

**LINEAMENT DENSITY ANALYSIS FOR
INVESTIGATING HIGH PERMEABLE ZONES IN NON-
VOLCANIC GEOTHERMAL SYSTEMS: CASE STUDIES
FROM SAUDI AND INDONESIAN NON-VOLCANIC
GEOTHERMAL FIELDS**

BY

DAFFA ARROFI

A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

GEOLOGY

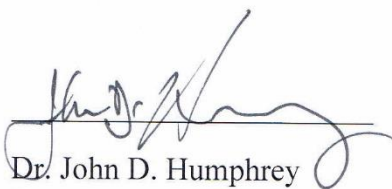
DECEMBER 2023

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

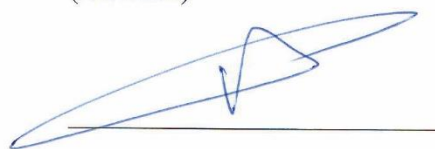
DEANSHIP OF GRADUATE STUDIES

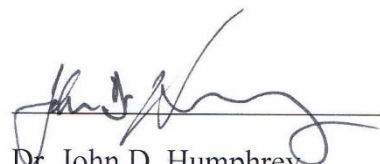
This thesis, written by **DAFFA ARROFI** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN GEOLOGY**.


Dr. John D. Humphrey
Department Chairman


Prof. Suliman Saleh Al-Homidan
Dean of Graduate Studies


Dr. Israa S. Abu-Mahfouz
(Advisor)


Prof. Pantelis Soupios
(Member)


Dr. John D. Humphrey
(Member)

Date



© Daffa Arrofi

2023

Dedication

To my beloved parents and sisters

ACKNOWLEDGMENTS

In the name of Allah, the most gracious, most compassionate, most merciful, and all the praises and thanks be to Allah that have given me the opportunity and capability to finish my study at KFUPM.

In general, I would like to express my heartfelt gratitude to all those who have supported and guided me throughout the research and writing of this thesis.

I would like to express my deep appreciation to my thesis Advisor, Dr. Israa S. Abu-Mahfouz, for her support, encouragement, patience, invaluable insights, and dedication almost over the past two years. Your mentorship has been instrumental in shaping this work.

I would like also to thank my thesis committee members, Prof. Pantelis Soupios, and Dr. John D. Humphrey, for their support and sharing their valuable feedback which greatly improved the quality of this thesis.

My thanks go to the remote sensing and digital services team, Mr. Jarvis Cline, Mutaz Al-Jafari, and Mr. Mohamed Al-Ghamdi for helping me collect the data from the field and generate the digital outcrop model for my fracture observation and analysis.

My sincere appreciation goes to my friends for their continuous encouragement and understanding during this academic journey. Your emotional support was a constant source of motivation. Thanks also to the KFUPM Indonesian community that I cannot mention one by one the names. Big thanks to Mr. Jawad Rafiq for helping me collect the data on the field.

Last but not least, thank you to my wonderful family: my parents, Papa and Mama, for their endless prayer, love, and support; my sister, Mbak Della, for keeping my spirit during this master journey.

Lastly, I extend my gratitude to all of the staff, faculty members, and professors, who help me throughout my academic journey at CPG-KFUPM.

My master's journey and thesis project were fully funded by the CPG KFUPM and King Fahd University of Petroleum and Minerals.

TABLE OF CONTENTS

ACKNOWLEDGMENTS	V
TABLE OF CONTENTS	VII
LIST OF TABLES.....	X
LIST OF FIGURES.....	XI
LIST OF ABBREVIATIONS	XV
ABSTRACT	XVI
ملخص الرسالة.....	XVIII
CHAPTER 1 INTRODUCTION.....	1
1.1 Background	1
1.2 Problem Statements	5
1.3 Objectives and Research Questions	7
CHAPTER 2 LITERATURE REVIEW.....	9
2.1 Northern Konawe Geothermal Field, Indonesia	9
2.1.1 Geological Framework.....	9
2.1.2 Geothermal Potential in Sulawesi	13
2.2 Jizan Geothermal Field, Saudi Arabia	15
2.2.1 Geologocical Framework	15
2.2.2 Geothermal Potential in Jizan.....	19
CHAPTER 3 METHODOLOGY.....	21
3.1 Lineament Analysis	21

3.2	Ground Truthing	24
3.3	Hydrochemical Analysis of Hotsprings	25
CHAPTER 4 RESULTS.....		28
4.1	Northern Konawe Geothermal Field, Indonesia	28
4.1.1	Lineament and Fault Length Statistical Analysis	28
4.1.2	Lineament and Fault Orientation	32
4.1.3	Lineament and Fault Density	33
4.1.4	Fracture Observation in Outcrop.....	36
4.2	Jizan Geothermal Field, Saudi Arabia	42
4.2.1	Lineament and Fault Length Statistical Analysis	42
4.2.2	Lineament and Fault Length Orientation.....	46
4.2.3	Lineament and Fault Density	47
4.2.4	Fracture Observation in Outcrop.....	49
4.2.5	Hydrochemical of Hotsprings	54
CHAPTER 5 DISCUSSIONS		58
5.1	Northern Konawe Geothermal Field, Indonesia	58
5.1.1	High Permeable Zone	58
5.1.2	Geothermal Prospect Area	62
5.2	Jizan Geothermal Field, Saudi Arabia	63
5.2.1	High Permeable Zone	63
5.2.2	Geothermal Prospect Area	68
5.3	Implications of Lineament Analysis for Non-volcanic Geothermal Exploration	72
5.3.1	Delineating High Permeable Zones.....	72
5.3.2	Predicting Fluid Flow in Geothermal Systems.....	77

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS	79
6.1 Conclusions.....	79
6.2 Recommendations	80
REFERENCES	82
VITAE	90
LIST OF PUBLICATIONS AND PRESENTATION GENERATED FROM THIS THESIS	92

LIST OF TABLES

Table 4.1	Automatically extracted lineaments, manually extracted lineaments, and fault length descriptive statistics in Northern Konawe.	31
Table 4.2	Ground truthing fracture measurements in Northern Konawe.	40
Table 4.3	Automatically extracted lineaments, manually extracted lineaments, and fault length descriptive statistics.....	45
Table 4.4	Ground truthing fracture measurements in Jizan.	52
Table 4.5	In situ physicochemical measurement of hot springs	54
Table 4.6	Hydrochemical composition of hydrothermal samples collected from Al Ardah hot springs. Jizan.....	56
Table 5.1	The ratios of different chemical elements with their respective indicator of the physical processes (Arrofi <i>et al</i> , 2023).	70

LIST OF FIGURES

Figure 1.1 Illustration of a non-volcanic geothermal system (Moeck, 2014).	4
Figure 1.2 Typical uncertainty and expenditure profile for a geothermal project (IGA, 2014).....	7
Figure 2.1 Study case area in the northern Konawe, Southeast Sulawesi, Indonesia.	11
Figure 2.2 (a) Tectonic map of Southeast Sulawesi, including Lawanopo Fault Systems (Simandjunta <i>et al.</i> , 1993; Surono and Simandjuntak, 1993; Tjokrosapoetra <i>et al.</i> , 1993; Martosuwito, 2012). Rectangle with black outline shows the study area (b) Geological map of the northern part of the study area (after Rusmana <i>et al.</i> , 1993). The rose diagram was generated based on interpreted faults by Rusmana <i>et al.</i> (1993).	12
Figure 2.3 Geothermal locations in the southeastern arm of Sulawesi (Idral, 2010).....	14
Figure 2.4 Geothermal surface manifestation in the northern Konawe (Jaya <i>et al.</i> , 2021). A and B are located in Wawolesea Village. C and D are located in Toreo Village... ..	15
Figure 2.5 (a) Types of geothermal systems along the Arabian Shield of Western Saudi Arabia (modified from Chandrasekharam <i>et al.</i> , 2014; Lashin & Al Arifi, 2014a). (b) The true color of Landsat 8 image view of the study area. The red circles show the locations of the hot springs in the study areas.....	17
Figure 2.6 (a) Geological Map of Jizan (modified from Fairer, 1985; Blank <i>et al.</i> , 1987; Oelkers <i>et al.</i> , 2022). (b) Geological cross-section of A-B along the red line of the geological map (modified from Oelkers <i>et al.</i> , 2022).. ..	18

Figure 2.7 (a) Highly fractured granite rock and whole structural pattern in Al Khouba. (b) Altered granitic rocks due to interaction with thermal water (Lashin and Al Arifi, 2014).....	20
Figure 3.1 Multidirectional hill shade of DEM STRM (a) Northern Konawe. (b) Jizan...	23
Figure 3.2 Hotsprings in Al Ardah Area, Jizan. (a) HS-1. (b) HS-2....	26
Figure 3.3 Study Flowchart.....	27
Figure 4.1 (a) Histogram showing the lengths of the automatically-extracted lineaments in Northern Konawe, (b) histogram showing the lengths of the manually-extracted lineaments, (c) histogram showing the lengths of the faults mapped.....	30
Figure 4.2 Log-log plot of lineament length versus cumulative frequency in Northern Konawe	31
Figure 4.3 Rose diagrams show the orientation of the extracted lineaments and mapped faults in Northern Konawe. (a) Orientation of automatically-extracted lineaments, (b) orientation of manually-extracted lineaments, (c) orientation of faults mapped/interpreted from literature (fracture data taken from Rusmana <i>et al.</i> , 1993).	32
Figure 4.4 The lineaments and faults density map in Northern Konawe. (a) Automatically-extracted lineament density map, (b) manually-extracted lineament density map, (c) fault density map.....	35
Figure 4.5 Location of outcrops observed in the Northern Konawe, Indonesia.	39
Figure 4.6 Fracture observed in Northern Konawe, Indonesia. (a) Carbonate veins observed in GT-2. (b) Schematic drawing of GT-2. (c) The crosscutting	

relationship observed in GT-4. (d) Schematic drawing of GT-4. (e) The crosscutting relationship of two silica vein sets observed at GT-8 (f) The N-S open fracture observed at GT-7 (g) rose diagram of measured fractures in Northern Konwe. (h) Histogram of dip angle distribution of fractures in Northern Konawe.....	41
Figure 4.7 (a) Histogram showing the lengths of the automatically-extracted lineaments in Jizan, (b) histogram showing the lengths of the manually-extracted lineaments, (c) histogram showing the lengths of the faults mapped in Jizan.	44
Figure 4.8 Log-log plot of lineament length versus cumulative frequency in Jizan.....	45
Figure 4.9 Rose diagrams show the orientation of the extracted lineaments and mapped faults in Jizan. (a) Orientation of automatically-extracted lineaments, (b) orientation of manually-extracted lineaments, and (c) orientation of faults mapped/interpreted from literature (Oelkers <i>et al.</i> , 2022).....	46
Figure 4.10 The lineaments and faults density map in Northern Konawe. (a) Automatically-extracted lineament density map, (b) manually-extracted lineament density map, (c) fault density map... ..	48
Figure 4.11 Ground truthing area with outcrops observed and hot spring sampling locations in Jizan, Saudi Arabia.....	49
Figure 4.12 Fracture observed in Al Ardah, Jizan. (a) conjugate opening fractures on the basalt at OC-2. (b) conjugate opening fractures on the basalt at OC-3. (c) veins were sheared due to the development of younger opening fractures at OC-4. (d) NNW-SSE opening fractures at OC-6, (e) Relatively highly dense	

crosscutting relationship on granite at OC-7. (f) vein was crosscut by the NNW-SSE opening fracture on granite at OC-7. (g) rose diagram of measured fractures in Al Ardah, Jizan. (h) Histogram of dip angle distribution of fractures in Al Ardah, Jizan.....	53
Figure 4.13 Cl-SO ₄ -HCO ₃ ternary diagram showing the type of thermal water.....	57
Figure 4.14 $\delta^{18}O$ vs δD of thermal water samples....	57
Figure 5.1 Fuzzy overlay map of lineaments (automatically-, and manually-generated lineaments) and faults in Northern Konawe geothermal system, Indonesia....	60
Figure 5.2 Geological map of Northern Konawe with the identified permeable zones... .	61
Figure 5.3 Fuzzy overlay map of lineaments (automatically-, and manually-extracted lineaments) and faults in the Jizan geothermal system, Saudi Arabia.....	66
Figure 5.4 (a) Geological map of Jizan with the identified permeable zones. (b) Geological map of ground-truthing area with permeable zone (Zone B) and fracture observation locations.....	67
Figure 5.5 Conceptual model of a geothermal system in Al Ardah, Jizan, Saudi Arabia (modified from Arrofi <i>et al.</i> , 2023; Blank <i>et al.</i> , 1987).....	71
Figure 5.6 The lineaments and faults density map in Jizan with ground-truthing location. (a) Automatically-extracted lineament density. (b) Manually-extracted lineament density. (c) Fault density. (d) Fuzzy 'AND' overlay.....	76

LIST OF ABBREVIATIONS

DEM : Digital Elevation Model

SRTM : Shuttle Radar Topography Mission]

ABSTRACT

Full Name : Daffa Arrofi

Thesis Title : Lineament Density Analysis for Investigating High Permeable Zones in Non-Volcanic Geothermal Systems: Case Studies from Saudi and Indonesian Non-volcanic Geothermal Fields

Major Field : Geology

Date of Degree : December 2023

Geothermal energy presents a promising and sustainable source of energy that has the potential to power the rapidly expanding economies of Indonesia and Saudi Arabia, which are distinguished by extensive geothermal fields. The identification of high permeable zones within a geothermal reservoir is a critical factor for successful development. This study conducted an extensive analysis of two non-volcanic geothermal fields, namely Northern Konawe in Indonesia and Jizan in Saudi Arabia. The study utilized both manual and digital analytical techniques of remotely sensed data to extract lineaments, faults, and fractures. The extracted lineaments were then analyzed to determine their orientation, length distribution, and density in each study area. The analysis of the remote sensing results was validated using field ground truthing observations and fracture measurements within the study areas. The study also employed the fuzzy "AND" overlaying method to recognize high surface fracture density areas that are not directly connected with the high permeable zone, that proves to be a powerful method for preliminary explorations. The study identified three permeable zones in the Northern Konawe Geothermal Field: Zone A near Lasolo, Zone B between Meluhu and Lembo, and Zone C around Amonggedo. Similarly, the Jizan Geothermal Field exhibited three permeable zones: Zone A in the northwestern part of Bani Malik, Zone B in the

eastern area of Al Ardah, and Zone C between Al Ardah and Al Khouba. Zone B was identified as the most promising geothermal area for geothermal development in both cases. This study provides valuable insights into the exploration and development of non-volcanic geothermal fields, which could help meet the growing demand for clean energy and reduce carbon emissions

ملخص الرسالة

الاسم الكامل: دافا عرفي

عنوان الرسالة: تحليل كثافة الخطوط لدراسة المناطق عالية النفاذية في أنظمة الطاقة الحرارية الأرضية غير البركانية: دراسات حالة من حقول الطاقة الحرارية الأرضية غير البركانية السعودية والإندونيسية

التخصص: جيولوجيا

تاريخ الدرجة العلمية: ديسمبر 2023

الاقتصادات سريعة النمو في تمثل الطاقة الحرارية الأرضية مصدرًا واعدًا ومستدامًا للطاقة لديه القدرة على دعم إندونيسيا والمملكة العربية السعودية، والتي تتميز بحقول الطاقة الحرارية الأرضية الواسعة. يعد تحديد المناطق ذات النفاذية العالية داخل خزان الطاقة الحرارية الأرضية عاملاً حاسماً لنجاح تطويرها. أجرت هذه الدراسة تحليلاً موسعاً لاثنتين من حقول الطاقة الحرارية الأرضية غير البركانية، وهما شمال كوناوي في إندونيسيا وجيزان في المملكة العربية السعودية. استخدمت الدراسة التقنيات التحليلية اليدوية والرقمية لبيانات الاستشعار عن بعد لاستخلاص الخطوط والصدوع والكسور. ثم تم تحليل الخطوط المستخرجة لتحديد اتجاهها وتوزيع الطول والكثافة في كل منطقة دراسة. تم التحقق من صحة تحليل نتائج الاستشعار عن بعد باستخدام الملاحظات الميدانية وقياسات " للتعرف على المناطق AND الكسور داخل مناطق الدراسة. استخدمت الدراسة أيضاً طريقة التراكب الغامضة " ذات الكثافة السطحية العالية للكسر والتي لا ترتبط مباشرة بالمنطقة عالية النفاذية، والتي تثبت أنها طريقة قوية للاستكشافات الأولية. حددت الدراسة ثلاث مناطق نفاذية في شمال كوناوي مجال الطاقة الحرارية الأرضية: المنطقة (أ) بالقرب من لاسولو، والمنطقة (ب) بين ميلوهو وليمبو، والمنطقة (ج) حول أمجيدو. وبالمثل، أظهر حقل جيزان للطاقة الحرارية الأرضية ثلاث مناطق نفاذية: المنطقة (أ) في الجزء الشمالي الغربي من بني مالك، والمنطقة (ب) في المنطقة الشرقية من العارضة، والمنطقة (ج) بين العارضة والخوبة. تم تحديد المنطقة باعتبارها منطقة الطاقة الحرارية الأرضية الواعدة لتطوير الطاقة الحرارية الأرضية في كلتا الحالتين. توفر هذه الدراسة رؤى قيمة حول استكشاف وتطوير حقول الطاقة الحرارية الأرضية غير البركانية، والتي يمكن أن تساعد في تلبية الطلب المتزايد على الطاقة النظيفة وتقليل انبعاثات الكربون.

CHAPTER 1

INTRODUCTION

1.1 Background

Geothermal energy represents the thermal energy (heat) stored in the subsurface of the Earth. The heat is derived from various sources, including the remaining primordial heat resulting from the planetary formation and the radiogenic heat generated through the radioactive decay of isotopes within the mantle and crust (Schubert *et al.*, 1980; Gando *et al.*, 2011). This energy is continuously being produced, making it a sustainable and renewable energy source (Owusu and Asumadu-Sarkodie, 2016). The geothermal gradient between Earth's high-temperature core and its colder surface facilitates a sustained heat transfer mechanism, predominantly through conduction and convection processes (Moeck, 2014; English *et al.*, 2023). The average surface heat flow is recorded at 65 mW m^{-2} in continental regions and 101 mW m^{-2} in oceanic regions, considering the global average at 87 MW m^{-2} (Pollack *et al.*, 1993). Old continental craton, characterized by its geological stability, exhibits a relatively low geothermal gradient. In contrast, regions characterized by active tectonism and volcanic activity display significantly higher geothermal gradients (Huttrer, 2020).

A geothermal system is characterized as a localized geological environment where extracting portions of the Earth's thermal energy is feasible by conveying natural or

artificially induced circulating fluids to the desired point of application (Moeck, 2014). Typical geothermal systems have three main components: a heat source, a permeable reservoir and a fluid capable of transporting thermal energy (Bogie and Lawless, 2000; Goff and Janik, 2000). There are two types of geothermal systems: volcanic and non-volcanic geothermal systems. The volcanic geothermal system is a highly dynamic and complex system that is characterized by the presence of active volcanoes and associated with volcanic activity (Vengosh, Helvaci and Karamanderesi, 2002; Möller *et al.*, 2004; Qin, Turner and Pang, 2005; Papp and Nițoi, 2006; Sanada, Takamatsu and Yoshiike, 2006). Such activity is often linked to the subduction of tectonic plates, resulting in the formation of magma chambers, thermal anomalies, and hydrothermal reservoirs that can be tapped for geothermal energy extraction.

In contrast, non-volcanic geothermal systems, such as those found in crystalline basement rocks, are characterized by the presence of granite intrusions and geological structures and faults (Yaguchi *et al.*, 2014). These intrusions and faults create fractures in the rock mass that facilitate fluid circulation and heat transfer. Non-volcanic geothermal systems are generally more stable than volcanic systems and are less affected by cyclic fluctuations in temperature and pressure.

Non-volcanic geothermal system may lack evidence of the occurrence of volcanic eruptions, but they are still characterized by the existence of thermal water or hot springs, which can indicate an active geothermal system (Wang *et al.*, 2016) (Figure. 1.1). The movement of thermal fluids is facilitated through faults, fractures, and contact between intrusive and surrounding rocks (Suryantini and Wibowo, 2010). Most non-volcanic geothermal systems fall under the category of low-medium enthalpy, with heat sourced

from the decay of radioactive elements in crystalline rocks, such as granitic rocks (Chandrasekharam *et al.*, 2014; Razdan, Agarwal and Singh, 2014; Wang *et al.*, 2016). Granitic rocks with high heat production commonly contain radiogenic heat-producing elements, including thorium (Th), uranium (U), and potassium (K) (Lashin *et al.*, 2014; Hasterok and Webb, 2017; Chandrasekharam and Baba, 2021). Metamorphic rocks also possess a high concentration of radiogenic elements, making them a viable heat source (Aisabokhae and Tampul, 2020). Moreover, specific regions exhibiting crustal thinning can produce high thermal gradients, making them particularly suitable for geothermal energy extraction (Moeck, 2014; Chandrasekharam *et al.*, 2015; English *et al.*, 2023).

Structural lineament analysis has proven to be a powerful tool in various fields of earth science research. It can be used in mineral exploration to identify potential mineral deposit locations and determine the orientation and intensity of deformation in the subsurface (Groves *et al.*, 2003; Liu *et al.*, 2019). Notably, lineament analysis using remote sensing techniques can provide critical insights into regional and subregional geological structures and improve our understanding of the underlying geological processes (Dasgupta and Mukherjee, 2019).

Any surface natural linear features on the Earth related to compression/extension/strike-slip movements or resulting from igneous or metamorphic activities might be defined and analyzed as lineaments (Prost, 2013). Structural lineaments mapped in the field usually reflect the subsurface structural phenomena (Allum, 1978).

Structural lineament analysis is a valuable technique used in the preliminary stage of geothermal exploration to identify the prospective geothermal reservoir, as permeability

is controlled by the density of lineaments, including fractures and faults (Grant *et al.*, 1982; Chen *et al.*, 2021). Although this technique has been applied in several fracture studies, including those focused on geothermal exploration (e.g., MacKnight IV *et al.*, 2004; Suryantini and Wibowo, 2010; Nahli *et al.*, 2016; Abuzied *et al.*, 2020; Arrofi *et al.*, 2022), only a few studies have used this technique in non-volcanic geothermal exploration (e.g., Suryantini and Wibowo, 2010; Nahli *et al.*, 2016; Arrofi *et al.*, 2022; Arrofi and Abu-Mahfouz, 2023).

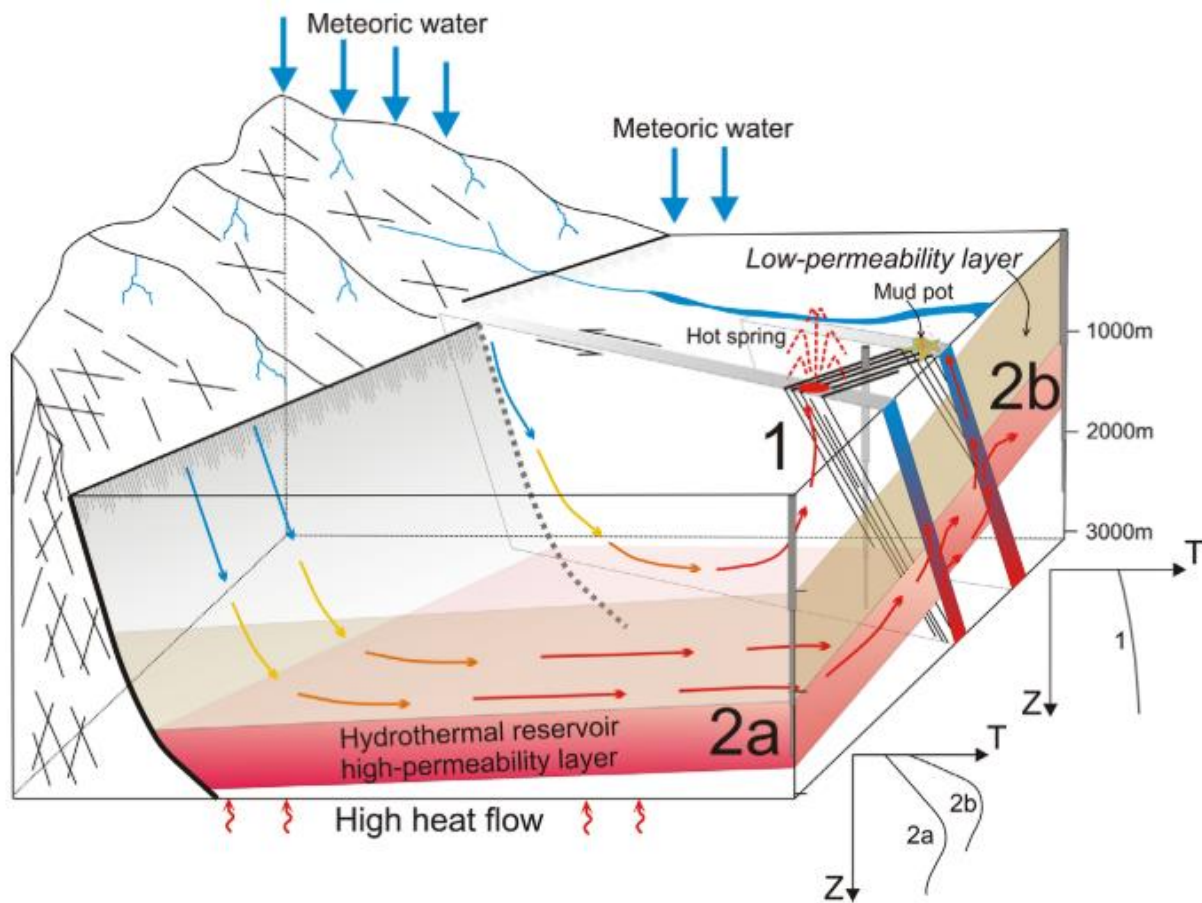


Figure 1.1 Illustration of a non-volcanic geothermal system (Moeck, 2014).

1.2 Problem Statements

Geothermal energy has become a prominent topic of discussion as the world moves towards reducing its reliance on fossil fuels and adopting renewable energy sources. Geothermal exploration is essential to uncovering the full potential of this renewable energy source and minimizing resource uncertainty (IGA, 2014) (Figure 1.2). To this end, a considerable amount of geothermal exploration efforts are being conducted worldwide, including in Indonesia and Saudi Arabia, which are known to host both volcanic and non-volcanic geothermal systems (Idral, 2010; Hochstein and Sudarman, 2015; Chandrasekharam *et al.*, 2016). However, exploration in non-volcanic geothermal systems remains limited in these countries. Moreover, geothermal energy in Saudi Arabia has not been well explored due to a lack of attention to this energy source in the past (Hashem and Abdullah, 2012). However, more recently, with the release of Vision 2030 by the Kingdom of Saudi Arabia, there has been a renewed effort to accelerate the transition to renewable energy, including geothermal energy (Vision 2030 Kingdom of Saudi Arabia, 2020). Therefore, geothermal exploration in both countries is critical to achieving the energy transition.

Among the various techniques employed in geothermal exploration, remote sensing for structural lineament analysis is increasingly utilized. Remote sensing analysis, including lineament density analysis, is essential in expediting the geothermal exploration process. Two techniques are commonly used for lineament extraction, manual and automated. Manual lineament extraction relies on human operators who use manual digitization and visual interpretation to identify lineaments and may

generate different outcomes based on the interpreter experience (Adiri *et al.*, 2017; Ahmadi and Pekkan, 2021; Sichugova *et al.*, 2021). Automated lineament extraction uses computer-assisted software to analyze digital images (Villalta Echeverria *et al.*, 2022), and depends on the parameter settings; different parameters generate different results. Therefore, both techniques may produce varying results, depending on the interpretation or the parameters employed. This uncertainty associated with the results generated by manual and automated lineament extraction techniques poses a challenge. These differences can affect the identified permeable areas, highlighting the need to integrate both techniques and support them with field mapping to improve the accuracy of the identified high permeable zones.

This study, therefore, attempts to establish the structural dataset for non-volcanic geothermal systems by analyzing the density of the structural features (lineaments, faults, and fractures) in the study areas and identifying zones with high permeability. It utilizes integrated manual-automated lineament extraction methods and ground truthing to investigate areas of high structural lineament densities (i.e. high permeable zones) in non-volcanic geothermal fields, with the ultimate goal of efficient and effective geothermal exploration.

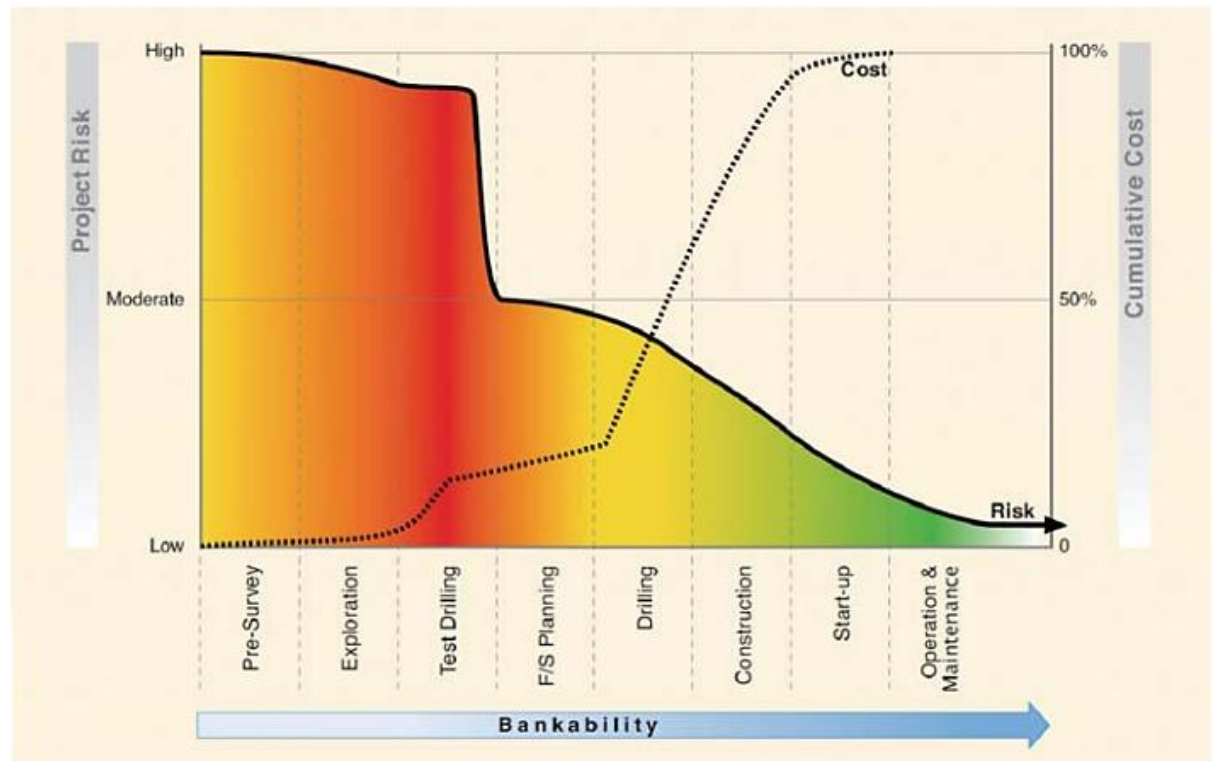


Figure 1.2 Typical uncertainty and expenditure profile for a geothermal project (IGA, 2014)

1.3 Objectives and Research Questions

The primary objective of this study is to examine the high permeable zones in two non-volcanic geothermal systems in Jizan (southwestern Saudi Arabia) and northern Konawe (Indonesia) using an integrated remote sensing lineament density analysis (of manually and automatically extracted lineaments) and field investigation. To achieve this goal, the following research questions will be addressed:

1. What is the surface spatial distribution and orientation of structural features, based on a comprehensive lineament analysis in both study areas?

2. How do the density and orientation of the lineaments identified through remote sensing lineament analysis compare with the fractures and faults mapped in the field?
3. What is the relative age of fractures and faults based on the analysis of crosscutting relationships?
4. What are the high permeable zones of the two case studies based on the analysis of fault and fracture density?
5. How reliable is the integration of lineament analysis (both automated and manual) with interpreted faults to delineate high permeable zones in non-volcanic geothermal systems?]

The answers to these research questions will enable us to better understand the high permeable zones in non-volcanic geothermal systems in Jizan, Saudi Arabia, and northern Konawe, Indonesia, which are critical for efficient and effective geothermal exploration. By examining the distribution, orientation, and age of structural features, and the reliability of integrating lineament analysis and interpreted faults, this study will contribute to a more comprehensive understanding of the potential of non-volcanic geothermal systems and support the transition to renewable energy.

CHAPTER 2

LITERATURE REVIEW

2.1 Northern Konawe Geothermal Field, Indonesia

2.1.1 Geological Framework

Sulawesi is located at the intersection of three major plates; the Indo-Australian, Pacific, and Eurasia (Nahli *et al.*, 2016). Hence, it experiences active tectonism, developing volcanic and non-volcanic geothermal systems (Nahli *et al.*, 2016). Most non-volcanic geothermal systems are spatially distributed in the central, south, and southeast parts of Sulawesi (Idral, 2010). Specifically, one of these systems is situated in the northern region of Konawe (Figure 2.1).

Two major tectonic events occurred during the Cenozoic in Sulawesi (Sompton, 2012). The first was the rifting and opening of the oceanic crust during the Paleogene in the western part of Sulawesi, and the second was the compressional event starting in the Miocene. This compression was influenced by continental collisions to the west, and ophiolite and island arc fragments to the east (Sompton, 2012). Calvert and Hall (2003) suggested that the collision affected the tectonic events in all parts of Sulawesi.

The main structures developed due to collision in the Southeast arm of Sulawesi are the Lawanopo fault system, the Konawe fault system, the Matarombeo fault, the Kolaka fault, and many others (Hamimu *et al.*, 2019). Among them, the main fault system within

the study area is the Lawanopo Fault, where the main structure formed was the shear faulting (Figure 2.2.a).

Idral (2010) suggests that active tectonic events probably control the geothermal system in the southeast arm of Sulawesi. In addition, the predominant geological structures crucial for the manifestation phenomenon area is characterized by the NW-SE and NE-SW fault strike orientation (Nahli *et al.*, 2016). The intersections of the faults increase the rock permeability, creating the pathway for the upward movement of hydrothermal fluid from the subsurface to the surface (Anna Yushantarti and Rezky, 2014).

Four central lithological units lie in the study area; these are (from the older to younger) Paleozoic, metamorphic rocks (Schist, Gneiss, Phyllite, Quartzite, Slate, and Marble), Tokala Formation (calcilutite, limestone, sandstone, shale, marl, and shale), Meluhu Formation (sandstone, quartzite, black shale, red shale, phyllite, slate, limestone, and siltstone), and alluvial sediments (pebble, gravel, sand, and clay) (Rusmana *et al.*, 1993) (Figure 2.2.b). Meluhu formation is interpreted to be intensely faulted with a dominantly NE-SW orientation.

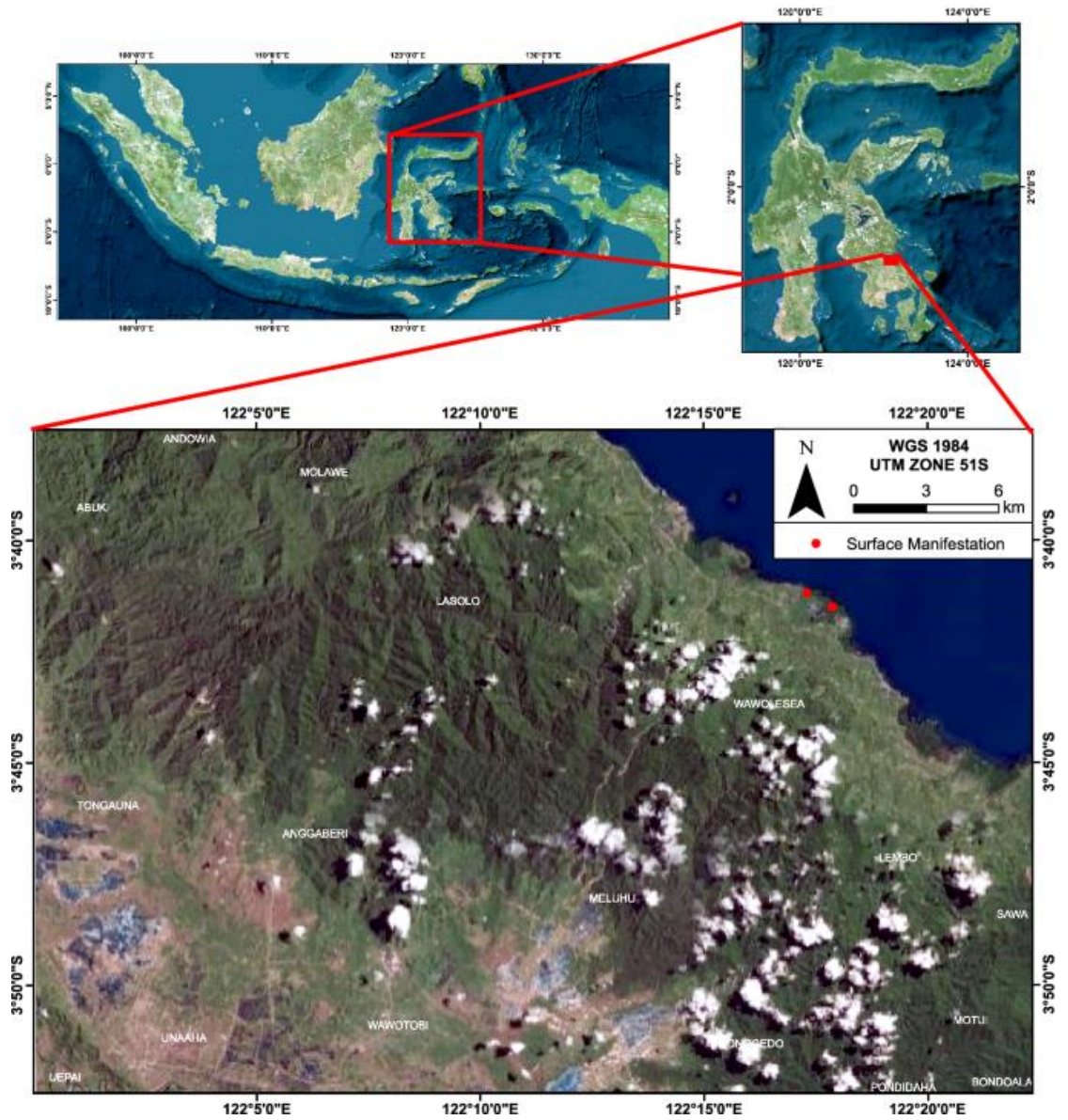


Figure 2.1 Study case area in the northern Konawe, Southeast Sulawesi, Indonesia.

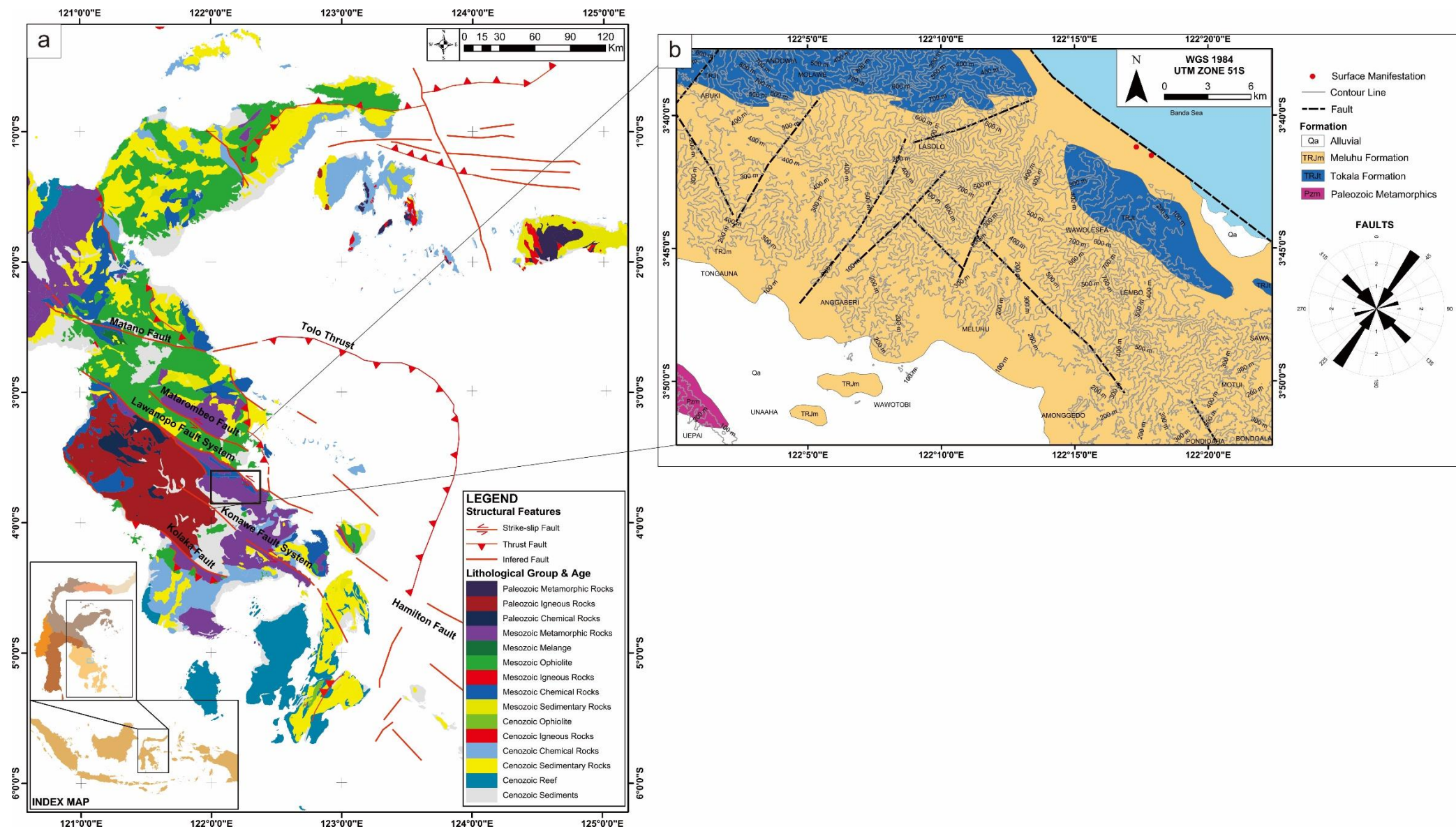


Figure 2.2 (a) Tectonic map of Southeast Sulawesi, including Lawanopo Fault Systems (Simandjunta *et al.*, 1993; Surono and Simandjuntak, 1993; Tjokrosapoetra *et al.*, 1993; Martosuwito, 2012). Rectangle with black outline shows the study area. (b) Geological map of the northern part of the study area (after Rusmana *et al.*, 1993). The rose diagram was generated based on interpreted faults by Rusmana *et al.* (1993)

2.1.2 Geothermal Potential in Sulawesi

Idral (2010) reports that the potential of geothermal energy in Sulawesi is primarily in the resource status, with the Northern part of Sulawesi holding the highest potential due to its location within the Quaternary volcanic belt. This region's resource potential is much higher compared to other regions in Sulawesi, even though the other regions have a significant number of geothermal areas. The central region has 15 areas, while the southern and southeastern regions have 17 and 13 areas, as shown in Figure 2.3. However, despite multiple geothermal areas in these regions, the total resource capacity remains relatively small, estimated to be 1299 MWe.

On the other hand, the Northern region contributes significantly to the geothermal resources of Sulawesi, with a capacity of 875 MWe, accounting for 41% of the total geothermal resources in Sulawesi (Idral, 2010). The geothermal potential dominance of the Northern region is due to the presence of active and potentially active volcanoes that generate heat in the area.

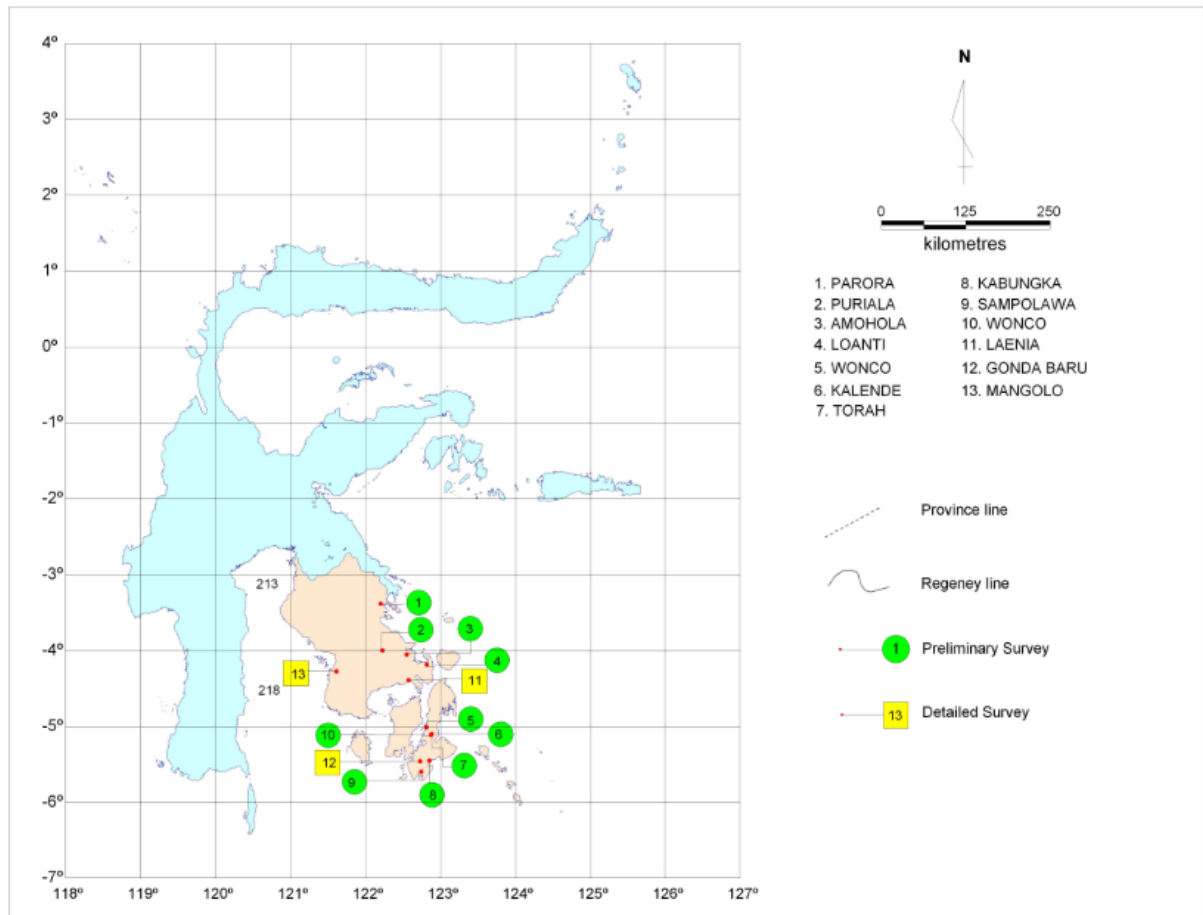


Figure 2.3 Geothermal locations in the southeastern arm of Sulawesi (Idral, 2010).

In the Northern Konawe Geothermal Field, in the southeastern arm of Sulawesi, Jaya *et al.* (2021) identified the anomaly of high surface temperature along the coastal line of Lasolo by conducting satellite image processing. They observed the geothermal manifestation in the area, particularly in the Wawoelesea and Toreo Village (Figure 2.4). In situ measurements of hot spring temperature range from 30.2 to 65.5°C (Jaya *et al.*, 2021). Further hydrochemical analysis of the hot spring was conducted, which concluded that the thermal water is chloride water type, indicating that it originated from a deep reservoir (Jamaluddin and Umar, 2017; Aulia *et al.*, 2022).



Figure 2.4 Geothermal surface manifestation in the northern Konawe (Jaya *et al.*, 2021). A and B are located in Wawolesea Village. C and D are located in Toreo Village.

2.2 Jizan Geothermal Field, Saudi Arabia

2.2.1 Geological Framework

The Arabian Shield is an active zone extends from the Gulf of Aqaba in the north to the Afar Triangle in the south (Johnson PR, 1998; Zahran *et al.*, 2016). It is characterized by a series of north-south trending faults that were associated with the opening of the Red Sea (Nehlig *et al.*, 2002). According to Nehlig *et al.* (2002), four main trends of structural features have developed in the Arabian Shield: (1) a N 135° E to N 150° E of Najd Trend, (2) a N 150° E to N 160° E of Red Sea Trend, (3) a minor N-S trend associated with the Nabitah fault zone, and (4) an E-W trend in the southern of Asir terrane.

Jizan is located at the Asir terrane of the Arabian Shield in southwestern Saudi Arabia. Geologically, it is bounded by the Red Sea to the west and the Arabian Platform to the east (Figure 2.5). The Red Sea separated the Arabian Shield from the adjacent African Shield during the Tertiary Period (Chandrasekharam *et al.*, 2014). The Jizan area is characterized by two main geological features: near-shore sedimentary deposits featuring multiple valleys that discharge into the sea and a crystalline basement composed of granite and metamorphic rocks in its eastern part (Chandrasekharam *et al.*, 2014; Lashin and Al Arifi, 2014) (Figure 2.6.a). The sedimentary coastal plain between the Red Sea and the shield's escarpment formed due to various geological processes over time (Chapman, 1978).

The circulation of fluids in the Jizan geothermal system is controlled by strike-slip transform faults and other faults exhibiting a NW-SE trend that is similar to the Red Sea trend (Chandrasekharam *et al.*, 2015; Arrofi and Abu-Mahfouz, 2023). Geophysical seismic surveys indicate that several NW-SE and ENE-WSW trending faults mainly control the deep geothermal fluids in the Al Hjouba Area (Chandrasekharam *et al.*, 2015). In addition, normal faults downthrown to the east area (antithetic fault) are also recognized in the subsurface (Oelkers *et al.*, 2022) (Figure 2.6.b). Furthermore, Al Malallah *et al.* (2021) observed several outcrops in the Jizan Basalts Group and identified four dominant fracture sets: (1) N 25°W/60° (2) N 30°E/70° (3) N-S/80° (4) N 60°W/60°. Sets 1 and 4 are calcite-filled fractures, while sets 2 and 3 are open fracture sets. These geological features and structural controls will be important to consider in this study.

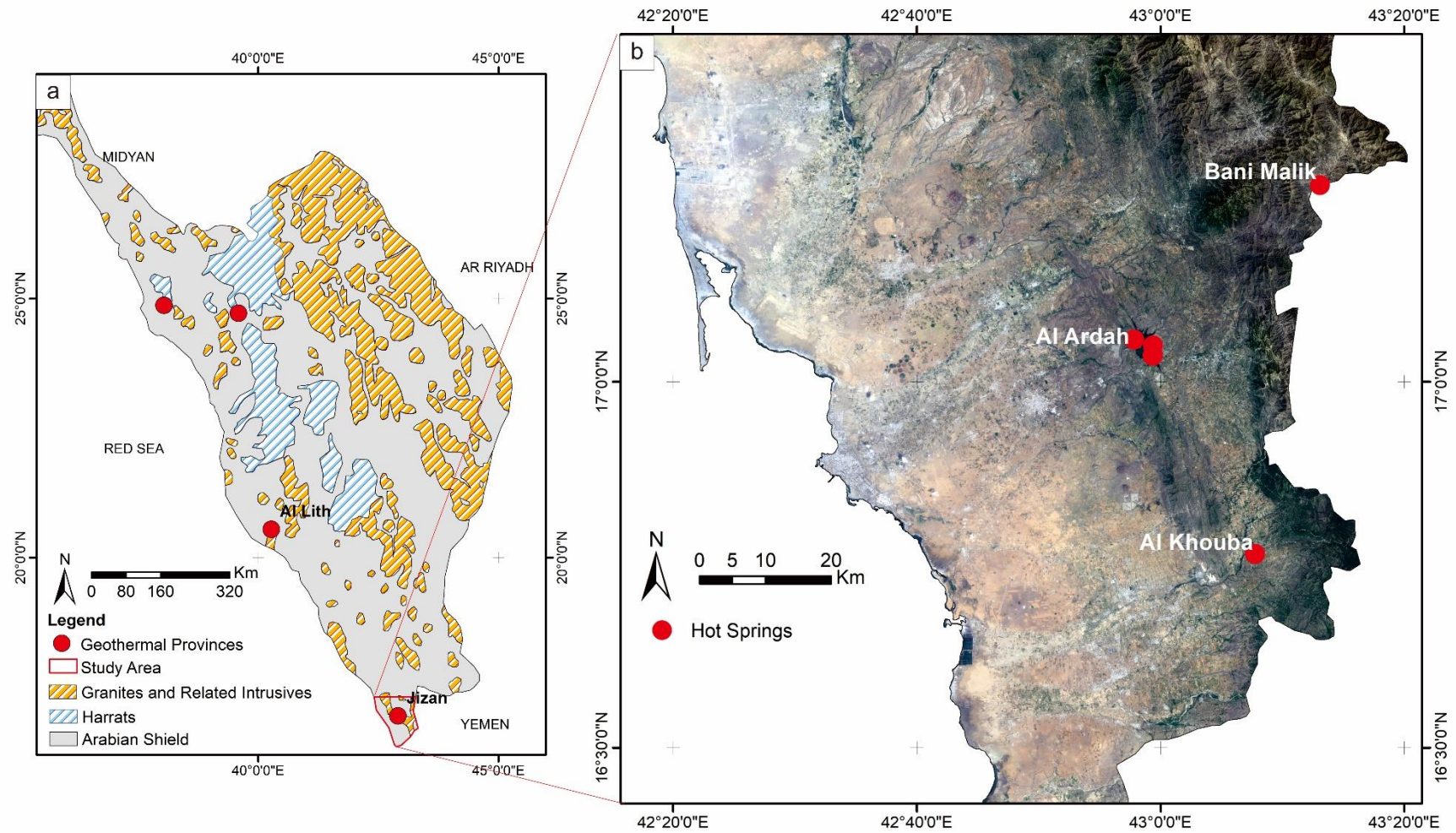


Figure 2.5 (a) Types of geothermal systems along the Arabian Shield of Western Saudi Arabia (modified from Chandrasekharam et al., 2014; Lashin & Al Arifi, 2014a). (b) The true color of Landsat 8 image view of the study area. The red circles show the locations of the hot springs in the study areas.

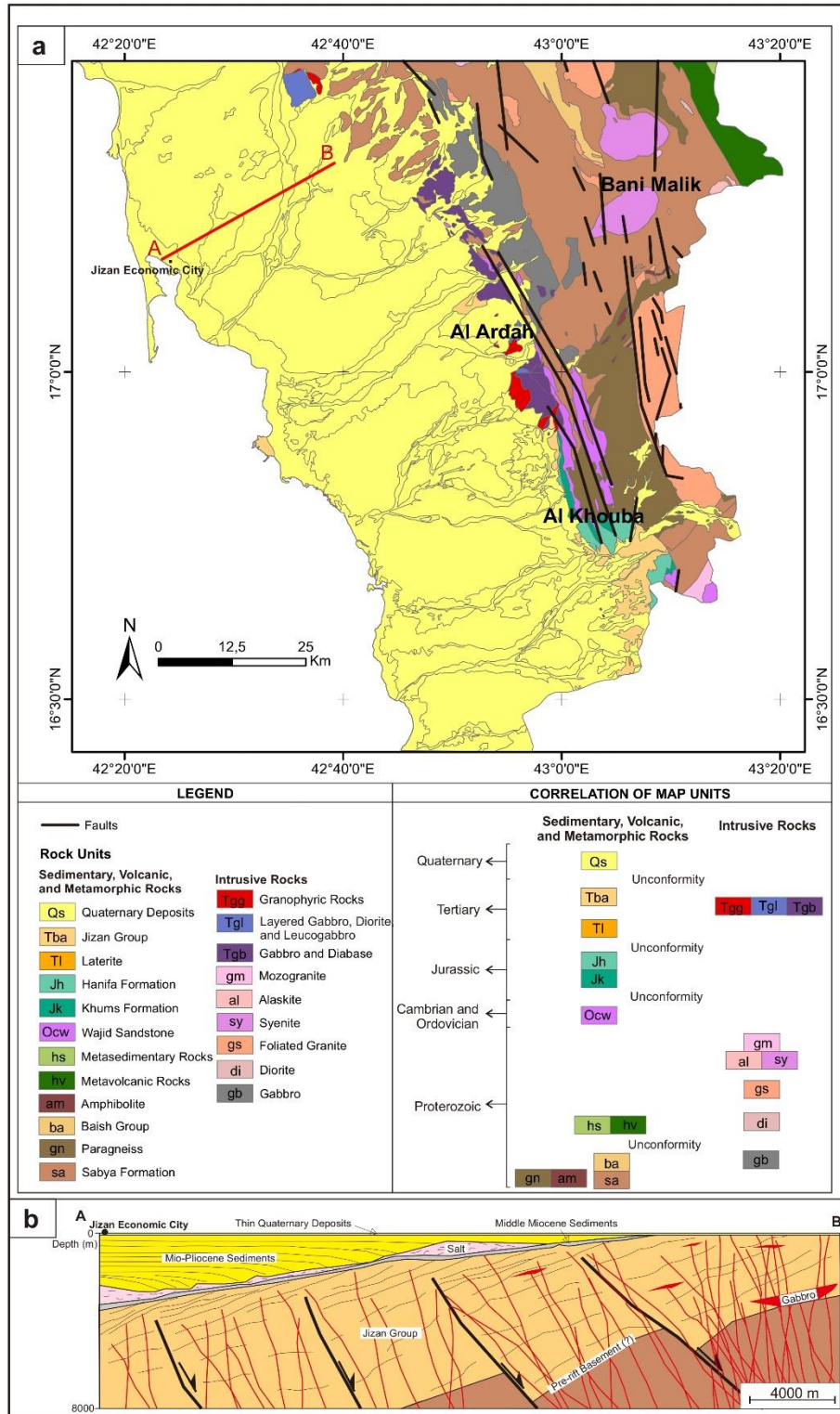


Figure 2.6 (a) Geological Map of Jizan (modified from Fairer, 1985; Blank *et al.*, 1987; Oelkers *et al.*, 2022). (b) Geological cross-section of A-B along the red line of the geological map (modified from Oelkers *et al.*, 2022)

2.2.2 Geothermal Potential in Jizan

Chandrasekharam *et al.* (2014) identified two different geothermal systems in the Arabian Shield (Fig 2.5.a), with one linked to volcanic activity related to the rifting of the Red Sea, and the other associated radiogenic felsic intrusive rocks that formed over several hundred million years (900-510 Ma). The former has been extensively studied in the Harrats of Saudi Arabia and in both Quaternary and Tertiary volcanic centres in Yemen (Chandrasekharam *et al.*, 2014). However, the latter remains largely unexplored, particularly in the Jizan region.

Recent studies have shed light on the potential of the Jizan area as a geothermal hotspot. One significant factor is the high heat production (HP: $2.19 - 8.04 \mu\text{Wm}^{-3}$) of radiogenic felsic intrusive rocks (southern granites) in this region of the Arabian Shield and heat generation unit (0.76 – 19.07 HGU) compared to that for the granite in the northeastern part (HP of $1.82 - 4.12 \mu\text{Wm}^{-3}$, and 4.31 -10.35 HGU) (Abbady and Al-Ghamdi, 2018). In addition, geophysical research has shown that the thinning of the Earth's crust and the presence of a shallow mantle contribute to the high heat flow in Jizan (Chandrasekharam *et al.*, 2015).

Furthermore, evidence for the existence of a geothermal system in Jizan comes from the geochemical analysis of hot springs in the area. Lashin and Al Arifi (2014) and Arrofi *et al.* (2023) conducted extensive studies on the hot springs in Al Ardah, Al Khouba, and Bani Malik, and found that they all originate from highly fractured basements and

metamorphic rocks. The surface temperatures of the springs range from 43 °C to 78 °C, with the reservoir temperature estimated to be 151.4°C using a silica geothermometer and 180-200 °C using a Na-K geothermometer (Lashin and Al Arifi, 2014). The intense interaction between thermal water and granitic rock is also revealed from hot spring hydrochemical analysis and the existence of alteration in granitic rock (Fig. 2.7.b). These findings suggest that granitic rocks may serve as the reservoir in the deep circulation of the geothermal system in Jizan (Lashin and Al Arifi, 2014).

Overall, the studies outlined here provide strong evidence for the existence of a significant geothermal system in the Jizan region of the Arabian Shield. Further investigation is needed to fully understand the potential of this system and the feasibility of exploiting it for energy production.

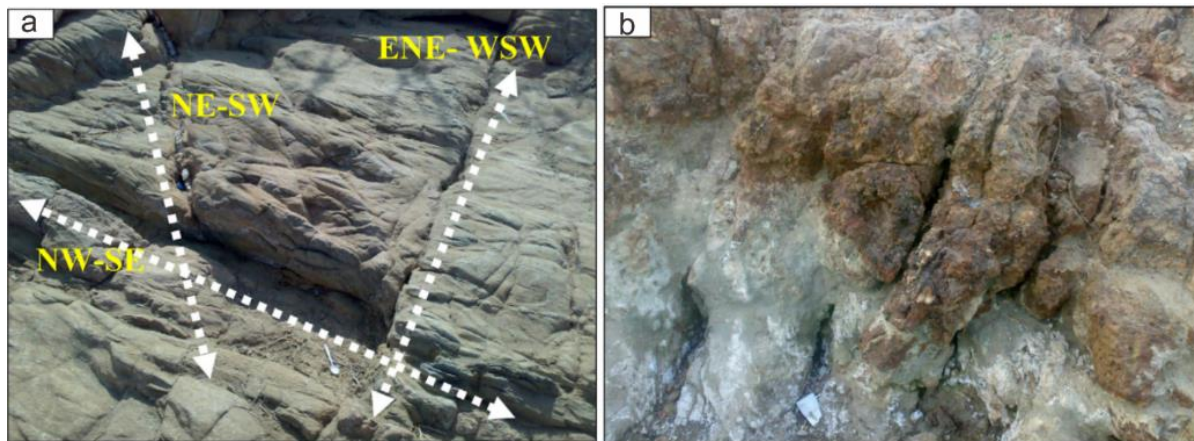


Figure 2.7 (a) Highly fractured granite rock and whole structural pattern in Al Khouba. (b) Altered granitic rocks due to interaction with thermal water (Lashin and Al Arifi, 2014).

CHAPTER 3

METHODOLOGY

This study aimed to investigate the permeable zones and possible fluid flow orientation by conducting structural lineament analysis in two study areas, namely the northern part of Konawe (Indonesia) and Jizan (Saudi Arabia). The lineament analysis results were supported by ground truthing through outcrop scale study and geological mapping. The details of the methodology are provided below.

3.1 Lineament Analysis

Lineaments were identified using both automatic and manual lineament extraction techniques. The primary data source for mapping lineaments in both study areas was the Digital Elevation Model (DEM.) obtained from the Shuttle Radar Topography Mission (SRTM), which was downloaded from the following website: <https://earthexplorer.usgs.gov/>. Geomatica 2017 software and ArcMap 10.8 were utilised for the data processing. Prior to lineament extraction, the DEMs were processed to generate multidirectional hill shade representations (Figure 3.1). Lineaments were then extracted based on this processing data. The LINE module in PCI Geomatica was employed to automatically extract the lineaments using the following parameters: filter radius [20], edge gradient thresholds [200], curve length threshold [100], line fitting error threshold [5], angular difference threshold [60], linking distance threshold [100]. Additionally, manual tracing of linear structural features was performed using ArcMap.

Furthermore, the faults interpreted from the geological map were digitized to support the validation of the generated lineaments.

After all structural lineaments/faults had been extracted, statistical analysis was done to see the lineament length distribution and their consistency with the power-law distribution model. Power-law distribution is commonly referred to as scale-independent, implying a likeness in the structural geometry across various scales and showcasing a significant variation in the quantity measured (Seebeck *et al.*, 2014). In addition, rose diagrams were also generated from lineaments and faults orientation data.

The density of lineaments (automatically- and manually-generated lineaments) and fault maps will be generated using the kernel density tool in ArcMap. The maps represent the length of lineaments and faults within a particular area. Detailed workflow on the lineament density analysis (known as the Fault Fracture Density, FFD, method) and how it can be applied are explained by Taucare *et al.* (2020). After generating the density maps (automatically- and manually extracted lineament density and fault maps), the maps were overlaid using Fuzzy 'AND' overlay technique. The Fuzzy 'AND' was successfully used to delineate permeable zones in non-volcanic geothermal exploration (Arrofi and Abu-Mahfouz, 2023). The result was then classified using the natural break method because its information loss is comparatively smaller when compared to other methods (Osaragi, 2002). This overlaying map shows the permeable area based on the high value of lineaments and faults.

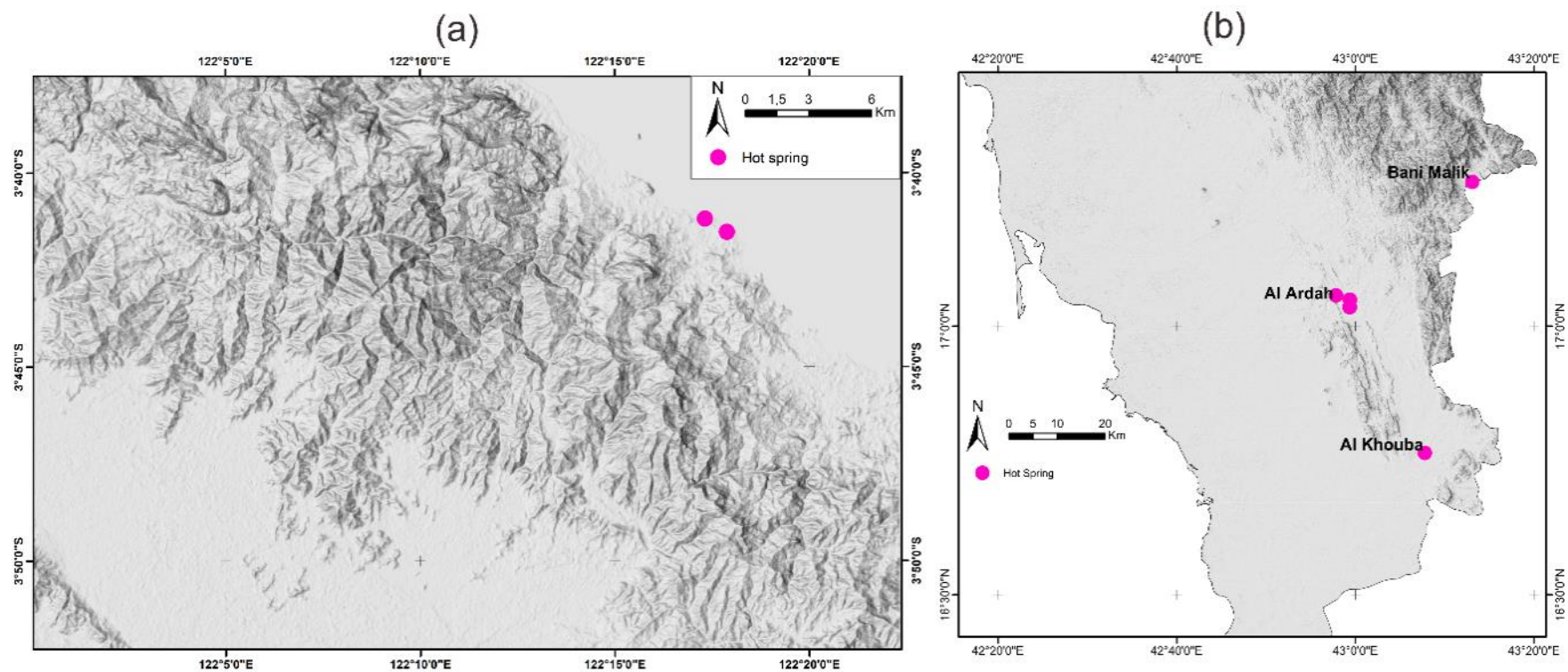


Figure 3.1 Multidirectional hill shade of DEM STRM (a) Northern Konawe. (b) Jizan

3.2 Ground Truthing

Fieldwork was conducted to validate remote sensing results and collect fault and fracture measurements from outcrops. Based on the remote sensing results, several representative localities were selected for fracture description and measurements in the study area. Eight locations in the Northern Konawe Geothermal Field, Indonesia, were chosen, covering each of the formations and the high to low-permeable zones within the study area. This allowed for a direct comparison of the remote sensing and ground-truthing results, providing valuable insights into the consistency of the remote sensing data, those related to fault and fracture density.

In Jizan Geothermal Field, Saudi Arabia, the prominent permeable zone identified from remote sensing results was selected for further investigation and validation. The ground truthing area was carefully selected to encompass both the permeable zones and their nearest hot springs areas. This strategic selection enabled the exploration of the potential relationship between the two features (i.e. the existence of hot springs and the permeable zone).

Fracture description included identifying the type and orientation of fractures, as well as their host lithology and filling material.. Fracture features measured included fracture azimuth orientation, dip angle, dip direction, and aperture size (for open fractures). Additionally, fracture intensity was counted using the scanline sampling technique to validate the lineament and fault density data obtained from remote sensing (Gross *et al.*,

1995). This technique counts the number of fractures for each meter that passes by the measurement line.

Fractures were then grouped into different sets based on their orientation and filling materials. The cross-cutting relationships among the different fracture sets were investigated to constrain the relative age of rock units and the timing of fracture development. The integration of fracture data and their cross-cutting relationships was also used to define the relative age of fractures relative to each other, and to support the interpretation of their relationship to major tectonic events.

3.3 Hydrochemical Analysis of Hotsprings

In the Jizan Geothermal Field study case, hydrochemical analysis of thermal water from hot springs was conducted to support the interpretation of hydrothermal fluid flow, construct a conceptual model of the geothermal system, characterize the thermal water, and estimate the reservoir temperature. Cation geothermometer of Na-K, developed by Giggenbach (1988), was used to estimate the reservoir temperature using the following equation:.

$$T = \frac{1390}{1750 + \log\left[\frac{Na}{K}\right]} - 273.15 \quad [(3.3)]$$

The thermal waters were collected from three hot springs (HS) in the Al Ardah Area on May 23rd, 2023. Spatially, the three hot springs were collected from mainly two locations: HS-1 (Figures 3.2.a and 4.10) is to the west, while HS-2 and HS-3 (Figures 3.2.b and 4.10) are towards the east. *In situ* measurements of water temperature, total dissolved

solution (TDS), and electroconductivity (EC), were also collected. To reduce measurement error, each parameter was measured three times, and the average was calculated. The samples were then transported to the College of Petroleum Engineering and Geosciences (CPG) Laboratories for further analysis. Major ions (cation and anion) were analyzed using Ion Chromatography, and trace elements were quantified using Inductively Coupled Plasma Mass Spectrometry (ICP – MS). Hydrogen and oxygen isotopic compositions were also measured to investigate the origin of the thermal water. A flowchart of the study is shown in Figure 3.3.



Figure 3.2 Hotsprings in Al Ardah Area, Jizan. (a) HS-1. (b) HS-2.

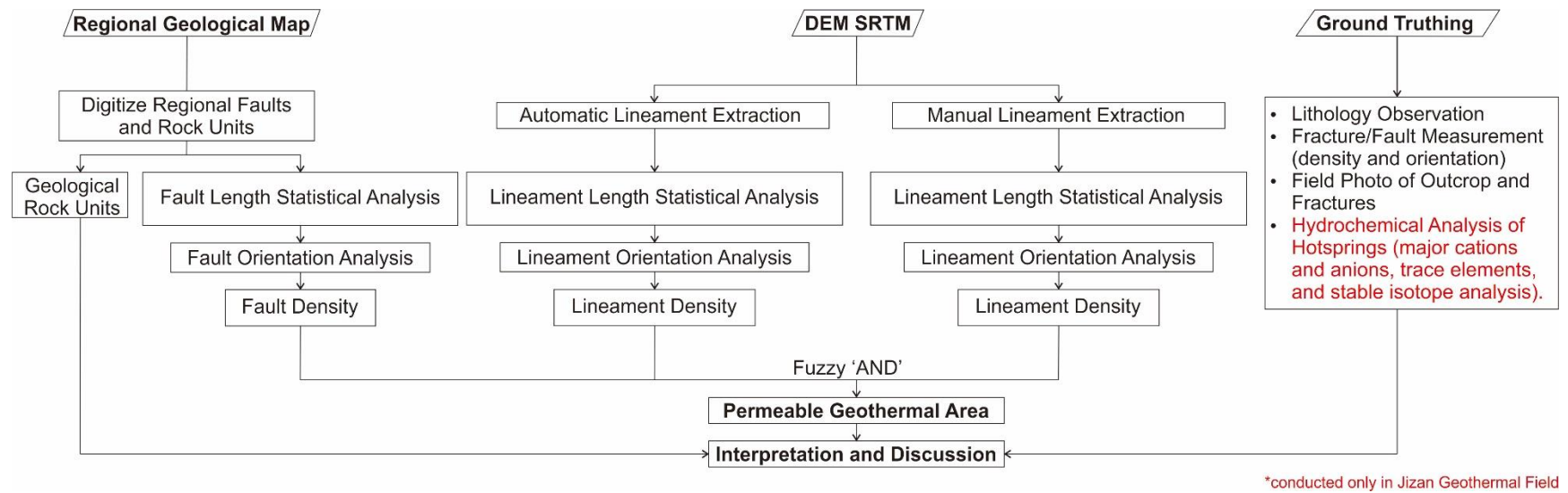


Figure 3.3 Study flowchart.

CHAPTER 4

RESULTS

4.1 Northern Konawe Geothermal Field, Indonesia

4.1.1 Lineament and Fault Length Statistical Analysis

Lineaments were extracted from the Digital Elevation Model (DEM) using automatic and manual lineament extraction, resulting in 392 and 1522 lineaments, respectively. In addition, 11 interpreted faults from Rusmana *et al.* (1993) were digitized for further analysis.

The length distribution of lineaments, including automatically- and manually-extracted lineaments, shows a positively skewed distribution. This means that most of the data are in the low value (Figure 4.1), indicating that shorter lineaments dominate the system compared to longer lineaments. The decreasing frequency with the increasing length is also observed in both automatically- and manually-extracted lineament data. In contrast, the length distribution of fault length distribution does not show a similar trend.

A log-log plot of cumulative frequency versus the length of lineaments (automatically- and manually-extracted lineaments) or faults shows that automatically-extracted lineaments significantly follow a power law distribution, with an R² value of

0.9615. It is followed by the faults (R-squared value of 0.8731) and manually-extracted lineaments (R-squared value of 0.6223) (Figure 4.2).

Descriptive statistical analysis of the lineament and fault lengths revealed that faults had the highest mean length (9.82 Km), followed by automatically-extracted lineaments (1.704 Km) and manually-extracted lineaments (0.756 Km). This indicates that faults have the widest range of length distribution compared to the other lineaments.

The length range of faults was also the highest (17.697 Km), followed by manually-extracted lineament (7.824 Km) and automatically-extracted lineament (4.921 Km). The high range value indicates a significant difference between the longest and shortest faults or lineaments. Table 4.1 shows the detailed descriptive statistics of the length of automatically- and manually-extracted lineaments and faults. The standard deviation of faults is 5.192 Km, while it is lesser for manually- and automatically-extracted lineaments (0.809 Km and 0.794 Km, respectively). This implies that faults have the highest range of length distribution compared to other lineaments.

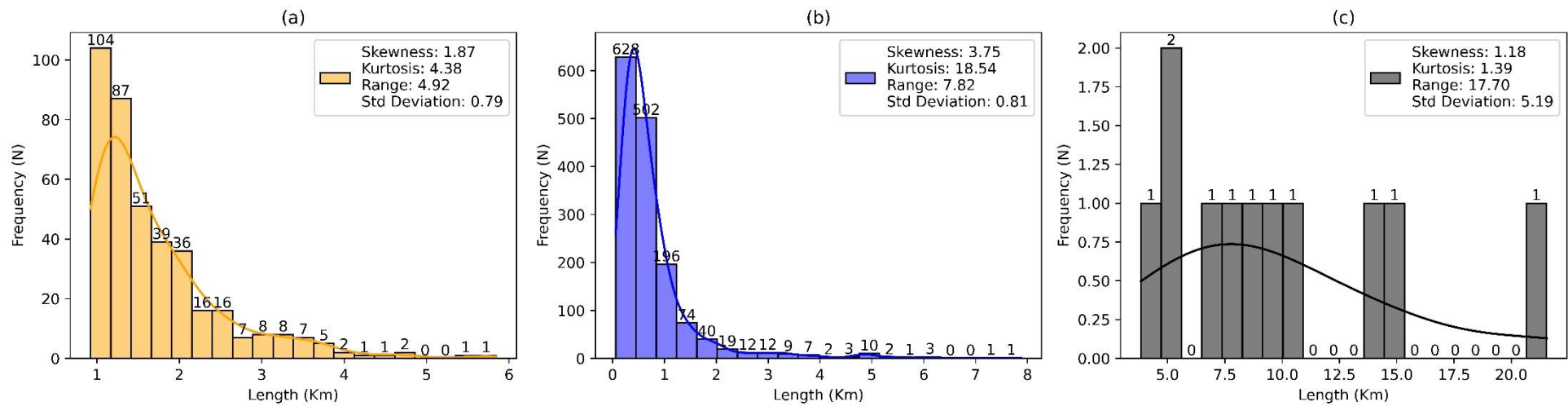


Figure 4.1 (a) Histogram showing the lengths of the automatically-extracted lineaments in Northern Konawe, (b) histogram showing the lengths of the manually-extracted lineaments, (c) histogram showing the lengths of the faults mapped.

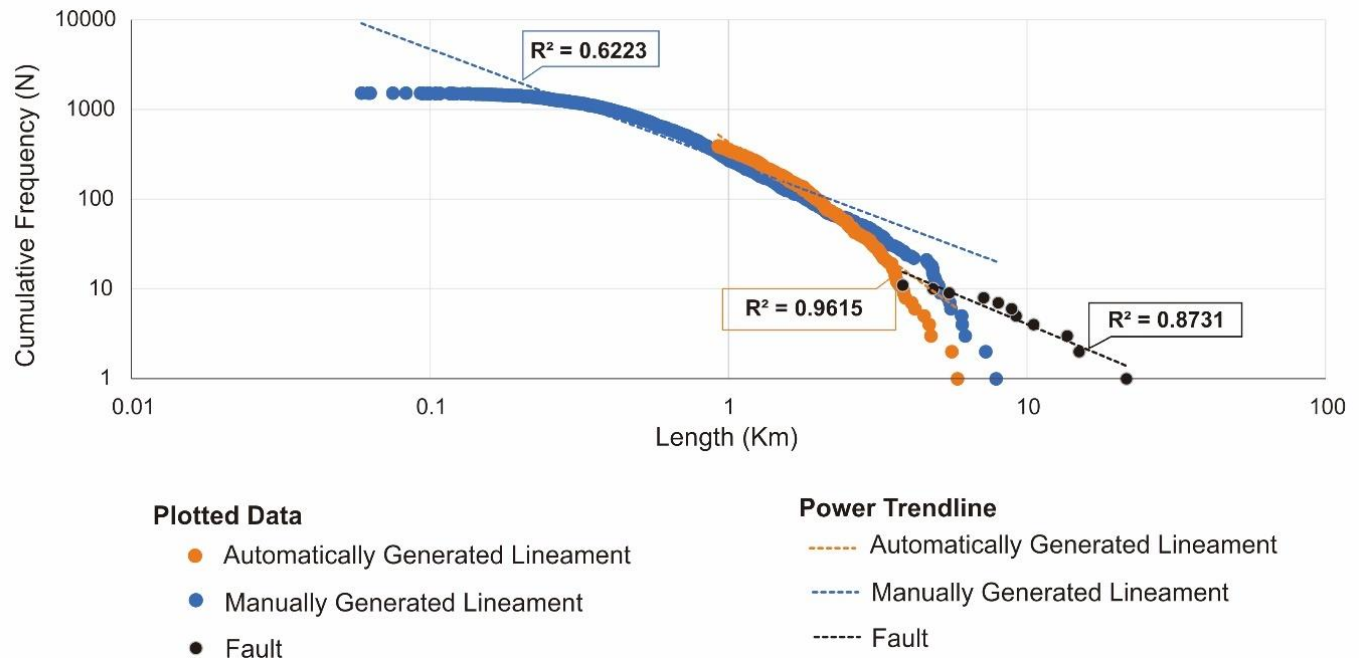


Figure 4.2 Log-log plot of lineament length versus cumulative frequency in Northern Konawe.

Table 4.1 Automatically extracted lineaments, manually extracted lineaments, and fault length descriptive statistics in Northern Konawe.

	Automatic Lineament Extraction (Km)	Manual Lineament Extraction (Km)	Fault (Km)
Count	392	1522	11
Mean	1.704	0.756	9.82
Median	1.434	0.52	8.871
Mode	0.992	0.483	N/A
Standard Deviation	0.794	0.809	5.192
Sample Variance	0.631	0.655	26.96
Kurtosis	4.384	18.543	1.392

Skewness	1.874	3.753	1.181
Range	4.921	7.824	17.697
Minimum	0.923	0.059	3.836
Maximum	5.844	7.883	108.02
Sum	668.123	1150.927	373.308

4.1.2 Lineament and Fault Orientation

The orientation of automatically- and manually-extracted structural lineaments and faults are shown in different rose diagrams in Figure 4.3. The major orientation (trend) of automatically generated lineaments and faults can be identified. Automatically extracted lineaments show high frequency in the N-S to NNE-SSW orientation, while the mapped faults are oriented NE-SW and NW – SE (Figure 4.3. a and c). In contrast, manually extracted lineaments show N-S, NW – SE, and NE – SW (Figure 4.3.b).

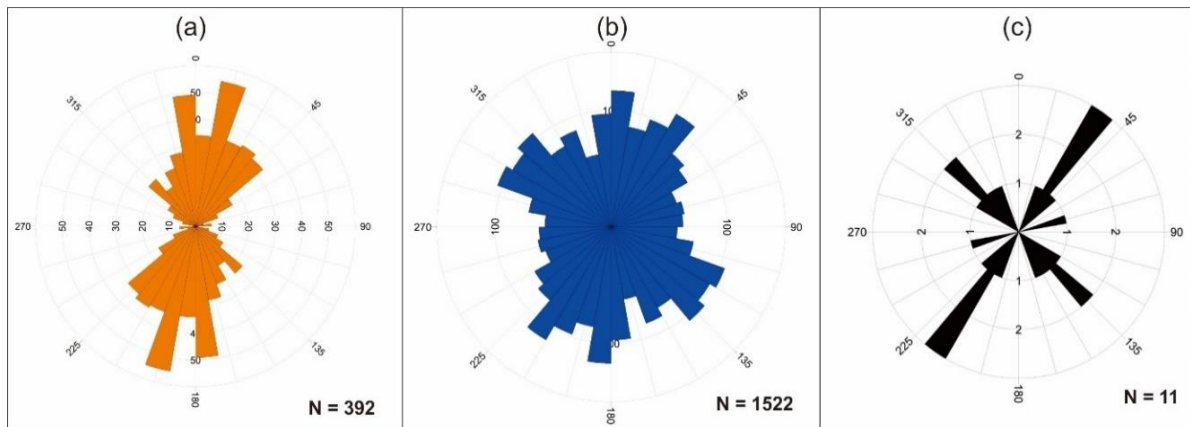


Figure 4.3 Rose diagrams show the orientation of the extracted lineaments and mapped faults in Northern Konawe. (a) Orientation of automatically-extracted lineaments, (b) orientation of manually-extracted lineaments, (c) orientation of faults mapped/interpreted from literature (fracture data taken from Rusmana *et al.*, 1993).

4.1.3 Lineament and Fault Density

Automatically-extracted lineament density, manually-extracted lineament density, and fault density maps were generated with Km/Km^2 units, and the value was classified into five classes using the natural break method into very low, low, moderate, high, and very high (Figure 4.4). Despite the predominant concentration of lineaments and faults in the Lasolo Region, automatically- and manually extracted lineaments and faults show the distinguished spatial distribution.

In particular, most automatically-extracted lineaments are situated in the Lasolo, Wawolesea, Meluhu, Anggaberu, the eastern part of Tongauna, Amonggedo, Motui, and the area in between of Meluhu and Lembo, showing high lineament densities, ranging from 1.19 to 1.97 Km/Km^2 (Figure 4.4.a). These high to very high densities are surrounded by lineaments' low to moderate density (0.4 - 1.97 Km/Km^2). Notably, the hot springs location is in the low lineament density area ranging from 0 to 0.4 Km/Km^2 .

Specifically to the manually-extracted lineaments, most of the lineaments are located in the Andowia, Lasolo, Amonggedo, and the area between Maluhu and Lembo (Figure 4.4.b). Therefore, those areas have high to very high lineament densities ranging from 2.07 to 3.45 Km/Km^2 . The moderate lineament density (1.38 – 2.07 Km/Km^2) surrounds those high to very high lineament density areas, with minor spatial distribution in the eastern part of Molawe, the southern part of Abuki, and the northwest part of Meluhu. Low lineament density (0.69 – 1.38 Km/Km^2) envelopes moderate to very high-density

areas. Like the automatically-extracted lineaments, the hot springs are within the very low lineament density area ($0 - 0.69 \text{ Km/Km}^2$).

Faults depict a distinguishable spatial distribution compared to automatically- and manually-extracted lineaments. Most of the interpreted faults are around Lasolo and a relatively small area around Abuki and Tongauna, showing the high density of faults, ranging from 0.21 to 0.35 Km/Km^2 (Figure 4.4.c). The low to moderate lineament density ($0.069 - 0.21 \text{ Km/Km}^2$) are spatially along the same area as the lineaments (automatically- and manually-extracted lineaments), with the difference in the area between the Wawolesea and Banda Sea, which notably includes the location of the hot springs. The very low fault density area ($0.069 - 0.14 \text{ Km/Km}^2$) occupies the rest of the study area.

In summary, the spatial distribution of lineaments and faults in Northern Konawe is distinct between automatically-extracted, manually-extracted, and fault lineaments. The hot springs are located in areas of very low lineament density for both automatically- and manually-extracted lineaments and in an area of low fault density. These findings suggest that the spatial distribution of lineaments and faults from remote sensing needs to be validated by ground-truthing observation to understand the location of hot springs in Northern Konawe.

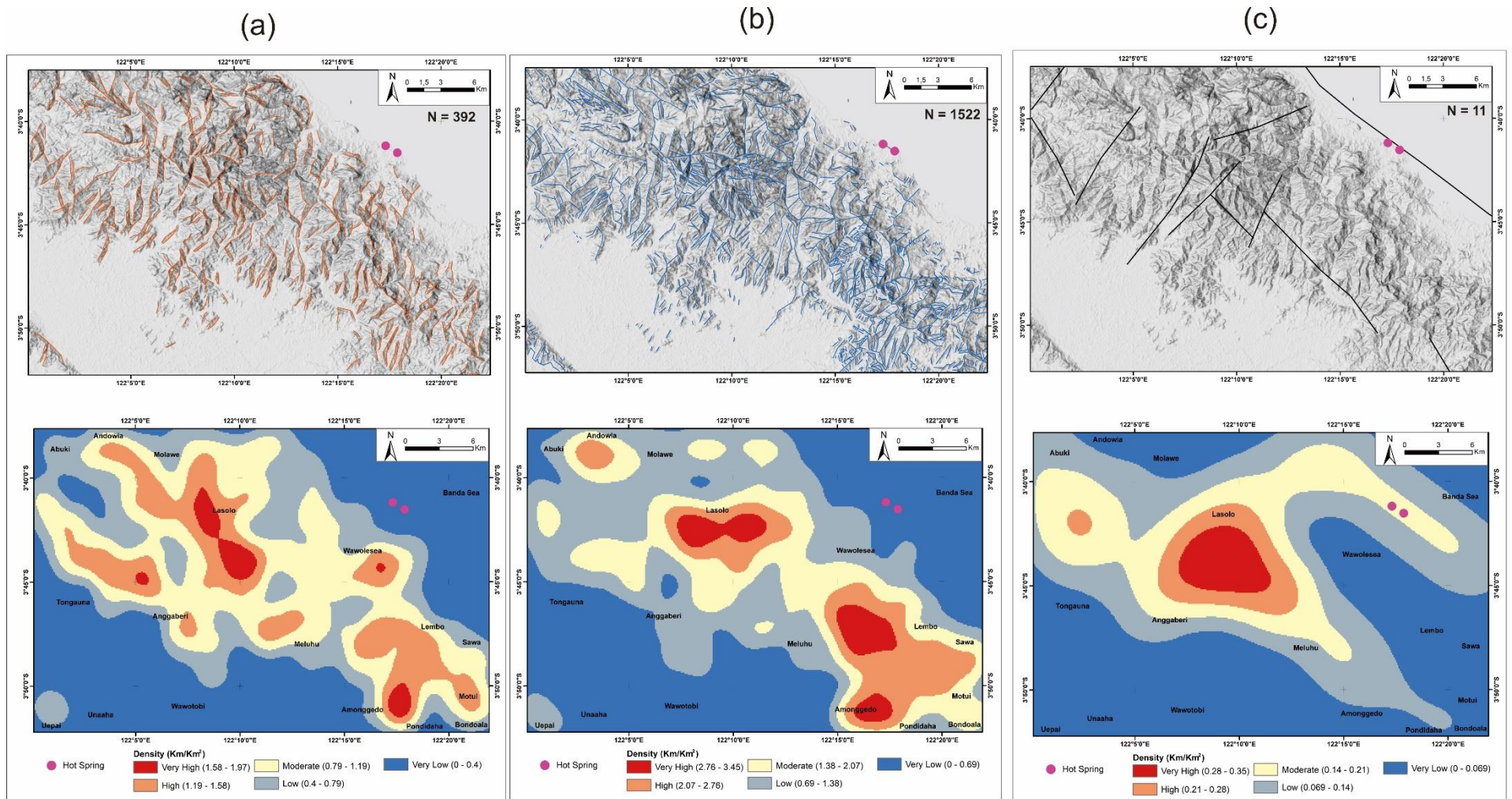


Figure 4.4 The lineaments and faults density map in Northern Konawe. (a) Automatically-extracted lineament density map, (b) manually-extracted lineament density map, (c) fault density map.

4.1.4 Fracture Observation in Outcrop

Field observations from eight ground-truthing locations revealed a diverse range of rock units and fracture characteristics within the Lasolo Region. A total of 298 fractures were mapped in these locations, spanning various rock types, including phyllite, marble, sandstone, and schist (Figure 4.5). The rock units encountered represent a stratigraphic sequence ranging from the Paleozoic Metamorphic Formation (oldest) to the Tokala Formation (youngest).

The Meluhu Formation exhibited the highest fracture density, with no fracture observed in the Tokala Formation (GT-1). This observation suggests a potential relationship between fracture occurrence and rock type or stratigraphic position.

Among the observed fractures, three distinct types were identified in the ground-truthing localities: mineralized fractures (veins), unmineralized fractures (open fractures or OF), and shear fractures. Interestingly, shear fractures (SF) were observed in both the sandstone of the Meluhu Formation (GT-6) and the schist of the Paleozoic Metamorphic rocks (GT-8).

Two types of vein-filling materials were encountered: carbonate veins (CV) and silica veins (SV). Carbonate veins were exclusively observed in the phyllite and marble of the Meluhu Formation (GT-2) (Figures 4.6 a and b), while silica veins were primarily observed in the sandstone of the same formation (GT-4, GT-5, GT-7) (Figures 4.6 c, d, and e).

Carbonate veins displayed a predominant NNE-SSW orientation, whereas silica veins exhibited a broader range of orientations, including NW-SE, NNW-SSE, and NNE-SSW, with the latter being the most prevalent. Additionally, the average aperture size of the carbonate veins is 2.59 mm, while silica veins exhibited a larger average aperture size of 17.27 mm. For a comprehensive overview of fracture characteristics at each ground-truthing location, refer to Table 4.2.

Most open fractures were primarily observed in the sandstone interval of the Meluhu formation (GT-4 and GT-7) (Figures 4.6 c and f). This finding suggests that the sandstone units in these locations are more prone to fracture development. The primary orientation of these open fractures is predominantly N-S, indicating a consistent pattern in fracture alignment. The average aperture size of these fractures is 11.14 mm. Shear fractures exhibit the main orientations of NNW-SSE and NNE-SSW. This implies that these fractures have formed under distinct stress conditions, resulting in preferential crack propagation along these orientations.

The relative age of the fractures can be assessed based on the crosscutting relationship observed at GT-4 (Figures 4.6 c and d). The NW-SE silica veins, followed by the NNE-SSW silica veins, and finally, the N-S open fractures, represent the order of relative fracture age from the oldest to the youngest. This sequence of fractures provides insights into the development of the fracture networks over time and aids in establishing a chronological framework for fracture growth within the formation.

The major fracture trend of most fractures measured from the eight study locations is NNE-SSW (Figure 4.6 g). This trend is mainly reflected by the open fractures (OF) and silica veins (SV) dipping to the west, indicating a regional control on fracture development. In contrast, in the remaining trends of NE-SW, NW-SE, and relatively E-W, veins with varying aperture sizes control the fracture network dynamics.

Analysis of the dip angles reveals that the majority of fractures exhibit steep angles, ranging from 60° to 90°, with 71 out of the 152 measured fractures falling within the 60° to 70° range (Figure 4.6. h). This steep dip angle prevalence suggests a significant control of tectonic stresses in fracture formation. Fractures with gentle dip angles are relatively scarce and require further investigation to understand their formation mechanism and implications within the broader fracture network. By incorporating these enhancements, the results provide a more comprehensive and detailed understanding of the observed fractures in the Meluhu formation. These findings offer valuable insights into fracture patterns, relative age determination, regional trends, and the structural behaviour of the formation.

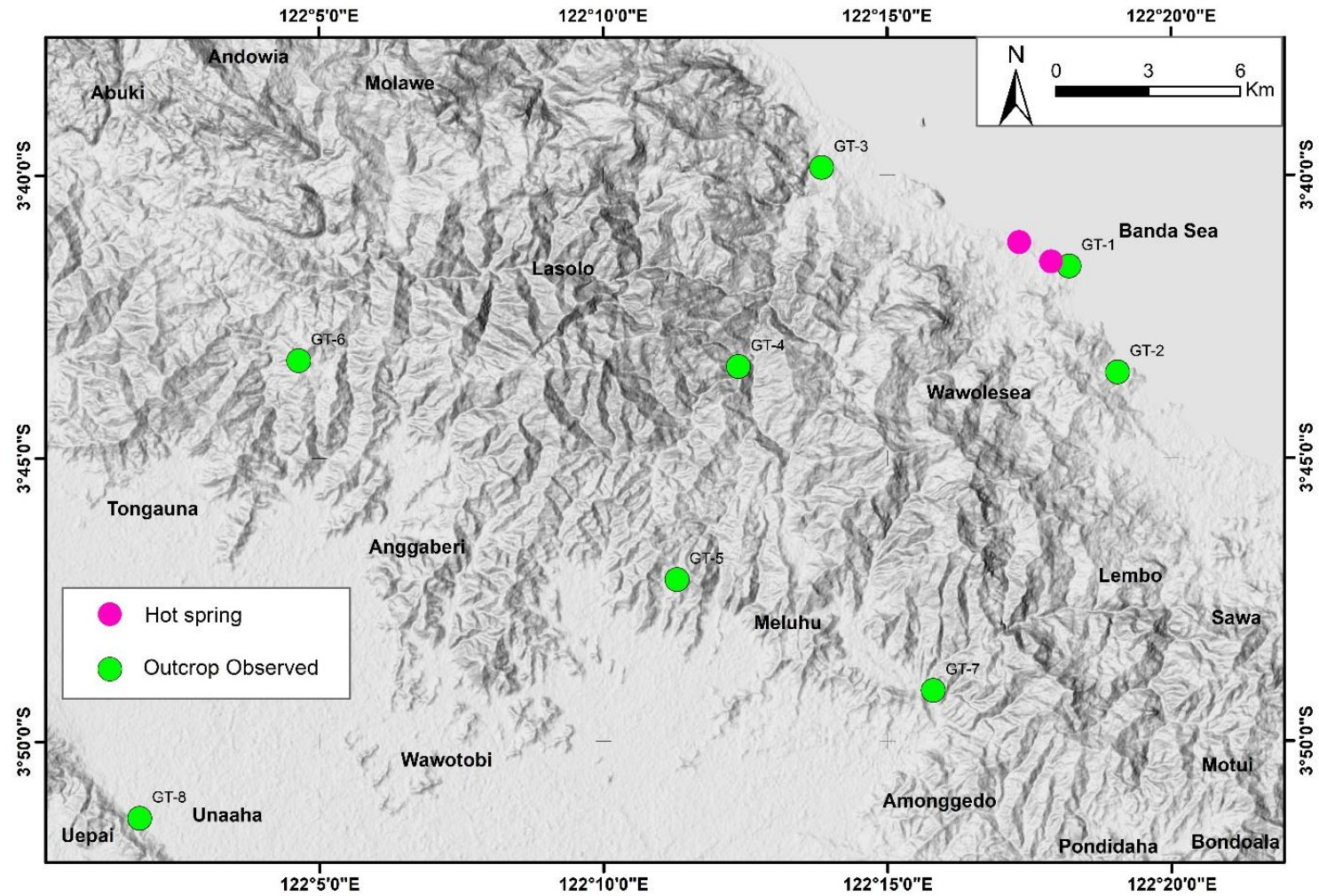


Figure 4.5 Location of outcrops observed in the Northern Konawe, Indonesia.

Table 4.2 Ground truthing fracture measurements in Northern Konawe

Location	Fracture Density (m⁻¹)	Type	Relative Fracture Orientation	Number of Fractures	Average Fracture Aperture (mm)
GT-1	-	-	-	-	-
GT-2	NM	CV	NNE-SSW	32	2.59
GT-3	-	-	-	-	-
GT-4	16.21	OF	N-S	29	3.71
		SV	NW-SE	18	20.36
			NNE-SSW	53	11.88
GT-5	7.8	SV	NNW-SSE	25	8.6
GT-6	4.63	SF	NNW-SSE and NNE-SSW	22	-
GT-7	NM	OF	N-S	18	18.56
		SV	NNE-SSW	41	28.22
GT-8	7.5	SF	NNW-SSE and NNE-SSW	50	-

*GT: ground-truthing location, NM: not measured, CV: carbonate vein, OF: open Fracture, SV: silica vein, SF: shear fracture

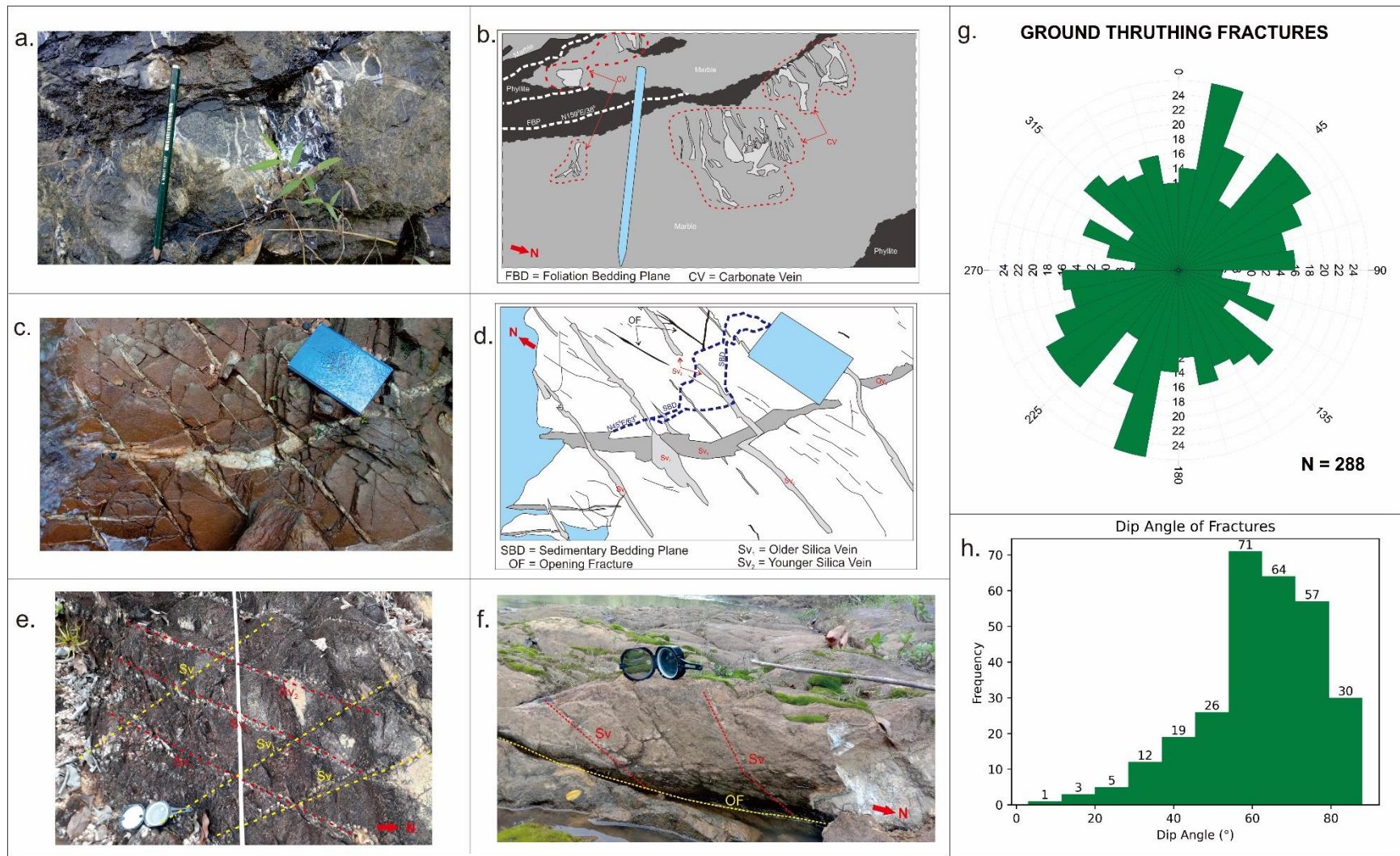


Figure 4.6 Fracture observed in Northern Konawe, Indonesia. (a) Carbonate veins observed in GT-2. (b) Schematic drawing of GT-2. (c) The crosscutting relationship observed in GT-4. (d) Schematic drawing of GT-4. (e) The crosscutting relationship of two silica vein sets observed at GT-8 (f) The N-S open fracture observed at GT-7 (g) rose diagram of measured fractures in Northern Konawe. (h) Histogram of dip angle distribution of fractures in Northern Konawe.

4.2 Jizan Geothermal Field, Saudi Arabia

4.2.1 Lineament and Fault Length Statistical Analysis

A total of 4874 automatically- and 2020 manually-extracted lineaments were extracted from the DEM. In addition, 44 faults were digitized and traced from the geological map by Oelkers *et al.* (2022). The length of both lineaments (automatically- and manually-extracted lineaments) and faults exhibit a positively skewed data distribution, indicating that the majority of the features show low length values (Figure 4.7). This suggests that shorter lineaments and faults dominate the study area. Moreover, the frequency of lineaments and faults decreases as their length increases, except for the fault's length distribution. When plotted on a Log-log diagram, both automatically- and manually extracted lineaments exhibit a strong relationship between their length and cumulative length, with high R^2 values of 0.9096 and 0.8253, respectively, following a power law distribution (Figure 4.8). In contrast, the R^2 value of fault length distribution is low (0.4771).

Statistically, the faults have a higher mean length of 8.494 Km compared to the automatically- and manually extracted lineaments, which have mean lengths of 2.564 Km and 0.949 Km, respectively. The standard deviation of fault lengths is also the highest (7.7752 Km), indicating a wider range of length distribution to lineaments (automatically and manually extracted lineaments). Additionally, the length range observed in faults also exhibits the highest value (28.227 Km) compared to automatically and manually extracted lineaments of 10.327 Km and 5.665 Km, respectively. Detailed

information of descriptive statistical analysis of the fault, automatically-, and manually extracted lineaments can be found in Table 4.3.

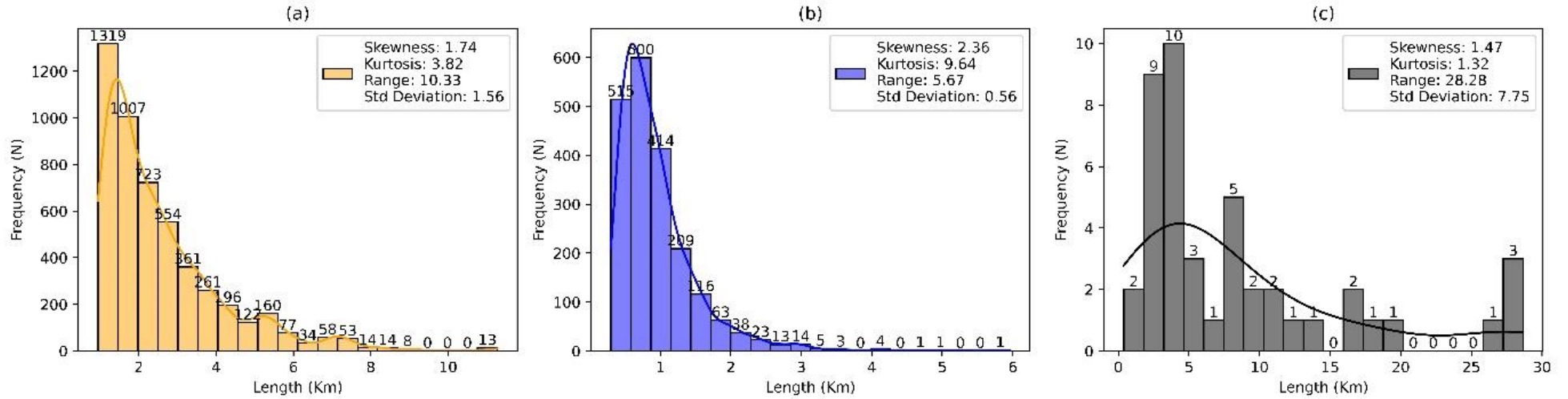


Figure 4.7 (a) Histogram showing the lengths of the automatically-extracted lineaments in Jizan, (b) histogram showing the lengths of the manually-extracted lineaments, (c) histogram showing the lengths of the faults mapped in Jizan.

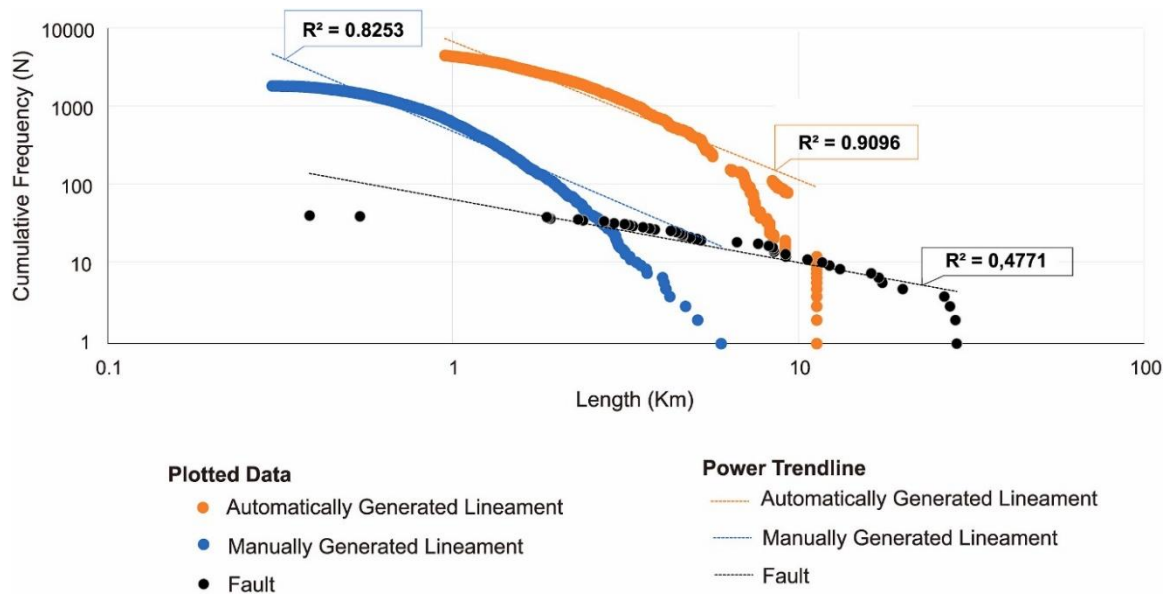


Figure 4.8 Log-log plot of lineament length versus cumulative frequency in Jizan

Table 4.3 Automatically extracted lineaments, manually extracted lineaments, and fault length descriptive statistics.

	Automatic Lineament Extraction (Km)	Manual Lineament Extraction (Km)	Fault (Km)
Count	4974	2020	44
Mean	2.563	0.949	8.484
Median	2.072	0.808	4.959
Mode	1.378	0.697	N/A
Standard Deviation	1.56	0.557	7.752
Sample Variance	2.435	0.31	60.088
Kurtosis	3.817	9.644	1.323
Skewness	1.738	2.365	1.466
Range	10.327	5.665	28.277

Minimum	0.946	0.299	0.384
Maximum	11.273	5.964	28.66
Sum	12748.887	1916.468	373.308

4.2.2 Lineament and Fault Length Orientation

The orientation of automatically and manually extracted lineaments and faults is shown in the rose diagrams in Figure 4.9. The rose diagrams demonstrate an overall NNW-SSE orientation. N 150°E to N 160°E or N 330°E to N345°E are the highest frequency orientations of automatically- and manually-extracted lineaments. Similarly, the N 165° E to N 180° E or N 345° E to N360° E trends are the main observed orientations of most faults. In addition, the automatically-extracted lineaments show other NNE – SSW to NE-SW trends (Figure 4.9 a), while manually-extracted lineaments and faults do not show any other discernible trends (Figure 4.9 b and c).

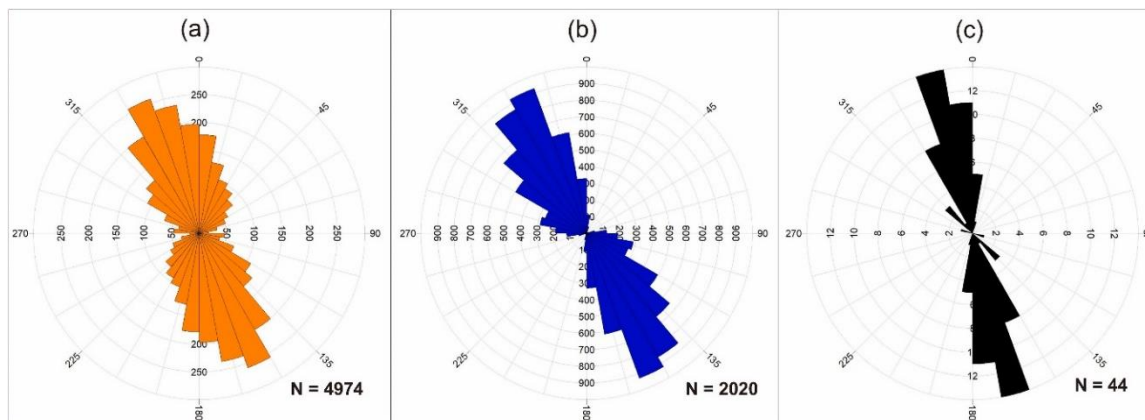


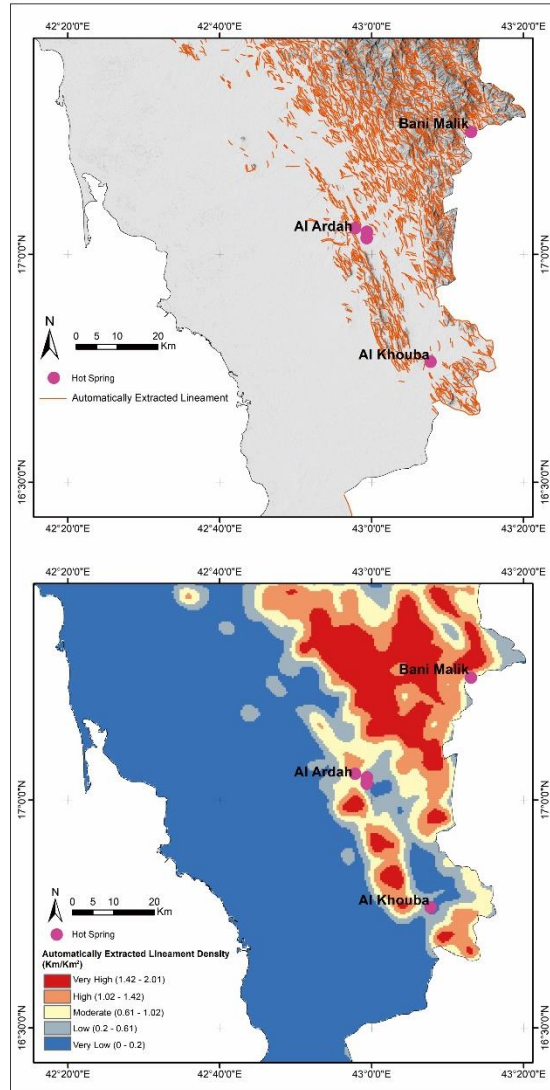
Figure 4.9 Rose diagrams show the orientation of the extracted lineaments and mapped faults in Jizan. (a) Orientation of automatically-extracted lineaments, (b) orientation of manually-extracted lineaments, and (c) orientation of faults mapped/interpreted from literature (Oelkers *et al.*, 2022).

4.2.3 Lineament and Fault Density

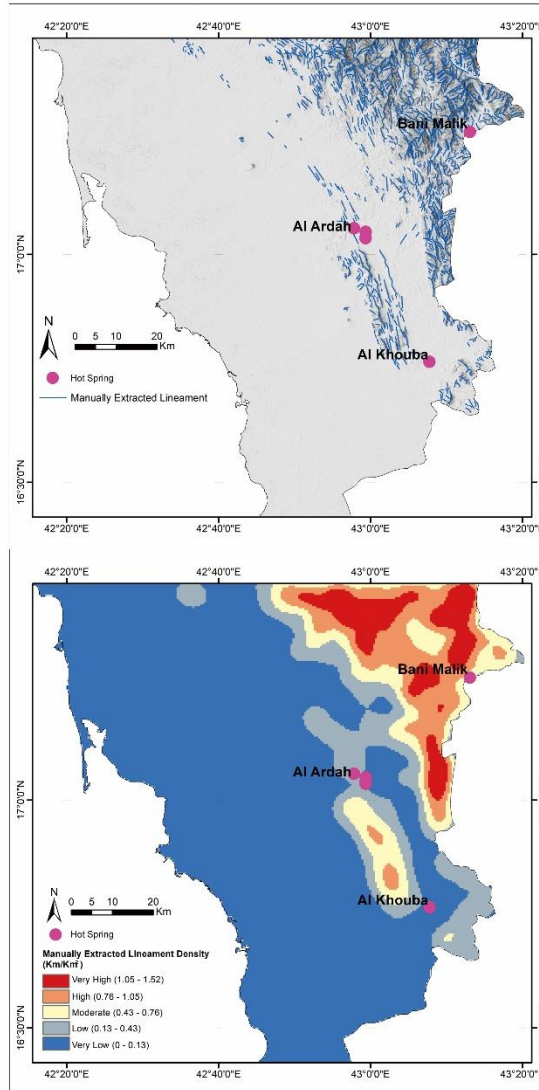
The spatial distribution of the automatically- and manually-extracted lineaments exhibit a similar pattern. The majority of lineaments are found distributed in northeastern Jizan, particularly around Al Ardah and Al Khouba (Figure 4.10). Consequently, moderate to very high lineament densities are concentrated within these areas. On the other hand, no lineaments were identified in the western part of Jizan, indicating a low to very low lineament density. The main difference between the lineament density maps of the automatically- and manually-extracted lies in the more extensive coverage of very high-density areas in the automatically-extracted lineament density map of several areas between Al Ardah and Al Khouba, as well as the southern part of Al Khouba, exhibit moderate to very high densities in the automatically-extracted lineament density map. In contrast, the manually-extracted lineament density map shows lower densities within those areas.

In contrast to the lineament density maps, the fault density map reveals a distinct spatial distribution. Most of the interpreted faults were traced around Al Ardah and Al Khouba and the area in the eastern part of Al Ardah, indicating moderate to very high fault density areas (Figure 4.10 c). In addition, the northern part of Jizan shows moderate to high fault-density areas.

(a) Automatically Generated Lineaments



(b) Manually Generated Lineaments



(c) Faults

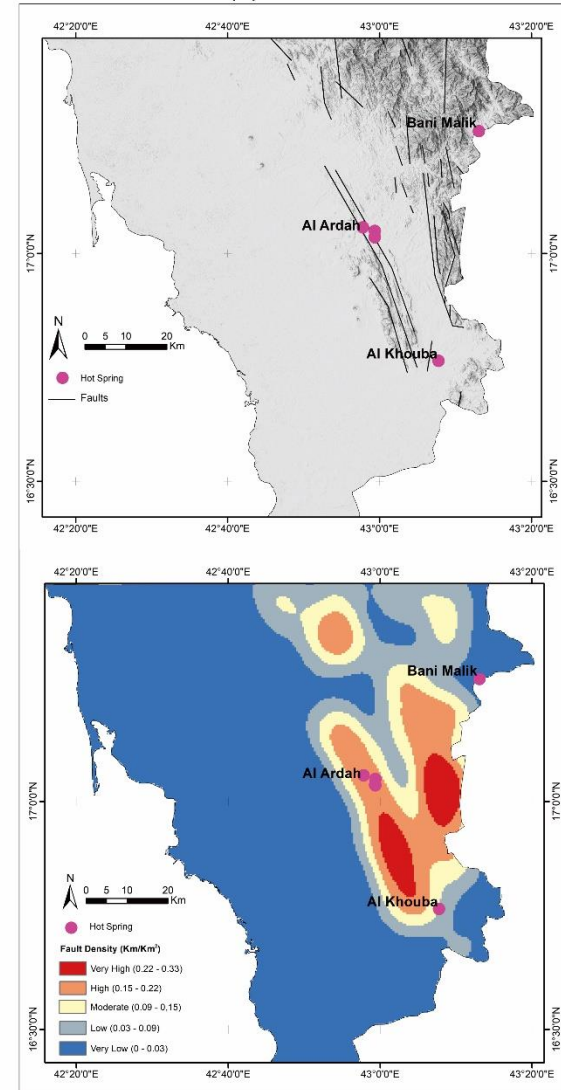


Figure 4.10 The lineaments and faults density map in Northern Konawe. (a) Automatically-extracted lineament density map, (b) manually-extracted lineament density map, (c) fault density map.

4.2.4 Fracture Observation in Outcrop

Ground truthing was conducted around the Al Ardah area to examine the fractures and rock units. Seven locations were selected as the observation locations based on the results obtained from the lineament density analysis (Figure 4.11).

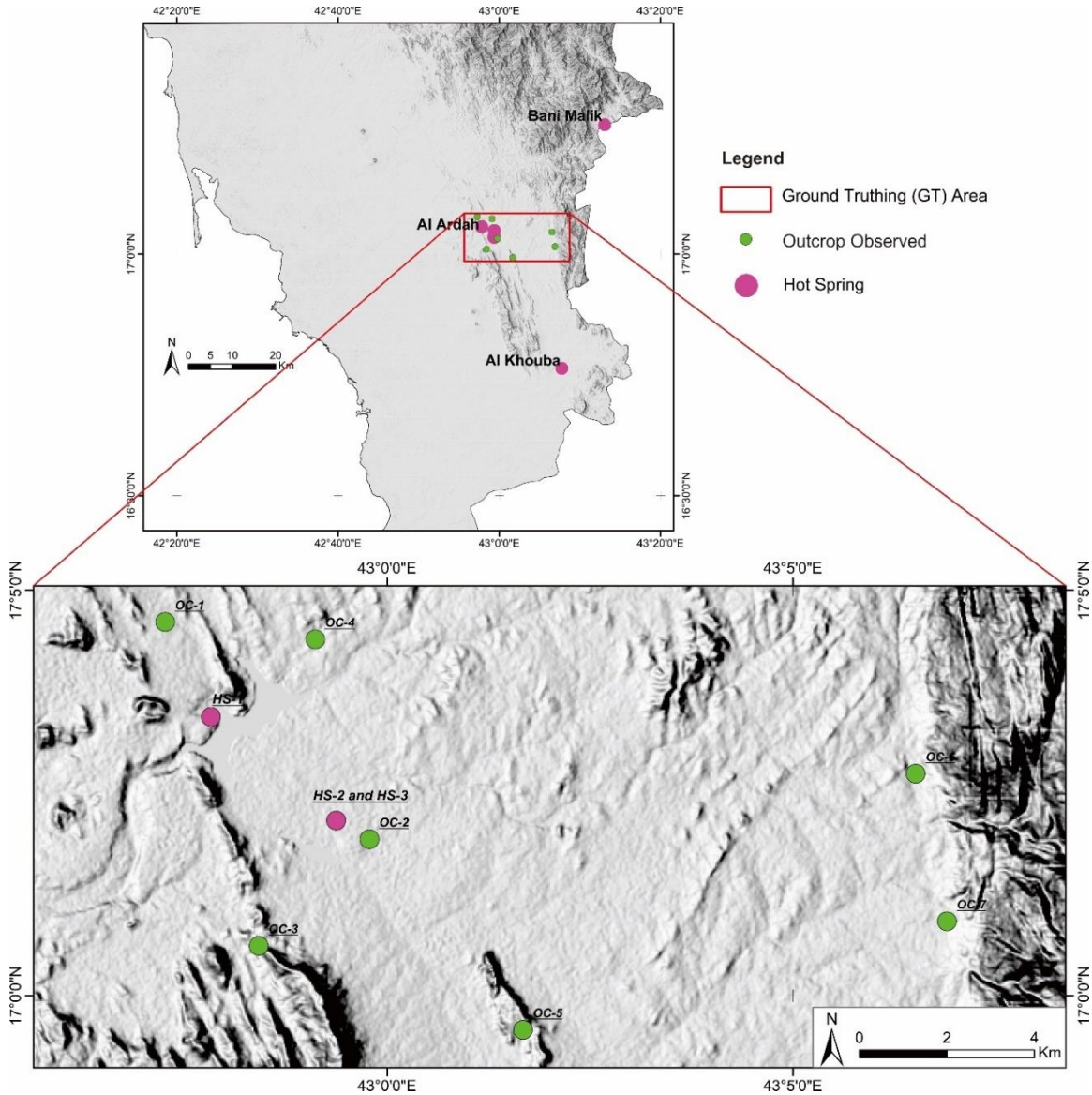


Figure 4.11 Ground truthing area with outcrops observed and hot spring sampling locations in Jizan, Saudi Arabia.

Within the selected study areas, various rock units were observed, including basalt in OC-1, OC-2, OC-3, and OC-4, sandstone in OC-5, metasedimentary rock in OC-6, and granite in OC-7. Mineralized fractures (veins) and unmineralized fractures or open fractures (OF) were observed in seven different locations representing these rock units. It was observed that the eastern part of the ground-truthing area had a higher density of fractured rocks compared to the western part (Figure 4.11 and Table 4.4).

In the western part, the open fractures dominate, with the primary orientation being NNW-SSE and the secondary orientation being N-S (Figures 4.12 a and b). These two sets intersect each other, creating a conjugate open fracture network, but the relative age is hard to determine. Additionally, silica veins with a WNW – ESE orientation were also observed, with the NNW-SSE open fractures cutting across them, indicating that the veins are relatively older than the open fracture set (Figure 4.12 c).

On the other hand, the eastern part of the ground-truthing area is dominated by veins with two major orientations, NNE – SSW and NE-SW (Figure 4.12 e). Both of these areas are filled with silica. The NNE-SSW vein set is relatively younger than NE-SW veins, as evidenced by the NNE-SSW shearing trend on the NE-SW veins (Figure 4.12 e). The NNW-SSE open fractures were also observed (Figure 4.12.d), but the density is relatively lower than the veins. This open fracture set is considered the youngest fracture because it crosscut the NNE-SSW silica vein (Figure 4.12.f).

Overall, 152 measured fractures were measured from seven locations, and the primary orientation was NNW-SSE, followed by a relatively N-S secondary orientation (Figure 4.12 g). Both trends are dominated by the open fractures (OF), with most of them dipping relatively towards the east. Veins with varying aperture sizes show a major trend of NE-SW and some relatively trending E-W. In terms of dip angle, out of 152 measured fractures, 61 have an almost vertical dip angle (ranging from 80° to 90°), followed by a gentler dip angle (from 60° to 80°) as the secondary major distribution (Figure 4.12 h). There are only a few fractures with gentle dip angles that were measured.

Table 4.4 Ground truthing fracture measurements in Jizan

Location	Relative Fracture Density	Type	Relative Fracture Orientation	Number of Fractures
OC-1	Moderate	OF	N-S	3
OC-2	Moderate	OF	NNW-SSE	5
		OF	N-S	5
OC-3	Moderate	OF	NNW-SSE	5
		OF	N-S	5
OC-4	High	OF	NNW-SSE	3
		CV	ENE-WSW	3
		SV	E-W	4
OC-5	Low	OF	ENE-WSW	48
OC-6	High	OF	NNW-SSE	3
OC-7	High	OF	NNW-SSE	51
		SV	NNE-SSW	12
		SV	NE-SW	5

*OC: outcrop, CV: carbonate vein, OF: open fracture, SV: silica vein

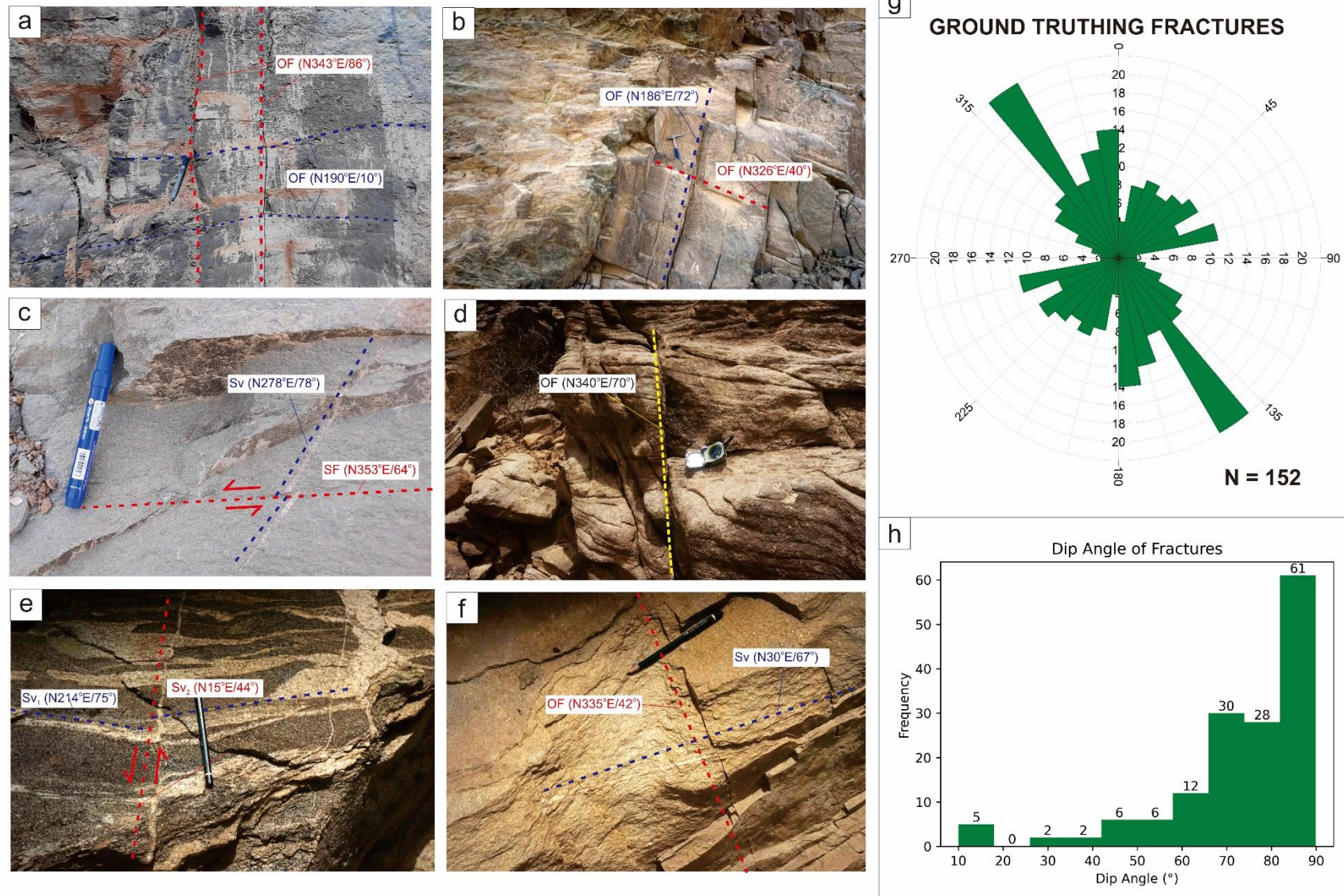


Figure 4.12 Fracture observed in Al Ardah, Jizan. (a) conjugate opening fractures on the basalt at OC-2. (b) conjugate opening fractures on the basalt at OC-3. (c) veins were sheared due to the development of younger opening fractures at OC-4. (d) NNW-SSE opening fractures at OC-6, (e) Relatively highly dense crosscutting relationship on granite at OC-7. (f) vein was crosscut by the NNW-SSE opening fracture on granite at OC-7. (g) rose diagram of measured fractures in Al Ardah, Jizan. (h) Histogram of dip angle distribution of fractures in Al Ardah, Jizan.

4.2.5 Hydrochemical of Hotsprings

The *in situ* measurements of three hot springs show 46.5 °C, 57.5 °C, and 54.5 °C for HS-1, HS-2, and HS-3, respectively (Table 4.5). Most samples have a neutral pH, around 7, with the Total Dissolved Solids (TDS) measured at 1842 ppm, 2632 ppm, and 2665 ppm, respectively. In addition, the Electroconductivity (EC) of the samples shows the value 2878 $\mu\text{S}/\text{cm}$ for SM-1, 4113 $\mu\text{S}/\text{cm}$ for SM-2, and 4164 $\mu\text{S}/\text{cm}$ for SM-3.

Table 4.5 In situ physicochemical measurement of hot springs.

No	Sample ID	Type	Surface Temperature (°C)	Elevation (m)	pH	TDS (ppm)	EC ($\mu\text{S}/\text{cm}$)
1	HS-1	Warm Spring	46.5	180	7.68	1842	2878
2	HS-2	Hot Spring	57.5	167	7.19	2632	4113
3	HS-3	Hot Spring	54.5	167	7.24	2665	4164

An ion balance (I.B) error of less than 5% was used to assess the quality of hydrochemical data analysis. Sodium (Na) dominates as the significant cation within the three samples. Regarding anion, chloride (Cl) has the most abundance concentration for HS-2 and HS-3, while sulfate (SO_4) is the most significant of anion followed by Cl (Table 4.6). Therefore, SM-1 is classified as the sulfate-chloride water, while SM-2 and SM-3 are the chloride water (Figure 4.13). In addition, the estimated reservoir temperature is around 180°C to 200°C from samples using Na-K geothermometers

(Equation 3.3). Regarding trace elements, Strontium (Sr) is the most abundant, followed by Li (Lithium) (Table 4.6)

Table 4.6 Hydrochemical composition of hydrothermal samples collected from Al Ardah hot springs. Jizan.

No	Sample ID	Major Cations (ppm)				Major Anions (ppm)				I.B	Other Elements (ppb)								
		Na	K	Ca	Mg	SO4	HCO3	Cl	F		Li	Ba	B	As	Sr	Fe	Al	Cu	Ni
1	HS-1	456.94	12.26	136.87	7.73	508.93	66.05	484.14	3.56	4.38	493	37.0	181	0.1	3851.2	5	29	43.1	14.7
2	HS-2	660.51	45.38	183.21	4.56	470.20	109.96	861.88	2.88	4.66	768	34.6	186	0.1	3643.2	447	25	73.3	22.3
3	HS-33	652.15	44.92	183.86	4.58	466.12	109.96	853.44	2.97	4.67	754	20.6	158	0.2	3926.1	204	28	84.4	28.1

I.B: Ion Balance (%)

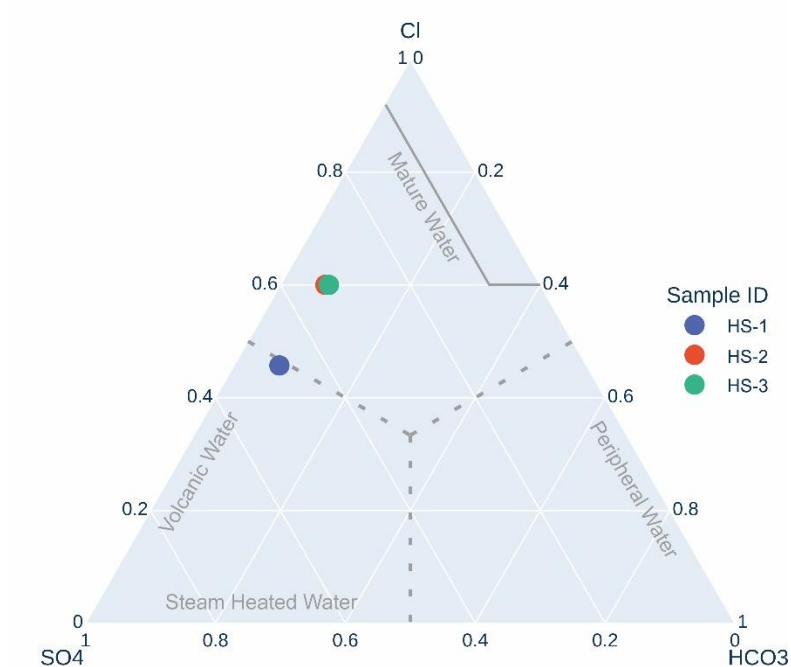


Figure 4.13 Cl-SO₄-HCO₃ ternary diagram showing the type of thermal water.

Additionally, the isotopic analysis shows $\delta^{18}O$ of HS-1, HS-2, and HS-3 values of -3.09 ‰, -3.19 ‰, and -2.93 ‰, respectively. The δD is -31.74 ‰, -12.1 ‰, and -10.9 for HS-1, HS-2, and HS-3. The cross-plot between $\delta^{18}O$ and δD can be seen in Figure 4.14.

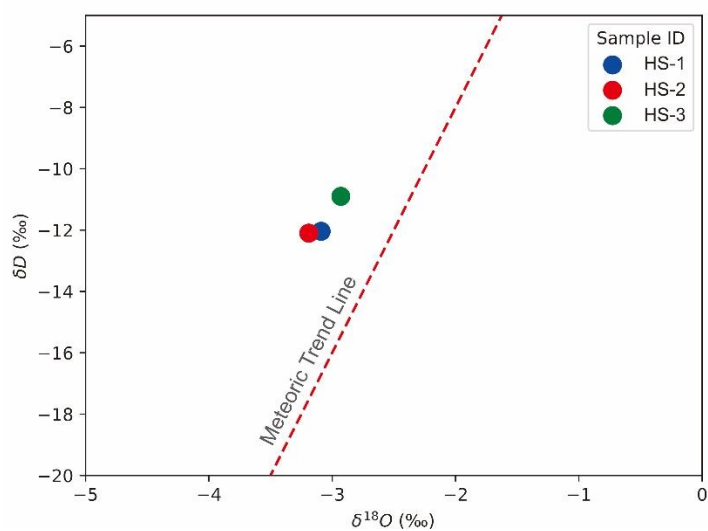


Figure 4.14 $\delta^{18}O$ vs δD of thermal water samples.

CHAPTER 5

DISCUSSIONS

5.1 Northern Konawe Geothermal Field, Indonesia

5.1.1 High Permeable Zone

The density of fractures with various lengths and widths, is known to typically control the permeability of geothermal reservoirs (Grant et al., 1982). A high lineament density value indicates a high number of faults and fractures in the study area, suggesting the presence of a highly permeable zone. To identify the permeable zones, Fuzzy 'AND' overlay approach was used in this study, involving the automatically- extracted lineaments, manually-extracted lineaments, and mapped faults. The resulting values ranged from 0 to 1, where 1 represents the highest value relative to the area within the study area. These results were then classified into five classes, where the very high class (0.68 – 1) was selected as the high permeable zone.

In the geothermal system of Northern Konawe, three high permeable zones (Zone A, B, and C) were identified (Figure 5.1). Zone A, located in the area around Lasolo, was the largest, with an area of 51.85 km², followed by zones B and C, with areas of 6.27 km² and 3.2 km², respectively. These zones are all connected and surrounded by the high class (0.48 – 0.68), implying the potential for fluid flow between the high permeable zones. Interestingly, the hot springs are spatially distributed in the low class (0.13 – 0.31) area rather than the high to very high-density areas.

The three permeable zones are spatially distributed in the Meluhu Formation, which predominantly consists of based on ground truthing. Sandstone was observed in the GT-3, GT-4, GT-5, GT-6, and GT-7, and these sandstones exhibited a relatively higher fracture density compared to other rock units in the other formations at GT-1, GT-2, and GT-8. Moreover, fractures were hardly observed in the Tokala Formation at GT-1, near the hot springs area. Therefore, lineament density analysis using remote sensing can be well used to delineate the highly fractured area. This is confirmed by highly fractured rock units that are spatially distributed in the high to very high-density area, and the very low fracture density in the low-density area (Figure 5.2). However, it is important to note that although high to very high-density areas based on remote sensing data are validated, they may not necessarily indicate high permeable zones as most of the fractures are mineralized. Therefore, considering the density of opening fractures based on outcrop observations is crucial in this case.

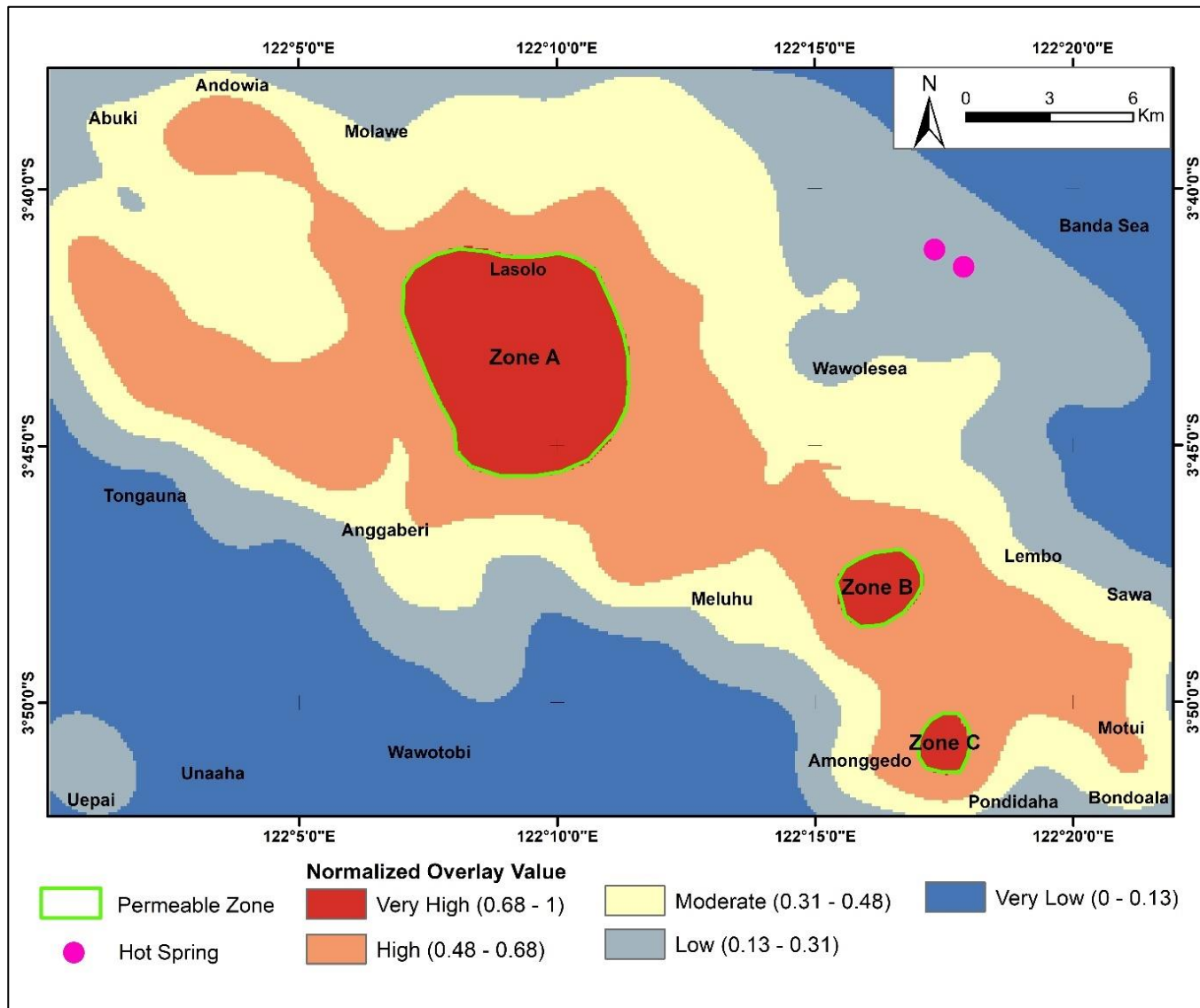


Figure 5.1 Fuzzy overlay map of lineaments (automatically-, and manually-generated lineaments) and faults in Northern Konawe geothermal system, Indonesia.

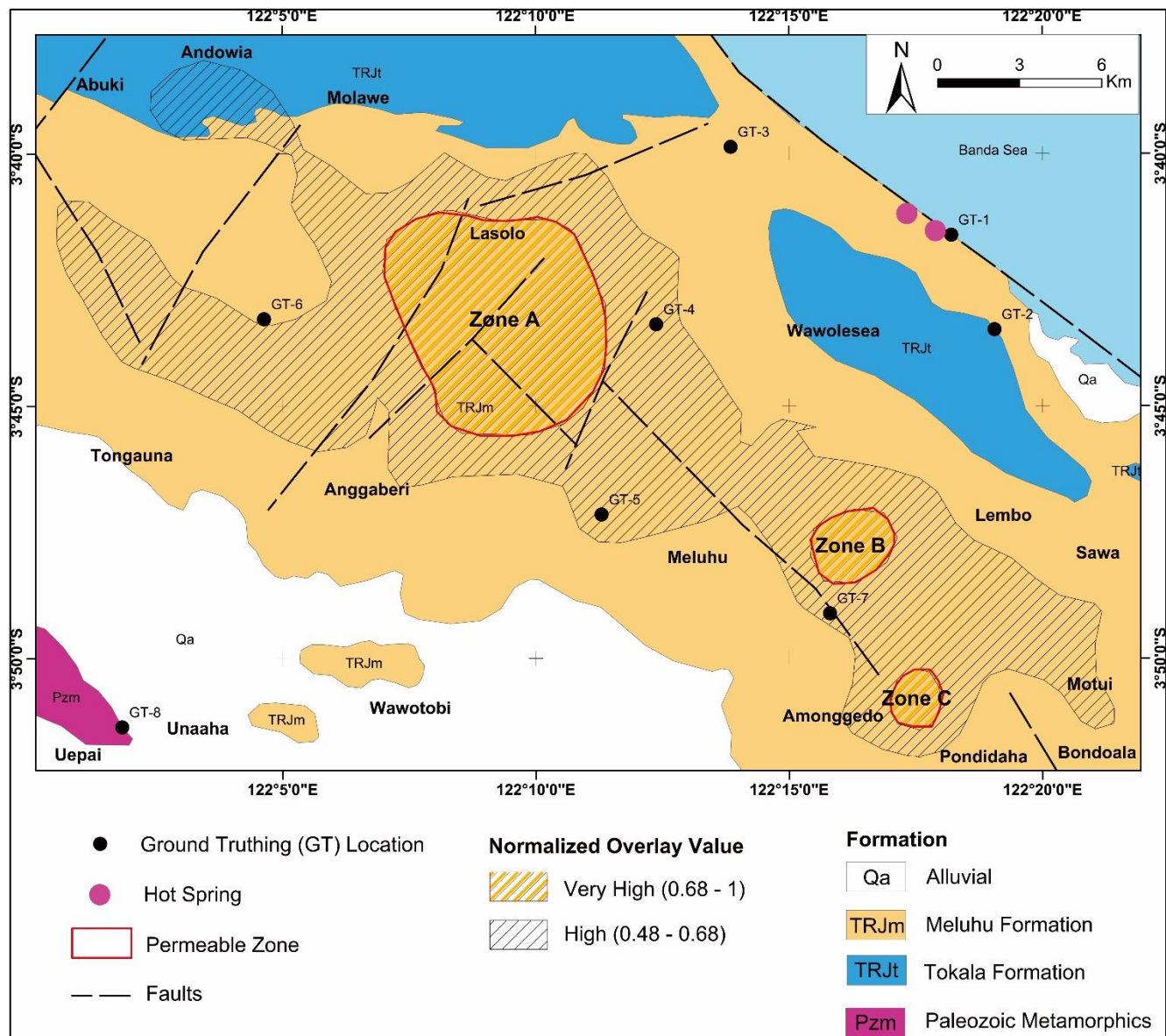


Figure 5.2 Geological map of Northern Konawe with the identified permeable zones

5.1.2 Geothermal Prospect Area

In this study, a combination of remote sensing and outcrop observation was utilized to identify the most promising geothermal area in the Northern Konwe region. The study focused on lineaments and faults density, orientations and permeable zones to gain insights into the hydrothermal fluid flow direction, potential source, and reservoir area.

To determine the suitable zones, three permeable zones were initially identified based on remote sensing analysis and then validated by the ground-truthing fracture measurements. Among these zones, Zone A is the most prospective area due to its larger size. However, automatically extracted lineaments exhibited an NNE-SSW orientation, suggesting that zone B and zone C might be the sources of hydrothermal fluid for the hot spring in the NNE area (Figure 5.2). This finding is supported by other fracture orientation data. While the manually-extracted lineaments show irregular orientation, the NNE-SSW trend was considered a high-frequency occurrence. Fault rose diagram, however, did not show a similar trend. In addition, the ground truthing fracture measurements revealed that the open fractures (OF) are the youngest set compared to the other fracture types observed, with an N-S trend (see Figure 4.6 d). This orientation aligns with the northwest-to-north vector direction of the Sulawesi collision that took place during the Miocene until the Pliocene (Sompton, 2012). Therefore, this event is believed to have influenced the formation of N-S opening fractures. Regarding the fluid flow within the current geothermal system, the primary hydrothermal fluid flow is interpreted to follow the N-S open fracture orientation as it facilitates fluid movement.

Other fracture sets (ex. silica- and carbonate-filled veins) do not conduct fluid flow anymore due to fracture mineralization that blocks the fluid movement. However, the presence of veins indicates the mineral deposition from hydrothermal fluids from paleo-geothermal systems (Edwards and Atkinson, 1985). Hence, following the trends of faults and lineaments (automatically-, and manually-extracted lineaments and the larger area of Zone B compared to Zone C), suggesting that Zone B is the most prospective area for the geothermal reservoir in the Northern Konawe, Indonesia (Figure 5.2). Zone B is also considered the recharge zone due to its high-density of open fractures, and the area around the hot springs is suggested to be the discharge zone.

5.2 Jizan Geothermal Field, Saudi Arabia

5.2.1 High Permeable Zone

The three permeable zones were delineated in Jizan, Saudi Arabia (Zone A, B, and C). They were identified based on the very high (0.57 – 1) normalized overlay value (Figure 5.3). Zone A is located in the northwestern part of Bani Malik, Zone B is in the eastern part of Al Ardah, and Zone C represents the area between Al Ardah and Al Khoubah. Zone B is the largest area, 195.89 Km², followed by Zone C and Zone A, 63.69 Km² and 32.59 Km², respectively. All zones are spatially separated, indicating different hydrothermal fluid circulation patterns among the zones. As in the case of Northern Konawe, Indonesia, all the hot springs in Jizan are located in the very low to low (0 – 0.21) value. Therefore, it is interpreted that the identified permeable zones are associated with highly fractured areas, which is not directly related to high fluid flow. Hence, further

investigation for fracture networks in outcrop is needed to determine the fracture type. Open fractures are the typical fracture type to conduct fluid flow.

The three zones are spatially distributed in the different rock units. Specifically, Zone A overlies in the various rock units, sabya formation (sa), gabbro (gb), foliated granite (gs), and quaternary deposits (Qs), from older to younger age (Figure 5.4.a). Most of them are Proterozoic basement rock units. Hence, these rock units are interpreted to have intensively fractured and faulted even though hot springs are identified within the location. However, it led to the interpretation that zone A could be the recharge zone, while the area around Bani Malik, near the hot springs, is suggested as the discharge zone. This interpretation is consistent with an outcrop study from Lashin and Al Arifi (2014), mentioning that hot springs in Balik Malik originated from highly fractured basement and metamorphic rocks.

Zone B covers the Proterozoic rock units, including paragneiss(gn) and foliated granite (gs) (Figure 5.4.a). Therefore, both rock units are believed to have a high density of fractures and faults despite that there was no hot spring identified within this zone. However, this zone is interpreted as a recharge zone similar to Zone A, whereas the hot springs area in Al Ardah is suggested as the discharge zone. Therefore, the fluid is believed to flow from the eastern part of Al Ardah, heated on the subsurface, and then flow through the normal faults to the surface in the western part, hot spring around the Al Ardah area.

Zone C is located within the Proterozoic to Tertiary Rock units, paragneiss (gn), Sabya Formation (sa), Wajid sandstone (Ocw), Khums Formation (jk), Hanifa Formation (jh), and Jizan group (Tba), from older to younger rock units, respectively (Figure 5.4.a). Therefore, these rock units are considered to have a high density of faults and fractures. Although there is no hot spring identified within this zone, within the wider study area, some hot springs are shown in Al Ardah and Al Khouba Areas. Hence, these hot springs are interpreted as discharged from the same fault or fracture system.

In order to validate the remote sensing analysis, ground-truthing activities were conducted in the area around Al Ardah and Zone B (Figure 5.4.b). This area was chosen for several reasons. Firstly, it covers the range of low to high values from the fuzzy 'AND' overlay, meaning it represents a diverse range of geological features. Additionally, the area contains various rock units and hot springs, indicating potential geothermal activity. Furthermore, compared to other zones, this area has the most extensive permeable zone, making it an ideal location for validation. During field observation, it was confirmed that the selected area is indeed a permeable zone based on the remote sensing analysis. However, it was also noted that the high density of fractures observed in the area is mainly due to the presence of veins. These veins, while indicating the presence of fractures, do not contribute significantly to the circulation of hydrothermal fluids.

This finding aligns with what was observed in the Northern Konawe geothermal system, where a high lineament density based on remote sensing analysis did not necessarily correspond to high fluid flow. Therefore, in order to accurately determine and quantify

the opening fractures in the area, it is crucial to rely on outcrop observation and not solely on remote sensing data.

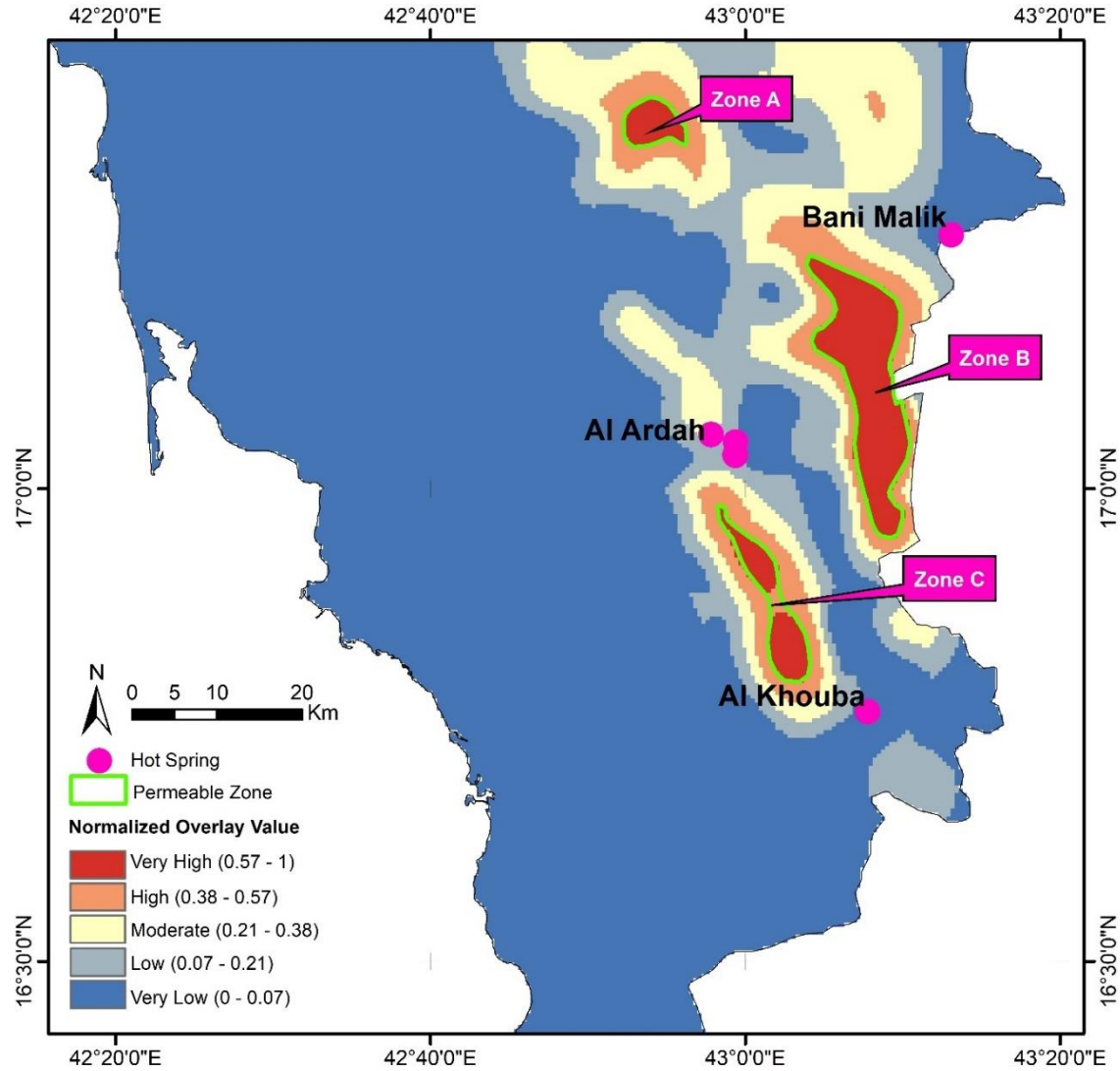


Figure 5.3 Fuzzy overlay map of lineaments (automatically-, and manually-extracted lineaments) and faults in the Jizan geothermal system, Saudi Arabia.

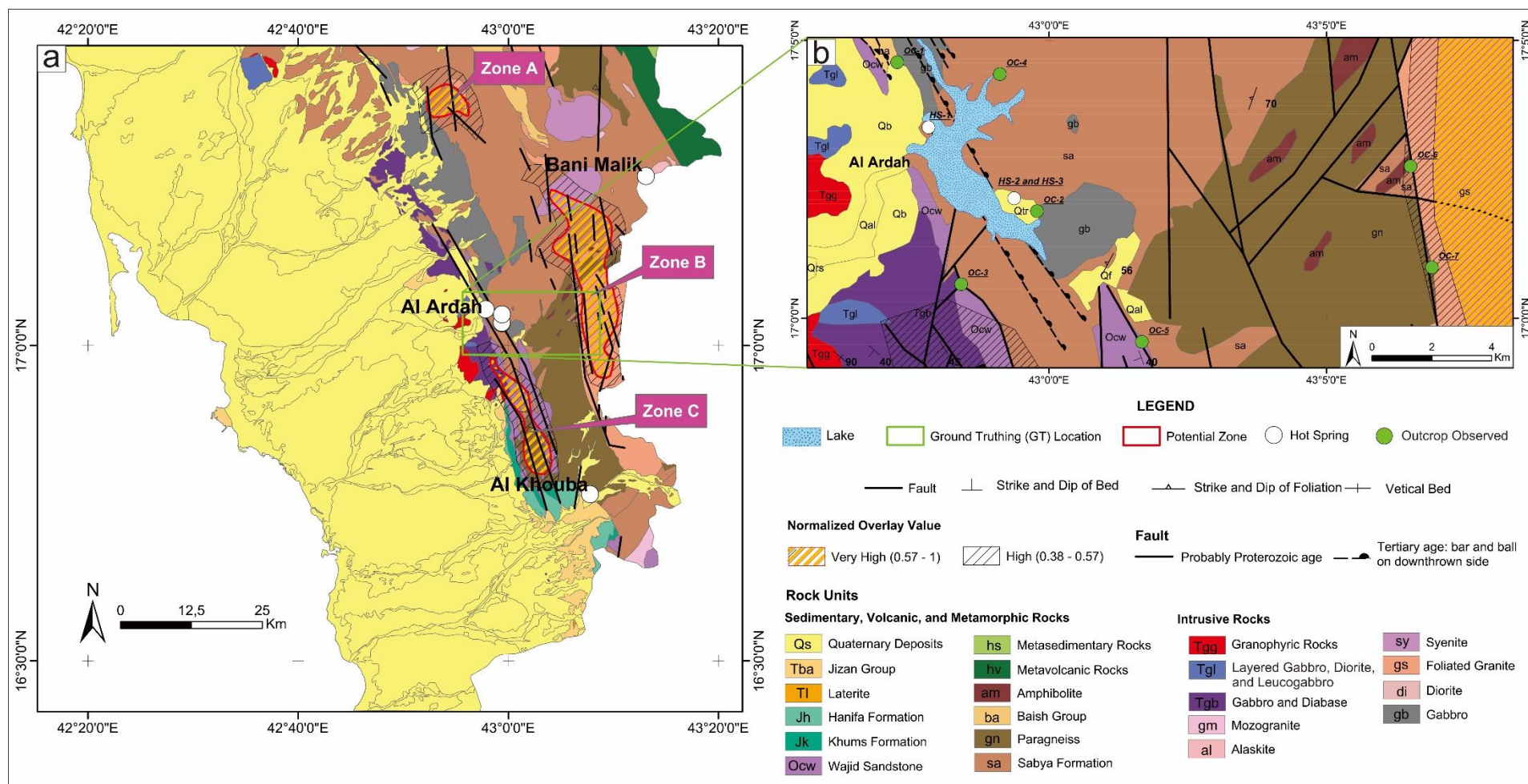


Figure 5.4 (a) Geological map of Jizan with the identified permeable zones. (b) Geological map of ground-truthing area with permeable zone (Zone B) and fracture observation locations.

5.2.2 Geothermal Prospect Area

Zone C is considered to be less prospective geothermal development. Analysis of all lineaments (automatically and manually generated lineaments), faults, and fractures from ground-truthing measurements confirms that the primary trend of structural features in Jizan is NNW-SSE, which agrees with the orientation of the Red Sea rifting (Blank *et al.*, 1987; Nehlig *et al.*, 2002). However, the calcite-filled veins show an NNW-SSE trend, as evidenced by fracture measurements through field investigation in several locations within Zone C (Al Malallah *et al.*, 2021). Therefore, these mineralized fractures could reduce the permeability along the NNW-SSE orientation in Zone C.

In contrast, the NNW-SSE fracture set around Zone B remains open to fluid flow based on observation within Zone B and the area on the western part of Zone B, near the hot springs in Al Ardah. These open fractures promote the circulation of hydrothermal fluids. In addition, the western area of Zone B is expected to enhance the fluid transmission due to conjugate open fractures. The comparison of zone B to A is only based on the permeable area measurement in this study, where zone B has a larger area. To conclude, Zone B is the most prospective zone unless further assessment is conducted, including subsurface geophysical and geochemical surveys, which might influence the primary prospective area for a geothermal reservoir in Jizan, Saudia Arabia.

In addition to the findings mentioned earlier, the hydrochemical analysis provided further insights into the geothermal system in zone B. It was interpreted that Zone B is a recharge zone in the eastern part, and a discharge area is in the western part. The isotopic

analysis of the hot spring water revealed negative $\delta^{18}O$ and δ^2H values around -3‰ and -12‰, respectively. This indicates that the recharge of hydrothermal fluids is predominantly influenced by precipitation. The fluids then penetrate the subsurface through the NNW-SSE trending open fractures within Zone B. Subsequently, they undergo heating in the subsurface, reaching temperatures estimated to be between 180°C to 200°C based on the Na-K geothermometer (Nicholson, 1993). The temperature is categorized as the medium enthalpy, suggesting that the heat source is of a non-volcanic nature. The hydrochemical analysis also revealed significant concentrations of Li relative to other trace elements, a positive K/Mg ratio, and Low Fe content. These observations indicate the intense interaction of hydrothermal water with the granitic rocks. Consequently, the granite is interpreted as the reservoir within this geothermal system, which is consistent with observed alteration within granitic rocks in Jizan (Chandrasekharam *et al.*, 2015). The heat is likely generated by the decay of radiogenic elements of the felsic intrusive rocks (Chandrasekharam *et al.*, 2014). After the fluids are heated, they are discharged through the NNW-SSE trending fractures and faults that dip towards the east. The east-to-west fluid flow is supported by the decreasing Cl/B and increasing B/Li ratios towards the east (Table 5.1). Additionally, the basaltic dykes are considered a conduit to fluid flow through the conjugate open fracture set observed in outcrops (Figures 4.12.a and b). The conceptual model of the geothermal system in Zone B can be seen in Figure 5.5.

Table 5.1 The ratios of different chemical elements with their respective indicator of the physical processes (Arrofi *et al*, 2023).

No.	Sample ID	Flow Direction		High Permeability/High-Temperature Zones					Ground Water Dilution	
		Dec.*	Inc.*	Low	Low	High	High	High	Low Na/K	High Mg
		Cl/B	B/Li	Na/K	Na/Ca	Cl/Mg	Cl/F	Cl/(HCO ₃ +CO ₃)		
1	HS-1	2.67	0.37	37.26	3.34	62.66	135.96	7.33	37.26	7.73
2	HS-2	4.63	0.24	14.56	3.61	188.88	299.68	7.84	14.56	4.56
3	HS-3	5.41	0.21	14.52	3.55	186.30	287.84	7.76	14.52	4.58

*Dec.: Decreasing, Inc.: Increasing

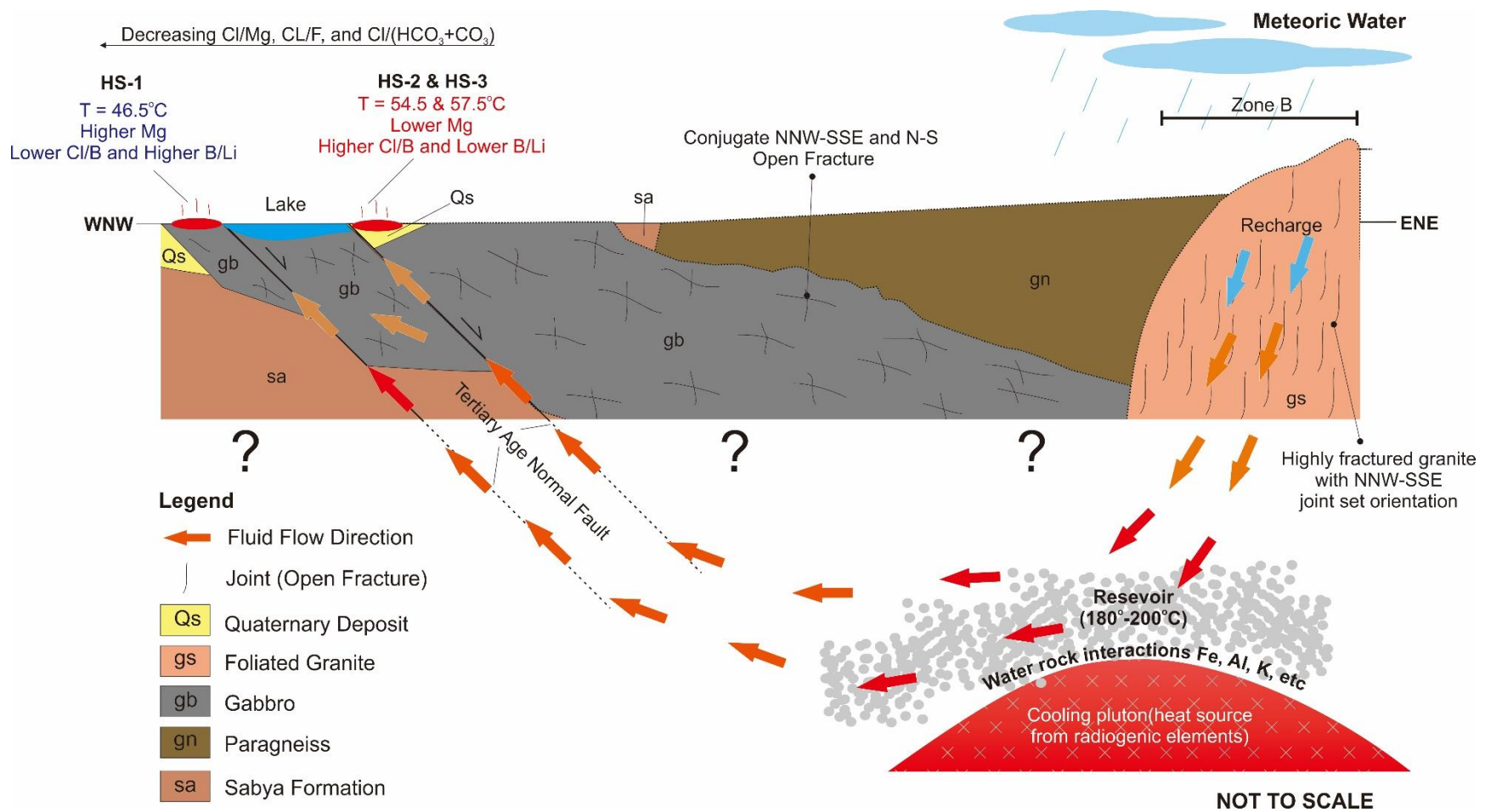


Figure 5.5 Conceptual model of a geothermal system in Al Ardah, Jizan, Saudi Arabia (modified from Arrofi *et al.*, 2023; Blank *et al.*, 1987).

5.3 Implications of Lineament Analysis for Non-volcanic Geothermal Exploration

5.3.1 Delineating High Permeable Zones

Lineament density analysis is a valuable tool for identifying areas of high fracture density. However, it should be noted that this analysis does not directly indicate the presence of high permeable zones, as not all fractures may be open. Additionally, lineament analysis has limitations in accurately defining the type of fractures due to resolution limitations. Therefore, it is important to complement lineament analysis with field observations of fractures in outcrops to obtain a more complete understanding of the subsurface characteristics. The integration of the different analytical techniques used in the present study plays a significant role in delineating highly fractured areas on the Fuzzy'AND' overlay.

In the Northern Konawe case study, the lineament density analysis, whether it was done automatically or manually, showed consistency with ground-truthing observations and fuzzy 'AND' overlay results. However, fault density analysis exhibited lower consistency with the ground-truthing observations (Figure 5.6).

Specifically, the automatically-generated lineament density analysis showed strong consistency with the ground-truthing observations at GT-4 and GT-5. These locations were found to reflect high to very high lineament density areas, indicating a higher fracture density ($>5\text{m}^{-1}$). This alignment between the lineament density and ground-

truthing results validates the effectiveness of the automatically generated lineament density analysis in accurately delineating highly fractured areas (Fig 5.6.a).

In contrast, GT-1, GT-3, and GT-6 exhibited lower fracture densities ($<5\text{m}^{-1}$) and were referred to as low to very low-density areas. Importantly, no fractures were observed at GT-1 and GT-3, which strongly aligns with the lineament delineation, indicating the very low density in those locations. This consistency serves as further evidence of the accuracy of the lineament density analysis in characterizing fracture distribution.

GT-8 was found to be the only location to have a high fracture intensity ($>5\text{m}^{-1}$), despite being located within the low-density area from lineament density analysis. Moreover, albeit GT-2 and GT-7 were not quantitatively measured for fracture density, fractures were observed in both locations, with GT-7 exhibiting a relatively higher density. This observation aligns with the lineament density analysis as GT-7 is located within the moderate-density area, while GT-2 is situated within the very low-density area. This consistency between the observed fractures and the delineation supports the accuracy of the lineament density analysis in capturing the distribution of fractures in the study area.

Manually extracted lineament density results were relatively similar to automatically extracted lineament density results when validating the lineament delineation. The only discrepancy was seen in GT-6, which was classified as the moderate-density area in the manually-extracted lineament density map but as the low-density area in the automatically-extracted lineament density map. However, this difference led to

inconsistency in the delineation process because GT-4 and GT-5, which had higher fracture densities, were located in the same zone as GT-6, which had a lower fracture density (Table 4.2 and Figure 5.6.b)

In contrast, fault density had the lowest consistency with the ground-truthing result when comparing the extracted lineaments from both methods. GT-4 and GT-5 are spatially distributed within the same zone as GT-1, GT-3, and GT-6, despite having different fracture density classifications. Moreover, GT-8, which had a high fracture density ($>5\text{m}^{-1}$), is located within a very low fault density area, highlighting the contrast between the ground-truthing observations and the lineament density map (Figure 5.6.c).

The fuzzy 'AND' overlay of lineaments and faults demonstrated the highest consistency to the ground truthing results (Figure 5.6.d). GT-4 and GT-5 are spatially distributed within the high-value area, excluding GT-8. GT-1, GT-3, and GT-6 are located in moderate to very low-value areas. Moreover, GT-7 qualitatively displayed a higher fracture density than GT-2 and was situated in a higher value zone than GT-2, indicating the successful validation of the fuzzy 'AND' overlay map.

In conclusion, lineament density analysis can effectively delineate high fracture density areas. However, it is not able to directly delineate the high permeable zones since not all fractures are open. Additionally, lineament analysis is limited in its ability to define the type of fractures due to resolution limitations. Therefore, observing fractures at the outcrop scale complements lineament analysis and allows for more comprehensive

investigation of permeable zones that promote fluid circulation. Despite these limitations, lineament analysis, specifically the integration of lineaments and faults using the fuzzy 'AND' overlaying method, remains a powerful tool in preliminary exploration for delineating high surface fracture density areas on a mega-scale.

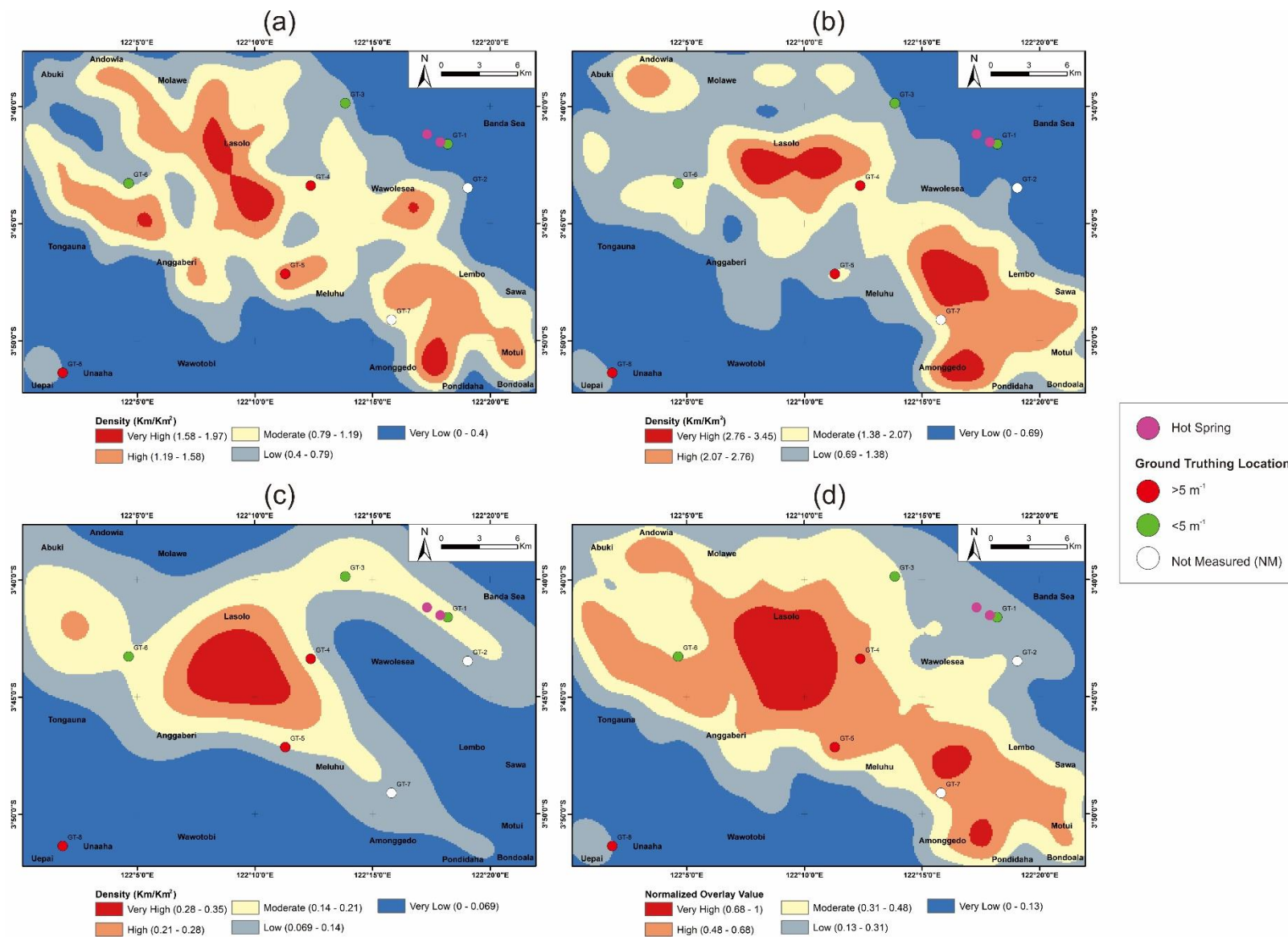


Figure 5.6 The lineaments and faults density map in Jizan with ground-truthing location. (a) Automatically-extracted lineament density. (b) Manually-extracted lineament density. (c) Fault density. (d) Fuzzy 'AND' overlay.

5.3.2 Predicting Fluid Flow in Geothermal Systems

The findings from both study cases indicate that the lineament density and orientation analysis supported by fracture field observations can be used as a reliable predictor to predict the fluid flow in the geothermal system. The possible orientation of fluid flow in geothermal systems can be determined based on the orientation and dip direction of open fractures or faults (Marrett, 1996). The fluid might flow along the strike of faults and fractures or the dip direction, depending on various parameters (Baraka-Lokmane *et al.*, 2001; Childs *et al.*, 2009; Faulkner *et al.*, 2010).

In the Northern Konawe study case, the N-S trend of open fractures suggests that the fluid flow is likely to follow the N-S strike of fractures or follow the dip direction of this fracture set to the west (Figures 4.6.c, g, and h). This is supported by the observation that the most prospective area, zone B, is located in the southern part of the hot spring area, indicating that fluid flow is oriented along the N-S direction (Figure 5.2). Although a major fault connecting Zone B and the hot springs area was not observed, open Fracture still plays a dominant role in fluid flow (Viswanathan *et al.*, 2022). Hence, the fluid flow in this case is mainly in the N-S orientation. The relative N-S trend is depicted in the automatically- and manually-extracted lineament rose diagrams but not in the faults rose diagram as their primary orientation. Thus, the lineaments extracted from automatic and manual extraction can be effectively used to determine the fluid flow orientation.

In the Jizan study case, the primary orientation of open fractures is NNW-SSE, with their major dip direction towards the east (Figure 4.12). The NNW-SSE orientation can be

seen on all of the rose diagrams. Therefore, all of them are consistent with the NNW-SSE open fractures trend. However, the hot springs are located in the western part of Zone B (Figure 5.4.b), the study most prospective geothermal area, suggesting that the fluid flow follows the dip direction rather than the strike. In this case, the fluid flows along the faults from Zone B to the western part (Figure 5.5).

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study has delineated the permeable zones for prospective geothermal reservoirs in two Indonesian and Saudi Arabian Geothermal Fields by integrating lineaments (automatically- and manually-extracted lineaments) and fault analysis. The conclusions of this study can be summarized as follows:

- In the Northern Konawe Geothermal Field, the lineaments extracted from both extraction methods are spatially distributed in Lasolo and around Meluhu and Lembo.
- In Jizan, the majority of the lineaments are clustered in Bani Malik and the area between Al Ardah and Al Khouba.
- Lineaments extracted from both methods show one major azimuth orientation for the Jizan Geothermal Field. While lineaments extracted from the Northern Konawe Geothermal Field show a wide range of trends. The fuzzy 'AND' overlay of lineaments (both automatically- and manually-extracted) and faults in Jizan show good agreement with ground-truthing results, particularly for the spatial distribution of fractures and faults. However, although the remote sensing and ground-truthing results show a similar major orientation of the structural features, there are additional secondary orientations that cannot be detected due to the spatial resolution limitation

in remote sensing analysis. Therefore, remote sensing can only help delineate major structural features in geothermal fields.

- It was observed that open fractures are the youngest set of fractures in both the Northern Konawe Geothermal Field and the Jizan Geothermal Field. In the Northern Konawe Geothermal Field, the N-S open fracture set was found to intersect with all other fracture sets. On the other hand, in the Jizan Geothermal Field, NNW-SSE open fractures were observed to intersect the other fracture sets. Based on Lineament density analysis, three permeable zones were identified in the Northern Konawe Geothermal Field: Zone A near Lasolo, Zone B between Meluhu and Lembo, and Zone C around Amonggedo. Similarly, in the Jizan Geothermal Field, three permeable zones were found: Zone A in the northwestern part of Bani Malik, Zone B in the eastern area of Al Ardah, and Zone C between Al Ardah and Al Khouba. Zone B in each study case is considered the most prospective geothermal area.
- The integration of lineaments and faults using the fuzzy 'AND' overlaying method proved to be a powerful in preliminary exploration to delineate areas with higher fracture density on the surface. However, it should be noted that these areas are not directly associated with the high permeable zones.

6.2 Recommendations

Areas for future work are listed as follows:

- Integrate geophysical data, such as seismic surveys or electrical resistivity tomography, with the remote sensing data to create a more comprehensive understanding of the subsurface structure and permeability distribution. This

could help refine the identification of high permeable zones and provide more precise targets for exploration drilling.

- Utilize machine learning algorithms to develop a predictive model that can identify high permeable zones based on the extracted lineaments, faults, fractures, and geophysical data. This model could be used to prioritize exploration efforts in areas with a higher likelihood of encountering high permeability zones.
- Characterize the reservoir properties through analysis of direct core samples from the geothermal fields to determine the porosity, permeability, and fluid saturation of the reservoir rocks. This information is crucial for assessing the potential for geothermal energy production.
- Conduct well-logging surveys to obtain detailed information about the subsurface stratigraphy, lithology, and fluid properties. This data can be used to create a more refined model of the geothermal reservoir and its potential for energy production.
- Radiometric dating of the granitic rocks can provide valuable insights into the heat source of the geothermal field and the overall thermal history of the area..

References

- Abbady, A.G.E. and Al-Ghamdi, A.H. (2018) 'Heat production rate from radioactive elements of granite rocks in north and southeastern Arabian shield Kingdom of Saudi Arabia', *Journal of Radiation Research and Applied Sciences*, 11(4), pp. 281–290. Available at: <https://doi.org/10.1016/j.jrras.2018.03.002>.
- Abu-Mahfouz, I.S., Rafiq, J. and Arrofi, D. (2023) 'Geological Structure Identification in Geothermal Fields, Southwestern Saudi Arabia', 2023(1), pp. 1–5. Available at: <https://doi.org/https://doi.org/10.3997/2214-4609.2023631012>.
- Abuzied, S.M. *et al.* (2020) 'Multi-criteria decision support for geothermal resources exploration based on remote sensing, GIS and geophysical techniques along the Gulf of Suez coastal area, Egypt', *Geothermics*, 88(May), p. 101893. Available at: <https://doi.org/10.1016/j.geothermics.2020.101893>.
- Adiri, Z. *et al.* (2017) 'Comparison of Landsat-8, ASTER and Sentinel 1 satellite remote sensing data in automatic lineaments extraction: A case study of Sidi Flah-Bouskour inlier, Moroccan Anti Atlas', *Advances in Space Research*, 60(11), pp. 2355–2367. Available at: <https://doi.org/10.1016/j.asr.2017.09.006>.
- Ahmadi, H. and Pekkan, E. (2021) 'Fault-based geological lineaments extraction using remote sensing and gis—a review', *Geosciences (Switzerland)*, 11(5). Available at: <https://doi.org/10.3390/geosciences11050183>.
- Aisabokhae, J. and Tampul, H. (2020) 'Statistical variability of radiation exposures from Precambrian basement rocks, NW Nigeria: Implication on radiogenic heat production', *Scientific African*, 10, p. e00577. Available at: <https://doi.org/10.1016/j.sciaf.2020.e00577>.
- Al Malallah, M. *et al.* (2021) 'Fracture network analysis for carbon mineralization in basalts of the Oligocene Jizan volcanics, Saudi Arabia', *EGU General Assembly Conference Abstracts*, (September), pp. EGU21-16442.
- Allum, J.A.E. (1978) 'Lineament, linear, lineation: Some proposed new standards for old terms: Discussion', *Bulletin of the Geological Society of America*, 89(1), pp. 159–159. Available at: [https://doi.org/10.1130/0016-7606\(1978\)89<159a:LLLSPN>2.0.CO;2](https://doi.org/10.1130/0016-7606(1978)89<159a:LLLSPN>2.0.CO;2).
- Anna Yushantarti and Rezky, Y. (2014) 'PENYELIDIKAN TERPADU GEOLOGI DAN GEOKIMIA DAERAH PANAS BUMI AMOHOLA, KABUPATEN KONAWE SELATAN PROVINSI SULAWESI TENGGARA', in *Pusast Sumber Daya Geologi*. Bandung.
- Armstrong F. Sompton (2012) *Struktur Geologi Sulawesi*. Bandung: Perpustakaan Sains Kebumian Institut Teknologi Bandung.

- Arrofi, D. and Abu-Mahfouz, I.S. (2023) ‘Delineating reservoir area using geologic remote sensing analysis, Jizan (Saudi Arabia): Implications for geothermal exploration’, *Geoenergy Science and Engineering*, 228(May), p. 212033. Available at: <https://doi.org/10.1016/j.geoen.2023.212033>.
- Arrofi, D., Abu-Mahfouz, I.S. and Humphrey, J. (2023) ‘Unearthing Insights Into Non-Volcanic Geothermal System: a Conceptual Model Through Hydrochemical Exploration in Southwestern Saudi Arabia’, 2023(1), pp. 1–5. Available at: <https://doi.org/https://doi.org/10.3997/2214-4609.202321081>.
- Arrofi, D., Abu-Mahfouz, I.S. and Prayudi, S.D. (2022) ‘Investigating high permeable zones in non-volcanic geothermal systems using lineament analysis and fault fracture density (FFD): northern Konawe Regency, Indonesia’, *Geothermal Energy*, 10(1), p. 29. Available at: <https://doi.org/10.1186/s40517-022-00241-3>.
- Aulia, R.N., Nur, I. and Ilyas, A. (2022) ‘ANALISIS GEOKIMIA AIR PANAS DAERAH WAWOLESEA’, *Jurnal Gecelebes*, 6(1), pp. 64–71. Available at: <https://doi.org/10.20956/gecelebes.v6i1.19672>.
- Baraka-Lokmane, S., Teutsch, G. and Main, I.G. (2001) ‘Influence of open and sealed fractures on fluid flow and water saturation in sandstone cores using Magnetic Resonance Imaging’, *Geophysical Journal International*, 147(2), pp. 263–271. Available at: <https://doi.org/10.1046/j.0956-540x.2001.01519.x>.
- Blank, H.R. *et al.* (1987) ‘Geologic Map of The Jizan Quadrangle, Sheet 16 F, Kingdom of Saudi Arabia’. Ministry of Petroleum and Mineral Resources, Deputy Ministry for Mineral Resources.
- Bogie, I. and Lawless, J. (2000) ‘Application of mineral deposit concepts to geothermal exploration’, *Proceedings World Geothermal Congress 2000*, (28 May–10 June), pp. 1003–1008.
- Calvert, S.J. and Hall, R. (2003) ‘The Cenozoic geology of the Lariang and Karama regions, Western Sulawesi: new insight into the evolution of the Makassar Straits region’.
- Chandrasekharam, D. *et al.* (2014) ‘Evolution of geothermal systems around the Red Sea’, *Environmental Earth Sciences*, 73(8), pp. 4215–4236. Available at: <https://doi.org/10.1007/s12665-014-3710-y>.
- Chandrasekharam, D. *et al.* (2015) ‘Geothermal energy resources of Jizan, SW Saudi Arabia’, *Journal of African Earth Sciences*, 109, pp. 55–67. Available at: <https://doi.org/10.1016/j.jafrearsci.2015.05.016>.
- Chandrasekharam, D. *et al.* (2016) *Red Sea geothermal provinces*. CRC Press.
- Chandrasekharam, D. and Baba, A. (2021) ‘High heat generating granites of Kestanol: future enhanced geothermal system (EGS) province in western Anatolia’, 30(9). Available at: <https://doi.org/10.3906/yer-2106-16>.

- Chapman, R.W. (1978) 'Geology', in S.S. Al-Sayari and J.G. Zötl (eds) *Quaternary Period in Saudi Arabia: 1: Sedimentological, Hydrogeological, Hydrochemical, Geomorphological, and Climatological Investigations in Central and Eastern Saudi Arabia*. Vienna: Springer Vienna, pp. 4–19. Available at: https://doi.org/10.1007/978-3-7091-8494-3_3.
- Chen, B.C., Perdana, T. and Kuo, L.W. (2021) 'Fluid flow and fault-related subsurface fractures in slate and metasandstone formations: A case study of the Jentse Geothermal Area, Taiwan', *Geothermics*, 89(300), p. 101986. Available at: <https://doi.org/10.1016/j.geothermics.2020.101986>.
- Childs, C. *et al.* (2009) 'Calibrating fault seal using a hydrocarbon migration model of the Oseberg Syd area, Viking Graben', *Marine and Petroleum Geology*, 26(6), pp. 764–774. Available at: <https://doi.org/10.1016/j.marpetgeo.2008.05.004>.
- Dasgupta, S. and Mukherjee, S. (2019) *Remote Sensing in Lineament Identification: Examples from Western India*. 1st edn, *Problems and Solutions in Structural Geology and Tectonics*. 1st edn. Elsevier Inc. Available at: <https://doi.org/10.1016/b978-0-12-814048-2.00016-8>.
- Edwards, R. and Atkinson, K. (1985) *Ore Deposit Geology And Its Influence on Mineral Exploration*. London: London New York Chapman and Hall.
- English, J.M. *et al.* (2023) 'An overview of deep geothermal energy and its potential on the island of Ireland', *First Break*, 41(2), pp. 33–43. Available at: <https://doi.org/10.3997/1365-2397.fb2023009>.
- Fairer, G.M. (1985) 'Geologic Map of The Wadi Baysh Quadrangle, Sheet 17F, Kingdom of Saudi Arabia'. Ministry of Petroleum and Mineral Resources, Deputy Ministry for Mineral Resources.
- Faulkner, D.R. *et al.* (2010) 'A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones', *Journal of Structural Geology*, 32(11), pp. 1557–1575. Available at: <https://doi.org/https://doi.org/10.1016/j.jsg.2010.06.009>.
- Gando, A. *et al.* (2011) 'Partial radiogenic heat model for Earth revealed by geoneutrino measurements', *Nature Geoscience*, 4(9), pp. 647–651. Available at: <https://doi.org/10.1038/ngeo1205>.
- Giggenbach, W.F. (1988) 'Geothermal solute equilibria. derivation of Na-K-Mg-Ca geoindicators', *Geochimica et cosmochimica acta*, 52(12), pp. 2749–2765.
- Goff, F. and Janik, C.J. (2000) 'Geothermal systems', *Encyclopedia of volcanoes*, 2000, pp. 817–834.
- Grant, M., Donaldson, I. and Bixley, P. (1982) 'Geothermal Reservoir Engineering', in New York: Academic Press, p. 369.
- Gross, M.R. (1995) 'Fracture partitioning: failure mode as a function of lithology in the

- Monterey Formation of coastal California', *Geological Society of America Bulletin*, 107(7), pp. 779–792. Available at: [https://doi.org/10.1130/0016-7606\(1995\)107<0779:FPFMAA>2.3.CO;2](https://doi.org/10.1130/0016-7606(1995)107<0779:FPFMAA>2.3.CO;2).
- Groves, D.I. *et al.* (2003) 'Gold deposits in metamorphic belts: Overview of current understanding, outstanding problems, future research, and exploration significance', *Economic Geology*, 98(1), pp. 1–29. Available at: <https://doi.org/10.2113/gsecongeo.98.1.1>.
- Hamimu, L. *et al.* (2019) 'Analysis of the Sub-Surface Distribution of Graphite Minerals Using the Geoelectrical Resistivity Method in the Sabilambo Village, Kolaka Regency, Southeast Sulawesi Province', *Journal of Geoscience, Engineering, Environment, and Technology*, 4(3), p. 149. Available at: <https://doi.org/10.25299/jgeet.2019.4.3.2406>.
- Hashem, B. and Abdullah, K. (2012) 'Geothermal development roadmap for the Kingdom of Saudi Arabia', *Journal of Geosciences* [Preprint], (August). Available at: <http://www.oit.edu/docs/default-source/geoheat-center-documents/quarterly-bulletin/vol-31/31-2/31-2-art6.pdf?sfvrsn=4>.
- Hasterok, D. and Webb, J. (2017) 'On the radiogenic heat production of igneous rocks', *Geoscience Frontiers*, 8(5), pp. 919–940. Available at: <https://doi.org/10.1016/j.gsf.2017.03.006>.
- Hochstein, M.P. and Sudarman, S. (2015) 'Indonesian Volcanic Geothermal Systems', *World Geothermal Congress 2015*, (April), p. 11.
- Huttrer, G.W. (2020) 'Geothermal power generation in the world 2010-2014 update report', in *World Geothermal Congress*. Reykjavik.
- (IGA), I.G.A. (2014) *Best Practices Guide for Geothermal Exploration*, IGA Service GmbH. Bochum.
- Idral, A. (2010) 'Potency of Non Volcanic Hosted Geothermal Resources in Sulawesi-Indonesia', *World Geothermal Congress 2010*, (April), pp. 25–29.
- Jamaluddin and Umar, E.P. (2017) 'KARAKTERISTIK FISIK DAN KIMIA MATAAIR PANAS DAERAH BARASANGA KABUPATEN KONAWE UTARA', *Jurnal Gecelebes*, 1(2), pp. 62–65. Available at: <http://journal.unhas.ac.id/index.php/gecelebes%0AJurnal>.
- Jaya, L.M.G. *et al.* (2021) 'Identification of non-volcanic geothermal manifestation in North Konawe Regency Indonesia using land surface temperature of Landsat satellite image', *IOP Conference Series: Earth and Environmental Science*, 622(1). Available at: <https://doi.org/10.1088/1755-1315/622/1/012040>.
- Johnson PR (1998) *Tectonic map of Saudi Arabia and adjacent areas*.
- Lashin, A. *et al.* (2014) 'High heat generating granites of Western Saudi Arabia', *Transactions - Geothermal Resources Council*, 38, pp. 635–638.

- Lashin, A. and Al Arifi, N. (2014a) 'Geothermal energy potential of southwestern of Saudi Arabia exploration and possible power generation: A case study at Al Khouba area - Jizan', *Renewable and Sustainable Energy Reviews*, 30, pp. 771–789. Available at: <https://doi.org/10.1016/j.rser.2013.10.037>.
- Lashin, A. and Al Arifi, N. (2014b) 'Geothermal energy potential of southwestern of Saudi Arabia exploration and possible power generation: A case study at Al Khouba area - Jizan', *Renewable and Sustainable Energy Reviews*, pp. 771–789. Available at: <https://doi.org/10.1016/j.rser.2013.10.037>.
- Liu, B. *et al.* (2019) 'Double-vein (ore-bearing vs. ore-free) structures in the Xitian ore field, South China: Implications for fluid evolution and mineral exploration', *Ore Geology Reviews*, 115(May), p. 103181. Available at: <https://doi.org/10.1016/j.oregeorev.2019.103181>.
- MacKnight IV, R.B. *et al.* (2004) 'Remote sensing analysis of structure and geothermal potential of the Humboldt Block, Nevada', *International Geoscience and Remote Sensing Symposium (IGARSS)*, 1(C), pp. 627–629. Available at: <https://doi.org/10.1109/igarss.2004.1369106>.
- Marrett, R.A. (1996) 'Permeability, porosity, and shear-wave anisotropy from scaling of open fracture populations', *Fractured Reservoirs- Characterization and Modeling, Chapter: Permeability, porosity, and shear-wave anisotropy from scaling of open fracture populations*, (January), pp. 217–226. Available at: https://www.researchgate.net/publication/259266199_Permeability_porosity_and_shear-wave_anisotropy_from_scaling_of_open_fracture_populations.
- Martosuwito, S. (2012) 'Tectonostratigraphy of the eastern part of Sulawesi, Indonesia. In relation to the terrane origins', *Jurnal Geologi dan Sumberdaya Mineral*, 22(4), pp. 199–207.
- Moeck, I.S. (2014) 'Catalog of geothermal play types based on geologic controls', *Renewable and Sustainable Energy Reviews*, 37, pp. 867–882. Available at: <https://doi.org/10.1016/j.rser.2014.05.032>.
- Möller, P. *et al.* (2004) 'Rare earth elements, yttrium and Pb isotope ratios in thermal spring and well waters of West Anatolia, Turkey: A hydrochemical study of their origin', *Chemical Geology*, 206(1–2), pp. 97–118. Available at: <https://doi.org/10.1016/j.chemgeo.2004.01.009>.
- Nahli, K. *et al.* (2016) 'Identifying Non-Volcanic Geothermal Potential in Amohola, Southeast Sulawesi Province, by Applying the Fault and Fracture Density (FFD) Method', *IOP Conference Series: Earth and Environmental Science*, 42(1), pp. 0–5. Available at: <https://doi.org/10.1088/1755-1315/42/1/012015>.
- Nehlig, P., Genna, A. and Asfirane, F. (2002) 'A review of the Pan-African evolution of the Arabian shield', *GeoArabia*, 7(1), pp. 103–124. Available at: <https://doi.org/10.2113/geoarabia0701103>.

- Nicholson K. (1993) *Geothermal Fluids Chemistry and Exploration Techniques*, Springer Verlag. Springer Verlag. Available at: <https://link.springer.com/content/pdf/10.1007/978-3-642-77844-5.pdf>.
- Oelkers, E.H. *et al.* (2022) ‘The subsurface carbonation potential of basaltic rocks from the Jizan region of Southwest Saudi Arabia’, *International Journal of Greenhouse Gas Control*, 120(December 2021), p. 103772. Available at: <https://doi.org/10.1016/j.ijggc.2022.103772>.
- Osaragi, T. (2002) ‘Classification Methods for Spatial Data Representation’, *UCL-Centre for Advanced Spatial Analysis-Working Paper Series*, 44(1), pp. 1–19. Available at: <http://www.casa.ucl.ac.uk/paper40.pdf%0Acasa@ucl.ac.uk>.
- Owusu, P.A. and Asumadu-Sarkodie, S. (2016) ‘A review of renewable energy sources, sustainability issues and climate change mitigation’, *Cogent Engineering*, 3(1), p. 1167990.
- Papp, D.C. and Nițoi, E. (2006) ‘Isotopic composition and origin of mineral and geothermal waters from Tușnad Băi Spa, Harghita Mountains, Romania’, *Journal of Geochemical Exploration*, 89(1-3 SPEC. ISS.), pp. 314–317. Available at: <https://doi.org/10.1016/j.gexplo.2005.12.008>.
- Pollack, H.N., Hurter, S.J. and Johnson, J.R. (1993) ‘Heat flow from the Earth’s interior: analysis of the global data set’, *Reviews of Geophysics*, 31(3), pp. 267–280.
- Prost, G.L. (2013) *Remote Sensing for Geoscientists*, *Remote Sensing for Geoscientists*. Available at: <https://doi.org/10.1201/b15638>.
- Qin, D., Turner, J. V. and Pang, Z. (2005) ‘Hydrogeochemistry and groundwater circulation in the Xi’an geothermal field, China’, *Geothermics*, 34(4), pp. 471–494. Available at: <https://doi.org/10.1016/j.geothermics.2005.06.004>.
- Razdan, P.N., Agarwal, R.K. and Singh, R. (2014) ‘Geothermal energy resources and its potential in India’, *Advanced Renewable Energy Systems*, I(I), pp. 389–402. Available at: <https://doi.org/10.1016/b978-1-78242-269-3.50015-2>.
- Rusmana, E. *et al.* (1993) ‘Geological Map of Lasusua Kendari Quadrangles, Sulawesi-Scale 1: 250.000’, *Transverse Mercator Projection*, *Copy Right: Pusat Penelitian dan Pengembangan Geologi* [Preprint].
- Sanada, T., Takamatsu, N. and Yoshiike, Y. (2006) ‘Geochemical interpretation of long-term variations in rare earth element concentrations in acidic hot spring waters from the Tamagawa geothermal area, Japan’, *Geothermics*, 35(2), pp. 141–155. Available at: <https://doi.org/10.1016/j.geothermics.2006.02.004>.
- Schubert, G., Stevenson, D. and Cassen, P. (1980) ‘Whole planet cooling and the radiogenic heat source contents of the Earth and Moon’, *Journal of Geophysical Research: Solid Earth*, 85(B5), pp. 2531–2538.
- Seebeck, H. *et al.* (2014) ‘Fluid flow in fault zones from an active rift’, *Journal of*

- Structural Geology*, 62, pp. 52–64. Available at: <https://doi.org/https://doi.org/10.1016/j.jsg.2014.01.008>.
- Sichugova, L. V, Jamolov, A.T. and Movlanov, J.J. (2021) ‘Statistical Analysis of Lineaments Using Landsat 8 Data: A Case Study of The Fergana Valley (East Uzbekistan)’, *The American Journal of Applied sciences*, 3(3), pp. 83–92.
- Simandjuntak, T.O., Surono and Sukido (1993) *Peta Geologi Lembar Kolaka, Sulawesi*. Pusat Penelitian dan Pengembangan Geologi.
- Surono, T.O. and Simandjuntak, R.L. (1993) ‘Peta Geologi Lembar Batui, Sulawesi’.
- Suryantini and Wibowo, H. (2010) ‘Application of Fault and Fracture Density (FFD) Method for Geothermal Exploration in Non-Volcanic Geothermal System; a Case Study in Sulawesi-Indonesia’, *Proceedings World Geothermal Congress*, (April), pp. 25–29.
- Taucare, M. *et al.* (2020) ‘Connectivity of fractures and groundwater flows analyses into the Western Andean Front by means of a topological approach (Aconcagua Basin, Central Chile)’, *Hydrogeology Journal*, 28(7), pp. 2429–2438. Available at: <https://doi.org/10.1007/s10040-020-02200-3>.
- Tjokrosapoetra, S., Budhitresna, T. and Rusmana, E. (1993) ‘Peta Geologi Lembar Buru, Maluku’.
- Vengosh, A., Helvacı, C. and Karamanderesi, I.H. (2002) ‘Geochemical constraints for the origin of thermal waters from western Turkey’, *Applied Geochemistry*, 17(3), pp. 163–183. Available at: [https://doi.org/10.1016/S0883-2927\(01\)00062-2](https://doi.org/10.1016/S0883-2927(01)00062-2).
- Villalta Echeverria, M.D.P. *et al.* (2022) ‘Lineament Extraction from Digital Terrain Derivate Model: A Case Study in the Girón–Santa Isabel Basin, South Ecuador’, *Remote Sensing*, 14(21), p. 5400. Available at: <https://doi.org/10.3390/rs14215400>.
- Vision 2030 Kingdom of Saudi Arabia (2020) ‘Government of Saudi Arabia’, *Government of Saudi Arabia*, pp. 1–85. Available at: <https://vision2030.gov.sa/download/file/fid/417>.
- Viswanathan, H.S. *et al.* (2022) ‘From Fluid Flow to Coupled Processes in Fractured Rock: Recent Advances and New Frontiers’, *Reviews of Geophysics*, 60(1), pp. 1–65. Available at: <https://doi.org/10.1029/2021RG000744>.
- Wang, P. *et al.* (2016) ‘Geochemical features of the geothermal fluids from the Mapamyum non-volcanic geothermal system (Western Tibet, China)’, *Journal of Volcanology and Geothermal Research*, 320, pp. 29–39. Available at: <https://doi.org/10.1016/j.jvolgeores.2016.04.002>.
- Yaguchi, M. *et al.* (2014) ‘Hydrochemistry and isotopic characteristics of non-volcanic hot springs around the Miocene Kofu granitic complex surrounding the Kofu Basin in the South Fossa Magna region, central Honshu, Japan’, *Geochemical*

Journal, 48(4), pp. 345–356. Available at:
<https://doi.org/10.2343/geochemj.2.0310>.

Zahran, H.M. *et al.* (2016) ‘On the development of a seismic source zonation model for seismic hazard assessment in western Saudi Arabia’, *Journal of Seismology*, 20(3), pp. 747–769. Available at: <https://doi.org/10.1007/s10950-016-9555-y>.

]

Vitae

Name : Daffa Arrofi

Nationality : Indonesia

Date of Birth : 9/5/1997

Email : arrofidaffa@gmail.com

Address : Sirsak St. No.5, Kemiling, Bandar Lampung 35158,
Indonesia

Academic Background : B.Eng in Geological Engineering from Diponegoro
University (2019)

Daffa joined KFUPM as a graduate student at the Geoscience Department in 2022. Prior to joining KFUPM he worked as an educational content developer in PT. Ruang Raya Indonesia for 2 years. He actively involved in the geoscience community as the project team leader in the Indogeo social enterprise. He led several projects, digitizing and creating thematic maps, developing an atlas of the Talang Akar Formation, and mapping the geothermal gradient of the North East Java Basin. His expertise is satellite-based remote sensing analysis and fracture characterization. His main research interest is low-enthalpy geothermal, including hydrothermal characterization and machine-learning applications for geoscience. During his master's, he was awarded to attend fully funded summer school, drone-based hyperspectral imaging at Universiti Tunku Abdul Rahman (UTAR) in Malaysia. He also attended online summer school at Universitas Padjajaran

(Indonesia) and Indian Institute of Technology Bombay (India). He received the best final project in one of those summer schools. He published two journals in internationally recognized ISI journals and two conference papers during his master's. He also presented his part of the thesis at two international conferences.

List of Publications and Presentation Generated from this Thesis

Journal Articles

Arrofi, D. and Abu-Mahfouz, I.S. (2023) 'Delineating reservoir area using geologic remote sensing analysis, Jizan (Saudi Arabia): Implications for geothermal exploration', *Geoenergy Science and Engineering*, 228(May), p. 212033. Available at: <https://doi.org/10.1016/j.geoen.2023.212033>.

Arrofi, D., Abu-Mahfouz, I.S. and Prayudi, S.D. (2022) 'Investigating high permeable zones in non-volcanic geothermal systems using lineament analysis and fault fracture density (FFD): northern Konawe Regency, Indonesia', *Geothermal Energy*, 10(1), p. 29. Available at: <https://doi.org/10.1186/s40517-022-00241-3>.

Conference Papers

Abu-Mahfouz, I.S., Rafiq, J. and **Arrofi, D.** (2023) 'Geological Structure Identification in Geothermal Fields, Southwestern Saudi Arabia', 2023(1), pp. 1–5. Available at: <https://doi.org/https://doi.org/10.3997/2214-4609.2023631012>.

Arrofi, D., Abu-Mahfouz, I.S. and Humphrey, J. (2023) 'Unearthing Insights Into Non-Volcanic Geothermal System: a Conceptual Model Through Hydrochemical Exploration in Southwestern Saudi Arabia', 2023(1), pp. 1–5. Available at: <https://doi.org/10.3997/2214-4609.202321081>.

Conference Presentations

Arrofi, D. and Abu-Mahfouz, I.S. Integrating Multiparameter Geological Remote Sensing Nalaysis to Delineate the Jizan Geothermal Reservoir, Soutwestern Saudi Arabia. *International Geomechanics Symposium (IGS)*, Session – 4 Geomechanics for Geothermal & New Energies, 2023.

Arrofi, D., Abu-Mahfouz, I. S. and Prayudi, S. D. Lineament Analysis and Fault Fracture Density (FFD) to Investigate High Permeable Zone in Non-Volcanic Geothermal System: A Study Case in Northern Konawe Regency, Indonesia, *Middle East Oil and Gas Geosciences Show (MEOS GEO)*, ID 1038, 2023.