the geographic location of the precipitation.

Table 4.6 Stable isotope data for three representative thermal spring water (Rafiq et al; In Submission).

Sample ID	Latitude (°N)	Longitude (°E)	Altitude (m)	δD (‰)	$\delta^{18}\text{O}$ (‰)
AH-01	20°27'41"	40°28'17.5"	166	-15.21	-3.38
AH-03	20°27'41.5"	40°28'13"	163	-12.75	-2.88
AH-05	20°27'40"	40°28'11.5"	162	-12.36	-2.84

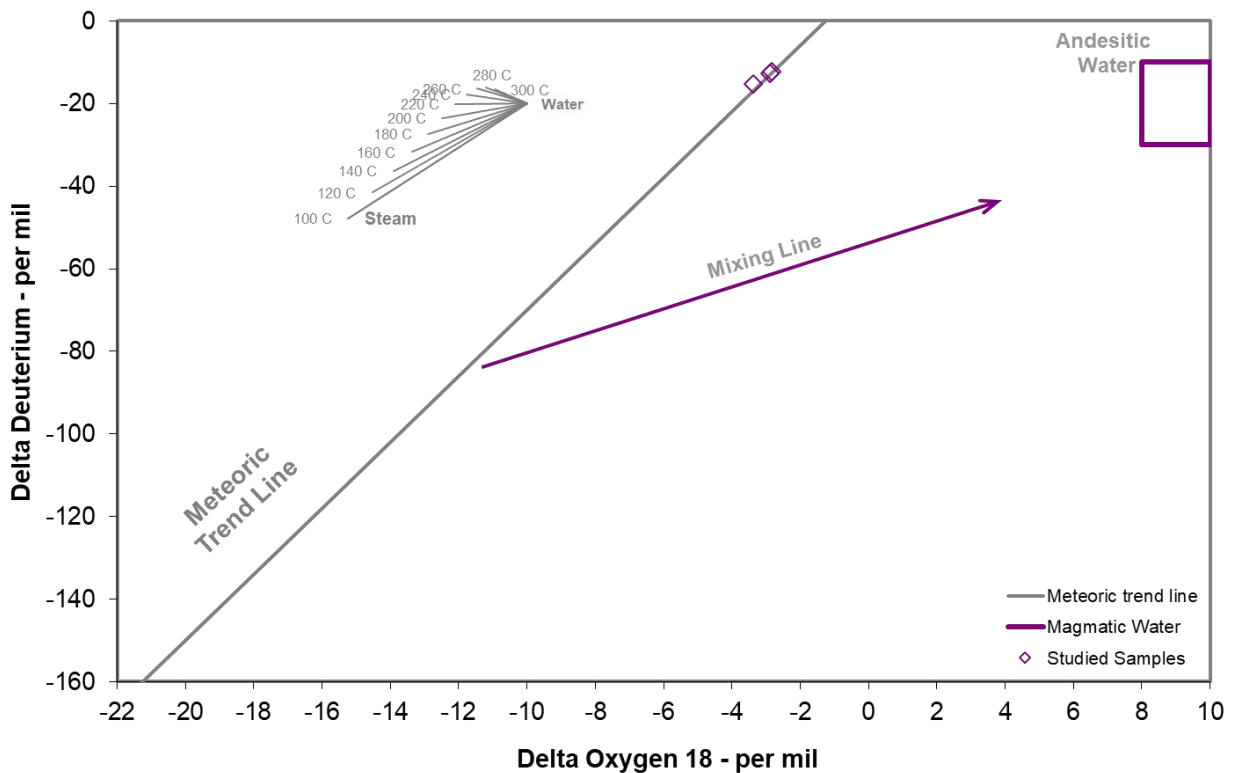


Figure 4.29: $\delta^{18}\text{O}$ - $\delta^2\text{H}$ diagram for the water samples (Purple squares) in the research area. Grey solid line represents Global meteoric water trend line (GWML) and purple line represents magmatic water (Rafiq et al., 2023; In Submission).

4.3.4 Evolutional conceptual model for Geothermal system

The Ain Al-Harrah thermal spring is a perennial hot spring that ranges in temperature from medium to high. Despite being situated in an area of volcanic activity, there is no indication that the thermal spring is connected to any recent or ongoing volcanic activity. The heat source for the geothermal spring is likely due to the slightly elevated geothermal gradient and the presence of high heat-generating post-tectonic granites in the region. Based on the hydrochemical analysis of the spring, the thermal water is mainly originated from meteoric water, which infiltrated the ground and got heated up as it rose to the surface through fractures or deep faults (Fig. 30). During its ascent, the interaction with silicate rocks, and to a lesser extent, igneous rocks and dikes, led to the production of HCO_3^- . On the other hand, SO_4^{2-} was probably formed due to the dissolution of

sulphate minerals like gypsum or sulphide minerals such as pyrite present in the host rock. When heated water enters a shallow up flow zone, it mixes with cold peripheral water through fractures.

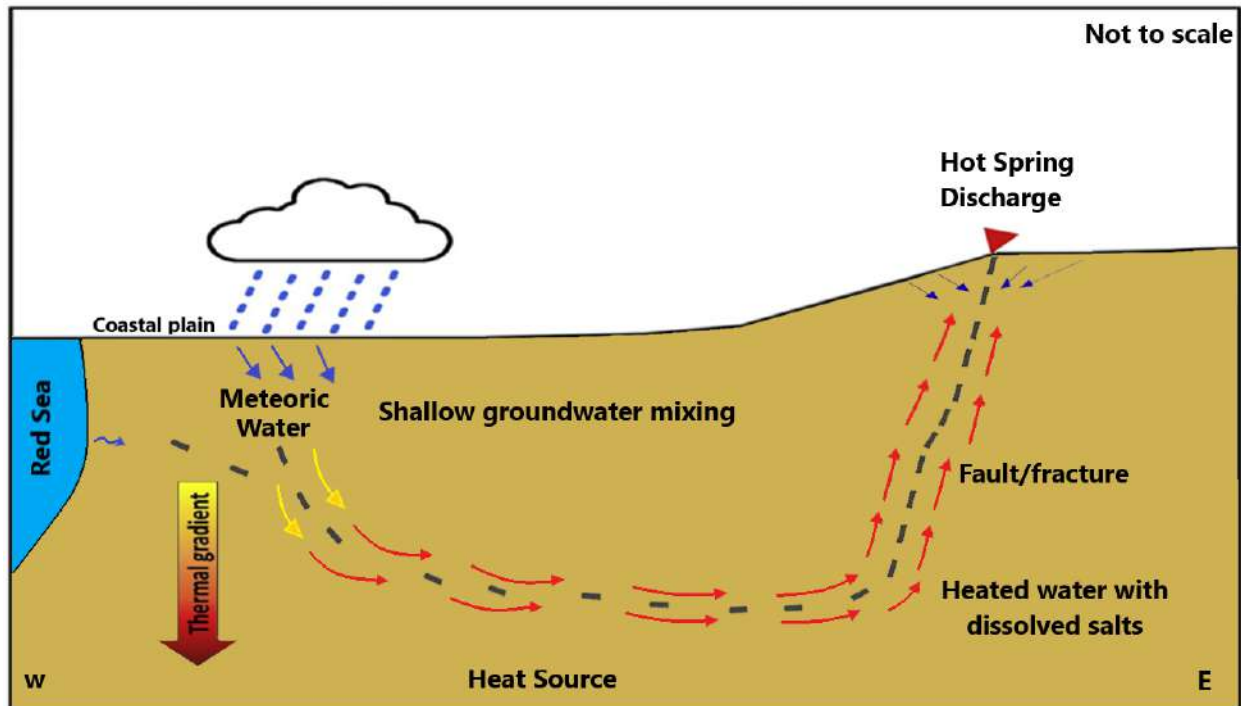


Figure 4.30: A conceptual schematic was developed to depict the model for the thermal spring in the study area. (Rafiq et al., 2023; In Submission).

CHAPTER 5

Discussion

The integration of data from different sources is crucial in building a reliable and accurate model of a geothermal systems. The integration of data from remote sensing, rock and fracture geochemistry, and hydrogeochemistry allows for a more detailed understanding of the geothermal system in the Al-Lith area. Remote sensing data can identify surface features that may be indicative of subsurface geology, and in this case, the identification of high permeable zones is useful for geothermal exploration. However, remote sensing data alone cannot provide information on the physical and chemical properties of the subsurface, such as lithology, mineralogy, and reservoir temperature. Thus, in order to better understand the whole geothermal system and have a thorough characterization of the area's geothermal potential, rock and fracture geochemistry, and hydrochemistry were utilized.

5.1 Analysis of Surface and Subsurface Structural Lineaments

A comparison of the results with existing geological maps and structural diagrams of various maps was carried out to determine the mapping, structural analysis, and structural interpretation of the study area. The ArcGIS software was used to produce the geological and structural map; it is observed that the study area has a variable lithological composition and structural constraints. The overlay of this geological and structural map with LANDSAT-8 satellite and DEM data from the research area aids in extracting and mapping various surface structural lineaments, such as faults, folds, and fractures. The structural lineaments derived from these images are usually precisely overlaid or only slightly shifted concerning the structural elements of the field or its prolongation. The mismatch between the satellite image and geological

lineaments can be explained by re-sampling and geo-coding, which produces some image imprecision and changes in the scale and projection system. Some favored orientations such as N-S, NE-SW, and NW-SE can be seen in the satellite images and DEM data. However, the order of length varies on the final synthetic lineament's extraction map. Other maps, such as the lineament density map, indicate that the studied areas vary in the density of structural lineaments. Generally, the lineaments-oriented NE-SW across the study area represent the major lineaments. Moreover, the 3D topographic model allowed us to attain a better insight into lithological and structural units in the research area. Data collected from the field indicated that the faults and fractures mapped in the study area show a general NW-SE trend (Figure 4.9), which is in line with the orientation of part of both manually and digitally extracted lineaments (Figures 4.3 and 4.4). Field data also allowed the evaluation of the accuracy of the imagery data and provided evidence that the main structures in the study area cut the land surface and show a NW-SE orientation (Figures 4.7 & 4.8), causing groundwater to form structural fissures and circulation of hot water through the fractures and fissures after heating, possibly by magma. Lineaments extracted from the subsurface using aeromagnetic data show a general NW-SE trend which is consistent with the trend of most of the surface lineaments extracted manually and digitally and the fractures mapped in the field. The five identified subsurface lineament density zones show a very good correlation with the surface lineaments density zones identified in the same area on the surface using remote sensing and ground truthing techniques, particularly between Zones A, B, E, I, and J on the surface and Zones A, D and partially E in the subsurface. This indicates that the subsurface fracture networks intersect and interact effectively in that areas with the surface fracture networks allowing the circulation of thermal fluids in the geothermal system. This high connectivity among both surface and subsurface fracture networks is crucial in the design, assessment, and development of the geothermal reservoir. On the other hand, in the southern part of the study area (away from the

thermal spring; surface manifestations and closer to the coastal plain), the correlation between the densities of surface and subsurface lineaments is weak. The high lineament density Zone B can only be seen in the subsurface, while on the surface the data shows low to moderate lineament density. This might be attributed to the impact of the uplift that mostly affected the areas close to the thermal spring (reflected by the high mountains).

5.2 Rock/Fracture Geochemistry

Rock and fracture geochemistry data provide information on the composition and characteristics of the rocks in the study area. This information is important for understanding the sub-surface geology, as different rock types have different physical and chemical properties that can affect geothermal resource potential. For example, granitic rocks are often associated with high-temperature geothermal systems, while metamorphic rocks may be more suitable for low-temperature systems. The identification of highly altered rock mineral grains that are deformed and altered may indicate areas of structural weakness and potential fluid pathways. The analysis shows that the rocks are composed of granitic and low-grade metamorphic rocks. The highly altered rock mineral grains and high degree of deformation, indicating that the rocks have undergone significant tectonic stresses and hydrothermal fluid circulations. The presence of secondary/ minerals such as epidote and chlorite are also an indicative of hydrothermal activity in the area. According to the minerals that have been identified by utilizing different geochemical techniques such as X-ray diffraction (XRD), Quantitative evaluation of minerals by and petrography, the Al-Lith geothermal field can be characterize as a medium to high temperature geothermal systems. The source of the heat within the area can be attributed to presence of granitic rocks in the area, shallow Moho's and high geothermal gradient in the area.

5.3 Hydrochemistry

Hydrochemistry data provide information on the origin and properties of the geothermal fluids, which is essential for understanding the geothermal system's behavior. Carbonate type facies suggest that the geothermal fluids have undergone chemical interactions with the surrounding rock, which can influence the fluid's chemical and physical properties, such as pH, salinity, and mineral content. The geochemical analysis was used to identify the geothermal fluids within the fractures, and the results indicated that the fluids are of a meteoric origin. The identification of the water's origin as meteoric and the path it takes to ascend to the surface through faults helps to identify potential areas of fluid upwelling and surface manifestations of geothermal activity. Finally, the determination of the reservoir temperature is crucial for understanding the potential of the geothermal resource. In this study, different geothermometers such as cation and Silica based geothermometer are used to estimate the reservoir temperature, and the results show that the temperature ranges from 150 - 205°C. This information is essential for determining the suitability of the geothermal resource for power generation and estimating the potential energy output.

The implications of this research are significant for the sustainable operation of the geothermal power plant in Al-Lith. The identification of the major fault zones and fracture systems that intersect with the geothermal reservoir can be used to optimize the placement of geothermal wells and enhance the efficiency of the geothermal system. Additionally, the information about the mineralogical and geochemical composition of the rocks and fractures can be used to improve reservoir modeling and enhance the understanding of fluid flow within the reservoir. Finally, the information about the chemical composition of the geothermal fluids and their sources can be used to improve the management of the reservoir and ensure its long-term sustainability.

CHAPTER 6

Conclusions

The Western continental margin of Saudi Arabia is characterized by geothermal systems that are associated with Harrats and high-heat-producing granites. These systems have evolved in conjunction with the tectonic and magmatic transformations of the Arabian shield's western continental margin. Al-Lith region is considered one of the auspicious geothermal targets, consists of two major hot springs of Ain Al Harrah and Ain Al-Markub with surface temperatures of 79°C and 46°C respectively. The area is present at a divergent plate boundary, and source of heat for the geothermal system is thought to be associated with Red sea rifting, the presence of Harrats and radioactive minerals within granitic rocks.

This dissertation provides a detailed investigation of a geothermal field located in Al-Lith, Saudi Arabia, utilizing an integrated approach that combines remote sensing, rock and fracture geochemistry, and hydrochemistry. By combining these different methods, the study aimed to provide a comprehensive understanding of the field's structure and characteristics, which are essential for the development of geothermal resources.

The remote sensing analysis used in this study involved the interpretation of satellite images to identify geological structures such as faults and fractures. Specifically, this research was focused to analyzed the density of the structural lineaments and prepared a knowledge base for the Al-Lith area using integrated, geological, remote sensing, field mapping, and geophysical techniques. Throughout this study, major and minor lineaments have been extracted both manually and digitally. The extracted lineaments have a broad trend, length (ranging from 23.5m to 1594m), and density range (from 0.48 to 5.35, characterized by very low to very high density, respectively).

The structural features delineated in the study area show a NW-SE general trend, while the extracted lineaments have NE-SW, N-S, and NW-SE main trends. Moreover, the findings demonstrate a positive relationship between the structural elements mapped (faults, fractures, and folds) and the dominating orientations of extracted major lineaments. Structural lineament analysis helped to identify the high fault fracture density zones in the study area, representing the zones of the potential high permeable zones associated with hot springs present in the area. This, in turn, allowed the characterization and delineation of the potential area as a target for geothermal exploration (Zones A and B, combined, and Zone B based on surface lineament density analysis, equivalent to Zones A and E in the subsurface). This information was critical as fractures and faults act as pathways for the circulation of geothermal fluids, making them an essential element in the design and development of geothermal systems.

The rock and fracture geochemistry analysis focused on identifying the petrographic, mineralogical and geochemical characteristics of the rocks in the geothermal field. Petrographic and mineralogical investigation of the study area shows the presence of medium to high temperature minerals and high degree of mineral alteration. Geochemically, the studied rock samples show significant similarity in composition, that can be expressed as comparable ranges of the major, minor and trace elements as well as major oxides. Hence the chemical similarity of the rocks suggested that they are genetically related to each other, and are result of similar magmatic processes. According to rock and fracture geochemistry, the Al-lith area can be classify as a medium-high enthalpy geothermal system due to the abundance of medium to high temperature hydrothermal altered minerals. Additionally, the presence of specific minerals such as zeolites, which are indicative of high-temperature hydrothermal systems, further supported the potential for geothermal resources in the study area. Thus, the Al-Lith geothermal system has direct relevance to applications in domestic and industrial power generation system.

Finally, the hydrochemistry analysis involved the analysis of geothermal fluids to identify their composition, temperature, and origin. In this regard, a detail and comprehensive investigation of the thermal water from hot spring (Ain Al-Harrah) in the Al-Lith region was conducted using various techniques, including chemical composition analysis, geothermometry, stable isotope analysis, and major ions and trace element analysis. The analysis revealed that the thermal water has a low to moderate level of total dissolved solids (TDS) and a mildly alkaline pH, and is predominantly of the sodium-bicarbonate type, providing evidence that the thermal fluids are circulating within the underlying basement rocks. The chemical composition of the thermal springs was found to be distinct from that of steam heated groundwater, indicating that the springs have their own unique characteristics. The use of geothermometers yielded comparable temperature predictions, with a reservoir temperature estimated to be between 150 and 205 °C. Furthermore, the δD and $\delta^{18}O$ stable isotope compositions of the thermal water pointed to a meteoric origin for the hydrothermal system, with precipitation responsible for recharging the thermal water supply. Based on the analysis of the major ions, trace elements, stable isotopes, and geological features of the area, the thermal spring are associated with shallow, low-concentration hydrothermal systems that are controlled by faults. The heat source for the thermal springs is likely provided by a slightly high geothermal gradient and high heat-generating post-tectonic granites. The findings collectively suggest the existence of an established geothermal system in the Al-Lith region, and further exploration and research of this resource may be warranted to unlock its potential as a sustainable energy source. This information is critical for understanding the geothermal system's characteristics and assessing its potential for development.

Overall, the integrated approach used in this study provided a comprehensive understanding of the geothermal field's structure and characteristics in Al-Lith, Saudi Arabia. The findings of this study have significant implications for the development of geothermal resources

in the region, which could contribute to the country's renewable energy goals and reduce its dependence on fossil fuels. Additionally, the integrated approach used in this study can serve as a framework for future studies in other geothermal fields around the world, aiding in the development of sustainable geothermal energy resources.

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Vitae

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ACADEMIC BACKGROUND

2014 – 2018 :**Bachelor of Science (Earth Sciences Major in Geology)**
Earth Sciences Department, Comsats University Islamabad,
Abbottabad Campus, Pakistan
2019 – 2021 :**Master of Science (Geology)**
Earth and Environmental Science Department (E & ES), Bahria
University Islamabad Campus, Pakistan
2021 – 2023 :**Master of Science (Geology)**
Geoscience Department, King Fahd University of Petroleum and
Minerals, Dhahran, Saudi Arabia

PUBLICATIONS

Journal Publications

1. Jawad Rafiq, Israa S. Abu-Mahfouz, Konstantinos Chavanidis, Pantelis Soupios, M. Idrees Farooqui. High Permeability Zone Delineation in a Geothermal Field: An Integrated Surface-Subsurface Structural Lineament Density Analysis in Western Arabian Plate (Al-Lith, Saudi Arabia). *Geothermal Energy* (IF; 3.92) - under review
2. Jawad Rafiq, Israa S. Abu-Mahfouz, Pantelis Soupios, Daffa Arrofi. Geochemical Analysis of the Potential Geothermal Field, Al-Lith Western Saudi Arabia. (In Preparation).
3. Jawad Rafiq, Israa S. Abu-Mahfouz, Pantelis Soupios, John D. Humphrey, Bassam S. Tawabini. Hydrochemical characterization of Ain Al-Harrah hot spring and its relationship to the geothermal system, Western Arabian Plate (Al-Lith Saudi Arabia). (In Submission).

Conference Papers/Presentations

1. Geothermal Potential Identification based on Remote Sensing and Fault Fracture Density (FFD) Techniques, Western Arabian Plate (Al-Lith, Saudi Arabia), MEOS-GEO, February 2023.

AWARD

Gold Medalist in BS from Comsats University Islamabad Abbottabad Campus, Pakistan; 2018.