



Geospatial Analysis of Surface and Subsurface Factors for Mapping Geothermal Potential Zones in Central-Western Taiz, Yemen

Anwar Abdullah¹, Ghareb Hamada^{2*} Abbas Al-Khudafi^{1,3}, Ibrahim Farea⁴, and Fahd Alakbari⁵

¹Geology Department, Faculty of Applied Sciences, Taiz University,
Habail Salman, Taiz City, At Ta'iziyah District, Taiz, Republic of Yemen.

²Oil and Gas Engineering Department, Arab Academy for Science, Technology & Maritime Transport,
Abu Qir Campus, Alexandria, Egypt.

³Oil and Gas Engineering Department, Emirates International University,
Beirut St, Hadda, Sana'a, Yaman.

⁴Petroleum & Natural gas Department, Sana'a University, Sana'a,
Sana'a University, Sana'a, Yaman.

⁵Interdisciplinary Research Center for Hydrogen Technologies and Carbon Management,
King Fahd University of Petroleum & Minerals,
Dhahran 31261, Saudi Arabia.

*Corresponding author: Ghareb Hamada (ghareb.hamada@aast.edu)

Ghareb Hamada: Scholar id: <https://scholar.google.com/citations?hl=en&user=rKaaJHkAAAAJ>

Received: 27 February 2026; Revised: in revised form 24 June 2026; Accepted: 06 August 2026
Available: online 30 September 2026.

ABSTRACT - This study evaluates the application of remote sensing and GIS techniques for mapping geothermal potential areas in the central-western Taiz, Yemen. The objective is to identify prospective areas for hydrothermal water exploration. Geothermal potential mapping was based on nine factors derived from remote sensing, geological, and geophysical datasets. Several steps were used to prepare these factors such as rasterization, re-projection, re-sampling, classification and weighting. The weighted values of the classes for each factor map were assigned based on their spatial correlation with eight known hydrothermal water locations. A GIS-based Weighted Overlay Technique (WOT) was applied. The resulting geothermal potential map categorizes the area into five classes: very high, high, moderate, low, and very low, covering 5.08%, 9.65%, 14.65%, 50.46%, and 20.16% of the study area, respectively. However, 7 of the 8 hydrothermal occurrences identified (87.5%) are located in the very high potential zone. The observed concentration is approximately seventeen times greater than random expectation, providing further evidence that the model is able to identify areas favorable for geothermal occurrence. This supports logical consistency but is not proof of independent validation. Independent field data are needed to validate the predictive power of the map. Given the limited number of validation points, the results should be considered as a regional screening tool.

Keywords: remote sensing, GIS, weighted overlay technique, geothermal potential mapping.

How to cite this article:

Anwar Abdullah, Ghareb Hamada, Abbas Al-Khudafi, Ibrahim Farea, and Fahd Alakbari, 2026, Geospatial Analysis of Surface and Subsurface Factors for Mapping Geothermal Potential Zones in Central-Western Taiz, Yemen, Scientific Contributions Oil and Gas, 49 (3) pp. 411-440.

1. Introduction

Geothermal energy represents a sustainable and reliable renewable energy resource derived from the Earth's internal heat and can be utilized for electricity generation, direct heating, and various industrial applications. Geothermal systems are commonly associated with regions characterized by elevated heat flow, active tectonics, and volcanic or magmatic processes, where fractures and faults facilitate the circulation of heated fluids within the crust (Zhou & Liu 2021; Kumar & Singh 2019; Macharia et al., 2018).

Hydrothermal systems form when meteoric water infiltrates the subsurface through fractures and permeable zones, is heated at depth by hot rocks or magmatic sources, and subsequently migrates upward, sometimes manifesting at the surface as hot springs (Baker & Johnson 2020). In other cases, hydrothermal fluids remain trapped at depth due to insufficient permeability and can only be accessed through drilling. Structural features such as faults, joints, and lithological contacts play a critical role in controlling fluid flow and geothermal reservoir development (Heasler et al., 2009; Taillefer et al., 2017).

Here, the term "hydrothermal water" is defined as naturally occurring groundwater heated by the Earth's internal heat during circulation through permeable rocks, fractures, and fault systems. Hydrothermal water represents the fluid component of hydrothermal geothermal systems and commonly occurs as hot springs or warm groundwater, although it may also remain confined at depth. In contrast, the term "geothermal systems" is broader and includes all geological environments capable of storing and transferring geothermal heat, including hydrothermal systems, vapor-dominated systems, and enhanced geothermal systems (EGS). Since the present study aims to identify zones favorable for hot-water resources, the term "hydrothermal water" is used throughout the manuscript to emphasize groundwater-based geothermal occurrences.

The Taiz Governorate in southwestern Yemen is located within a tectonically active zone influenced by the opening of the Red Sea and the Gulf of Aden (Abdullah et al., 2010; Abdullah et al., 2013; Nassr & Abdullah 2015). This regional extensional regime has resulted in complex fault systems trending predominantly NW–SE and NE–SW, creating favorable conditions for geothermal activity. Numerous geothermal manifestations, including hot springs and warm domestic wells with temperatures ranging from approximately 32 °C to 75 °C, have been reported in the Taiz region (Alnethary et al., 2024). However, these studies mainly provide regional-scale information and they do not offer a detailed assessment of geothermal potential in the study area. These characteristics indicate a significant but underexplored geothermal potential. There are no published heat-flow measurements or detailed geothermal gradient data for the study area. Thus, the evaluation of geothermal potential is based mainly on geological, geomorphological, hydrothermal and geophysical indicators.

Recent advances in remote sensing and Geographic Information Systems (GIS) have facilitated the efficient integration of surface and subsurface geospatial data for geothermal exploration (Ramsey 2013). Furthermore, GIS-based multi-criteria approaches, particularly weighted overlay techniques, have been extensively employed to delineate geothermal potential zones by integrating geological, geomorphological, and geophysical controlling factors (Ramsey & Harris 2013; Haselwimmer & Prakash 2013; Bernard 2020; El Morabit et al., 2021; David & Pablo 2019; Reda et al., 2022; Abdulkadir et al., 2022). More recently, machine learning techniques have been coupled with GIS and remote sensing datasets for improved geothermal prospectivity mapping. For example, Kehinde et al. (2023) showed the success of GIS-based machine learning algorithms for geothermal energy potential modeling in Southwestern Nigeria based on geophysical and remote sensing data. Al-Kadasi et al. (2020) analyzed aeromagnetic data to estimate Curie point depths in southwestern Yemen. Their results revealed relatively shallow magnetic sources, suggesting areas of increased subsurface heat flow. This evidence further reinforces the view that southwestern Yemen has promising geothermal potential.

Recent advances in artificial intelligence (AI) have significantly improved geothermal exploration by integrating machine learning with geological, geophysical, and remote sensing data. In Yemen, Al-Fakih et al. (2025) developed Bayesian-optimized machine learning models for geothermal temperature prediction, while Al-Gathe et al. (2025) proposed a hybrid AI framework that further enhanced prediction accuracy. Similarly, Aydinli et al. (2026) demonstrated the effectiveness of combining remote sensing and machine learning for early-stage geothermal prospecting in Türkiye. A recent review by Aliyu et al. (2026) further highlighted that AI-driven

approaches are becoming the preferred methodology for geothermal prospectivity mapping worldwide. These advances indicate that AI techniques provide a promising direction for future geothermal exploration in Yemen, complementing conventional GIS-based approaches adopted in the present study.

Despite the presence of known hydrothermal manifestations in the Taiz region, geothermal exploration remains limited and largely unsystematic. Existing studies are fragmented and do not provide a comprehensive spatial assessment of geothermal potential that integrates surface and subsurface controlling factors. Moreover, field-based investigations are constrained by accessibility, cost, and security challenges, highlighting the need for an efficient, data-driven, and reproducible methodology to identify prospective geothermal zones. To date, no integrated GIS-based geothermal potential mapping framework has been systematically applied to the central–western part of the Taiz Governorate.

The main objective of this study is to delineate geothermal potential zones in the central–western Taiz region, Yemen, using an integrated remote sensing and GIS-based weighted overlay approach. Note that this study is for hot water dominated geothermal systems and does not include high enthalpy steam or EGS systems. We suggest that structural features (faults, lineaments) are the main controls on geothermal potential in this rift-influenced setting.

This study investigates the geospatial factors influencing geothermal resource distribution in the central–western Taiz region, evaluates the integration of remote sensing, geological, and geophysical data within a GIS-based framework to identify geothermal potential zones, maps their spatial distribution, and quantifies their areas. It also assesses the correspondence between predicted high-potential zones and known hydrothermal water occurrences to validate the model's accuracy. [Figure 1](#) illustrates the location of the Taiz region in Yemen and the detailed study area.

2. Methodology

In geothermal exploration, hydrothermal mapping is concerned with identifying surface and subsurface conditions that control the circulation, storage, and discharge of thermally heated groundwater. In this study, remote sensing, geological, and geophysical datasets are integrated within a GIS framework to delineate zones favorable for geothermal and hydrothermal water occurrence in the central–western Taiz region. The chosen methodology places a strong emphasis on subsurface geophysical indicators—such as those affecting permeability, fluid pathways, and heat transfer—along with structural controls (faults, lineaments, and lithological contacts) and geomorphological factors.

The methodology consists of five main sequential stages: data acquisition, data pre-processing, factors maps generation, application of the Weighted Overlay Technique (WOT), and validation of the final geothermal potential map. [Figure 22](#) presents overall workflow of the methodology used to map geothermal potential, illustrating the main stages of the study, including data acquisition, preprocessing, preparation of thematic factor maps, factor weighting, weighted overlay analysis, and validation of the final results.

2.1 Data acquisition

Three categories of datasets were used to generate nine geospatial factors controlling geothermal occurrence. DEM processing and drainage extraction was carried out using PCI Geomatica. Lineament interpretation and weighted overlay modelling was done using ILWIS. Density mapping and raster processing was done using ArcGIS.

2.2 Digital data

Shuttle Radar Topography Mission (SRTM) digital elevation data with a spatial resolution of 30 m were used to generate a Digital Elevation Model (DEM) ([Figure 2](#)). The DEM was further processed to produce a shaded relief image ([Figure 3](#)) and to derive slope, drainage, and lineament information.

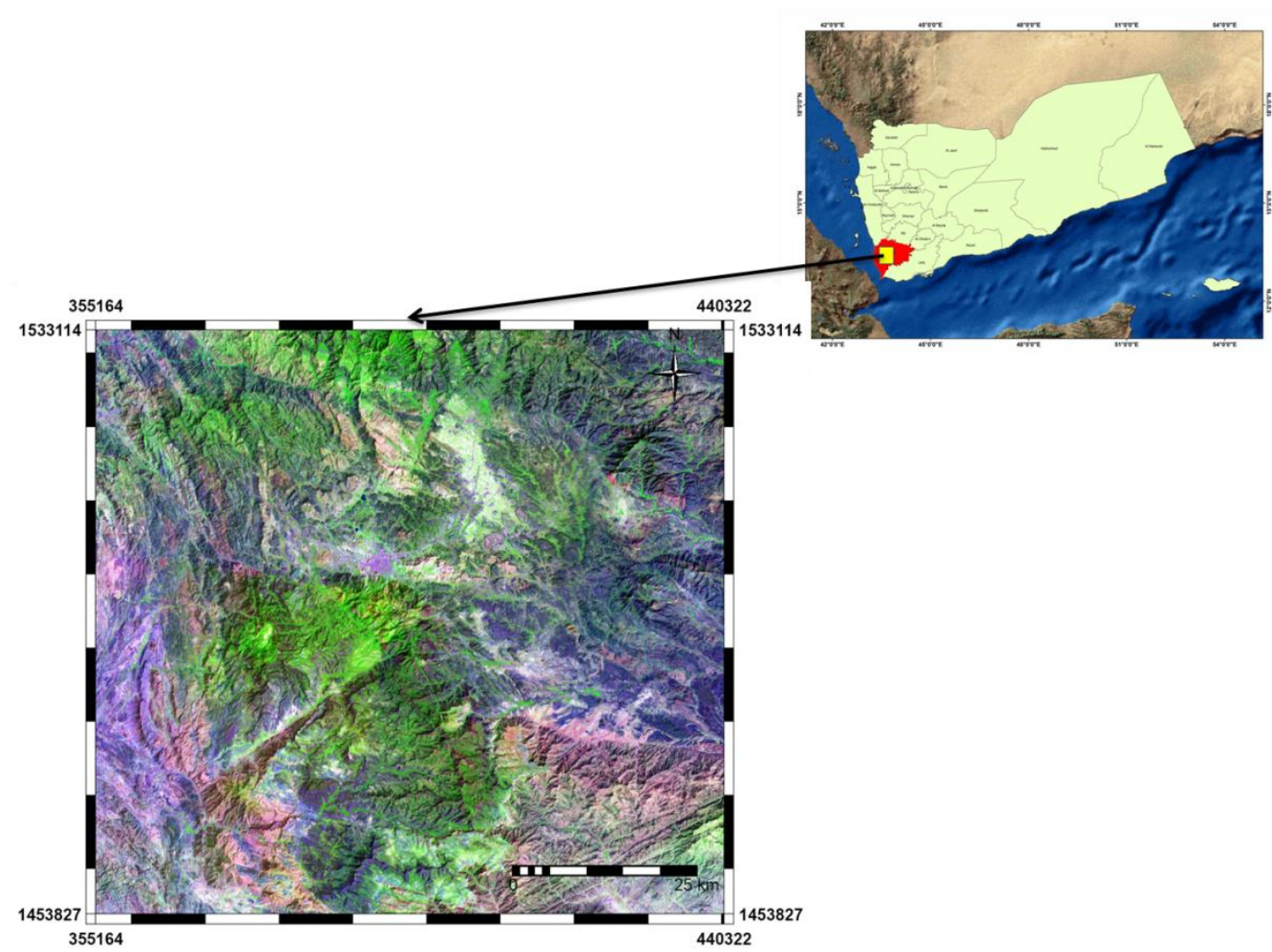


Figure 1.
Location of the Taiz region in Yemen (red) and the detailed study area (yellow).

The slope layer, derived from the DEM, represents terrain steepness. It is a critical factor influencing surface runoff, infiltration rates, and hydrothermal fluid circulation.

Gentle slopes generally favor water infiltration, while steep slopes promote rapid runoff. Geothermal manifestations and hydrothermal waters are often associated with relatively low topographic areas; therefore, the slope elevation steepness factors was used to assess the relationship between terrain characteristics and geothermal potential.

Drainage networks were automatically extracted from the DEM using the DRAIN function in PCI Geomatica. Drainage patterns may indicate structural controls and pathways favorable for hydrothermal fluid migration (Figure 4).

Lineaments, representing natural zones of structural weakness within the crust (Rutty 1993; Bai et al., 2010, Abdullah et al., 2013, Nassr & Abdullah 2015), were manually interpreted from the shaded relief image using ILWIS software based on visual interpretation and user experience (Figure 5). These features are important indicators of potential pathways for geothermal fluid movement. The SRTM 30 m DEM used in this study has a typical absolute vertical accuracy of about ± 10 m. While such uncertainty may be acceptable for local topographic details, it is generally acceptable for local and regional-scale analysis of slope, drainage pattern and structural features (lineaments) mapping. Hence, the impact of the DEM vertical error on the results is expected to be limited.

Although some degree of interpreter subjectivity is involved in the manual extraction of lineaments, all lineaments were identified and digitized by the same experienced analyst, applying uniform interpretation criteria to ensure methodological consistency throughout the study.

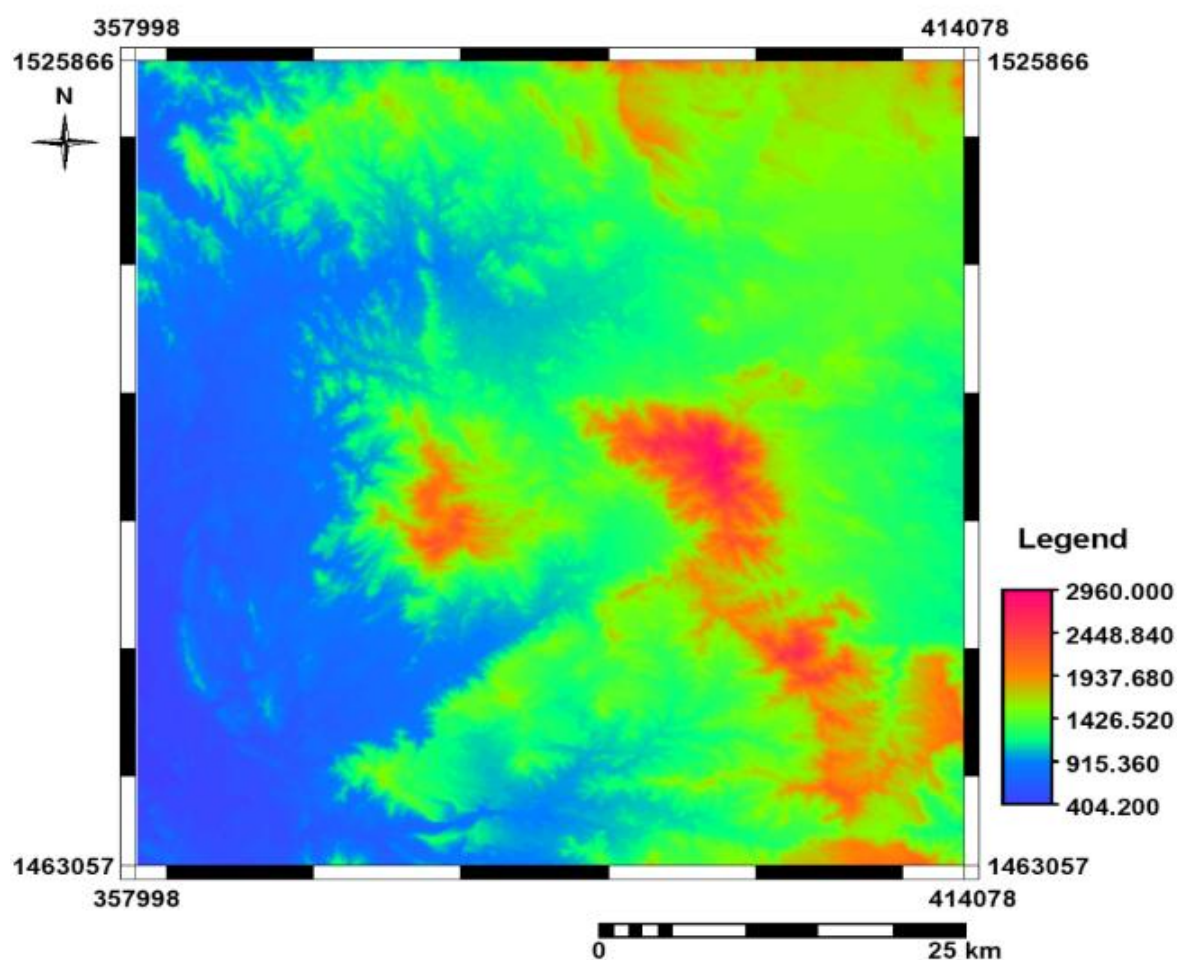


Figure 2.
Digital elevation model of the study area derived from SRTM data.

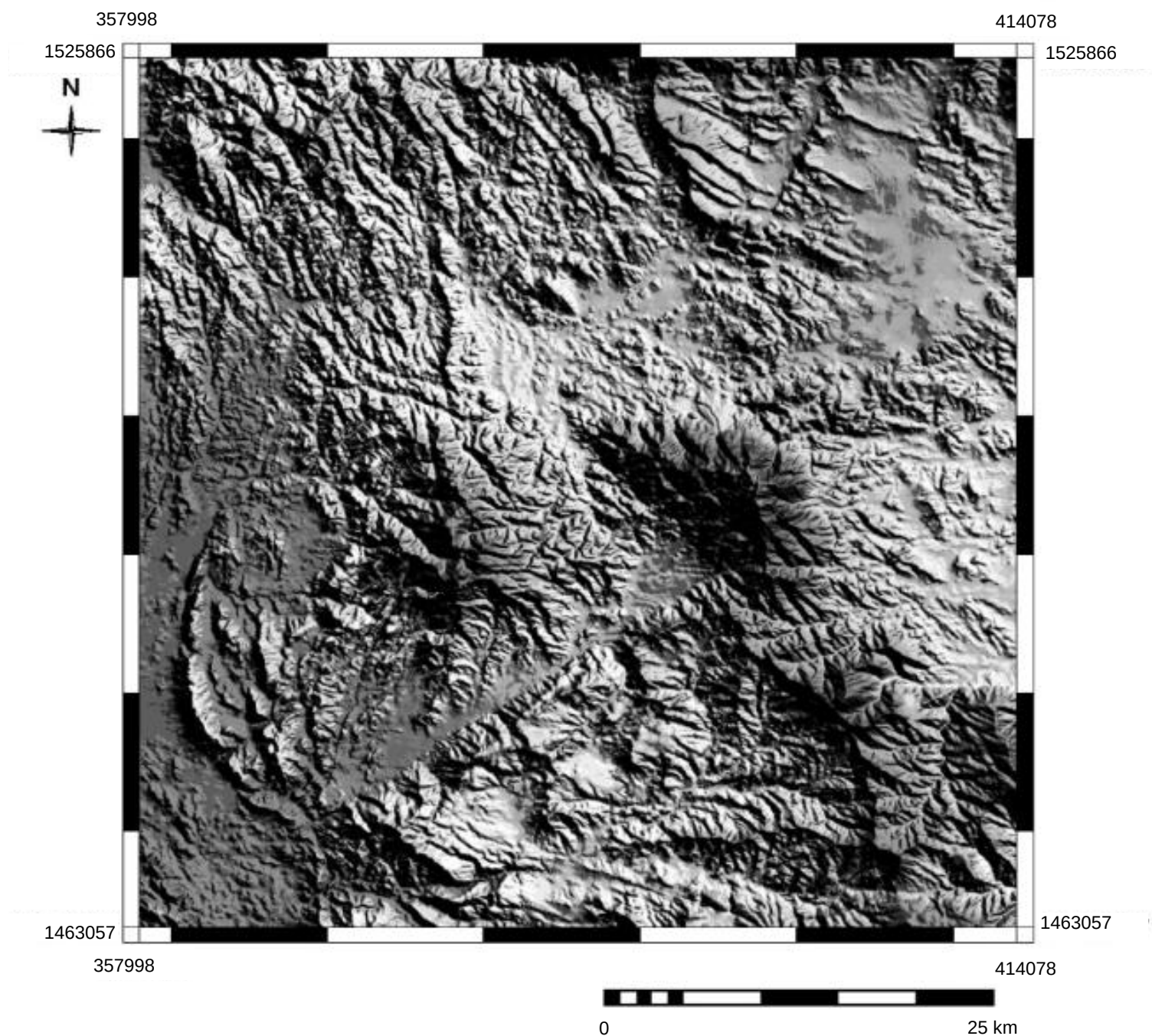


Figure 3.
Shaded relief map generated from the DEM of the study area.

2.3 Geological data

A 1:250,000 scale geological map of the Taiz area ([Geological Survey of Yemen \(GSY 1990\)](#)) was used to create three factors.

- **Rock Units:** The different rock units were digitized from the geological map ([Figure 6](#)). Variations in porosity, permeability, and the presence of joints, fissures, and fractures influence hydrothermal water movement.

- Geological Faults: Faults were digitized from the geological map (Figure 7). These structures act as critical conduits for the movement of hydrothermal fluids from depth to the surface (Ibrahim & Juhari 1990).
- Lithological Contacts: Contacts between different rock types were digitized (Figure 8). These zones often represent planes of weakness that can facilitate fluid movement.

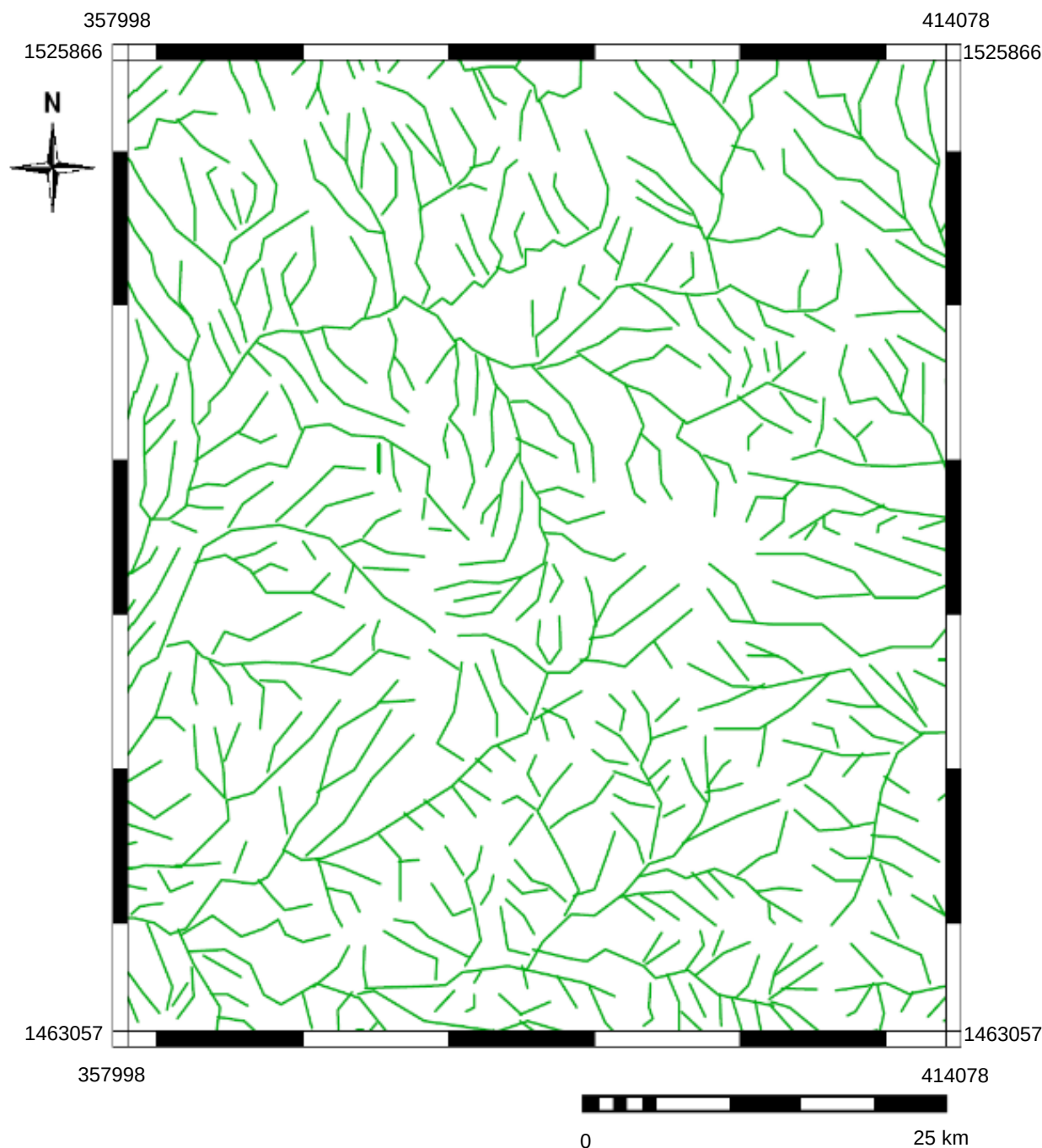


Figure 4.
Drainage pattern extracted from the DEM of the study area.

Geophysical data reveal subsurface geological structures such as faults. Three faults' datasets at different depths were interpreted from residual, regional, and reduced-to-pole aeromagnetic anomaly maps. Datasets at different depths, derived from magnetic data analysis by Al Kadasi (2014), were used:

Faults at -38.3 m depth from residual magnetic anomalies (Figure 9). Faults at -95.5 m depth from the regional magnetic map (Figure 10). Faults at -144.4 m depth from the reduced-to-the-pole (RTP) aeromagnetic map (Figure 11).

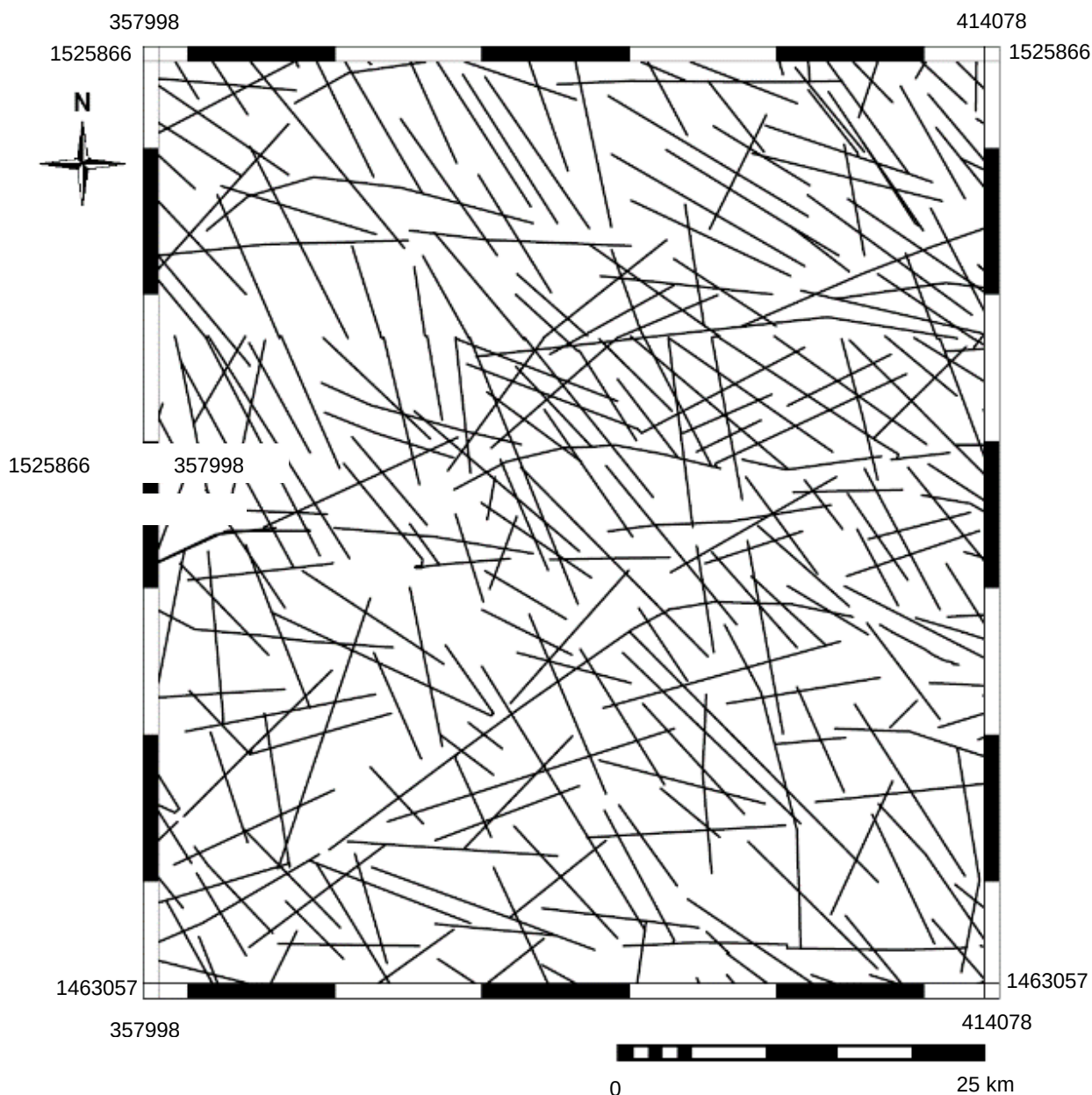


Figure 5.
Lineament map interpreted from the shaded relief image of the study area

The depths of -38.3 m, -95.5 m, and -144.4 m represent the quantitative results of spectral analysis applied to the aeromagnetic data (Al-Kadasi 2014). These values were derived from the slope of the power spectrum curve during the transformation from the spatial to the frequency domain. It is important to note that the decimal precision reflects the mathematical outcome of the Fourier analysis and the subsequent depth calculation formula $\text{Depth} = -\text{Slope}/4\pi$, rather than an absolute vertical measurement accuracy.

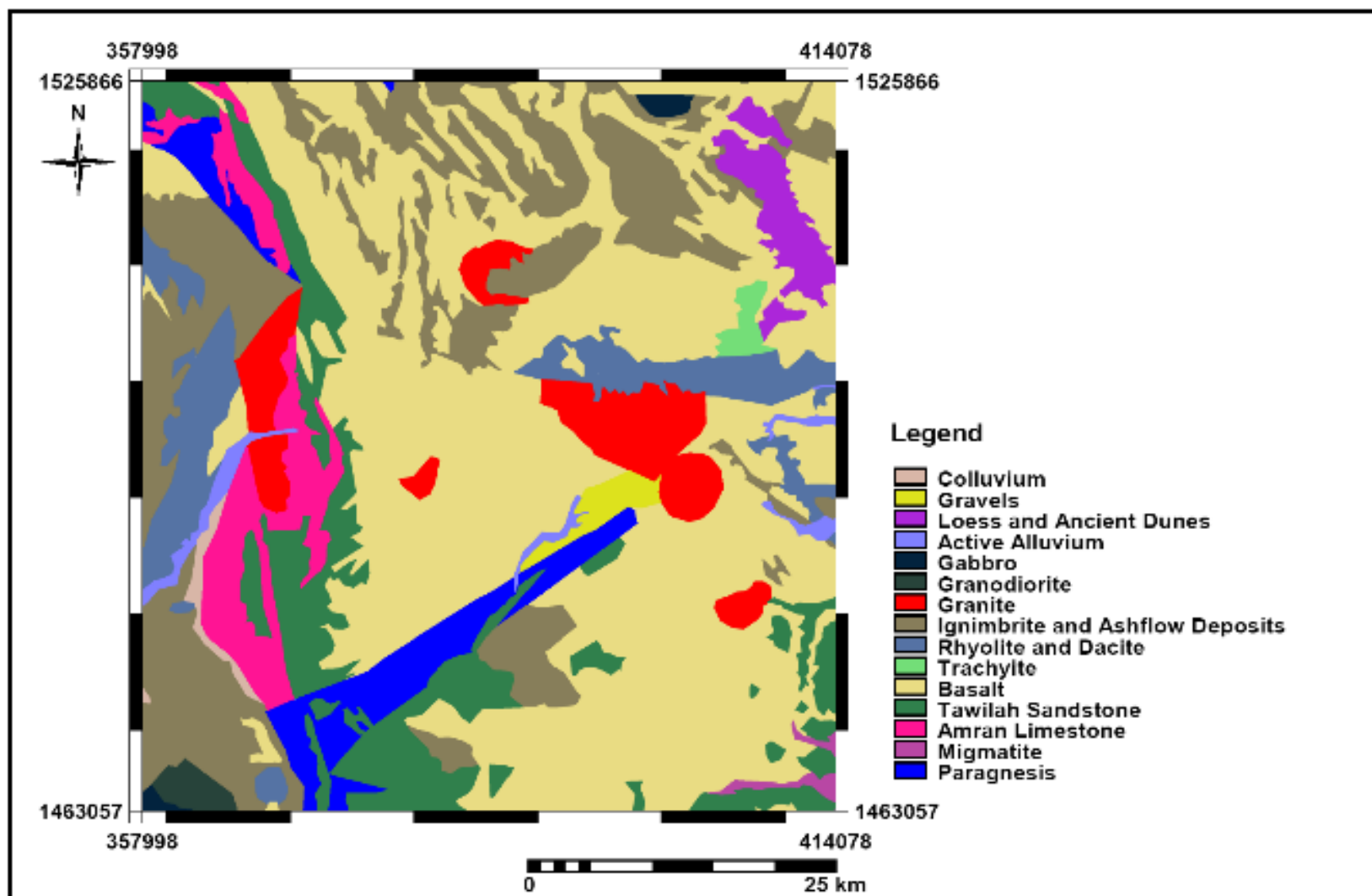


Figure 6.

Digitized rock units of the study area (Digitized and adapted from [Geological Survey of Yemen \(1990\)](#) with modifications for GIS integration)

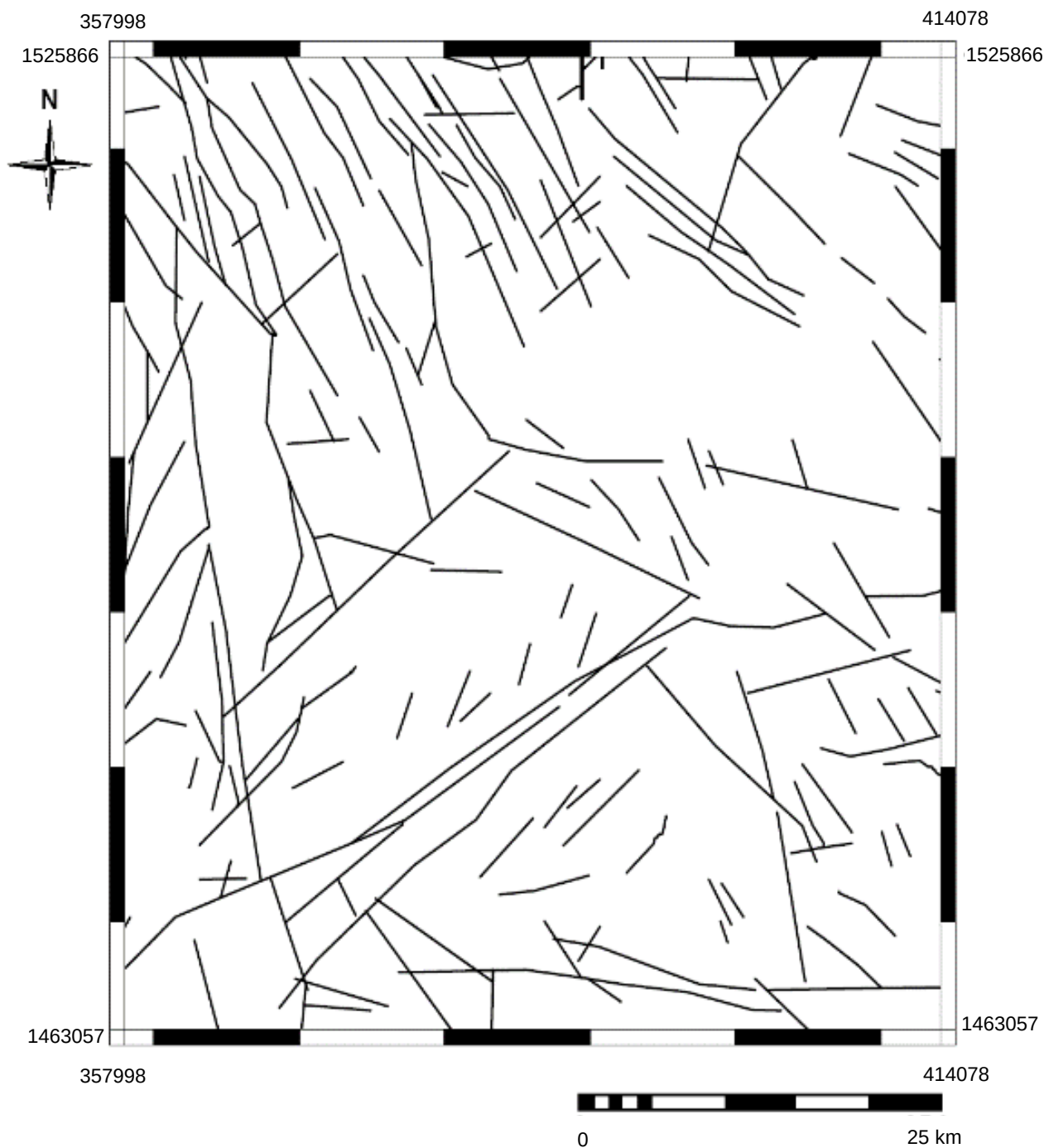


Figure 7.
Digitized geological faults of the study area
(digitized and adapted from [Geological Survey of Yemen 1990](#), with modifications for GIS integration).

2.4 Geophysical data

The depths of -38.3 m, -95.5 m, and -144.4 m represent the quantitative results of spectral analysis applied to the aeromagnetic data ([Al-Kadasi 2014](#)). These values were derived from the slope of the power spectrum curve during the transformation from the spatial to the frequency domain. It is important to note that the decimal precision reflects the mathematical outcome of the Fourier analysis and the subsequent depth calculation formula $\text{Depth} = -\text{Slope}/4\pi$, rather than an absolute vertical measurement accuracy.

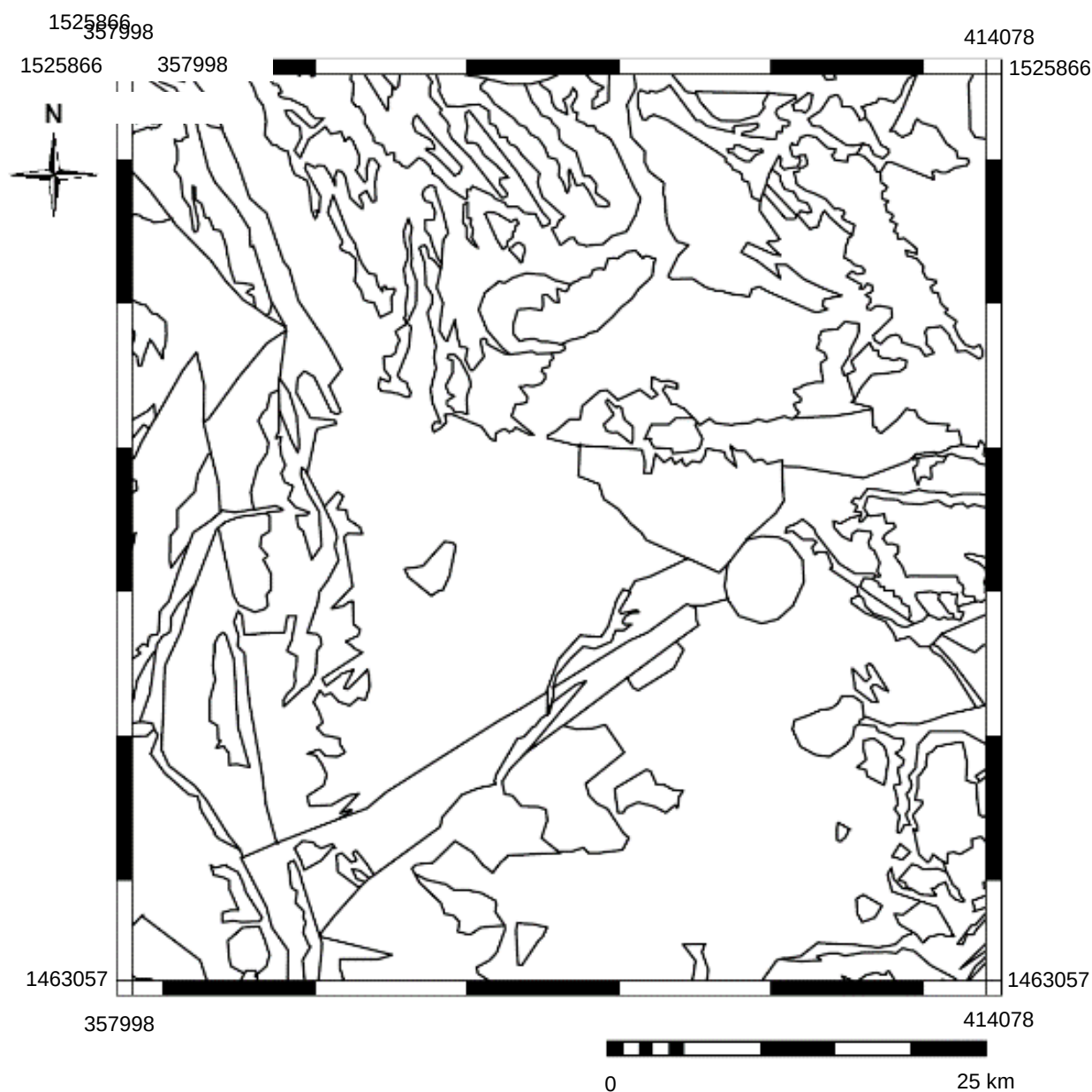


Figure 8.

Digitized lithological contacts of the study area
(digitized and adapted from [Geological Survey of Yemen 1990](#), with modifications for GIS integration).

2.5 Data pre-processing

The following steps were applied to prepare the datasets for GIS integration:

- Generation of the DEM (elevation) and creation of a gradient shader image for lineament extraction.
- Automatic extraction of the drainage network using the DRAIN function in PCI Geomatica.
- Manual digitization of rock units, geological faults and lithological contacts, from the geological map. And subsurface geophysical faults with different depth (shallow, intermediate and deep) from previous work.
- Reprojection and spatial alignment of all datasets to a unified coordinate system.
- Conversion of all vector layers (drainage, lineaments, faults, contacts) into raster density maps using a circular search radius of 1000 m. Because the original datasets have a spatial resolution of 30 m, a circular search radius of 1000 m was used to generate the density maps. This radius was chosen as it offers a practical balance between preserving local spatial variations and reducing noise. As a result, the

generated density maps are smoother, more reliable, and easier to interpret while still retaining the key spatial patterns relevant to the analysis.

- All vector layers—including drainage networks, lineaments, geological faults, lithological contacts, and faults determined from magnetic anomaly map systems were converted into raster density maps using the Line Density tool in ArcGIS (equivalent kernel density functions in PCI Geomatica and ILWIS). This tool calculates the density of linear features within a neighbourhood surrounding each raster cell. A circular search radius of 1000 m was applied based on the spatial distribution of known hydrothermal manifestations and the average spacing of structural features in the study area. The density calculation follows the kernel density estimation principle, where a smooth curved surface is fitted over each line segment, with the surface value highest at the line location and decreasing to zero at the search radius distance. The density at each output raster cell is computed by summing the values from all overlapping kernel surfaces.

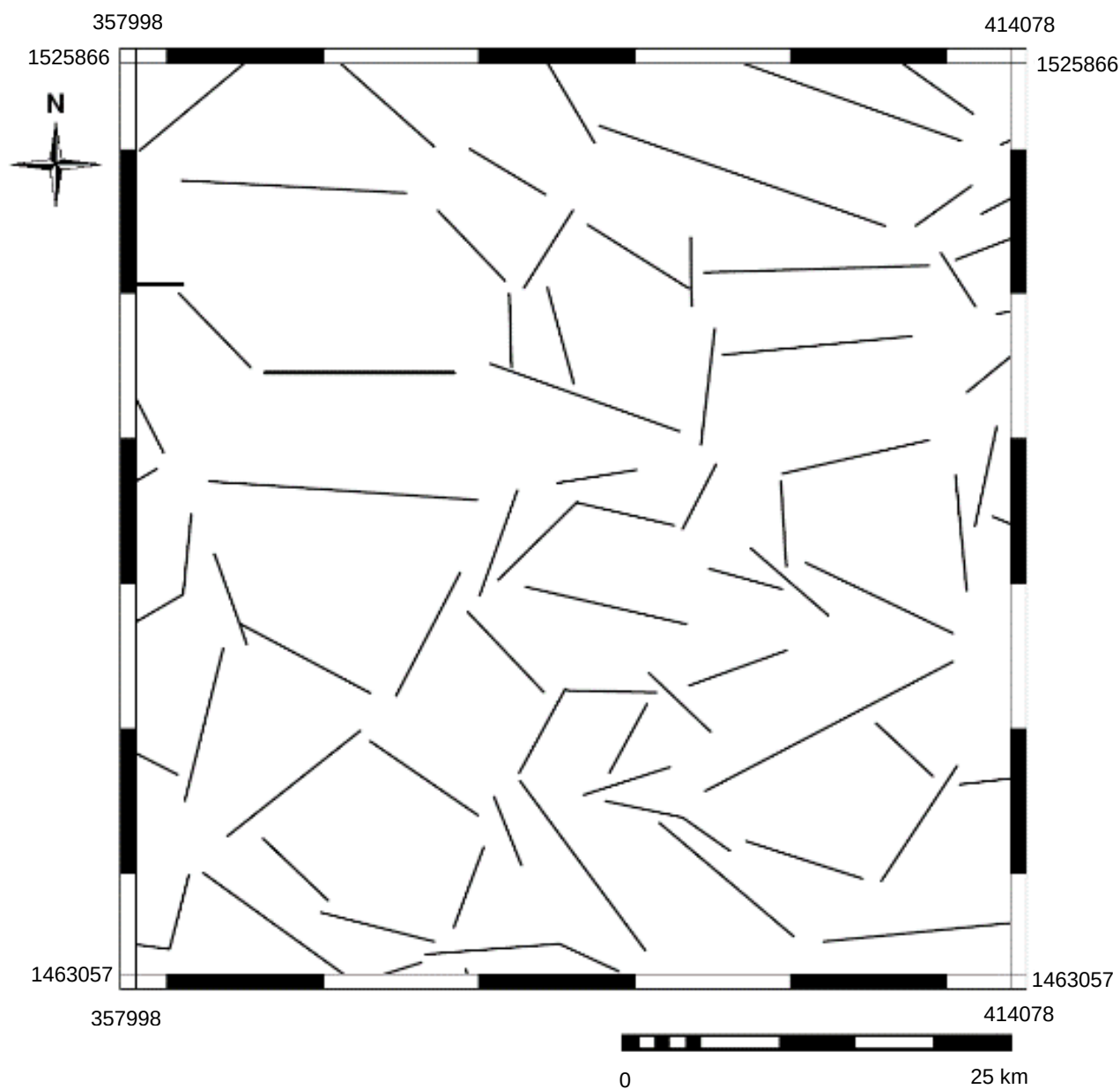


Figure 9.

Shallow faults interpreted from residual magnetic anomalies at a depth of -38.3 m (digitized and adapted from Al-Kadasi 2014, with modifications for GIS integration).

The search radius of 1000 m was chosen to be twice the average nearest-neighbor distance between known hydrothermal points (~500 m), so that each point would influence at least one adjacent cell.

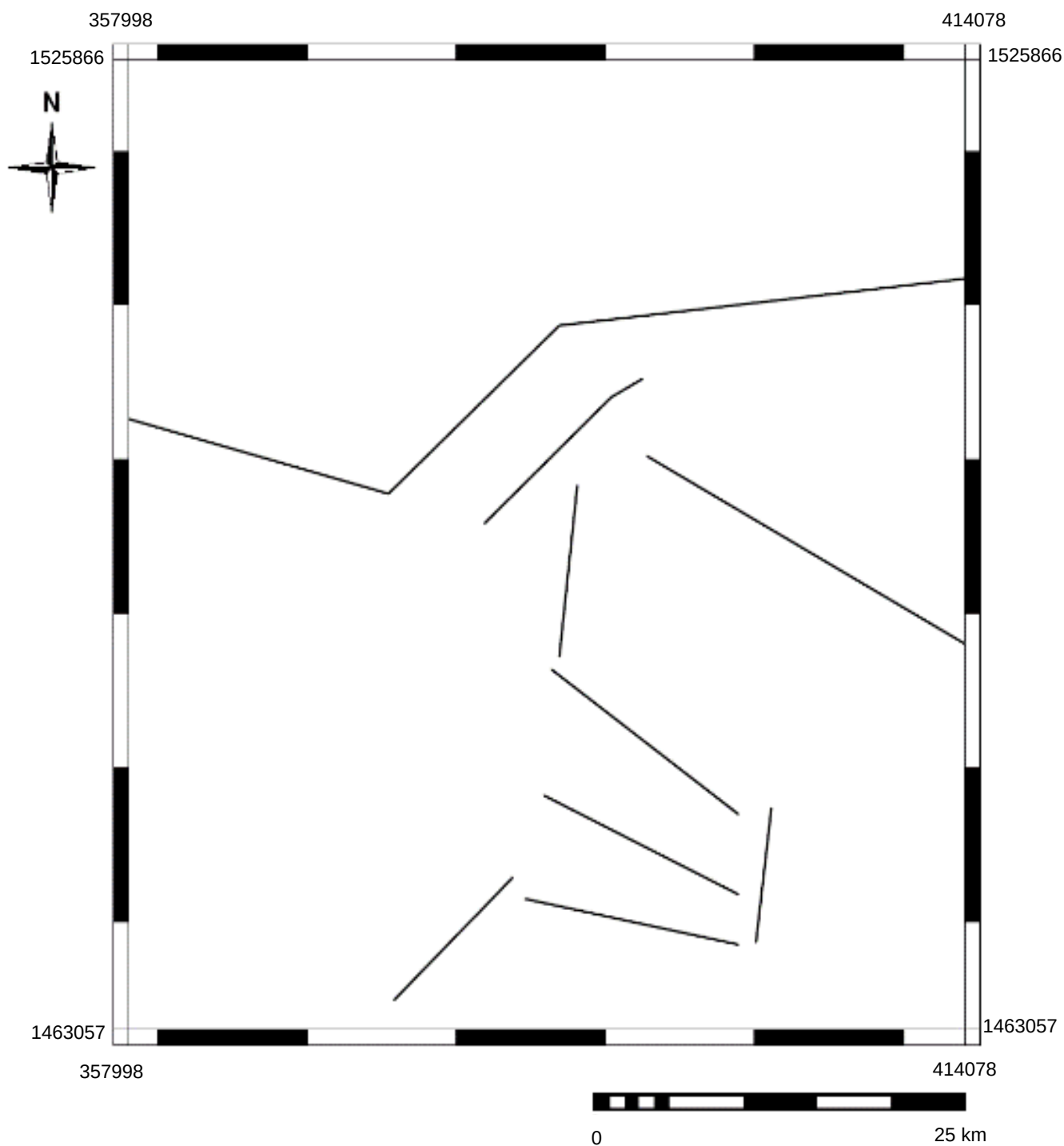


Figure 10.
Intermediate faults interpreted from residual magnetic anomalies at a depth of -95.5 m
(digitized and adapted from Al-Kadasi 2014, with modifications for GIS integration).

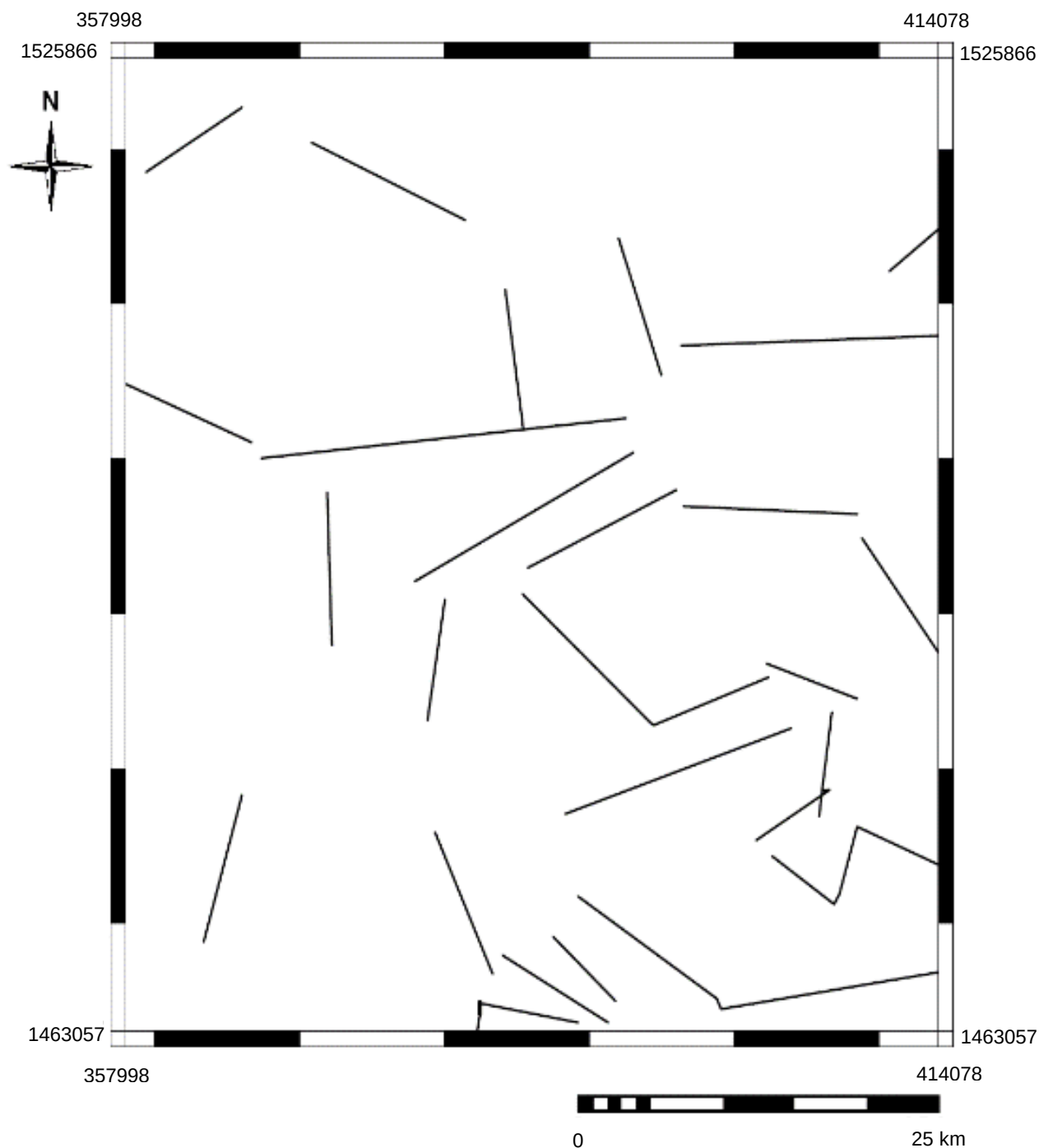


Figure 11.
Deep faults interpreted from residual magnetic anomalies at a depth of -144.4 m
(digitized and adapted from Al-Kadasi 2014, with modifications for GIS integration).

2.6 Factor Maps Generation

Nine geothermal controlling factor maps were produced, including elevation steepness, drainage density, lineament density, geological fault density, lithological contact density, three levels of faults determined from magnetic anomaly map density, and rock unit distribution. Each raster layer was reclassified into five categories representing different levels of geothermal influence. The resulting reclassified factor maps are presented in Figure 13–Figure 20. In general, the chart of workflow used in this study was illustrated in the Figure 12.

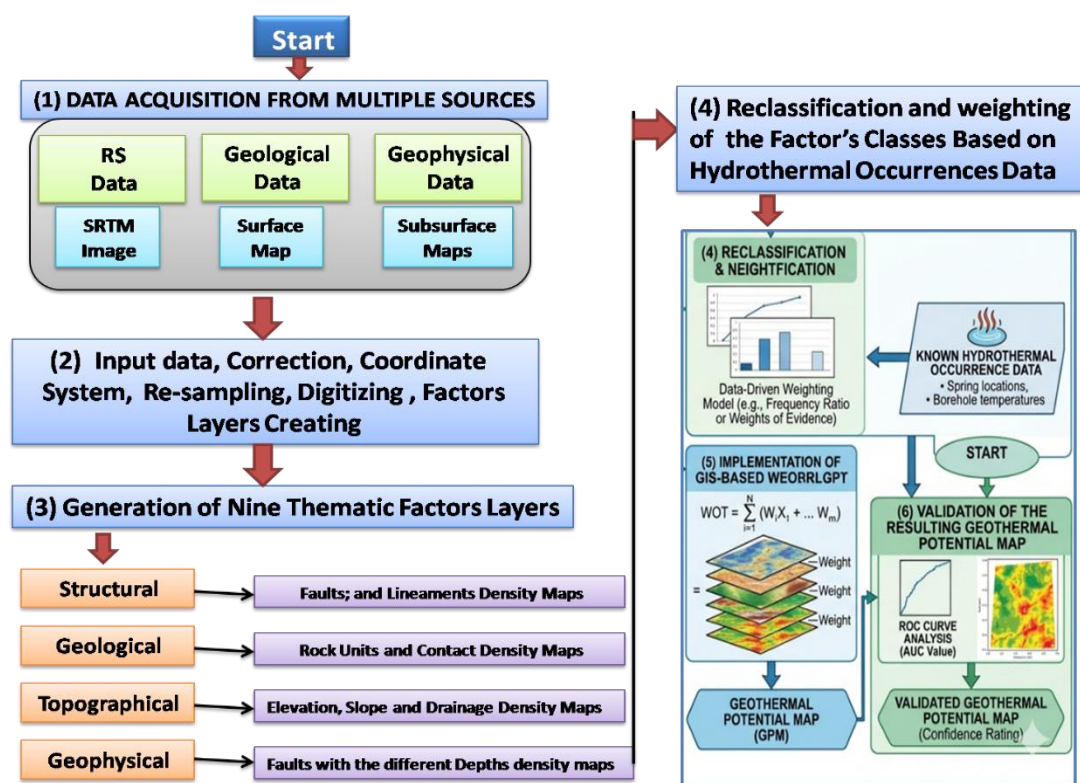


Figure 12.
Workflow for geothermal potential mapping

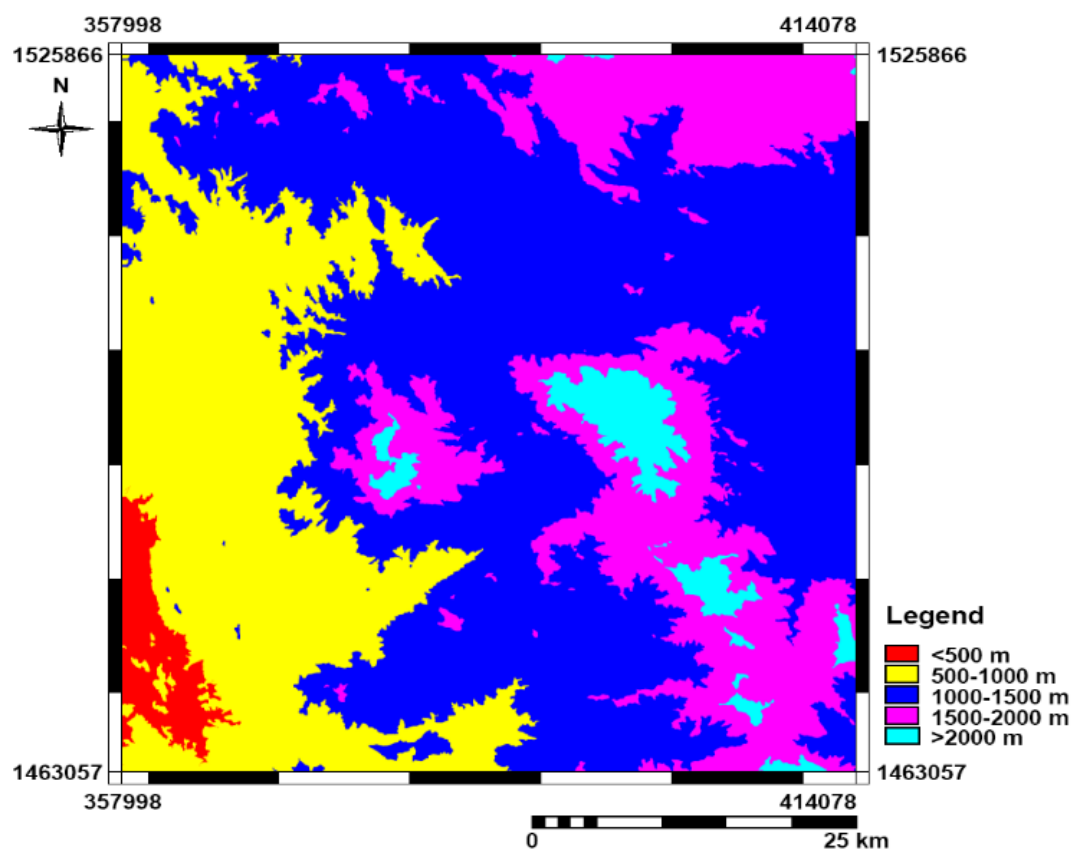


Figure 13.
Reclassified elevation steepness map of the study area.

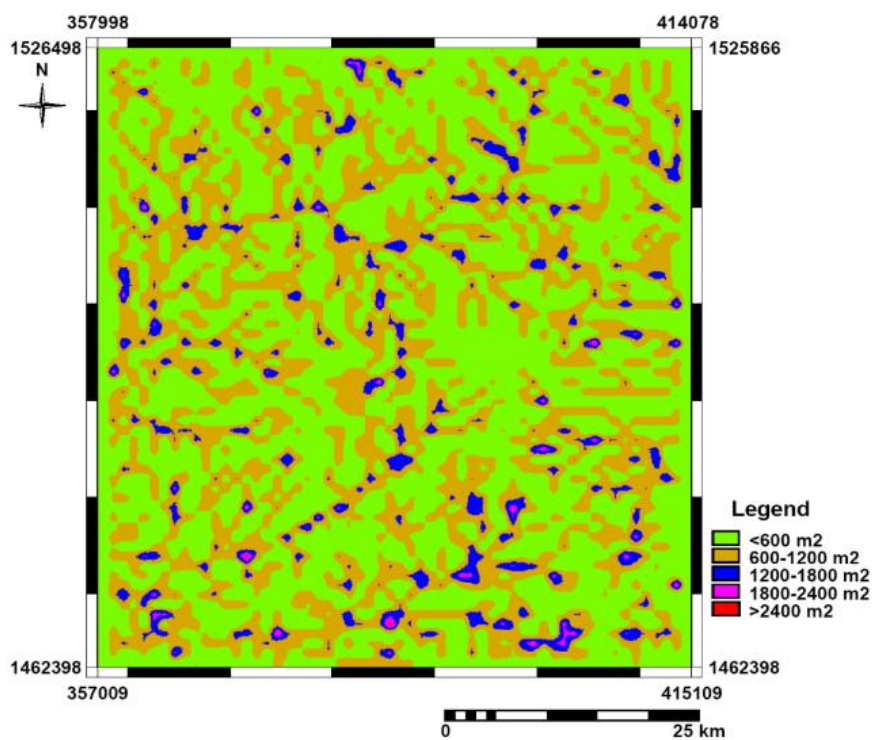


Figure 14.
Drainage density map of the study area.

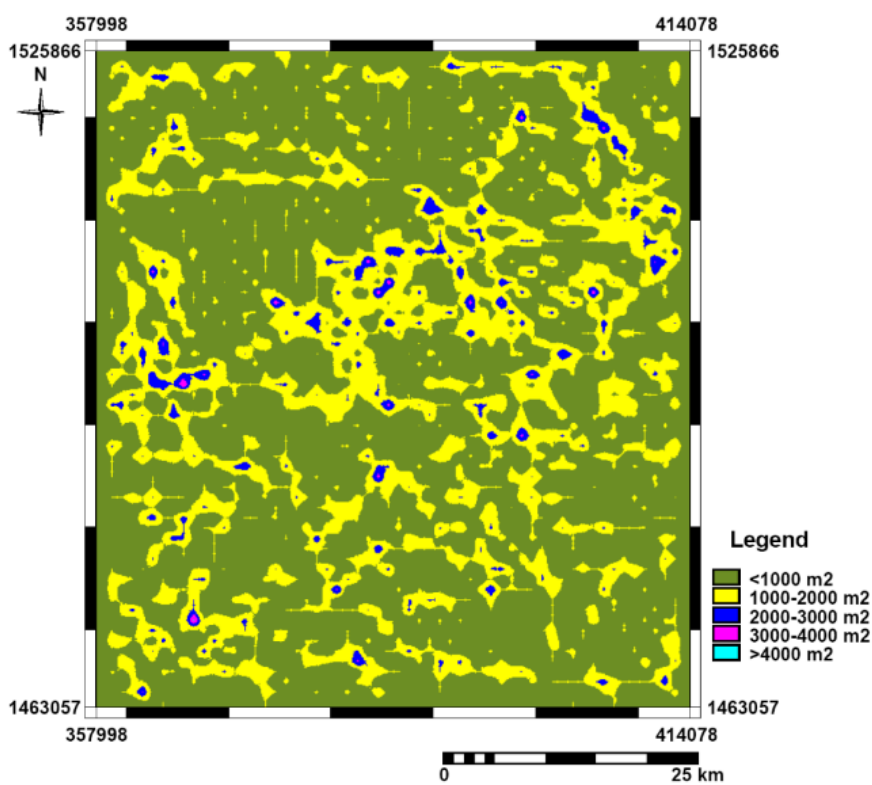


Figure 15.
Lineament density map of the study area.

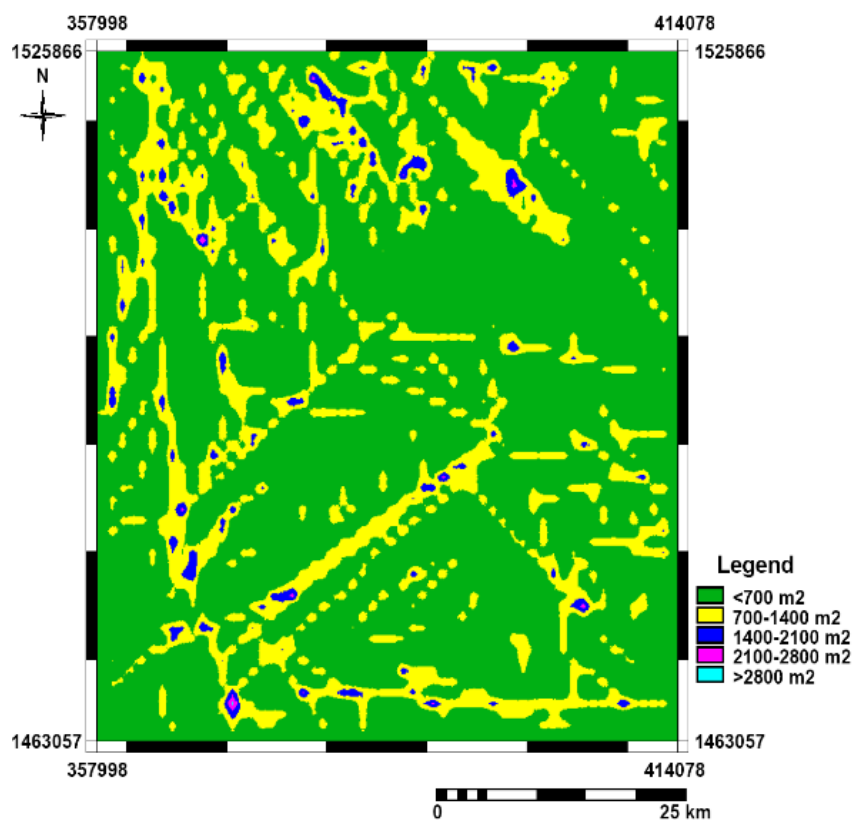


Figure 16.
Geological fault density map of the study area

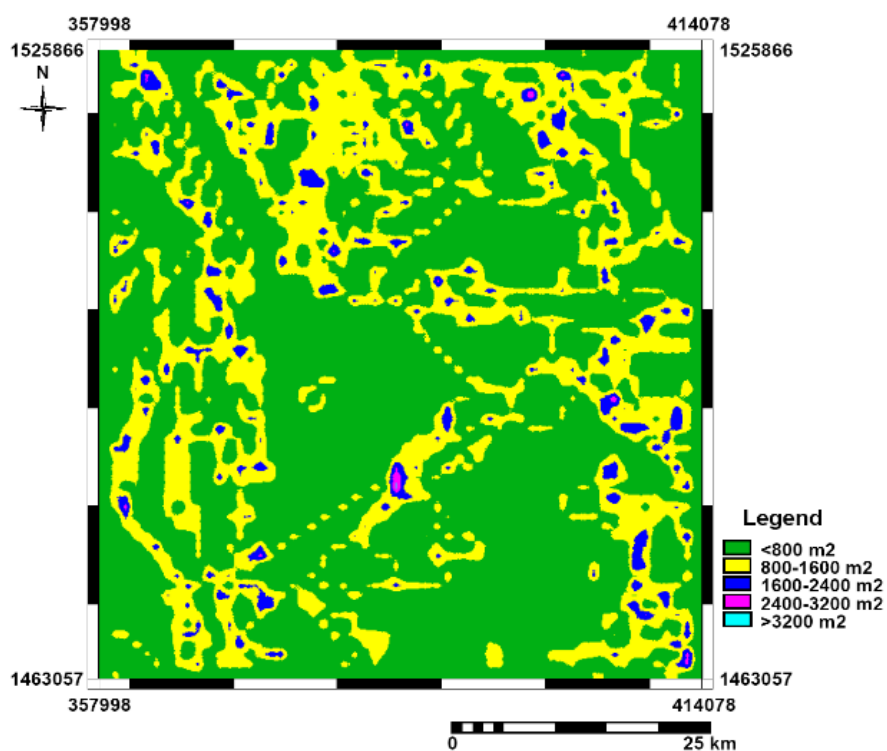


Figure 17.
Lithological contacts density layer of the study area

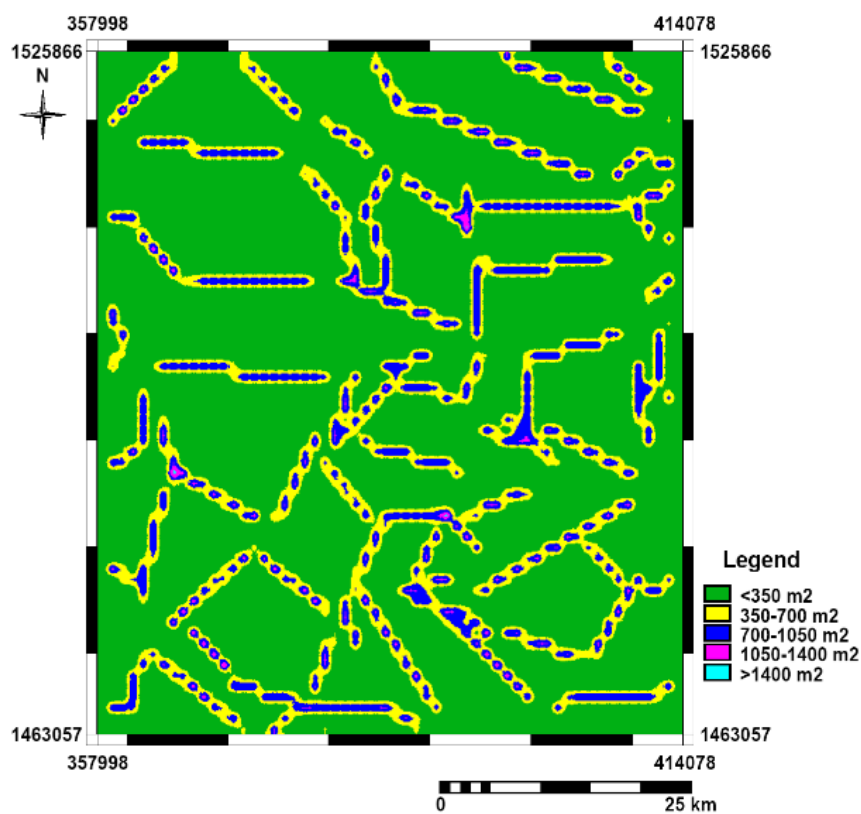


Figure 18.

Faults determined from magnetic anomaly maps with -38.3 m in depth density layer of the study area.

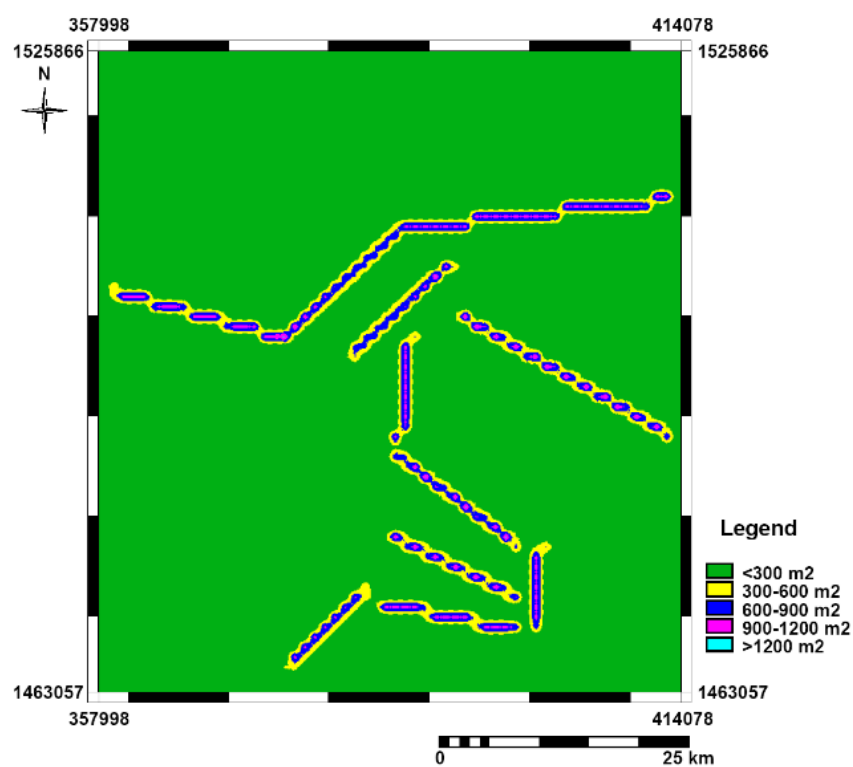


Figure 19.

Density map of intermediate-depth faults determined from magnetic anomaly maps at -95.5 m.

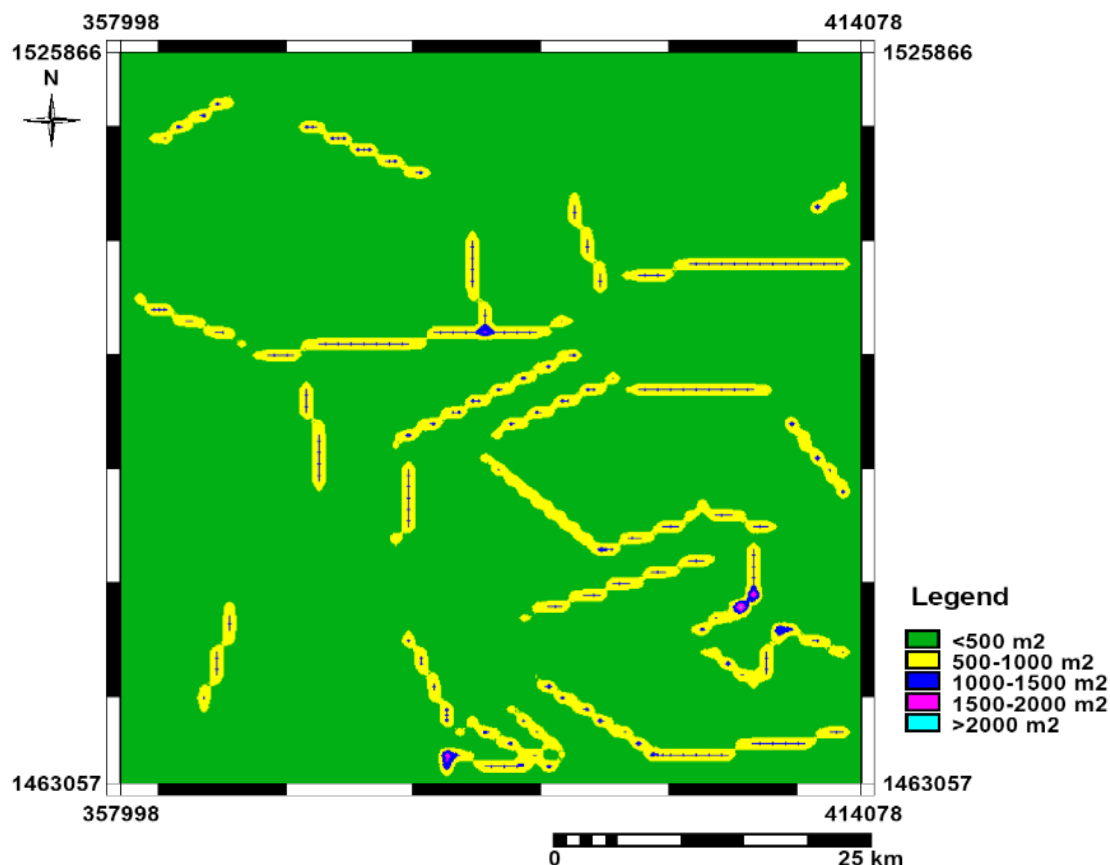


Figure 20.

Density map of deep faults determined from magnetic anomaly maps at -144.4 m depth.

2.7 Weighted overlay analysis

A point map of eight known hydrothermal water locations was generated (Figure 21). A matching analysis was performed between these points and the classes of each sliced factor map. The number of matching points per class was used to calculate a weight value (WV) using equation (1):

If 8 hydrothermal locations correspond to the weight value (WV) for each class was calculated based on the number of hydrothermal locations (N_{HLC}) falling within that class, scaled to a maximum weight of 5, as follows:

$$WV = \frac{N_{HLC} \times 5}{8} \quad (1)$$

where WV , and N_{HLC} are weight value of class, the number of hydrothermal locations matching the class, respectively.

The calculated weights for all classes across the nine factor maps range from 0 to 5 and are presented in Table 1. A weight of 5 indicates a class highly correlated with known hydrothermal sites, while 0 indicates no correlation.

The limited number of known hydrothermal points ($n=8$) is an acknowledged limitation and the weighting scheme and validation should be considered preliminary until further field data become available.

2.8 Justification of the weighting scheme

The weighting scheme applied here is based on an empirical frequency-ratio approach in which the class weights are proportional to the spatial coincidence with known hydrothermal manifestations. This is based on the

assumption that areas with higher numbers of known sites per class are more prospective. The linear scaling from 0 to 5 is heuristic but preserves the relative ranking of factor classes without introducing arbitrary expert bias. The geothermal relevance labels reported in Table 1 were assigned consistently with the empirically calculated class weights derived from the spatial correspondence between hydrothermal occurrences and each factor class. However, this approach does not take into account nonlinear interactions between factors, a limitation that should be addressed in future studies using probabilistic or machine learning models.

Table 1.
Thematic map layers and weighted values for mineral potential mapping

A.

Topographic and geophysical data

Map layer	Classes	Number of points	Weighted value	Geothermal relevance
Elevation (m)	<500 m	0	0	Very Low
	500-1000 m	3	1.875	Low
	1000-1500 m	3	1.875	Low
	1500-2000 m	1	0.625	Very Low
	>2000 m	0	0	Very Low
Reduced to Pole Aeromagnetic Faults	<500 km/km ²	4	2.5	Moderate
	500-1000 km/km ²	3	1.875	Low
	1000-1500 km/km ²	1	0.625	Very Low
	1500-2000 km/km ²	0	0	Very Low
	>2000 km/km ²	0	0	Very Low
Residual Magnetic Anomalies	<350 km/km ²	5	3.125	High
	350-700 km/km ²	1	0.625	Very Low
	700-1050 km/km ²	2	1.25	Low
	1050-1400 km/km ²	0	0	Very Low
	>1400 km/km ²	0	0	Very Low

B.

Structural features

Map layer	Classes	Number of points	Weighted value	Geothermal relevance
Drainage Pattern	<500 km/km ²	0	0	Very Low
	500-1000 km/km ²	3	1.875	Low
	1000-1200 km/km ²	0	0	Very Low
	1200-1500 km/km ²	0	0	Very Low
	1500-1800 km/km ²	0	0	Very Low
	1800-2400 km/km ²	0	0	Very Low
	>2400 km/km ²	0	0	Very Low
Faults	<700 km/km ²	6	3.75	High
	700-1400 km/km ²	0	0	Very Low
	1400-2100 km/km ²	2	1.25	Low
	2100-2800 km/km ²	0	0	Very Low
Regional Magnetic Faults	>2800 km/km ²	0	0	Very Low
	<300 km/km ²	5	3.125	High
	300-600 km/km ²	2	1.25	Low
	600-900 km/km ²	0	0	Very Low
	900-1200 km/km ²	1	0.625	Very Low
Lineaments	>1200 km/km ²	0	0	Very Low
	<1000 km/km ²	3	1.875	Low
	1000-2000 km/km ²	5	3.125	High
	2000-3000 km/km ²	0	0	Very Low
	3000-4000 km/km ²	0	0	Very Low
	>4000 km/km ²	0	0	Very Low

C.
Lithological Units

Map layer	Classes	Number of points	Weighted value	Geothermal relevance
Rock Units	Paragneiss	0	0	Very Low
	Amran limestone	0	0	Very Low
	Tawilah sandstone	2	1.25	Low
	Basalt	3.5	2.187	Moderate
	Trachyte	0	0	Very Low
	Rhyolite and dacite	1	0.625	Very Low
	Ignimbrite and ashflow deposits	1.5	0.937	Very Low
	<800 km/km ²	7	4.375	Very Low
	800-1600 km/km ²	1	0.625	Very Low
	1600-2400 km/km ²	0	0	Very Low
Contact Types	2400-3200 km/km ²	0	0	Very Low
	>3200 km/km ²	0	0	Very Low
	Granite	0	0	Very Low
	Granodiorite	0	0	Very Low
	Gabbro	0	0	Very low
	Active alluvium	0	0	Very Low
	Gravels	0	0	Very Low
	Loess and ancient dunes	0	0	Very Low
	Colluvium	0	0	Very Low

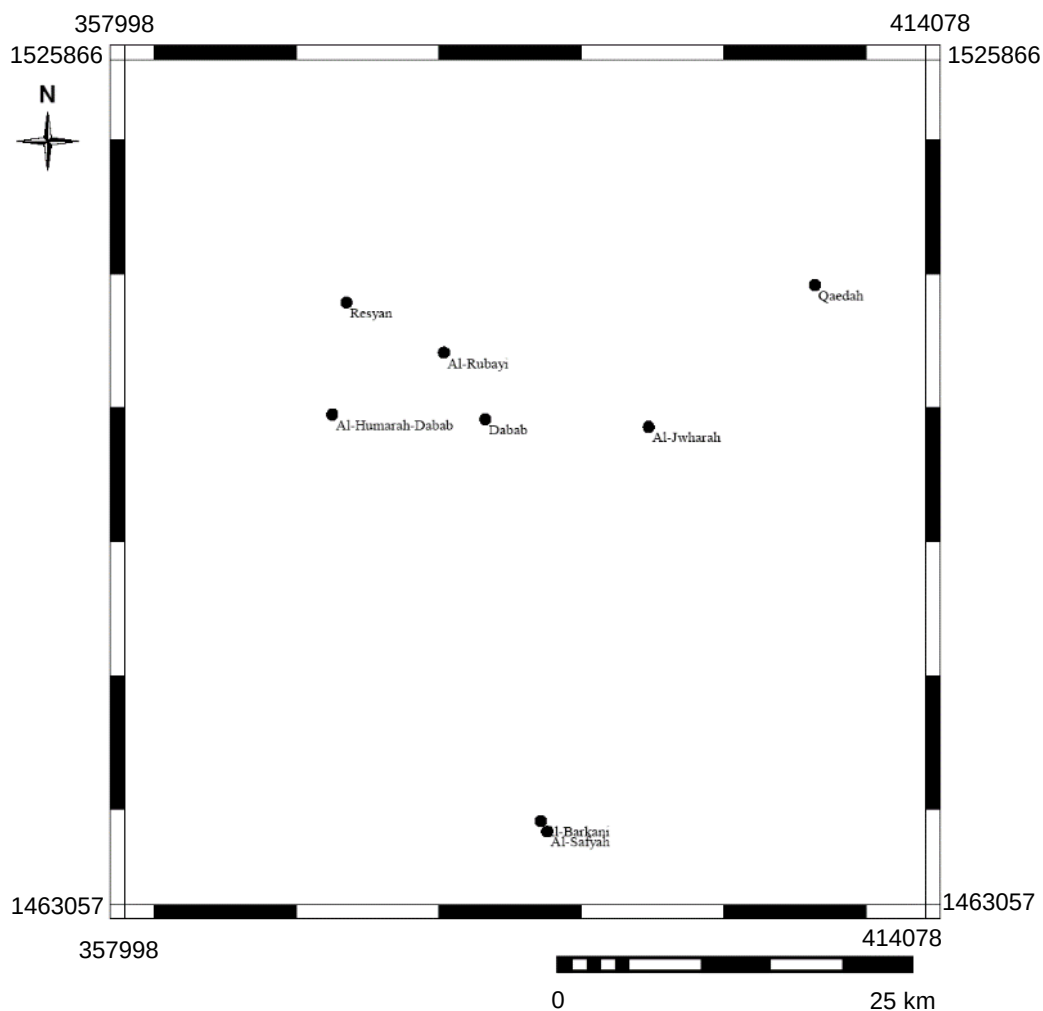


Figure 21.
Field locations of known hydrothermal water occurrences used for model validation.

2.9 GIS model and the geothermal potential map

All geo-factors layers used in the geothermal potential assessment were first converted into raster format and standardized before being combined. To maintain spatial consistency across the analysis, all datasets were re-projected to the Universal Transverse Mercator (UTM) coordinate system, Zone 38N, and re-sampled to a uniform spatial resolution of 100 m. This pre-processing step ensured that the different geothermal conditioning factors could be directly compared and accurately overlaid.

The weighted factor maps were imported into a GIS model within ILWIS software. All maps were re-projected, geo-referenced, and re-sampled spatially to a uniform 100 m resolution. The cell size was selected to align with the spatial resolution of the available hydrothermal occurrence data and the regional scope of the geothermal assessment. Then the thematic layers were combined using Weighted Overlay Technique (WOT). Factor classes were weighted according to their spatial correspondence to known occurrences of hydrothermal activity. For each thematic layer, class weights were assigned according to the number of hydrothermal manifestations within each class using the empirical weighting approach described in previous section. Then the weighted layers were combined to give the final map of geothermal potential.

The final geothermal potential map was generated using the WOT model by calculating the arithmetic mean of the nine weighted factor maps using the Equation 2. The resulting continuous suitability values were then classified into five geothermal potential categories: very high, high, moderate, low, and very low (Figure 22).

$$\text{Potential Map} = \frac{1}{9} \sum_{i=1}^9 WFM_i \quad (2)$$

where *WFM* and 9 are weighted factor maps, total number of factors being integrated, respectively.

3. Result and Discussion

Although the sample size was small ($n = 8$), a preliminary receiver operating characteristic (ROC) analysis was performed by binarizing the potential map (very high + high = positive; moderate, low, and very low = negative). The resulting area under the ROC curve (AUC) was 0.81, indicating moderate predictive discrimination. Because the analysis was based on only eight validation points, the AUC estimate is subject to considerable statistical uncertainty and should therefore be interpreted as exploratory rather than definitive.

However, this result is exploratory and should be interpreted with caution given the circularity noted above. This study represents the first effort to integrate remote sensing data, geological mapping, and aeromagnetic fault interpretations at multiple depths within a GIS-based weighted overlay framework to assess geothermal potential in the Central-Western Taiz region. In this study, the term 'Elevation' is used to refer to the absolute value in meters above sea level, while the term 'Slope' is used to refer to the degree of terrain inclination measured in degrees ($^{\circ}$). Nine key controlling factors were selected: elevation steepness, slope, drainage density, lineament density, rock units, rock contact density, and faults determined from magnetic anomaly map density at three depths.

Spatial analysis revealed elevations ranging from 404 m to 2690 m above sea level (Figure 13). Slope values in the study area range from 0° to $>45^{\circ}$, with gentle slopes ($<10^{\circ}$) covering approximately 35% of the area, predominantly in valleys and low-lying regions. Analysis of the relationship between slope classes and known hydrothermal sites indicates that areas with gentle slopes ($0-10^{\circ}$) show higher correlation with geothermal manifestations, as these areas typically facilitate groundwater recharge and hydrothermal fluid circulation (Figure 12). Lower elevations (<500 m) also correlate with higher geothermal potential, likely due to their association with regional base levels and fault-controlled valleys. A total of 354 lineaments and 216 geological faults were identified with a predominant NW-SE and NE-SW trends (Figure 5 and Figure 15). High densities of lineaments, faults, and lithological contacts were consistently associated with enhanced secondary porosity and permeability, thereby correlating with elevated geothermal potential (Figure 7 – Figure 8 and Figure 16 – Figure 17). Similarly,

areas of low drainage density favored groundwater infiltration and fluid movement (Figure 4 and Figure 14). Geological analysis identified fifteen rock units, with Early Tertiary basalts and fractured Cretaceous sandstones showing strong association with hydrothermal manifestations.

Applying the weighted overlay technique, the final potential map classified the area as: Very High (5.08%± X%), High (9.65%± X%), Moderate (14.65%± X%), Low (50.46%± X%), and Very Low (20.16%± X%). Very high geothermal potential zones are concentrated in central-northeastern (Taiz city to Qaedah), central-southern (Dabab), central-northwestern (Rubayi to Resyan), and southern sectors (J. Habashi, Maafir, Brakani to Safyah). Validation was performed using the eight documented hydrothermal occurrences available in the study area. Seven out of eight points (87.5%) fall within the “very high” potential zone.

Table 2.
Preliminary confusion matrix for the binary geothermal potential classification

		Predicted	
		(Very High + High)	(Moderate + Low + Very Low)
Actual	Hydrothermal occurrence present	7	1
	Hydrothermal occurrence absent	-	-

Binarizing the map (very high + high = positive) yielded a true positive rate of 0.875. A preliminary receiver operating characteristic (ROC) analysis gave an AUC of 0.81 (95% CI wide due to small n), suggesting moderate predictive discrimination. However, this result is exploratory and must be interpreted with caution given the circularity noted above (Table 2).

Although the small number of validation sites limits statistical robustness, the observed spatial agreement is substantially higher than random expectation and provides indicative support for the model's predictive capability. Therefore, the map should be interpreted primarily as a regional screening tool rather than as a rigorous quantitative assessment of predictive accuracy. It should be emphasized that the current validation reflects internal consistency rather than independent predictive validation because the weighting procedure and the model evaluation relied on the same hydrothermal occurrence dataset. Therefore, future studies should validate the proposed framework using an independent dataset collected from additional hydrothermal occurrences, field investigations, drilling results, or newly acquired geothermal observations to provide a more rigorous assessment of the model's predictive capability.

While seven of the eight documented hydrothermal manifestations (87.5%) were successfully identified within the very high geothermal potential zone, occurrence was located in an area classified as having lower geothermal potential. This discrepancy may reflect local geological characteristics that are not fully captured by the regional-scale datasets used in the present study. In particular, the occurrence may be associated with small-scale fractures, localized zones of enhanced permeability, or subsurface fluid pathways that fall below the spatial resolution of the available geological, geophysical, and remote sensing data. Furthermore, the weighted overlay method is primarily designed to highlight broad regional patterns and therefore may not adequately represent isolated geothermal features that are weakly connected to the dominant structural controls recognized across the study area. This limitation underscores the need for integrating higher-resolution geophysical investigations, detailed structural field mapping, and hydrochemical analyses in future research to improve the identification and characterization of localized geothermal systems.

Lineament density, geological faults, and shallow faults determined from magnetic anomaly maps emerged as the most important factors, showing a strong spatial relationship with areas of high geothermal potential and existing hydrothermal manifestations. This finding supports the widely recognized role of structural features in controlling fluid movement within geothermal systems, particularly in extensional tectonic environments such as

the East African Rift and the margins of the Red Sea (Macharia et al., 2018; Levi & Antony 2014; Reda et al., 2022). The observed relationship may also be linked to the tectonic influence of Red Sea and Gulf of Aden rifting processes, which has likely contributed to geothermal activity in southwestern Yemen, as suggested by recent work of Alnethary et al. (2024). Nevertheless, although these spatial patterns provide valuable insights, the underlying processes governing geothermal occurrence in the study area remain uncertain. Additional field investigations, geophysical surveys, and subsurface studies are needed to confirm these relationships and better understand the mechanisms controlling geothermal resource distribution.

Al-Kadasi et al. (2020) reported Curie point depths of approximately 10–15 km in the Taiz region, indicating a comparatively warm crust and higher thermal gradients. These findings provide independent geophysical support for the geothermal manifestations and potential zones mapped in this study.

Methodologically, while the GIS-based weighted overlay approach follows established frameworks (Abdullah et al. 2025; Bernard 2020; El Morabit et al., 2021), this study advances prior work by integrating multi-depth aeromagnetic fault data to explicitly model subsurface structural controls (Figure 9 – Figure 11, Figure 18 – Figure 20). The resulting framework offers a transferable, optimized tool for site selection in future geothermal or groundwater drilling campaigns, enhancing exploration success rates in underexplored rift settings. A cross-analysis between the factor layers and the high-potential zone area was performed to determine the relative importance of each factor (Table 3). Lineaments (73.6%), geological faults (65.9%), and shallow faults determined from magnetic anomaly maps (−38.3 m depth, 60.4%) were the most significant factors, underscoring the strong relationship between geothermal potential and geological structural features. This highlights the important role of the regional tectonic setting (Red Sea and Gulf of Aden rifting) in geothermal occurrence in the study area.

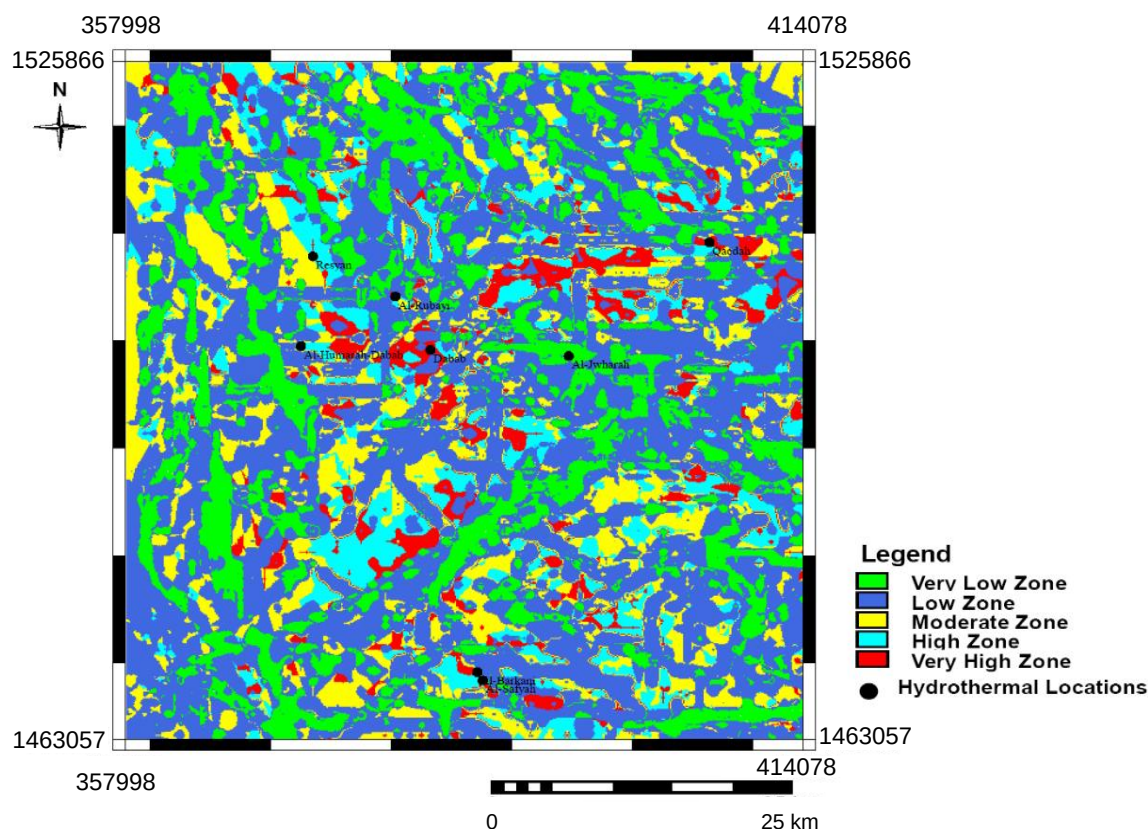


Figure 22.

Final geothermal potential zonation map of the study area produced using the weighted overlay technique.

Table 3.
Relative contribution of each factor to the high geothermal potential zones

No.	Factors	Importance, %
1	Elevation Steepness	18.3
2	Drainage	44.2
3	Lineament	73.6
4	Geological Faults	65.9
5	Rock Units	43.6
6	Rock Contacts	46.8
7	Faults from magnetic anomaly maps at -38.3 m depth	60.4
8	Faults from magnetic anomaly maps at -95.5 m depth	27.4
9	Faults from magnetic anomaly maps at -144.4 m depth	31.7

In this study, a purely deterministic GIS-based weighted overlay approach is adopted. Such methods are good for regional screening, but do not provide a measure of uncertainty in the prediction, or learn complex nonlinear relationships. Future geothermal potential mapping in Yemen should explore complementary pathways such as recent advances in machine learning (e.g. random forest, MaxEnt) and probabilistic Bayesian networks, once a larger validation data set becomes available. The deterministic GIS-based weighted overlay approach adopted in this study offers high interpretability and is particularly suitable for data-scarce environments such as Yemen. Nevertheless, recent studies suggest that machine learning algorithms—including Random Forest, Gradient Boosting, Bayesian Optimization, and hybrid ensemble models—can better capture nonlinear interactions among geothermal controlling factors when sufficiently large training datasets are available (Al-Fakih et al., 2025; Al-Gathe et al., 2025; Aydınli et al., 2026). Therefore, the geothermal potential map developed in this work may serve as an initial knowledge base for future AI-assisted geothermal exploration and probabilistic resource assessment. There are no published heat-flow measurements or detailed geothermal gradient data for the study area. Thus, the evaluation of geothermal potential is based mainly on geological, geomorphological, hydrothermal and geophysical indicators. A limitation of the present study is the lack of direct thermal subsurface data, which points to the need for future geothermal gradient measurements, heat-flow investigations, and exploratory drilling to confirm the predicted zones of geothermal potential.

Although the model shows a strong spatial relationship with known hydrothermal occurrences, it should be viewed as a tool for generating hypotheses rather than providing definitive confirmation. The mapped geothermal potential zones highlight areas that are more likely to host geothermal resources based on the integration of surface and subsurface geospatial indicators, but they do not serve as direct proof of their existence. Therefore, these results are best used to prioritize exploration efforts and guide field investigations. Ultimately, any predicted geothermal systems must be verified through independent studies, including hydrogeological surveys, geochemical and geophysical analyses, and exploratory drilling.

3.1 Thermal characteristics of Central-Western Taiz

The geothermal potential of the central–western Taiz region is controlled not only by geological structures but also by the regional thermal conditions linked to the tectonic evolution of south western Yemen. The study area lies within the Red Sea–Gulf of Aden rift system, a major extensional zone characterized by crustal thinning, faulting, and enhanced upward heat transfer from deeper parts of the Earth. Such tectonic settings are widely recognized as favorable environments for geothermal activity because they often exhibit elevated geothermal gradients and increased heat flow. Although direct measurements of geothermal gradients, heat flow, and subsurface temperatures are scarce in the study area, several indirect indicators point to favorable thermal conditions. Thermal manifestations, including hot springs and warm groundwater wells with temperatures ranging from about 32°C to 75°C, have been reported across southwestern Yemen (Alnethary et al., 2024). These features suggest that groundwater is circulating through deep-seated fractures and faults, where it is heated before returning to the surface. Regional magnetic studies provide further evidence of elevated subsurface temperatures.

Using aeromagnetic data, Al-Kadasi et al. (2020) estimated Curie Point Depth (CPD) values for south western Yemen. The Curie Point Depth corresponds to the depth at which magnetic minerals lose their magnetic properties due to high temperatures, typically around 580°C for magnetite. In general, shallower CPD values are associated with higher geothermal gradients and greater crustal heat flow. The CPD estimates reported for south western Yemen indicate relatively warm crustal conditions that are consistent with the region's active rift-related tectonic setting. While the main focus of this study is the identification of structural and hydrogeological controls using remote sensing, geological, and geophysical data, the available thermal evidence provides important support for the geothermal interpretation. The regional rift setting, the presence of thermal manifestations, and the Curie Point Depth results collectively suggest the existence of a favorable heat source at depth. Therefore, the geothermal potential zones identified in this study are interpreted as locations where permeable fault systems and fracture networks coincide with a thermally favorable geological environment, creating conditions that may support hydrothermal circulation and geothermal resource development.

3.2 Sensitivity analysis of search radius selection

A sensitivity analysis was conducted for the lineament, fault, and contact density maps using a kernel search radius of 1000 m as the baseline. Additional analyses were performed using search radii of 500 m and 1500 m. Compared with the baseline (1000 m), the area classified as very high potential changed by approximately -12% for the 500 m radius and +18% for the 1500 m radius.

These values represent relative percentage changes in the area of the very high potential zone with respect to the baseline result, rather than absolute percentage-point changes relative to the total study area. The results indicate a moderate sensitivity of the final geothermal potential map to the selected search radius. Therefore, the choice of a 1000 m search radius is influential and should be further optimized in future studies using approaches such as variogram analysis, spatial optimization, or spatial cross-validation.

3.3 Study limitations and future work

Several limitations should be kept in mind when interpreting the results of this study. Both the weighting process and the model evaluation were based on the same eight known hydrothermal occurrences, meaning that the reported validation reflects internal consistency rather than a truly independent assessment and may therefore present an overly optimistic view of model performance. The small number of hydrothermal sites also made it impossible to divide the data into separate calibration and validation datasets, limiting the statistical strength of the evaluation. In addition, all hydrothermal occurrences were treated equally because temperature, discharge, and geochemical information were not available, even though some sites are likely to have greater geothermal significance than others. The geological framework was derived from the most recent publicly available geological map of the area, while lineaments were identified through manual interpretation by a single operator, which may introduce subjectivity and affect reproducibility. Other sources of uncertainty include the spatial resolution of the input datasets, the lack of direct hydrogeological evidence such as groundwater flow measurements, hydraulic tests, drilling records, and hydrogeochemical analyses, as well as the use of a weighted overlay method that simplifies the complex and potentially non-linear relationships among geothermal controlling factors. As a result, the geothermal potential map produced in this study should be viewed as a regional exploration screening tool that highlights promising target areas rather than confirmed geothermal resources. Future work should aim to expand the hydrothermal database through additional field surveys, geochemical studies, and drilling data; incorporate updated geological information and higher-resolution geophysical datasets; collect hydrogeological and temperature measurements; compare automated and multi-operator lineament extraction approaches; and apply data-driven, machine learning, and spatially explicit validation techniques, such as k-fold spatial cross-validation, to improve the robustness and predictive capability of the model.

4. Conclusion

This study successfully demonstrated the effectiveness of integrating remote sensing, geological, and geophysical data within a GIS-based weighted overlay framework for geothermal potential mapping in central–western Taiz, Yemen. Nine controlling factors were derived and analyzed, with structural features such as faults and lineaments identified as the primary controls on geothermal occurrence. The final geothermal potential map showed a strong spatial correspondence with known hydrothermal occurrences, suggesting that the proposed approach is effective for regional-scale geothermal exploration and preliminary screening. The resulting geospatial database provides a practical decision-support tool for geothermal exploration, groundwater development, and resource management. Beyond the central–western Taiz region, the proposed GIS-based weighted overlay framework provides a transferable methodology for geothermal prospectivity mapping in other tectonically active rift settings where geothermal systems are predominantly controlled by structural features such as faults and lineaments. By integrating remote sensing, geological, and geophysical datasets within a unified GIS environment, the approach can support regional-scale exploration and preliminary site screening in geologically comparable rift environments, while recognizing that local weighting schemes and validation datasets should be adapted to the specific geological conditions of each study area. The adopted approach is transferable and can be applied to similar tectonically active regions. At a minimum, application of the proposed workflow in other regions requires a Digital Elevation Model (DEM), geological maps containing lithological units and fault information, and remotely sensed or geophysical data that allow the extraction of major structural features (e.g., lineaments or fault networks), together with a limited number of known hydrothermal occurrences for empirical weighting and preliminary validation.

5. Acknowledgement

The authors thank all staff of the Geology Department, Faculty of Applied Science, Taiz University, Yemen.

6. Declarations

6.1 Author contributions

All authors are equally contributed all segments of research; data collection, analysis and writing and editing manuscript.

6.2 Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

6.3 Competing interest

This research has no conflict of interest with any other work.

6.4 The Use of AI or AI assisted Technologies

The authors use the available soft wares to assist completing the work, then reviewed the content and the auths take full responsibility the published content of the paper.

7. Glossary of terms and symbols

Terms and symbols	Definition	Unit
GIS	Geographic information system	
RS	Remote sensing	
DEM	Digital elevation model	
SRTM	Shuttle radar topography mission	
WOT	Weighted overlay technique	
WV	Weight value	
NHLC	Number of hydrothermal locations corresponding to a class	
ROC	Receiver operating characteristic	
AUC	Area under the roc curve	
UTM	Universal transverse mercator	
RTP	Reduced-to-the-pole	
CPD	Curie point depth	
GSY	Geological survey of yemen	
ILWIS	Integrated land and water information system	
PCI Geomatica	Pci geomatica software	
ArcGIS	Arcgis geographic information system software	
m	Meter	
km	Kilometer	
km	Kilometer	
km ²	Square kilometer	
°C	Degree celsius	
m a.s.l.	Meters above sea level	
m	Meter (depth/elevation)	
%	Percentage	
Symbol meaning		
WV	Weight value	
N_{HLC}	Number of hydrothermal locations corresponding to the class	
WFM_i	Weighted factor map of factor i	
i	Factor index	
n	Number of geothermal controlling factors (9)	

8. References

- Abd Manap MA (2013) A knowledge-driven GIS modeling technique for groundwater potential mapping at the Upper Langat Basin, Malaysia. *Arabian Journal of Geosciences* 6(5):1621–1637. <https://doi.org/10.1007/s12517-012-0599-1>
- Abdulkadir YA, Fisseha S, Jothimani M (2022) Digital elevation model and satellite gravity anomalies and their correlation with geologic structures at the Borena Basin, Southern Main Ethiopian Rift. *European Journal of Remote Sensing* 55(1):540–550. <https://doi.org/10.1080/22797254.2022.2130096>
- Abdullah A, Aziz AA, Isnain Z (2025) The weighted values of factor classes based on different approaches for groundwater potential zone mapping using remote sensing data and GIS techniques in the Taiz region, Yemen. *Indonesian Journal of Geoscience* 12(1):105–131. <https://doi.org/10.17014/ijog.12.1.105-131>
- Abdullah A, Nassr S, Ghaleeb A. (2013) Remote sensing and geographic information system for fault segment mapping: a study from Taiz area, Yemen. *Journal of Geological Research* 2013:201757. <https://doi.org/10.1155/2013/201757>
- Abdullah. A, Akhir M. J, and Abdullah. I, (2010). Automatic mapping of lineaments using shaded relief images derived from digital elevation model (DEMs) in the Maran—Sungi Lembing area, Malaysia,” *Electronic Journal of Geotechnical Engineering*, vol. 15 pp. 949–957.

- Abullah A, Nassr S, Ghaleeb A. (2013). Landsat ETM-7 for Lineament Mapping using Automatic Extraction Technique in the SW part of Taiz area, Yemen. *Global Journals Inc. (USA)*. 13 :49-52.
- Al Kadasi A (2014) Interpretation of aeromagnetic data in terms of surface and subsurface geologic structures, southwestern Yemen. *Arabian Journal of Geosciences* 7(2):505–516. <https://doi.org/10.1007/s12517-013-1238-1>
- Al-Fakih AM, Al-Khudafi AM, Koeshtidayatullah A, Kaka SI, Al-Gathe AA (2025) Forecasting geothermal temperature in western Yemen with Bayesian-optimized machine learning regression models. *Geotherm Energy* 13:1
- Al-Gathe, A., Al-Khudafi, A., Hamada, G., Almuafa, N., Farea, I., & Abdullah, A. (2025). A hybrid approach for accurate geothermal temperature prediction in the western region of Yemen. *Journal of African Earth Sciences*, 231, 105777. <https://doi.org/10.1016/j.jafrearsci.2025.105777>
- Aliyu, A., et al. (2026). Review on geothermal prospectivity mapping: Global trends, challenges and future directions. *Renewable and Sustainable Energy Reviews*.
- Al-Kadasi, A. N., Al-Aydrus, A., & Mustafa, M. S. A. D. (2020). *Estimation of Curie point depth in southwestern Yemen from spectral analysis of aeromagnetic data*. *Arabian Journal of Geosciences*, 13(5), 238. <https://doi.org/10.1007/s12517-020-5196-0>
- Alnethary M, Sharian A, Mattash M, Minissale A (2024) Evaluation of geothermal exploration in Yemen (western area and the Red Sea). In: *Proceedings of the 49th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, USA. SGP-TR-227.
- Aydınli, H., Kaplan, G., & Çabuk, S. N. (2026). Early-phase geothermal prospecting using remote sensing and machine learning: Application to Buharkent and Germencik fields, Türkiye. *Geothermics*.
- Bai S, Wang J, Lü G, Zhou P, Hou S, Xu S (2010) GIS-based logistic regression for landslide susceptibility mapping of the Zhongxian segment in the Three Gorges area, China. *Geomorphology* 115(1–2):23–31. <https://doi.org/10.1016/j.geomorph.2009.09.025>
- Baker L, Johnson T (2020) Geospatial analysis of geothermal resources using GIS: case studies from North America. *Geothermal Energy* 8:12. <https://doi.org/10.1186/s40517-020-00167-8>
- Bernard MO (2020) Geothermal well site suitability selection using geographic information systems (GIS) and remote sensing: case study of the Eburru geothermal field. In: *Proceedings of the 45th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, USA.
- David LG, Pablo RG (2019) Detection of geothermal potential zones using remote sensing techniques. *Remote Sensing* 11(20):2403. <https://doi.org/10.3390/rs11202403>
- El Morabit I, Soufiane M, Ahmed F (2021) Geothermal potential mapping of northeast Morocco (Bekrane–Ahfir) using remote sensing data and GIS. *E3S Web of Conferences* 234:00093. <https://doi.org/10.1051/e3sconf/202123400093>
- Geological Survey of Yemen (1990) Geological sheet map of Taiz Governorate, scale 1:250,000. Geological Survey of Yemen, Sana'a.
- Haselwimmer C, Prakash A (2013) Thermal infrared remote sensing of geothermal systems. In: Kuenzer C, Dech S (eds) *Thermal Infrared Remote Sensing: Sensors, Methods, Applications*. Springer, Dordrecht, pp 453–473. https://doi.org/10.1007/978-94-007-6639-6_22
- Heasler HP, Jaworowski C, Foley D (2009) Geothermal systems and monitoring hydrothermal features. In: Young R, Norby L (eds) *Geological Monitoring*. Geological Society of America, Boulder, pp 105–140.
- Ibrahim A, Juhari MA (1990) *Dictionary of Basic Geological Terms*. National University of Malaysia, Bangi.

- Kehinde AM, Oluwafemi TA, Akinola AK (2023) Geothermal energy potentiality modeling using a GIS-based machine learning algorithm in southwestern Nigeria: insights from geophysical and remote sensing datasets. Research Square [Preprint]. <https://doi.org/10.21203/rs.3.rs-3266721/v1>
- Kumar P, Singh R (2019) Thermal remote sensing for identifying hot springs: insights from the Himalayan region. *Journal of Environmental Management* 245:1–10. <https://doi.org/10.1016/j.jenvman.2019.05.082>
- Levi S, Antony W (2014) GIS applications in heat source mapping in Menengai geothermal field. In: Proceedings of the 5th African Rift Geothermal Conference (ARGeo-C5), Arusha, Tanzania.
- Macharia MW, Gachari MK, Mariita NO, Mundia CN, Kuria DN (2018) A GIS-based approach for exploring geothermal resources along part of the Kenyan Rift. *Journal of Applied Science, Engineering and Technology Development* 3(1):1–34.
- Nassr S, Abdullah A (2015) The delineation of linear features from different image resolutions using edge modelling techniques in the Al-Mawasit area, Taiz, Yemen. *American Journal of Geophysics, Geochemistry and Geosystems* 1(1):7–18.
- Ramsey MS, Harris AJL (2013) Volcanology 2020: how will thermal remote sensing of volcanic surface activity evolve over the next decade? *Journal of Volcanology and Geothermal Research* 249:217–233. <https://doi.org/10.1016/j.jvolgeores.2012.05.011>
- Reda TM, Gebrehiwot WZ, Jothimani JM, Tirusew SY (2022) Assessing the effect of volcano-tectonic activity on the spatial distribution of surface temperature in the Main Ethiopian Rift using an integrated remote sensing approach. *European Journal of Remote Sensing* 55(1):86–102. <https://doi.org/10.1080/22797254.2021.2021555>
- Rutty LA (1993) The basement fracture pattern of southern Ontario: a tectonic interpretation based on Landsat TM imagery, air photos and field data. Master's Thesis, University of Waterloo, Waterloo, Canada.
- Taillefer A, Soliva R, Guillou-Frottier L, Le Goff E, Martin G, Seranne M (2017) Fault-related controls on upward hydrothermal flow: an integrated geological study of the Têt fault system, eastern Pyrénées (France). *Geofluids* 2017:8190109. <https://doi.org/10.1155/2017/8190109>
- Zhou Y, Liu J (2021) Integrating remote sensing and GIS for assessing geothermal potential: a case study from China. *International Journal of Applied Earth Observation and Geoinformation* 95:102257. <https://doi.org/10.1016/j.jag.2020.102257>