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Exploration of Geothermal Resources in Peninsular Malaysia: A Review of Geological, Geochemical, and Geophysical Techniques

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Abstract

More than sixty thermal springs have been detected across Peninsular Malaysia, with about 75% conveniently located in easily accessible areas. The potential for thermal energy growth has been recognized at four hot spring localities: Lojing, Dusun Tua, Ulu Slim, and Sungai Klah. This article analyses Peninsular Malaysia's geothermal development's geological, geochemical, and geophysical research to assess its appropriateness and performance. The geological data provide insights into the structural characteristics and spatial distribution of thermal springs within the studied area. Geochemical studies measure reservoir temperatures, revealing the highest recorded temperature exceeds 189°C. The review shows that the hot springs are derived from a recharge region linked to high-altitude topography, with their source being meteoric water. Several geophysical techniques, such as transient electromagnet (TEM), gravity, land and satellite magnetic, ground penetration radar (GPR), seismic, resistivity, and induced polarization (IP), have been employed to examine the geothermal system in Malaysia. The sole magnetotelluric (MT) investigation at Ulu Slim deviates from this pattern. The source suggests uncertainty regarding accuracy related to station distance, highlighting these concerns. Most studies indicate that magma intrusion is the most likely heat source. To offer a comprehensive understanding of Peninsular Malaysia's geothermal potential, this study reviews previous research and presents a feasible model that incorporates all current facts.

1. Introduction

The global energy consumption pattern, propelled by economic advancement, has resulted in extensive dependence on conventional fossil fuels. Consequently, the aforementioned circumstances have led to the depletion of resources and the infliction of environmental damage. As a result, there has been an increasing body of study and a surge in the demand for alternative energy sources as a direct reaction to these concerns. Geothermal resources have emerged as a compelling solution, offering substantial, eco-friendly reserves [1, 2]. Utilization of geothermal energy resources, harnessed from the Earth's interior heat, has witnessed a significant upsurge in recent decades, primarily spurred by growing concerns over climate change. This unique form of energy taps into the Earth's inner heat, generated by the Earth's core and ongoing radioactivity, with heat rising through conduction and convection to manifest as soothing hot springs. The thermal origin can fluctuate, whether molten rock infiltrations in volcanic geothermal frameworks or heated rock at the foundations of the convection cycle in non-volcanic geothermal frameworks [3, 4]. Regardless of the heat source, the mechanism for water circulation remains constant, providing a consistent and reliable energy source less

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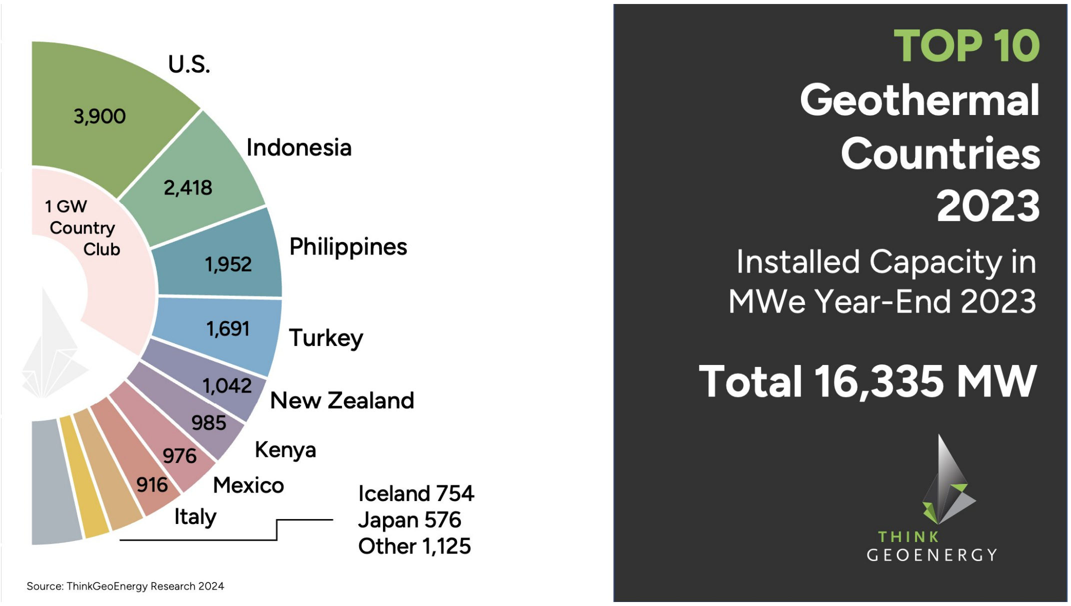
susceptible to seasonal production fluctuations compared to solar and hydrological sources [5, 6] Geothermal energy and hot springs are inherently interconnected, as they both exploit the Earth's internal thermal energy resources. Hot springs, commonly known as thermal springs, exhibit the distinctive feature of groundwater that possesses temperatures much higher than the ambient environment. This phenomenon arises due to the heating effect caused by intrusions originating from magmatic sources [7]. According to [8] the process involves the upward movement of hot fluids across fractures or faulted planes. Beyond their appeal as natural spas, hot springs serve as surface manifestations of deeper geothermal systems, where electricity generation becomes possible by tapping into aquifers with high temperatures, depending on geological conditions. Geothermal hot spring systems can be broadly categorised into high-temperature resources suitable for conventional electricity production and low-temperature resources ideal for direct applications or electricity generation using low-enthalpy technology [3, 9, 10]. Intriguingly, these geothermal systems also exhibit elevated concentrations of dissolved minerals, distinguishing them from local non-hot spring groundwater. The interplay between heat, water, and rocks at specific locations gives rise to hot springs, which are not only celebrated for their therapeutic qualities but also hold the potential to provide sustainable and reliable sources of clean energy.

Despite not being located near an active plate boundary or volcanic region, Malaysia is home to numerous thermal springs. These springs are connected to the Malaysian Rift System, which is one of the primary tectonic structures of the earth and allows heat to escape from the earth's interior to the near surface. The origin of these thermal springs has been genetically linked to the tectonic activity of the region, presenting promising geothermal sites that can be harnessed as an alternative energy source. Extensive investigations have identified over sixty locations of thermal springs in Peninsular Malaysia [8, 11-16]. Based on the geological and chemical composition of their fluids, some of these studies have indicated a nonvolcanic origin for these hot springs. While the majority of Malaysia's geothermal resources fall within the classification of low-enthalpy thermal fields, there are exceptional occurrences of medium-enthalpy thermal fields in Southern Perak, Dusun Tua, and Sg. Ber, Lojing, Kelantan [16]. The generation of geothermal energy has experienced significant growth in various countries worldwide, including the United States, Iceland, Italy, Turkey, Kenya, and Indonesia. Global geothermal renewable energy reported a total installed capacity of 16,127 MW as of the end of 2023 and the beginning of 2024 [17], (Figure 1). According to statistical data provided by the Department of Statistics Malaysia in 2020 [18], the proportion of power generation sources in Malaysia for 2018 can be outlined as follows: 62.4% originated from natural gas, 29.2% from crude oil, 5.7% from hydropower, 1.5% from coal and coke, 0.6% from biodiesel, 0.2% from biomass, and 0.2% from biogas. Unfortunately, Malaysia's geothermal potential as an energy resource has yet to be fully realized. In contrast, neighbouring nations such as Thailand and Indonesia have successfully harnessed these energy resources over the past three decades. Many hot springs in Malaysia have been developed into onsen or spa facilities catering to the recreational and health tourism industries. Throughout Malaysia, approximately 15 such locations have garnered significant attention from both tourists and individuals seeking therapeutic benefits [16, 19]. Novel geothermal energy applications have been found in many studies. Hot spring energy could be used to dry cocoa beans sustainably [12], reducing energy expenditures and weather issues while preserving quality. Research on low-temperature geothermal sources for freshwater fishpond design [21] may improve aquaculture efficiency and sustainability. The precise findings of these studies are not revealed, providing the possibility for additional research and deployment of energy-efficient technologies in relevant businesses. On the other hand, green energy could offer an alternative to fuel-based energy, a crucial consideration for nations like Malaysia. This shift has the potential to lessen dependence on fossil fuels benefiting both the economy and the environment. Malaysia is currently experiencing a surge in demand for electricity underscoring the importance of reducing reliance on fuels from both environmental standpoints. Given Malaysia's increasing energy needs there is a push, towards embracing a range of renewable energy sources as part of its energy security strategy outlined in the Twelfth Malaysia Plan (12MP). The coexistence of hot springs as both a sanctuary for relaxation and a potential hub of green energy represents a harmonious blend of tradition and innovation. This offers an exciting glimpse into the promising path towards a sustainable and prosperous future for Malaysia and the world.

This paper provides a comprehensive examination of prior geological, geophysical, and geochemical studies conducted on geothermal systems in West Malaysia. The fundamental goals of this investigation are to carry out an all-encompassing analysis of antecedent research endeavours, with particular emphasis on the approach employed, and to assess their appropriateness within the distinct milieu of geothermal systems in Malaysia. This review is pivotal in enhancing our understanding of Malaysia's geothermal system, and we also assess Malaysia's current progress in comprehending and harnessing geothermal energy.



Source: ThinkGeoEnergy Research 2024

Figure 1. The installed capacity of geothermal power generation in the top ten countries (ThinkGeoEnergy, 2024) [17]

2. The tectonic environment and its significance for geothermal energy exploration in Peninsular Malaysia

West Malaysia, part of Sundaland, Southeast Asia's continental core, has a complex tectonic history that affects its geothermal potential. East Malaya, Indochina, Sibumasu, West Burma, and Southwest Borneo were continental blocks in Sundaland near Gondwana's eastern edge. [22, 23] In the Early Permian, the Palaeo-Tethys Ocean split the Sibumasu block (Siam, Burma, Malaysia, and Sumatra) from the East Malaya block. Subduction during the Middle to Late Permian created a volcanic belt between these blocks and closed the Palaeo-Tethys Ocean in the Triassic [22]. This tectonic backdrop and a Late Cretaceous thermo-tectonic event that caused faulting, granitoid intrusions, and paleomagnetic shifts affect the region's geothermal dynamics. These geological changes affect crustal heat flow and fluid movement, shaping West Malaysia's geothermal characteristics [24, 25].

The Malay Peninsula has been extensively reported and classified into three longitudinal north-south belts: the Western Belt, Central Belt, and Eastern Belt [24]. The peninsula is divided into several belts based on its stratigraphy, structure, magmatism, geological development, and volcanism [22] as shown in Figure 2. The Western Belt, which is a component of the Sibumasu Terrane, originated from the northwestern region of Australian Gondwana in the late Early Permian period, as stated by [29]. The Central and Eastern Belts, now classified as part of the East Malaya Block, were formerly a component of the Indochina-East Malaya Terrane. This terrane detached from Gondwana during the Devonian period [27].

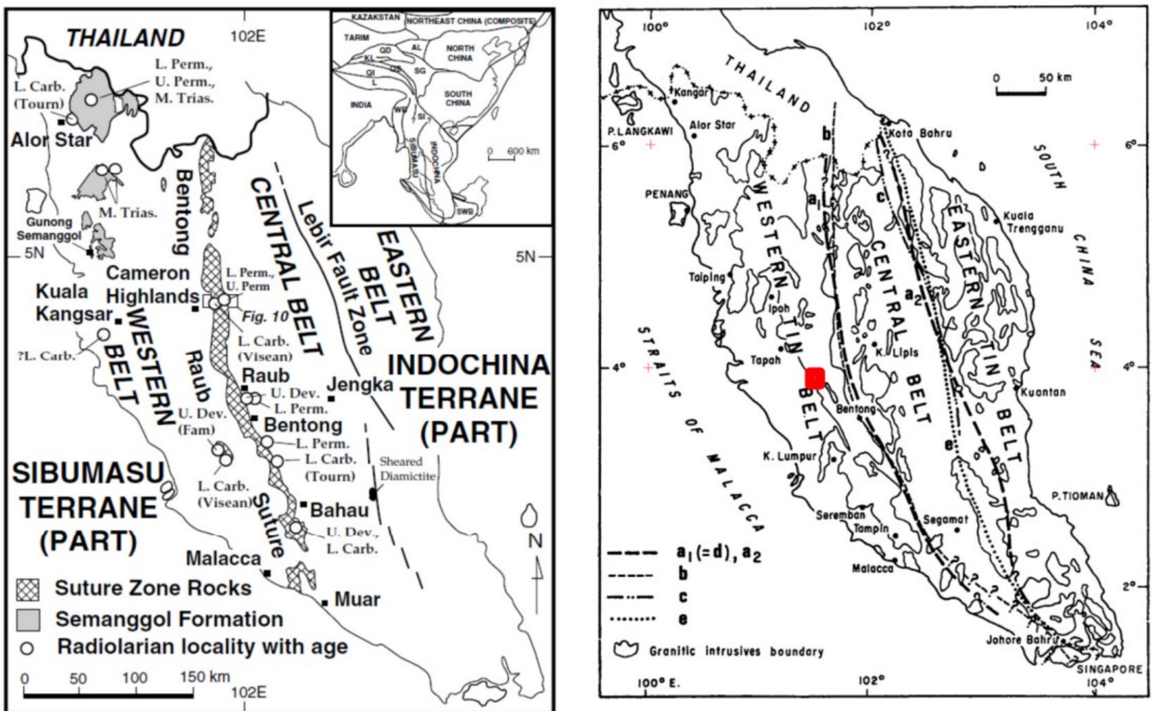


Figure 2. Shows the Western, Central, and Eastern "Belts" of Peninsular Malaysia, with the distribution of cherts, argillites, melange, serpentinites, and turbidites in the Semanggol Formation. Also shown are radiolarian locales and ages. [26]

The Bentong-Raub Suture Zone (BRSZ) represents a significant tectonic entity within the Western Belt. This comparatively narrow zone extends in a north-south direction and serves as the demarcation between the Western and Central Belts. The suture zone indicates the closure of the Paleo-Tethys Ocean and comprises ophiolitic complexes, deep-sea sedimentary sequences, and volcanic edifices [24]. The BRSZ has undergone substantial strike-slip movements, with numerous gold extraction sites and geothermal resources in Peninsular Malaysia linked to its essential geological features [22, 43]. In addition, the suture zone marks the limit of the Paleo-Tethys Ocean, which formed during the Devonian era. The Middle Devonian ribbon-bedded cherts are the earliest known stratigraphic deposits found inside this ocean [26, 22].

The Central Belt is located next to prominent north-south fault lines on its eastern side, with the most famous one being the Lebir Fault. The Late Paleozoic tectonics created volcanic arcs including the Peusangan-Palepat Volcanic Arc in the Lower to Middle Permian and the East Malaya Volcanic Arc in the Middle to Upper Permian and Triassic periods. This occurrence also signalled the beginning of A-type subduction. Afterwards, there was a buildup of volcaniclastic materials and the creation of the Semanggol Formation in the Semantan basin, located in the forearc/intra-arc area [22].

Granitoids are a common feature across Peninsular Malaysia, having been formed by tectonic events such as the sinking of the Ceno-Tethys oceanic crust and post-collisional magmatic activity [24]. S-Type granites are abundant in the West Malaya Main Range, occurring from the Late Triassic to the very beginning Jurassic, whereas I-Type granites are found in the Eastern Malaya area and range from the early-Middle Permian to the early-Late Triassic [24, 26, 25, 28-31]. Genarlly, these granitoids are notable for their elevated levels of radiogenic elements, including uranium, thorium, and potassium. Although there is a scarcity of research that precisely measure the specific impact of these factors on geothermal potential in West Malaysia, it is established that they gradually diminish with time. This decay has the ability to enhance geothermal gradients and overall heat flow [32- 37]. Although there is now no conclusive proof of their direct geothermal impact, the existence of these elements indicates a potential involvement in the area geothermal dynamics.

3. The Role of Fault in Geothermal Systems Activity in West Malaysia

Fault systems serve as crucial for the establishment and long-term existence of geothermal systems in Peninsular Malaysia, even in the absence of active volcanic activity [8, 15, 16]. These geological formations increase the ability of the Earth's crust to allow the flow of fluids, such as water heated by the Earth's internal heat where this process helps to circulate the fluids and concentrate them in specific areas [38-40]. The region's complex tectonic framework, influenced by its position within the Pacific Ring of Fire, includes numerous significant fault systems such as the Bukit Tinggi, Bok Bak, Kuala Lumpur, Lebir, Lepar, Seremban, and Mersing faults, which substantially impact hot spring distribution [8, 15, 16, 41-45]. Recent studies have further elucidated the importance of these fault systems in formating the geothermal [45-48].

Field observations in Peninsular Malaysia reveal a distinct distribution pattern of geothermal manifestations, primarily hot springs, situated at low altitudes across diverse geographic settings [8, 13]. These thermal features predominantly follow two geographic trends: a West-East alignment from Langkawi Island to eastern Kelantan and Terengganu, and a North-South trend from northern Kedah to southern Johor, potentially extending to Singapore [12]. This NNW-SSE orientation aligns with the primary tectonic trend of the Malay Peninsula.

Various types of faults significantly influence geothermal potential by controlling fluid migration and reservoir formation. Strike-slip faults, such as those in the NW-SE direction aligned with the Main Range granite in the Western Belt of Peninsular Malaysia, generate fracture networks that enhance permeability, facilitating geothermal fluid movement [42] as well as the Magnetic anomaly data indicates that the depth to basement structures ranges from 1.0 to 20.0 km, with an average of 5.0 km, underscoring the variability in sedimentary cover and the impact of these fault systems on geothermal potential [43].

The Bukit Tinggi fault zone in Peninsular Malaysia shows recent tectonic activity, evidenced by microseismic events and displacements in Late Quaternary deposits [49, 50]. Hot springs like Bentong and Sungai Serai are associated with this fault, highlighting its role in hydrothermal fluid circulation. Reactivated Paleozoic structures, including the Hulu Kelang, Kongkoi, Lepar, Kenus, Karak, and Mersing faults, also correlate with hot spring locations. For example, the Hulu Kelang fault influences the Dusun Tua hot spring, and the Lepar fault impacts Sungai Lembing geothermal activity. The Karak and Benus faults demonstrate the alignment between fault systems and geothermal features, providing pathways for geothermal fluids. Johor's eastern thermal features are connected to the Mersing fault. These systems collectively highlight how tectonic features shape regional geothermal activity.

Thrust and reverse faults, driven by compressional stresses, trap geothermal fluids, creating high-pressure zones favorable for geothermal reservoirs, especially in regions with elevated heat flow [25, 51]. Fault systems in suture zones, such as the Bentong-Raub Suture Zone and Lebir Fault Zone, are critical tectonic boundaries that influence structural patterns and promote hot fluid movement, essential for geothermal resource development [22, 43]. The Bentong-Raub Suture Zone, marking the closure of the Palaeo-Tethys Ocean, intersects radiogenic Main Range Granites, creating optimal conditions for geothermal energy production [26, 43, 52]. The Batu Ampar Fault recently showed normal displacements, while the Kledang Fault experienced dextral ductile to brittle shear followed by normal activity [51, 52]. These fault systems are crucial for assessing geothermal potential by facilitating fluid movement and heat transfer within the Earth's crust. NW-SE trending faults in the Western Belt, intersected by smaller normal faults, are key conduits for geothermal fluid movement [43].

The Slim River and Hulu Langat areas showcase significant geothermal potential, where fault systems are vital in facilitating geothermal fluid movement. Normal faults, often located near riverbanks and wetlands, serve as natural conduits for these rising fluids [55]. The strong link between hot springs and surrounding fault systems highlights the importance of tectonic structures in shaping geothermal activity across Peninsular Malaysia. However, to precisely map geothermal resource spatial distribution in relation to fault systems, more research is needed. In their study, [56] examined the Ulu Bendul area, focusing on the east-west trending Ulu Bendul Fault, which exhibits characteristics of a normal fault system that may influence the region's geothermal resources. Fragmented fault networks and structural limitations may create pathways for high-temperature water to ascend from deep within the Earth, potentially forming geothermal reservoirs. Additionally, the detection of water-saturated zones through electrical resistivity supports the idea that these faults promote subsurface fluid flow, enhancing the potential for geothermal activity, as evidenced by nearby hot springs.

4. Literature Evaluation Strategy

In order to investigate geothermal systems in West Malaysia, we undertook an extensive literature assessment by methodically searching academic databases, critically reviewing pertinent studies, and selecting those that conformed to our established criteria. This endeavor aimed to consolidate existing research, underscore advancements in the discipline, pinpoint prospective research voids, and tackle prevailing challenges within the field. Through an in-depth analysis of the chosen literature, we cultivated a thorough comprehension of the current landscape of geothermal exploration and delineated avenues for subsequent inquiry.

4.1. A Review of Geological Setting and Distribution of Hot Springs in Peninsular Malaysia

Geological surveys are essential for characterizing regions of interest and providing insights into structural features, lithology, and petrography. These surveys extend their observations from the surface into the subsurface, often utilizing borehole data. Additionally, they examine the geochemistry of thermal waters to establish connections with subsurface geothermal sources. Geological data, including rock compositions and prominent fault and fracture networks, play a pivotal role in comprehending the geothermal system. These structural concepts, associated with basement tectonics, are pertinent regardless of whether the geothermal source is situated in a sedimentary or volcanic setting [57].

Peninsular Malaysia, situated at the southernmost extremity of the Asian continent within the Malay Basin, displays a notably elevated surface heat flow, estimated at approximately 33-42 milliwatts per square meter (mW/m^2). The interpretation of this heat flow anomaly attributes its origin to the thinning of the lithosphere during the process of basin formation, as articulated by [58]. Peninsular Malaysia's geological setting is marked by three north-south trending tectonic belts (western, central, and eastern) distinguished by differences in stratigraphy, magmatism, and geological evolution [22, 26, 59, 60]. Numerous authors [11, 12, 15, 16, 41, 42, 63] have observed that the majority of hot springs in the western belt are distributed in the NNW-SSE direction, often found within granitic structures, near granite rocks, or along major faults or shear zones as shown in Figure 3.

Several studies have shed light on the geological factors influencing the presence of thermal springs in Peninsular and East Malaysia. The research conducted by [64] provides insights into the existence of a clearly defined structural control and a potential genetic correlation between these springs and the intrusion of granite, subsequently accompanied by post-magmatic phenomena. Hot springs are primarily located near significant fault lines within the granitoid of the western main range, enabling the rapid infiltration of meteoric water to depths where the rocks generate sufficient warmth for convective upsurges. Notably, many thermal springs are concentrated along main fault lines, as observed by [41]. The geographic distribution of these hot springs aligns in the NNW-SSE direction, corresponding to the primary tectonic trend in the Malayan Peninsula, particularly in areas with large fault zones [42]. A geological study conducted in the Sungai Rengas and Mata Ayer regions by [65] showed that faults and joint zones greatly influence the hydrothermal system in Sungai Rengas, and the hot spring there is thought to be caused by the intrusion temperature of granitoid rocks that date from the Permian to Triassic periods. In contrast, the cold spring in Mata Ayer lacks heat flow from Mesozoic granitoids due to the absence of faults and joints, resulting in a relatively lower ambient temperature in this region than in others. According to [66], the Ulu Slim complex hot spring experiences a force exerted from both the east and west directions. This conclusion was drawn based on a microscopic examination of oriented samples of mylonite and cataclasite. The displacement of the fault resulted in the creation of fractures and fissures within the granite, which afterwards served as conduits for the ingress of water. When this water entered the fractures, the cooling of the granite facilitated a heating process. This elucidates the phenomenon of hot springs. The identification of metasediment xenolith and porphyry quartz inside the granite suggests that it is a granite of high-level origin.

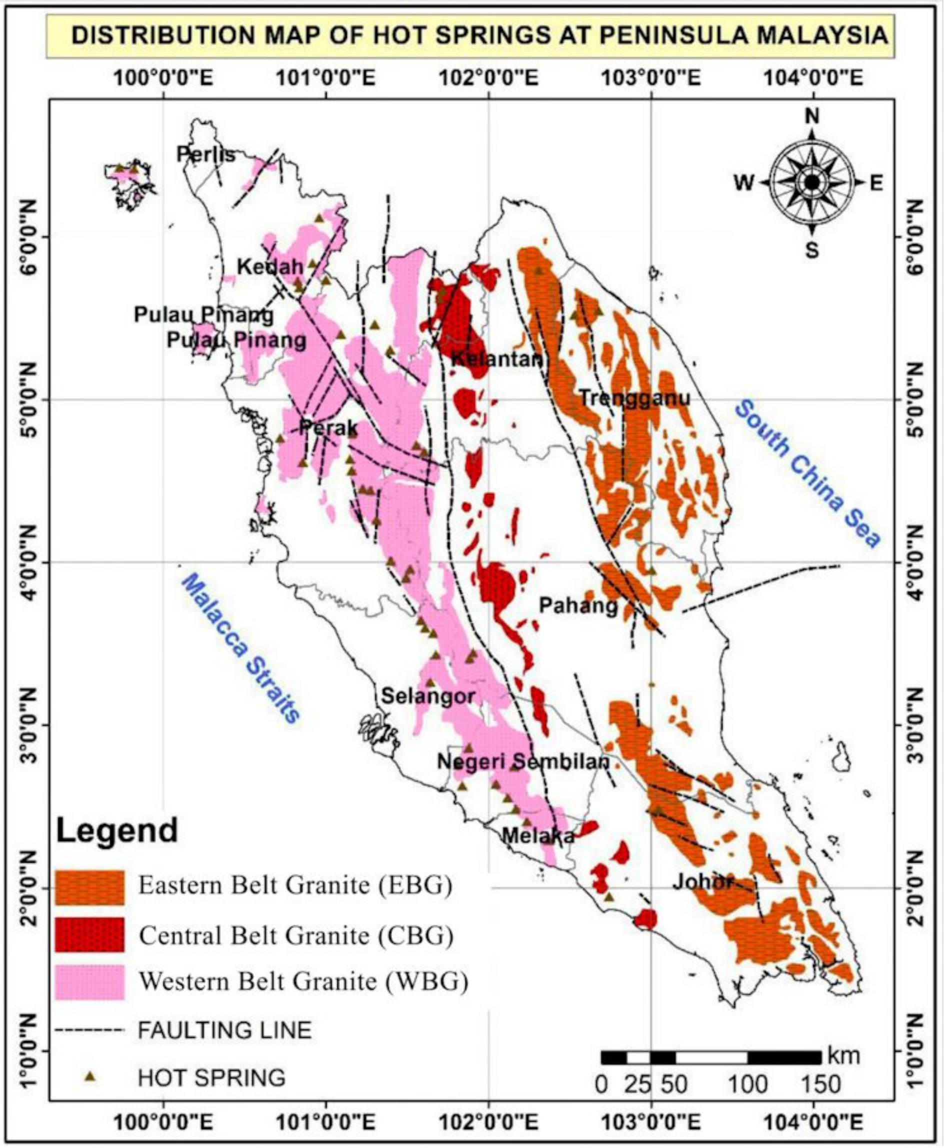


Figure 3. Geological and spatial delineation of geothermal springs based on their locations within the main granite batholith in the Peninsular Malaysia region. Source: [16].

It was observed and verified that a significant number of thermal springs are situated within or near granitic formations, as well as along major fault or shear zones, as noted in previous studies [12]. This pattern is particularly evident in West Malaysia, where the majority of hot springs are concentrated along the western Main Range Granite batholith. There is a prevailing belief that once incorporated into the Earth's crust, granite batholiths continue to emit thermal energy after their solidification. According to [67], it is likely that the residual temperature falls between the range of 700 to 1200°C. A portion of the thermal energy is likely produced by the process of radioactive decay occurring inside the minerals present in these geological formations. In contrast, a limited number of these thermal springs are situated within the vicinity of sedimentary rock and close to the granite formation. The majority of these thermal springs are typically found in low-lying regions, often adjacent to stream channels or emerging along fractures on exposed bedrock surfaces. In rare instances, they may also be observed in marshy areas. [68] investigated a hot spring situated along the Kajang-Semenyih Highway. The study primarily emphasized the geological aspects, geochemical data analysis, spring flow regulation, and the subsequent presentation of results via the use of diagrams and charts. The discharge rate of the spring has a positive correlation with precipitation, suggesting the presence of a hydrological system with limited depth. Additionally, the flow of the hot spring is impacted by the presence of fractures, joints, and the force of gravity. According to [13], the hot springs in question exhibit a range of elevations, with the lowest spring being at an elevation of 3 meters and the highest spring at 420 meters.

In a solitary research effort, comprehensive studies were aimed at evaluating the geoheritage and geotourism potential of Jeli Hot Spring in Jeli, Kelantan. [69] qualitative research involved field surveillance, geological mapping, and rock sampling analysis to create a detailed geological map of the area, with the primary objective of assessing Jeli Hot Spring as a prospective tourism destination and emphasizing its geological characteristics for future tourism development. [70] constructed geological mapping and a seismic refraction survey in the same location to examine surface and subsurface geological conditions and understand the geological structures influencing the formation of the hot spring. The individual research endeavours provided an understanding of the geotourism and geological importance of Jeli Hot Spring.

A study was conducted in the Kinta Valley, Perak, Malaysia, to detect rock deformations and provide an overview of the region's geological structures [71]. In addition, the research explored hot springs to evaluate how the fracture system influences fluid flow, encompassing various levels of investigation, including regional, outcrop, hand specimen, and microscopic scales. Additionally, [63] conducted research by gathering general first-hand information about hot springs through desk exploration and a scientific reconnaissance study, focusing on retrieving data related to surface and sub-surface aquifer temperatures, flow rates, and geochemical analysis. Employing methods such as resistivity surveys and research drills, they gathered information about the hot springs and assessed the depth required for drilling rigs. In addition, they utilized remote sensing techniques to update a comprehensive map of hot spring locations in Malaysia. Through this research, they successfully identified 39 out of 57 hot springs by combining various data sources and conducting 27 site visits.

West Malaysia is home to 40 hot springs, according to earlier studies [12], while JMG (2013) reported 56 hot springs. The occurrence of these hot springs in Peninsular Malaysia is associated with non-volcanic activities. Additionally, geological studies [8, 15] identified and visited another 20 hot springs. The spatial distribution and geological context of these thermal springs suggest their existence along two distinct trends. The west-east trajectory persists from the Ayer Hangat hot springs located on Langkawi Island towards the Kg. Labok hot springs in Machang, Kelantan, and the Kg. La hot springs in Hulu Besut and Terengganu in the eastern region. The north-south trajectory spans from the Kg. Legong hot spring, located in Baling, Kedah, in the northern region, to the Parit Gerisik hot spring, situated in Batu Pahat, Johor, in the southernmost part. Moreover, depended on geological and geochemistry found the existence of hot springs in Peninsular Malaysia as a non-volcanic origin and interpreted all the formation of hot springs in Peninsular Malaysia as a non-volcanic origin also confirmed that most of these hot springs located along the western main granite batholith, as well as hot water formed at the granite-sediment boundary or in sedimentary rocks close to granite rocks, and the main factor of the heat source in Peninsular Malaysia, is the geothermal gradient. Besides, Peninsular Malaysia’s hot springs have an average surface temperature of around 50–80 °C.

In a series of geological investigations, Kelantan's Jeli Hot Spring was thoroughly studied by [72], known for its igneous rocks, including granites and micro-granites. The investigation started by examining aerial photographs to interpret the lineament structure of the Jeli Hot Spring area. Subsequently, a thorough geological mapping was carried out throughout a region spanning 25 square kilometres. The analysis showed that there is an alignment of lineament features, in the North West and South East directions at Jeli Hot Spring with joints being the geological structures. The area displays a variety of features such as hills, plains and rivers with joints found in types of rocks although there are no clear signs of significant tectonic deformation. The orientation of Jeli Hot Spring corresponds to the NNW and SSE directions aligning with the lineament features. Subsequently, [73] carried out a study and chemical analysis to determine the depth of groundwater circulation at the Tok Bok hot spring in Machang, Kelantan to update the geological map of the hot spring region. This research involved collecting rock samples for experimental petrology analysis. As per [74] research findings he proposed a model suggesting that hot springs are commonly found along fault lines and at the boundary, between intrusions and metasediments. Aside from that, [75] conducted a study to identify springs, in Pos Hendrop, Lojing, Gua Musang, Kelantan. By utilizing mapping and a 2D resistivity approach it was concluded that the hot spring is associated with granite rocks.

The improvements in energy research in Malaysia were the focus of a number of research initiatives that were carried out by [16]. Specifically, this entailed revising the map to incorporate a newly discovered hot spring and classifying sixty hot spring locations that were already known to exist within the primary granite batholith, as demonstrated in Table 1. We were able to get insights into the diversity of thermal springs in peninsular Malaysia as well as their spatial distribution thanks to the systematic classification method that was utilized. In continuation of these efforts, [76] carried out a study on the geology, geophysics, and geochemistry of springs located in Peninsular Malaysia in a number of different places. Lineament patterns were analyzed as part of the study, which led to the discovery of critical directions that play a role in the creation of hot springs. The findings of this investigation showed that the direction of the lineaments that influence the formation of hot springs is practically identical for all of the study locations, which are located in the north-south, northwest-southeast, and northeast-southwest directions respectively.

An in-depth analysis of the geological characteristics and water quality of Kelantan's Jeli and Tok Bok hot springs was conducted by [77], offering a deeper exploration into the subject. As part of the research, the map was maintained up to date, hydrological data was compared, and the landscape and structural characteristics of the region were investigated. In addition, a comprehensive analysis of both chemical properties was carried out in order to evaluate the quality of the water. This analysis revealed geological formations from different geological ages in the Jeli hot spring area, such as the Lawar Granite and Tiang Schist formations.

4.2. A Review of Geochemistry Applications in Geothermal Resources in Peninsular Malaysia

Studying systems involves analyzing the fluids, vapours, gases and rocks, in the reservoir from a geochemical perspective. This analysis is crucial for evaluating properties estimating subsurface temperatures identifying water sources and understanding flow patterns within the reservoir. Previous studies have highlighted the importance of analyzing water and gas samples [8, 16, 78, 79]. The compositions of anions and cations can help identify fluids such as alkali chloride, acid sulfate, and bicarbonate [80]. Geochemical methods have become popular for exploring and exploiting resources due to their cost effectiveness compared to methods and drilling procedures. Initial geochemical investigations typically involve on-site measurements like temperature and pH assessments of springs. Samples from nonthermal springs are collected near each other to study correlations between different features. The analysis focuses on elements, like cations, anions, silica (SiO_2) gas composition, isotope composition (of oxidized species) and alkalinity. Geochemical interpretation of thermal springs uses many analytical methods to improve initial analysis. These methods include the Cl-SO_4-HCO_3^- triangular plot, Piper plot diagram [71], Ludwig-Langelier plot [80], Schoeller diagram, Cl-Li-B, Cl-F-B, and dispersed diagrams. Silica (quartz and chalcedony), Na-K, and Na-K-Ca geothermometers measure reservoir temps [16, 79, 83-88]. Geothermal fluid isotopes reveal water sources, rock interactions, and mixing processes [84, 89, 90].

The initial investigations of geothermal springs in Malaysia were conducted in Selangor and Melaka states by [91], who collected samples to analyze the chemical composition of hot water and gaseous emissions from thermal springs. However, geothermal exploration for electricity generation in Peninsular Malaysia faced limitations until 1979. [11] primarily focused on geothermometric evaluations of hot springs in Perak and Kedah, using silica tests. Results revealed thirteen locations with promising characteristics, including temperatures ranging from 100ºC to 166ºC. Furthermore, [64] conducted a preliminary study on Peninsula Malaysia's thermal springs, assessing their potential applications by evaluating flow rate and quality. The research examined the viability of utilising hot spring water as mineral water by comparing its quality to commercial mineral water from France, Indonesia, Scotland, and Malaysia. In addition, [66] studied the Ulu Slim hot spring, which displayed a temperature of 90ºC with a pH of 9.4 and an H_2S odor. Using the Na-K-Ca geothermometer method, the estimated temperature ranged from 145ºC to 150ºC, suggesting the heat source was likely related to the penetration of a granite body, with meteoric water as the likely source.

Table 1. shows the classification of hot springs based on their location in the Main Range Granite Batholith Peninsular Malaysia [16].

No.	Granite Group	Hot spring name	State
1.	Eastern belt	Tok Bok, Machang	Kelantan
2.		Kampung La	Terengganu
3.		Sungai Jin	Pahang
4.		Labis	Johor
5.	Central Belt	Batu 9	Kelantan
6.		Pergau	Kelantan
7.		Sg Belimbing, Jeli	Kelantan
8.		Sungai Gersik, Batu Pahat	Johor
9.	Western Belt	Tanjung Didih	Langkawi
10.		Ayer Hangat	Langkawi
11.		Selat Panchor	Langkawi
12.		Ulu Muda	Kedah
13.		Ulu Legong, Baling	Kedah
14.		Sira Ko, Baling	Kedah
15.		Kampung Tas	Kedah
16.		Kampung Sira	Kedah
17.		Pengkalan Hulu	Perak
18.		Kampung Air Panas, Gerik	Perak
19.		Kampung Temor	Perak
20.		Sg Denak	Perak
21.		Kubu Legap	Perak
22.		Ulu Kuang	Perak
23.		Trong	Perak
24.		Manong	Perak
25.		The Banjaran	Perak
26.		Lubuk Timah	Perak
27.		Ulu Geroh	Perak
28.		Ulu Kampar Estate, Gopeng	Perak
29.		Kuala Who	Perak
30.		Sungai Klah, Sungkai	Perak
31.		Pos Gesau	Perak
32.		Pos Bersih	Perak
33.		Ulu Slim	Perak
34.		Lojing Complex	Kelantan
35.		HS 1	Kelantan
36.		HS 2	Kelantan
37.		HS 3	Kelantan
38.		HS 4	Kelantan
39.		HS 5	Kelantan
40.		Kalumpang	Selangor
41.		Kerling	Selangor
42.		Kuala Kubu Baru	Selangor
43.		Hulu Tamu, Batang Kali	Selangor
44.		Ulu Kalong	Selangor
45.		Selayang	Selangor
46.		Batu 16 Dusun Tua	Selangor
47.		Ikbn Dusun Tua	Selangor
48.		Sungai Serai	Selangor
49.		Semenyih	Selangor
50.		Setapak	Kuala Lumpur
51.		Jalan Ayer Hijau	Kuala Lumpur
52.		Bentong	Pahang
53.		Ladang Kombok, Mantin	Negeri Sembilan
54.		Sime Darby Plantation, Labu	Negeri Sembilan
55.		Wet World Resort, Pedas	Negeri Sembilan
56.		Ulu Bendul	Negeri Sembilan
57.		Kampung Lada	Negeri Sembilan
58.		Cherana Putih	Melaka
59.		Gadek	Melaka
60.		Air Panas Bembang, Jasin	Melaka

A comprehensive investigation of forty hot springs located on Peninsular Malaysia was conducted in different studies across various years [12, 92, 93]. These investigations aimed to analyze geological attributes, temperature fluctuations, flow rates, and water quality. They also assessed the potential for developing these hot springs as tourist attractions. While the studies concentrated on established locations, they did not explore the potential of nearby, less accessible sites. The research identified nine hot springs with substantial development potential, fourteen with moderate potential, and seventeen with low or minimal potential for development.

An in-depth examination of the hot springs and cold water along the Kajang-Semenyih Highway was conducted by [68], revealing that water is influenced by granite weathering, ion exchange, and rock-water interactions. These findings emphasize the need to ensure that water meets safety requirements set by health authorities for drinking. Another investigation by [13] explored the chemical and physical properties of fluid data from various hot springs across Peninsular Malaysia, after [64]. This data, collected by the Geological Survey Department of Malaysia, led to an evaluation of hot spring water quality and its potential economic uses. Notably, in Perak, only two hot springs in Sungai Siput Selatan met stringent criteria for both drinking and mineral water. However, three or four additional hot springs show potential for future development, despite their average flow rate of 2.03 liters per second. The study also found hydrogen sulfide odors in 17 thermal springs, with strong smells in Trong, Kampung Legong Baling, Pedas, and Kampung Sungai Bersih Ulu Slim. Additionally, [94] classified Peninsula Malaysia's geothermal resources as moderately warm (100°C to 200°C), ideal for single-phase geothermal energy sources, with an estimated capacity of 10–40 MWe, recommending a binary cycle power plant.

The suitability of spring water in Perak for drinking, with a focus on safety and quality, was studied by [95]. Meanwhile, [96] explored the potential of Perak's springs for health tourism, examining their benefits and challenges in promoting regional growth. Additionally, [97] evaluated chemical and radionuclide compositions in spring water across 43 locations with 67 sources in Peninsular Malaysia. Variations in chemical levels were linked to rock formations, with uranium and thorium traced to granite, while other ions came from various rocks. Most hot springs were categorized as type III (Na-HCO_3), though many did not meet balneotherapy or drinking safety standards. Notably, Air Hangat Langkawi, Gersik, and Air Panas Terong (type II, Na-Cl) were deemed suitable for balneotherapy. Furthermore, [98] focused on the geoheritage and water quality of Pos Hendrop hot spring in Kelantan, highlighting its potential as a significant geoheritage site.

A variety of geothermometric techniques were employed to ascertain reservoir temperatures in a comprehensive evaluation of geothermal resources within Peninsular Malaysia. The temperature ranges of T-quartz (105.3–154.2°C), T-Na/K (127.3–199.7°C), and T-Na-K–Ca (115–208°C) are illustrated in Figure 4, respectively, according to references [8, 99]. These findings furnish an extensive understanding of the temperature spectrum exhibited by geothermal reservoirs, underscoring its potential for geothermal energy generation. Additionally, the study offers significant insights into the geochemical and hydrochemical characteristics of hot springs in West Malaysia, indicating the likelihood of water mixing between thermal and cooler sources in close proximity to the surface.

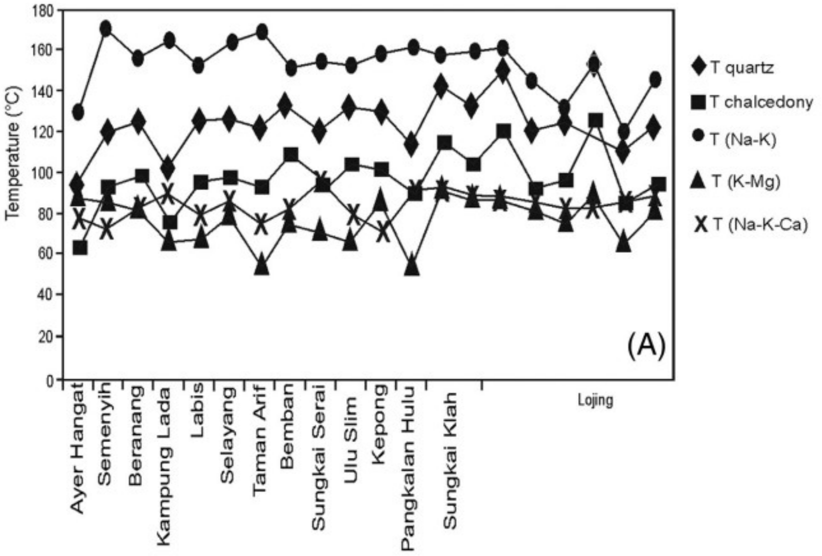


Figure 4. Subsurface temperature measurements of hot springs from various sites in West Malaysia, highlighting differences among different geothermometer methods [8].

Recent research has explored the geothermal potential at Ulu Slim spring in West Malaysia. An extensive study by [100] involved collecting thirteen water samples from the hot springs, with temperatures reaching up to approximately 104°C. The analysis utilized the Cl-SO_4-HCO_3 triangular plot (Figure 5a) and Piper's diagram (Figure 5b), revealing a consistent Na-K-HCO_3 composition across the samples, suggesting a common meteoric origin. Additionally, the Cl-Li-B Ternary Diagram (Figure 6a) showed that Ulu Rasau Hot Springs samples were linked to basaltic rocks, while Ulu Slim samples exhibited affinities with rhyolite. The Cl-F-B Ternary Diagram (Figure 6b) provided further insights into the geochemical characteristics. Reservoir temperatures, estimated using silica and cation geothermometers, ranged from 104°C to 135°C. Most Ulu Slim samples clustered in the immature water field near the $Mg^1/_2$ corner, possibly due to mixing with partially equilibrated geothermal water, cold shallow groundwater, or meteoric water. This complicates their use in geothermal reservoir evaluation and raises questions about the reliability of cationic geothermometers. However, some samples indicated direct feeding from the reservoir, with temperatures between 120°C and 190°C and reduced Mg and K content. Overall, all samples fell within the Na-HCO_3 water category, potentially indicating gas-enriched meteoric fluids.

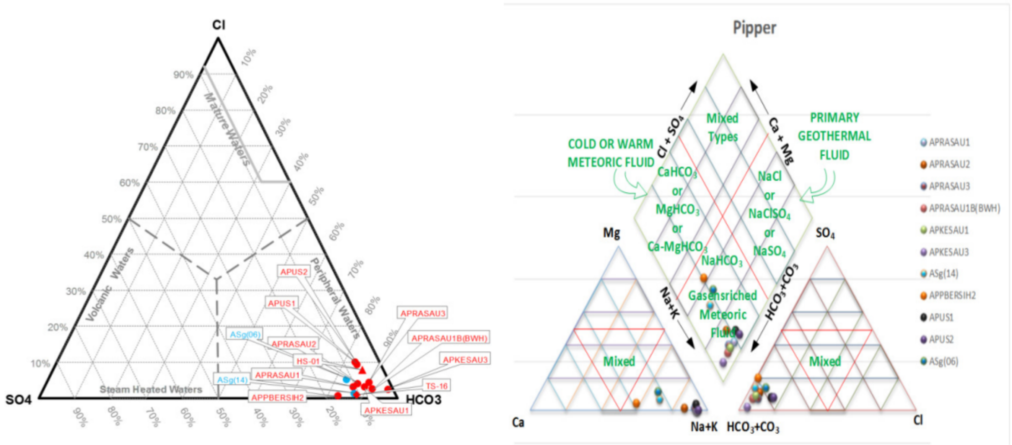


Figure 5. displays the water composition from Ulu Slim. Panel (a) presents a Cl-SO_4-HCO_3 triangle plot that illustrates the chemistry of the samples. Panel (b) shows a Piper diagram that classifies the different kinds of water [100].

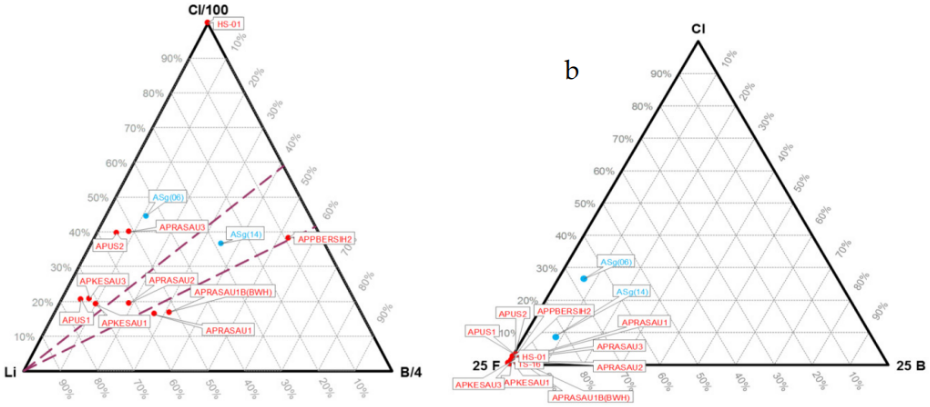


Figure 6. shows the Ulu Slim ternary diagrams: (a) displays rock type affinities in the Cl-Li-B diagram, while (b) highlights concentrations in the Cl-F-B diagram [100].

Recent studies have applied environmental isotope techniques to enhance our understanding of geothermal systems by [78]. One such study at Ulu Slim used isotopes such as Oxygen-18 (^{18}O), Deuterium (^{2}H), and Tritium (^{3}H) alongside hydro-geochemical methods to identify recharge zones and trace the origin of water sources. The findings revealed that tritium (TU) values in hot springs closely resemble those in groundwater, indicating a shared origin that predates surface water. The stable isotope composition of the hot springs showed significant depletion compared to surface water and groundwater, suggesting recharge from distant, higher-altitude regions within the geothermal system. This pattern of isotopic depletion is illustrated in Figure 7. Furthermore, the amounts of bicarbonate and tritium provide further information on the distinct features of the hot springs. The lack of mixing between surface water and spring water was verified by a trilinear Piper diagram, even with fluctuations in salt content. The knowledge of the region's hydrogeochemical processes and geothermal potential has improved as a result of these integrated investigations.

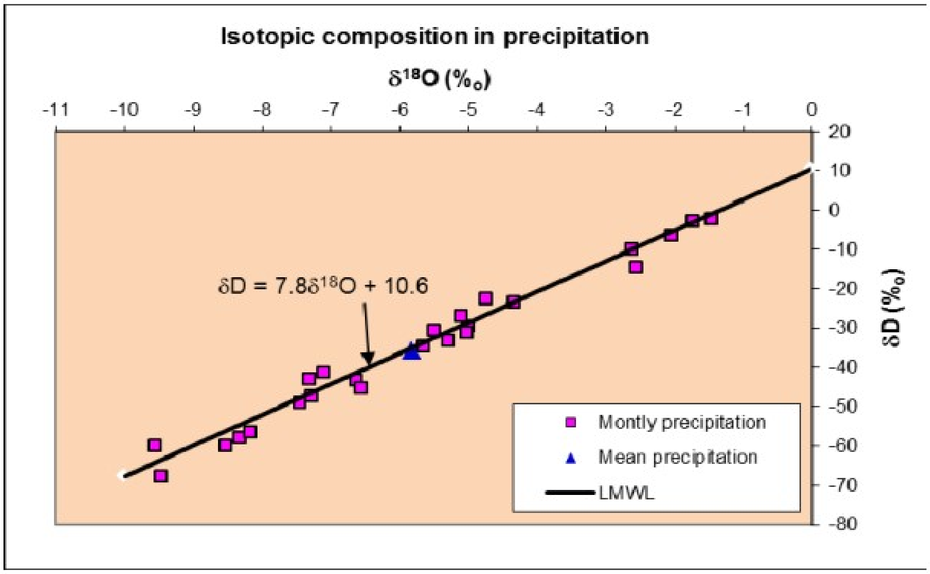
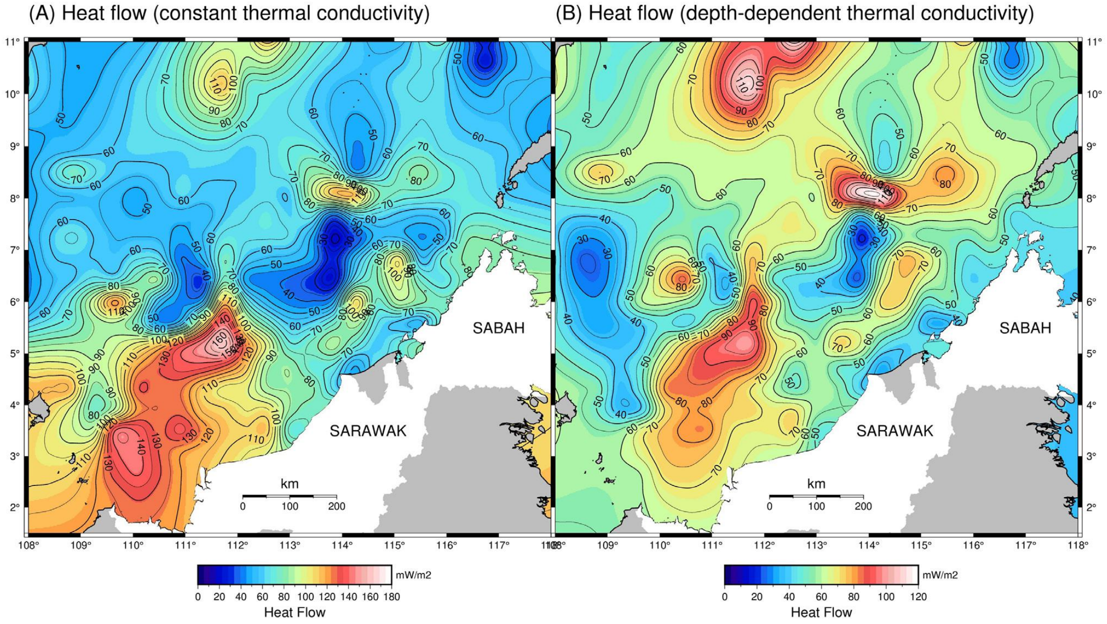


Figure 7. Determination of the Local Meteoric Water Line (LMWL) for the analysis of isotopic information and the discernment of recharge origins in geothermal waters [78].

Geological map updates at Tok Bok Spring in Machang, Kelantan, by [73], showed groundwater circulation depths from 0.079 to 2.16 kilometres, with river water influencing water composition, silica, chloride, and total dissolved solids levels, and all samples meeting drinking water standards for cations and anions. A thorough investigation into the geochemistry and geothermometry of springs by [16] showed that decreasing sulfate concentrations correlated with magma cooling and temperature changes. The high presence of potassium sodium bicarbonate in the springs suggested geological homogeneity and the impact of hydrochemical processes. This research explored geothermal energy potential at Ulu Slim, Sungai Klah, Lojing Complex, Dusun Tua, and Bembang hot springs, with temperatures ranging from 93°C to 154°C. Studies in the Hulu Langat region of Selangor expanded knowledge of geology, water quality, and geotourism potential. For example, the geology and water quality at Sg. Serai Hot Spring were reviewed, while the geotourism prospects of the area were emphasized, highlighting tourism appeal and health benefits based on physical and chemical analysis [101, 102]. Further investigations into thermal springs across various Malaysian sites, including Lojing, Tok Bok, Sungai Jin, and Labis hot springs, revealed temperatures ranging from 85°C to 231°C using quartz geothermometry, and 56°C to 207°C with chalcedony geothermometry, indicating significant thermal energy in the geological system [76]. In addition, geochemical insights identified Jeli hot spring water as magnesium bicarbonate type, while Tok Bok hot spring water was categorized as calcium chloride type using the Piper Trilinear Diagram [77].

Attempting a numerical assessment, process design, and techno-economic analysis of harnessing geothermal energy from decommissioned oil wells in Malaysia, [103] addressed the country's renewable energy requirements. The findings suggest that the Levelized Cost of Electricity (LCOE) for the Organic Rankine Cycle (ORC) system in Malaysian wells is nearly twice as high as that of traditional geothermal technologies, mainly due to the comparatively lower temperature profile. To decrease the LCOE, having a minimum of four nearby abandoned wells is necessary.

An updated analysis of geothermal gradients and heat flow in offshore Malaysia incorporates recent data from the oil and gas industry, including bottom-hole temperature (BHT) measurements and seabed heat flow probe data [104]. This research enhances our understanding of geothermal characteristics across various offshore basins and their tectonic settings. The study reveals that the Malay Basin exhibits relatively high geothermal gradients, averaging 47 °C/km, with even higher gradients in the basin's center attributed to crustal thinning due to extension. In contrast, the Sarawak Basin and Sabah Shelf show lower gradients due to their distinct underlying tectonic conditions. Additionally, the paper establishes empirical relationships between sediment thermal conductivity and burial depth, offering valuable insights into thermal conductivity models for different offshore regions. It provides average heat flow data for the Malay Basin, Sarawak Shelf, Sabah Shelf, and deeper areas such as the Sabah Trough and North Luconia, contributing significantly to our understanding of the thermal regimes and geological processes in these offshore areas. The study does not specifically mention heat flow from West Malaysia, focusing instead on updating geothermal gradient and heat flow maps of offshore Sarawak and Sabah regions, as illustrated in Figure 8.


(A) Heat flow (constant thermal conductivity)

(B) Heat flow (depth-dependent thermal conductivity)

Figure 8. Heat flow maps for the offshore Sarawak and Sabah regions. (A) Map using a constant bulk thermal conductivity. (B) Map using a variable, depth-dependent bulk sediment thermal conductivity model [104].

A study was conducted in the Jasin region to investigate the necessity of using techniques such as gravity and geochemistry methods to assess samples for their properties, origins, and adherence to quality standards set by organizations like the World Health Organization (WHO) and the Ministry of Health (MOH) [105]. This investigation followed the recommendation [14].

Hot spring potential at Ulu Slim, Perak, Malaysia, was assessed by [106]. The study involved examining preexisting data, including surface temperature, flow rate, geothermal gradients, geothermometer readings, hydraulic head variations, and fault and fracture distribution. Thermodynamic model computations revealed a heat source depth of 1,250–3,140 meters, aperture sizes of 0.36–0.77 millimeters (0.55 mm), and an outflow temperature of 92°C. A dry rock model with injector wells suggested an initial electric power potential of 700–1,600 kWe, compared to 200 kWe from surface outflow. However, narrow fracture pathways led to a rapid decline in saline temperature and reduced energy production over 30 years, limiting the well's average power potential to 200 kWe. The evaluation concluded that utilizing heat from springs like Kampung Ulu Slim might not be optimal for generating electric power and recommended exploring alternative options, such as hot dry rock systems. The research also highlighted the need for improved imaging of fault and fracture pathways to prevent cooling and ensure effective heat retrieval, addressing the current lack of knowledge about fracture shape and arrangement.

4.3. A Review of Geophysics Applications in Geothermal Resources in Peninsular Malaysia

Geophysical techniques, an aspect of exploring resources, alongside geology and thermal fluid chemistry involve a range of methods each with its own strengths and limitations [3, 107, 108]. The effective methods, known as approaches, focus on features directly influenced by hydrothermal activity. These include well logs, self-measurements, geoelectrical techniques, and thermal procedures. On the other hand, indirect or structural approaches prioritize examining the properties of the host rock such as magnetic properties, density, and seismic velocity. Direct methods offer insights into characteristics that are impacted by geothermal activity while indirect techniques provide details on geological aspects that could reveal significant structures or geological formations within the geothermal system.

In the 20th and early 21st centuries, extensive research was conducted across Peninsular Malaysia to study hot springs and their geothermal potential. Various researchers and organizations, including the Department of Minerals and Geosciences Malaysia, carried out geological, geochemical, and geophysical assessments [108]. Pioneering work utilizing the Time Domain Electromagnetic (TEM) technique was initiated by [110], leading to significant advancements in understanding the underlying rock formations and fault systems associated with hot springs. Studies were conducted in numerous locations, including Selangor, Kelantan, Terengganu, and Perak, employing a range of methods such as gravity surveys, seismic refraction, and electrical resistivity [111, 116-119]. These investigations revealed important insights into the geological structures, fracture systems, and thermal water pathways associated with hot springs. Subsequent research has expanded the scope of geophysical studies, providing a more comprehensive understanding of Malaysia's hot springs and geothermal resources, including their structural characteristics and potential for tourism and energy development [70, 112-115, 121].

In a significant advancement in geothermal system research in Peninsular Malaysia, [100] conducted a comprehensive Magnetotellurics (MT) survey in the Ulu Slim area, covering 127 km². The survey also incorporated time-domain electromagnetic (TDEM) surveys and gravity assessments to analyze the region's geological structure. The MT results provided valuable insights into the geothermal potential of the area. The resistivity data revealed two key zones with intermediate resistivity: a southern zone extending from northwest to east, and a northern zone with resistivity values exceeding 1 ohm·m, which may indicate geothermal reservoirs or heat sources (Figure 9). Discontinuities in resistivity associated with the N-S fault were observed down to a depth of -500 m, beyond which high resistivity values dominated. Additionally, a low-to-intermediate resistivity zone in the southwestern region, extending to considerable depths, suggested the presence of a substantial lithological boundary between metasediments and granite.

Further analysis using 2D MT inversion revealed shallow low-resistivity layers (< 15 ohm·m), likely corresponding to sediments or clay, and deeper low-to-intermediate resistivity zones (15 to 100 ohm·m), potentially indicating geothermal reservoirs at depths up to -750 m. In southern sections as illustreted in Figure 10, high resistivity pipe-like structures (100–500 ohm·m) were identified, possibly representing heat sources surrounded by granite formations.

3D MT inversion provided a more detailed resistivity structure based on depth. Shallow depths (0 to 1000 m) displayed heterogeneous resistivity distributions, with low-resistivity gaps in northern sections like Lines E and I, possibly related to geological features illustrated in figure 11. At greater depths, the resistivity structure was dominated by high resistivity (> 1000 ohm·m), though certain areas showed low resistivity zones (100–200 ohm·m) forming pipe-like structures extending down to 5000 m, which could indicate deeper geothermal reservoirs. These findings aligned with the 2D MT results, reinforcing the interpretation of these zones as potential geothermal systems.

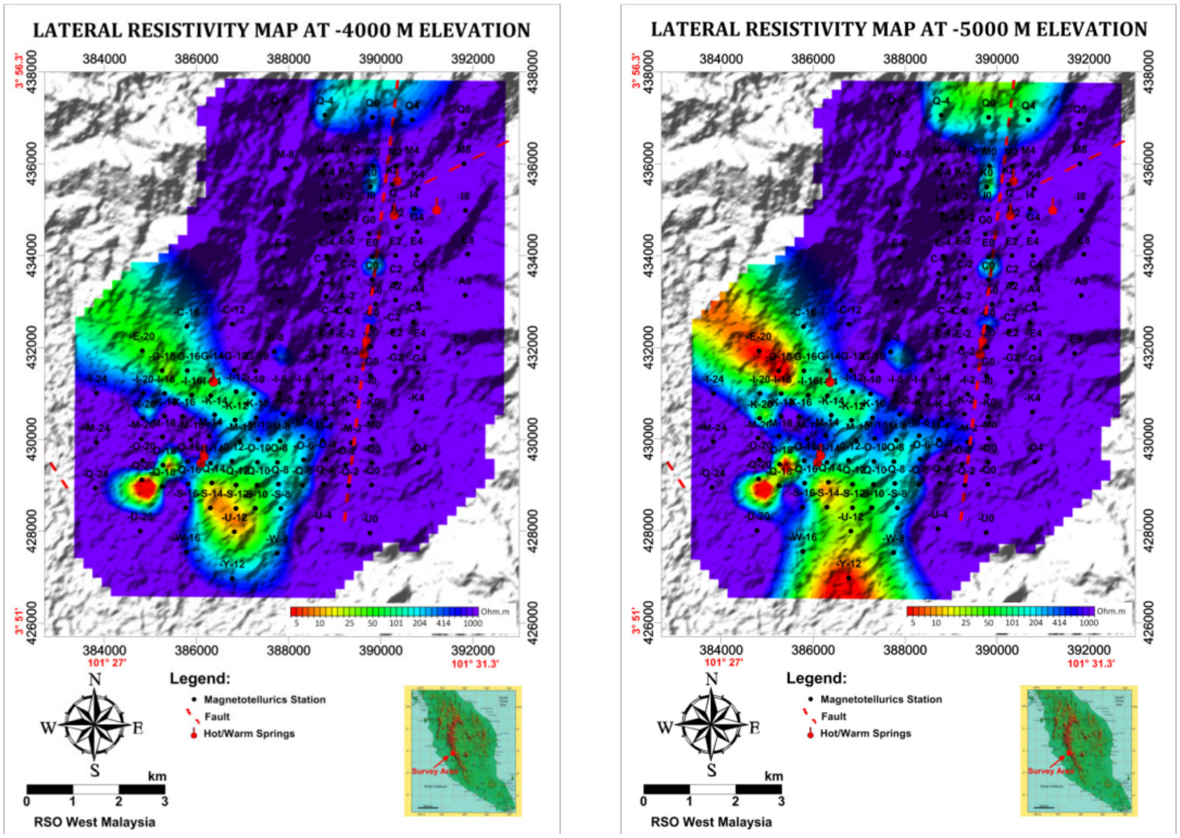


Figure 9. shows the lateral resistivity distribution at depths greater than 500 meters below sea level. The profile reveals deep subsurface resistivity fluctuations, which are important for assessing geothermal potential [100].

A re-examination of geochemical data provided a more comprehensive understanding of the Ulu Slim geothermal system, highlighting a convective geothermal environment in low-porosity, fracture-permeability settings with high to normal regional heat flow. The research estimated the potential for electricity generation of up to 148 megawatts (MWe) across various reservoirs. The report recommended drilling two wells in areas with favorable resistivity values and emphasized the need for additional data collection, including MT, gravity, magnetic, geochemical, and geological information. Reducing station spacing for a more detailed analysis was advised before advancing to the next phase of the project.

The composition of the granite bedrock and its structural effects at the Jeli hot spring location were explored using a 2D resistivity technique, as detailed by [122]. Significant advancements in our understanding of the Ayer Hangat spring and the Wet World Hot Spring Complex for future development were achieved through seismic reflection and MASW analysis, as reported by [123, 124]. These studies provided valuable insights into these features. In contrast, [75] revealed that the energy sources in the subsurface of the Pos Hendrop hot spring region in Kelantan were generally located about fifteen meters below ground using 2D resistivity inversion models.

Integration techniques were extensively employed in comprehensive hot spring analysis across peninsular Malaysia, as demonstrated by [16]. This research utilized various methods including geoelectrical resistivity, induced polarization (IP), transient electromagnet (TEM), gravity, seismic, and ground penetration radar (GPR) to develop a theoretical framework for hot springs, successfully constructing shallow models in four locations. The study identified Ulu Slim, Sungai Klah, Sungkai, Loging Complex, Trong, Taiping, and Dusun Tua, Hulu Langat as top sites for future geothermal energy development, recommending prioritization and increased investment in exploration to depths exceeding 5 km. In a separate study, [125] focused on the Jasin hot springs using resistivity and IP methods, revealing subsurface resistivity values from 1 ohm-m to 5000 ohm-m as illustrated in Figure 12 which was interpretated as hot sprig potential. A subsequent drilling project in 2018 by Water Jaya Enterprise reached 102.0 metres, uncovering a hot spring with temperatures increasing from 40°C at 50.0 metres to 47°C at 102.0 metres depth. The researchers suggested that additional methods, particularly gravity surveys, could further strengthen these findings and aid in the development of the Jasin hot spring site.

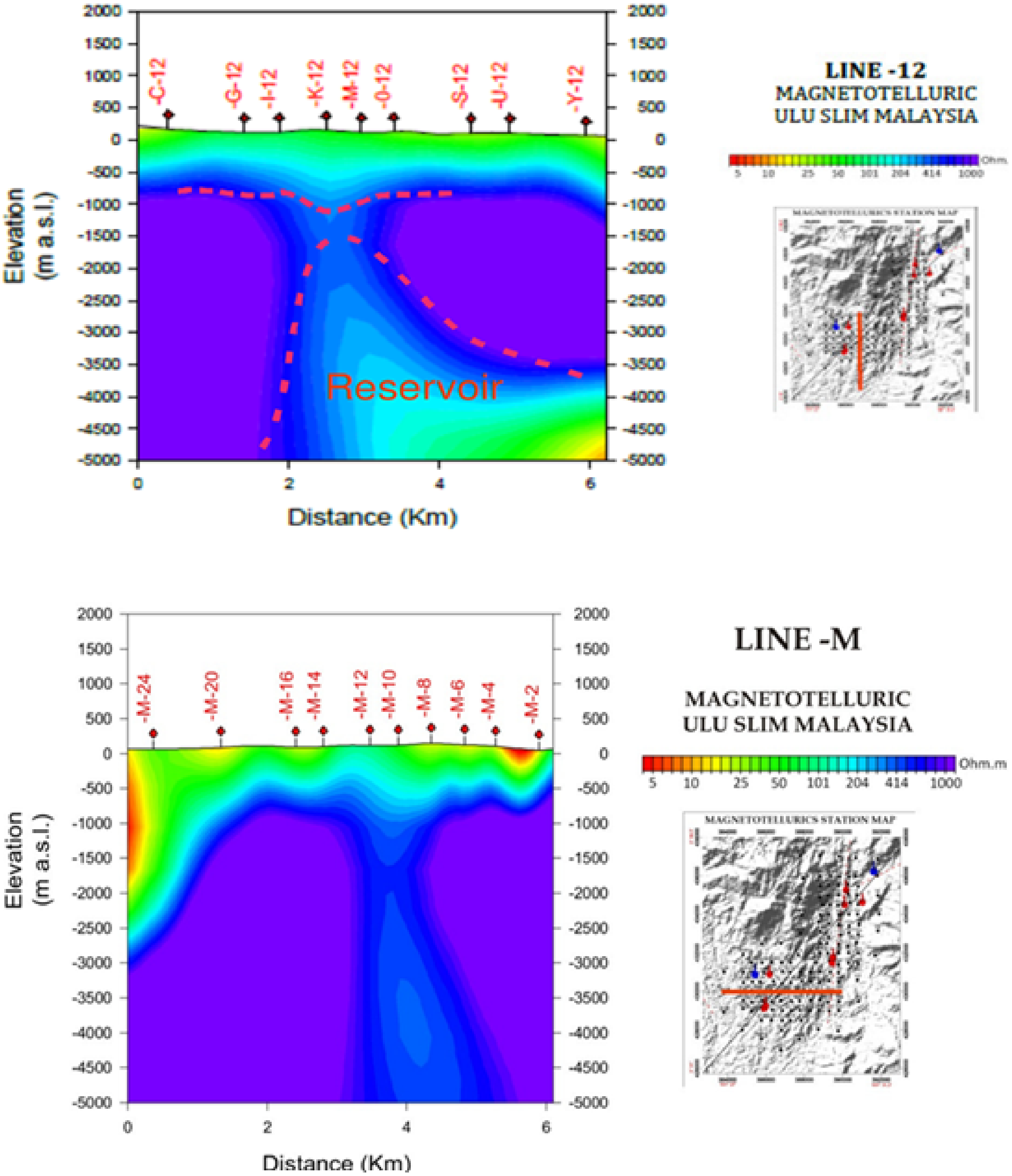


Figure 10. depicts the 2 Magnetotelluric (MT) inversion results by showcasing shallower layers with low resistivity levels and deeper sections that could possibly indicate geothermal reservoirs along with pipe like structures of high resistivity observed in the southern region pointing towards heat sources, from granite formations [100].

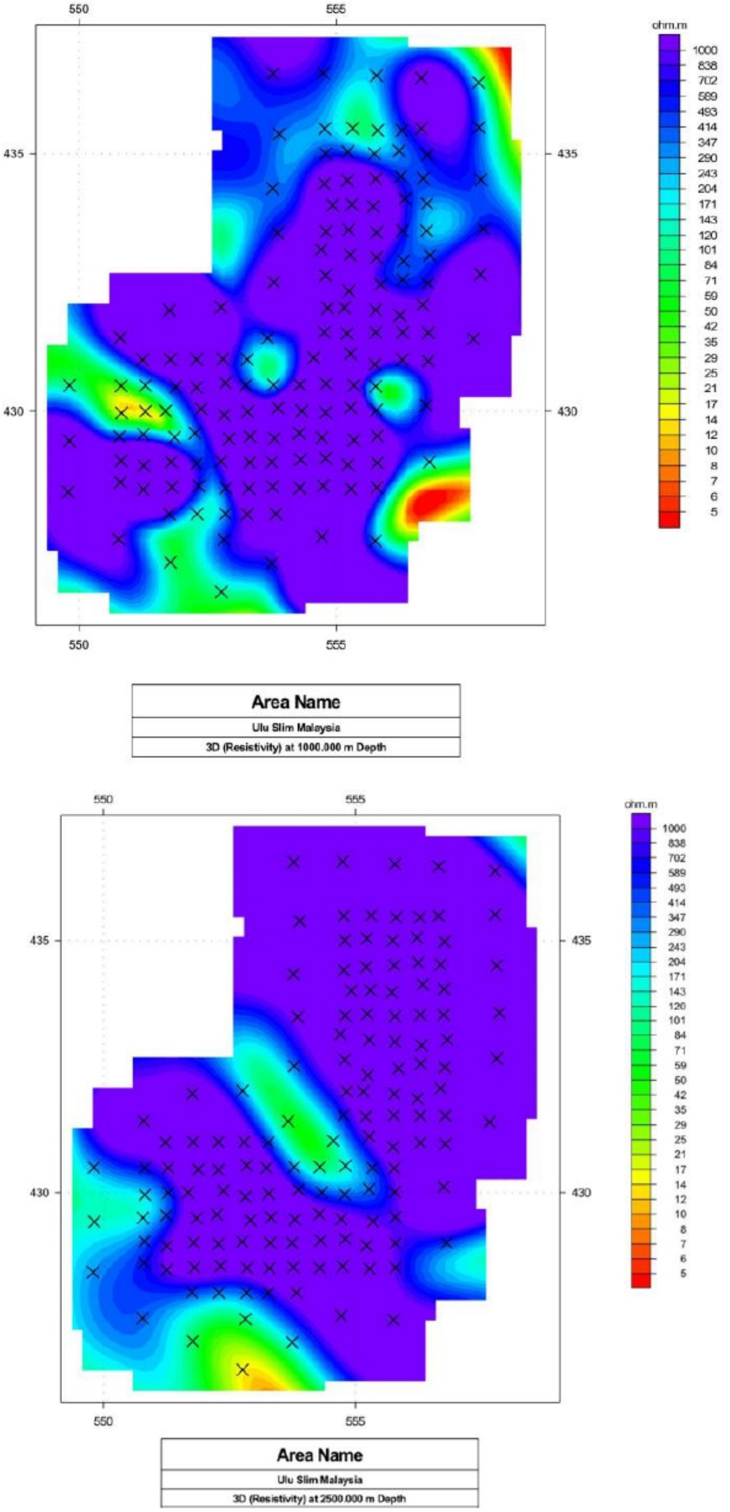


Figure 11. 3D MT inversion illustrating detailed resistivity structures, with shallow heterogeneous resistivity distributions and deeper low-resistivity pipe-like formations extending to 2500 m, potentially indicating deeper geothermal reservoirs, consistent with 2D MT findings [100].

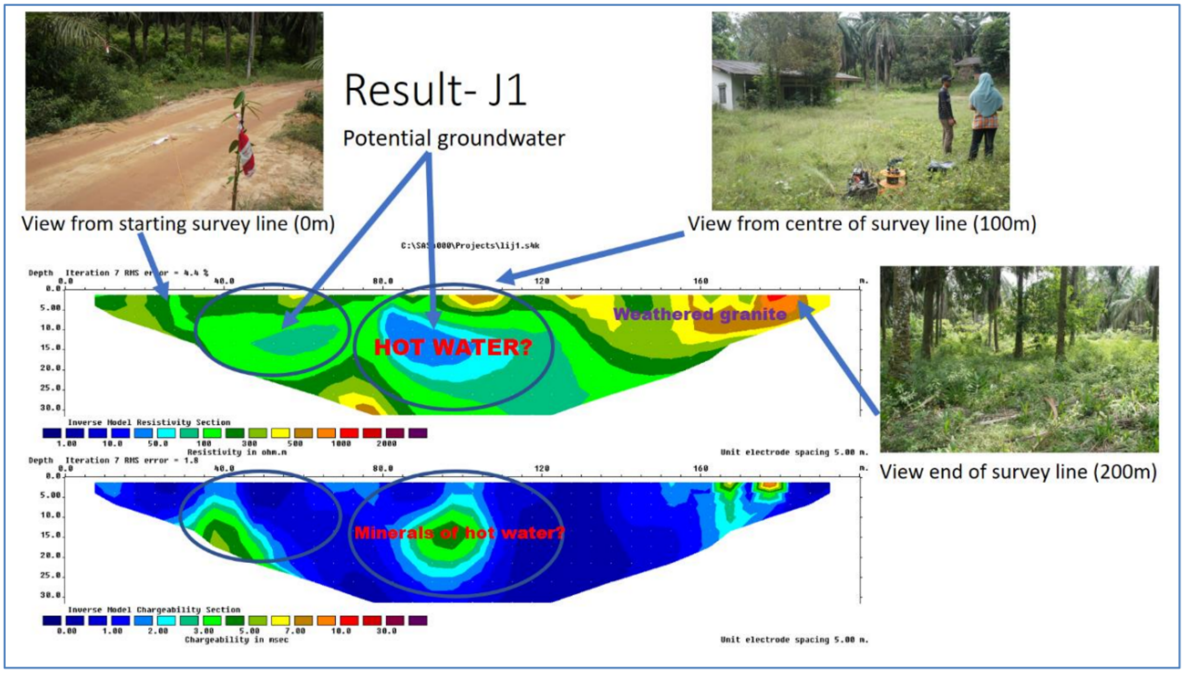


Figure 12. Resistivity and IP study of the Jasin hot springs showed low-resistivity zones indicating potential hot spring locations. Successful drilling encountered the hot spring at depths of 50.0 to 102.0 meters, with temperatures ranging from 40°C to 47°C [125].

In early 2019, there was a notable surge in interest and diverse applications of geophysical methods across Malaysia to deepen our understanding of hot springs and geothermal potential. Researchers employed a variety of techniques in different regions of the country, demonstrating the growing complexity and scope of these studies. For example, [126] used gravity and magnetic methods at Sungai Klah to identify structural trends influencing hot spring aquifers. At Gadek Hot Spring, [127] applied resistivity and induced polarization (IP) studies to locate hot water sources at depths between 130 and 280 meters. Similarly, [128] utilized resistivity-IP and magnetic methods at Sg. Ber field to visualize fault systems, linking high magnetic values (above 1.934 nT) and low resistivity to fractures conducive to thermal spring formation. In the Ulu Slim area, [129] employed seismic refraction and Multi-Channel Analysis of Surface Waves (MASW) to explore the spring structure, identifying three distinct strata with a depth penetration of 15-40 meters. Additionally, a comprehensive study [76] across various Malaysian locations integrated geophysical, geological, and geochemical methods to reveal relationships between hot spring sites and basic-granite formations, confirm their non-volcanic nature, and identify lineaments through gravity surveys and resistivity-IP profiles.

A recent investigation assessed the geothermal and mineral potential of West Malaysia by analyzing the Earth Magnetic Anomaly Grid 2 Version 3 (EMAG2-V3) alongside Digital Elevation Model (DEM) data. The research highlighted the considerable role of faults in determining the area's resources [43]. The analysis of magnetic anomalies and DEM data, illustrated in Figures 13A and 14B, reveals significant magnetic anomalies oriented in NW-SE, NWW-SEE, N-S, and E-W directions. These anomalies indicate the existence of substantial geological structures that may harbor geothermal and mineral resources. The depth of basement structures ranges from 1.0 to 20.0 km, averaging around 5.0 km, which signifies a decrease in sedimentary cover. Key fault zones include the Bentong-Raub Suture Zone and the Lebir Fault Zone. The Bentong-Raub Suture Zone is a prominent north-south fault associated with gold deposits and considerable lateral displacement. Conversely, the Lebir Fault Zone, which defines the eastern limit of the Central Belt, is a crucial component in the local geology. Nevertheless, it presents challenges for magnetic study due to being obscured by mudstone and sandstone layers. The primary magnetic faults, trending northwest-southeast, correspond with hot springs and intersect minor normal faults. These faults are thought to act as conduits for the flow of geothermal and mineral fluids. The findings correspond with the occurrence of S-type granites that intruded between 251-254 Ma. These granites are noted for their narrow thermal aureoles and limited deformation, aside from fault-related cataclasis. There are signs of smaller faults trending northeast to southwest, likely linked to concealed regions with geothermal activity and precious mineral deposits, potentially including gold.

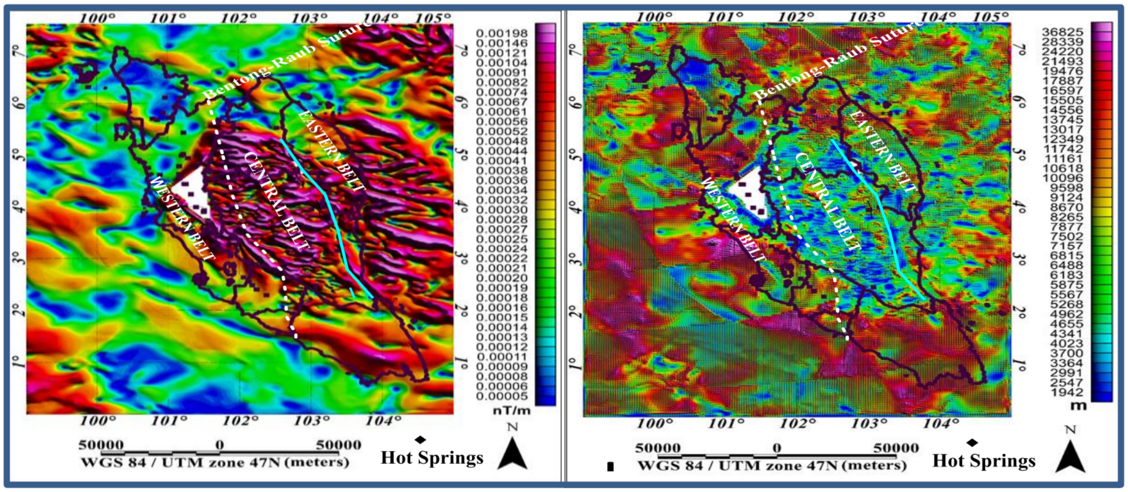


Figure 13. (a). THD map revealing the predominant magnetic lineaments in NW-SE and E-W of the Peninsular Malaysia. (b) Depths map obtained from the ratio of Analytic Signal map of magnetic data to that of the first vertical derivative of the Analytic signal using structural index of 1 [43].

The study finds significant correlations between AS and ED depth measurements, revealing previously neglected areas with both significant and minimal depths. Figure 14 shows how geophysical anomalies match the geological framework, revealing the area's geothermal and mineral potential. This emphasises the need for more research on mineralisation, gold extraction, and industrial and tourism advancement.

In the investigation carried out by [105], gravity surveys were conducted in the Jasin area as well, where the interpretation of Bouguer anomalies provided valuable insights into the subsurface geological structure of the Jasin hot spring area. This analysis led to identifying two promising geothermal potentials that could be exploited in the future. However, further investigation is warranted, specifically employing magnetotelluric methods to penetrate the deep subsurface and gain a comprehensive understanding of the identified geothermal resources.

The subsurface depth of magnetic sources (DBMS) located beneath the Malay Peninsula and adjacent areas was analyzed by [130] employing a de-fractal approach, which yielded depth estimations ranging from 7.3 to 49.3 kilometers, with a mean depth of 21.4 kilometers. Importantly, shallow DBMS measurements of approximately 7 kilometers were detected in the western Malay Peninsula, indicating considerable geothermal potential, especially in locales characterized by hot springs. Conversely, Sumatra Island presented the most profound DBMS, attaining depths of 49 kilometers. The research also suggested that the DBMS within the Malay Peninsula is typically less deep than the Mohorovičić Discontinuity (Moho), inferring that the Curie surface acts more as a thermal boundary layer rather than an indicator of variations in mineral composition (Figure 17). Moreover, a heat flow map generated from DBMS information displayed values ranging from 45 to 175 mW/m², with an average of 80 mW/m², signifying heightened geothermal activity in regions with thermal springs (Figure 15A). Additionally, a geothermal gradient map illustrated gradients from 12 to 79 °C/km, averaging at 31 °C/km, with elevated geothermal gradients recorded in western Peninsular Malaysia, corresponding to the shallower DBMS values in these areas (Figure 15B). These results imply that the crust beneath the western Malay Peninsula exhibits a relatively stable character compared to other regions, as evidenced by deeper Moho depths and consistent DBMS measurements.

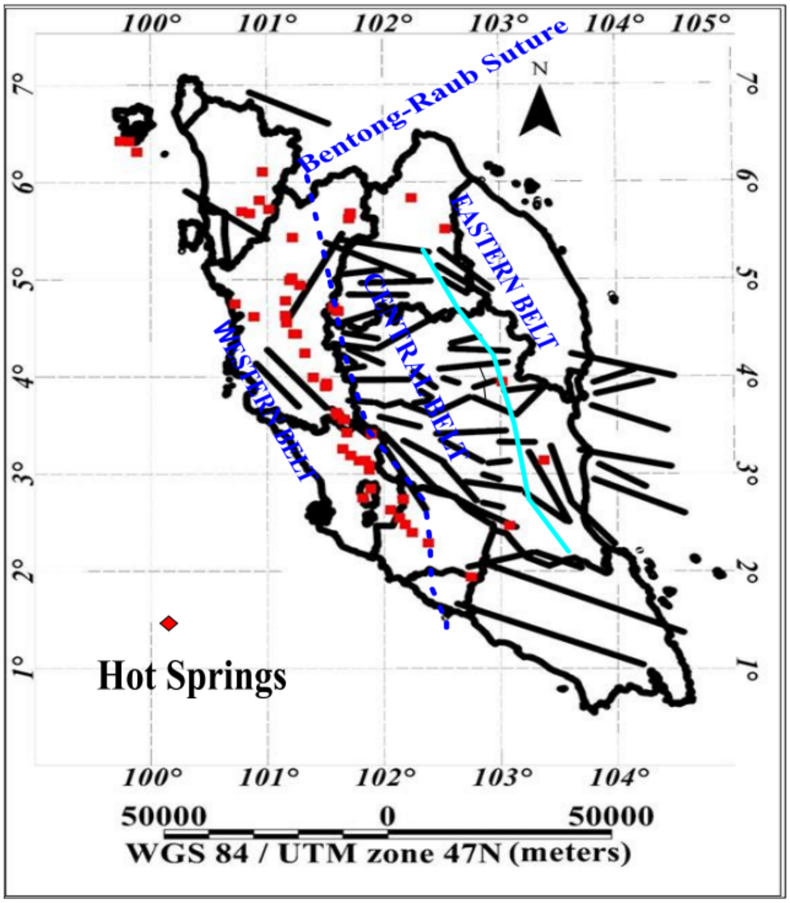


Figure 14. shows lineaments map derived from magnetic anomalies of West Malaysia, depicting major geological structures and their spatial distribution with red marked hot springs. The map highlights faults oriented in NW-SE, NWW-SEE, N-S, and E-W directions, indicating potential zones for geothermal and mineral resources [43].

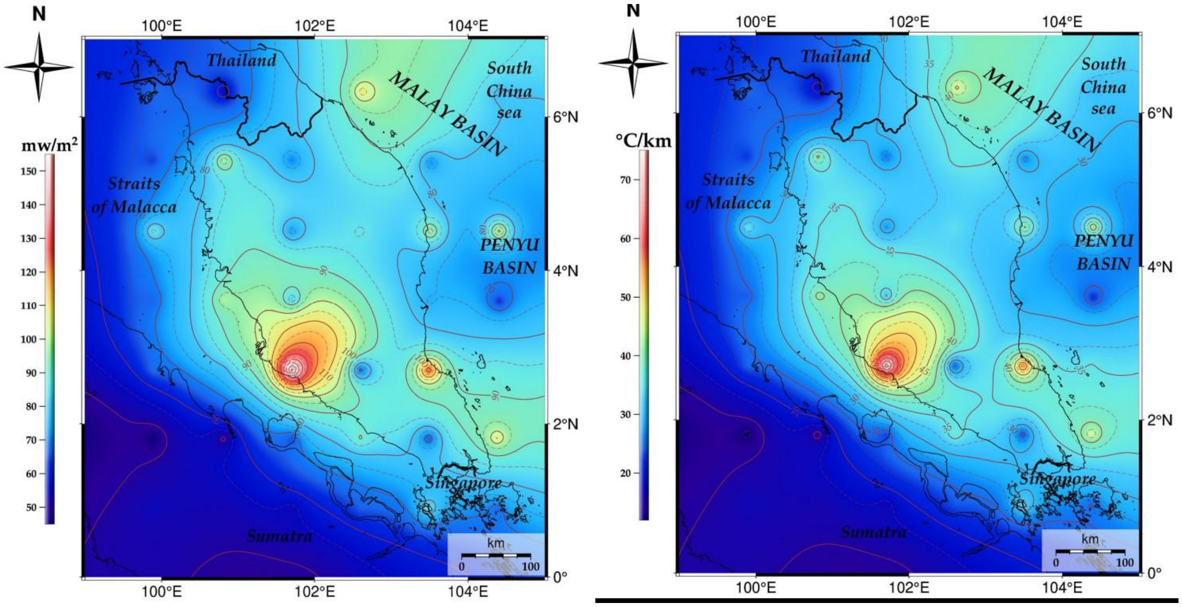


Figure 15. (A) Heat flow map derived from the estimated Depth to the Bottom of Magnetic Sources (DBMS), illustrating spatial variations in heat flow across the region. (B) Geothermal gradient map derived from the estimated DBMS, highlighting temperature variations with depth and potential geothermal activity [130].

A scholarly investigation introduced a framework elucidating the geological architecture and crustal depth of Peninsular Malaysia and its adjacent territories, constructed utilizing data acquired from satellite measurements of gravitational and magnetic fields [131]. The estimated crustal thickness varies between about 28 and 35 kilometers, with an average value of around 31 kilometers (Figure 16A and B). The majority of Peninsular Malaysia exhibits elevated Curie depths (ranging from 20 to 25 km) and deeper Moho depths (ranging from 30 to 34 km), suggesting the presence of typical thermal conditions and deeper crustal structures. Notably, beneath the older rock formations of the Sibumasu region in northwestern Peninsular Malaysia and southern Thailand, the Curie and Moho boundaries reach deeper depths, ranging from 30 to 40 km. Another significant discovery was the identification of a magnetic upper mantle under Sumatra, Singapore, the Malay basin, northwestern Peninsular Malaysia, and southern Thailand, indicating stability and minimal heat flux in these regions, which may be favorable for geothermal research.

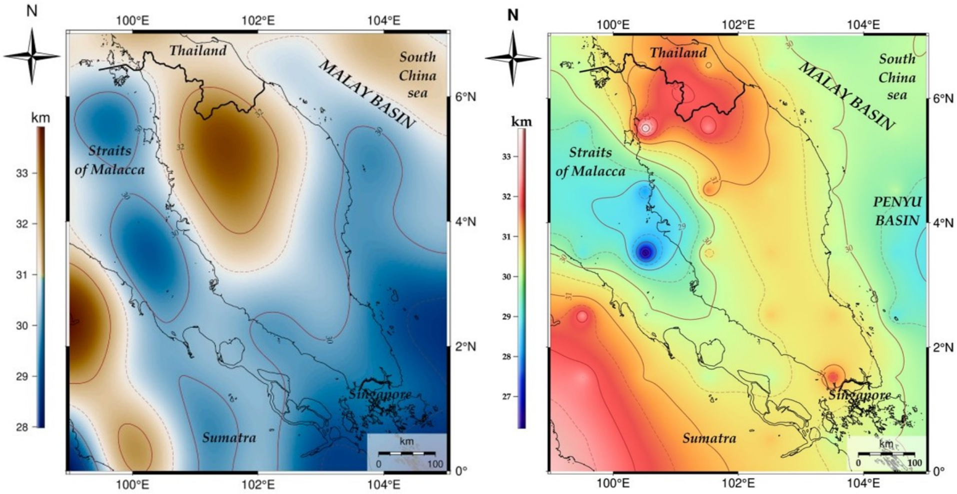


Figure 16. Crustal thickness in the study area: (A) Map derived from gravity inversion (Yaro & Abir 2023). (B) Estimates based on the Crust 1.0 model, enhanced with magnetic data [130, 131].

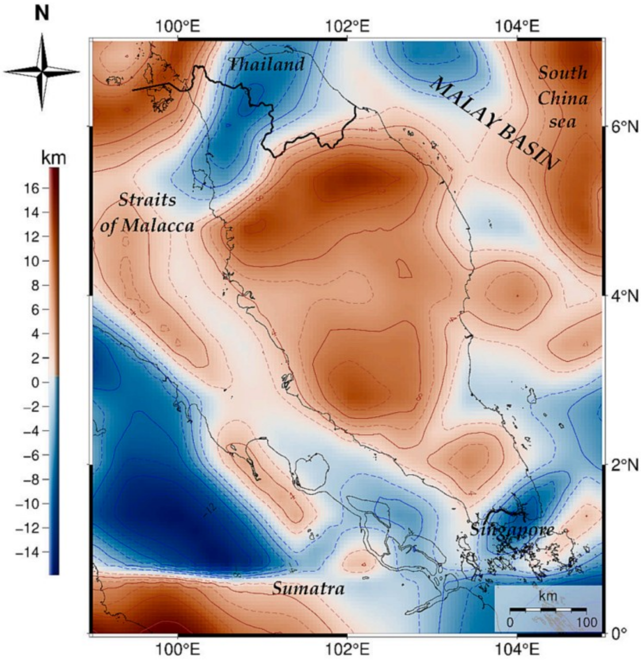


Figure 17. Map of the difference between the estimated crustal thickness and the curie point depth. Positive areas indicates where the Moho is deeper than the curie depths and vice versa [131].

5. Discussion

5.1. Geological Setting and Distributions of Hot Springs in Peninsular Malaysia

The geological settings in peninsular Malaysia are of significant importance concerning the formation and dispersion of hot springs. Numerous investigations have yielded research findings demonstrating a robust correlation between the occurrence of thermal springs and distinct geological parameters. Hot springs are frequently linked to a granitic or sedimentary rock near granite formations, predominantly along the western Main Range Granite batholith. The continuous release of heat from this formation is believed to be caused by its connection to the Earths crust and the resulting thinning of the lithosphere, as the basin forms. As a result, residual temperatures within the feature range from 700 to 1200°C. The heat source in these geological formations is additionally attributed to the operation of radioactive decay occurring within the minerals. The spatial arrangement of springs is affected by fault lines with their positioning corresponding to the predominant tectonic patterns observed in the area, especially in regions known for extensive fault systems. Research conducted over time has provided insights, into the factors that impact the distribution and features of springs in Peninsular Malaysia. [64] highlighted an association between springs and granite intrusion often located near significant fault lines, which facilitate the emergence of hot water. [41] also underscored this relationship. [65] demonstrated how granitoid rocks from the Permian to Triassic periods, influenced by faults and joints, play a pivotal role in hot spring formation. Meanwhile, [31] conducted microscopic examinations to understand how fault-induced fractures within granite serve as conduits for hot water. [8] confirmed that many thermal springs are associated with granitic formations and major fault zones. [63] conducted extensive fieldwork, providing information on hot spring locations and their alignment with tectonic trends. Further studies, including those by [8,14,15], reinforced the prevalence of non-volcanic hot springs, primarily associated with the western Main Range Granite batholith and their potential heat source through radioactive decay. [72] constructed geological mapping around Jeli Hot Spring highlighted the complex tectonic activity and lineament features. [73] focused on the Tok Bok hot spring's geological mapping and depth of groundwater circulation. [75] centered on hot springs in Pos Hendrop, Lojing, Gua Musang, confirming their association with granite. [74] proposed a model linking fault levels and granite-metasediment contact zones to hot springs. [16] updated the geological map and categorized 60 desirable spring locations within the primary granite batholith. [76] investigated hot springs across various locations in Malaysia, mapping their distribution and analyzing lineament patterns. [77], as an in-depth research, concentrated on geological mapping and evaluating water quality in Jeli and Tok Bok hot springs, known for their granite and schist formations. A complete and current geothermal map that includes all pertinent information regarding geothermal areas has yet to be developed. Therefore, it is advisable to conduct a comprehensive geological investigation that encompasses all relevant geological details on thermal springs. This will accentuate the structural and geological interconnections among these thermal features.

5.2. Geochemistry Approach

Numerous studies have contributed to an enhanced understanding of geothermal resources and hot springs in Malaysia. Geochemical studies, in Peninsular Malaysia have primarily concentrated on evaluating the variety of cations and anions found in the hot springs. Previous research endeavours have primarily evaluated water quality and its potential significance for geotourism. Moreover, the analysis of adjacent cold water, such as lakes or rivers, is frequently conducted in conjunction with this study. Many researchers have conducted limited investigations about geochemical, geothermometric, and isotope analyses. Eminent individuals in this specific field include [8, 11, 16, 66, 76, 78, 97, 99, 100]. These research endeavors have divulged that hot springs in Peninsular Malaysia result from precipitation. It is worth noting that the hot springs in this area have varying surface temperatures that range from, around 27°C to 98°C. Particularly noteworthy is that certain areas, such as South Perak, even surpass the 100°C threshold.Moreover. As per estimations obtained through geothermal measurements analysis methods and techniques; it has been suggested that the temperature, beneath the surface falls within the range of 130 to 180 degrees Celsius. The infiltrated water undergoes heating from a non-volcanic heat source, and these findings are substantiated by earlier research based on the existence of low concentrations of sulphate (SO^{2}_{4}). The discernible distinction between discharge and reservoir temperatures suggests the presence of a mixture of thermal and cold water, which arises from the infiltration of precipitation into the Earth's crust at considerable depths.

5.3. Geophysical Approach

Geophysical key conclusions from reviewed studies have emerged in the context of geothermal research in Malaysia, emphasizing the ongoing use of several geophysical techniques, such as gravity, magnetic, time domain electromagnetic (TEM), resistivity, induced polarization (IP), and seismic techniques, to characterize subsurface structures and hot water sources. Indeed, in certain instances, the efficacy of these geophysical techniques has been proven beyond doubt through a highly significant and noteworthy case study conducted by [16]. This particular study focused on utilizing resistivity and induced polarization (IP) methods, specifically concerning shallow-depth exploration. The results of this rigorous investigation led to the discovery of a heretofore undiscovered geothermal spring near Jasin, Melaka. It is essential to highlight that the harmonious combination of resistivity and induced polarization (IP) methodologies was augmented by an impeccably executed drilling operation, thus exemplifying the outstanding efficacy of these geophysical methods in geothermal exploration.

Although geophysical methods have their nuances, it is important to recognize their constraints, particularly in their ability to delve deep, which can affect the assessment of geothermal possibilities. In West Malaysia, the exploration of geothermal reserves has been limited until now due to a scarcity of techniques available for deep investigation. Still, one investigation involving the use of magnetotelluric (MT) techniques sticks out [98]. These approaches allowed for excellent depth penetration but had certain limitations in terms of accuracy. To improve dependability, it is recommended to reduce the distances between stations for verification. This research is notable for being the most comprehensive investigation of the geothermal system in West Malaysia to date, albeit limited in terms of accuracy. Meanwhile, recent worldwide studies [132-137] have emphasized the importance of deep investigation techniques, particularly in exploiting high-temperature resources at depth. Magnetotellurics (MT) is becoming one of the most successful methods for deep geothermal investigation and identifying the heat source, according to global study. However, in Malaysia as a whole, with the exception of the aforementioned study in West Malaysia, the application of such advanced deep investigation techniques remains limited. This gap between global advancements and local practices highlights the potential for further development and application of deep investigation methods in Malaysia's geothermal exploration efforts.

In examining the geothermal and mineral prospects of West Malaysia, [43] emphasized the substantial role of geological faults in influencing the accessibility of geothermal resources. The integrated results of [130, 131] provide significant insights into the thermal and crustal properties of the regions under investigation. These insights yield critical data pertaining to the geothermal potential and magnetic characteristics of the upper mantle. The researchers utilized a de-fractal methodology to ascertain the depth of magnetic sources located beneath the Malay Peninsula. This approach is instrumental in elucidating the geothermal potential, particularly in areas characterized by hot springs. Furthermore, the researchers produced heat flow and geothermal gradient maps.

6. Challenges of Geothermal Prospecting Methods in West Malaysia

Exploring resources, in West Malaysia offers information, about underground formations and sources of hot water. Nevertheless, it's crucial to recognize that these methods have their constraints. The predominant focus on surface-level features and the neglect of associated geological subsurface data from boreholes and other sources limit the comprehensiveness of these studies. The lack of a current geothermal map limits our ability to fully visualize the extent of geothermal resources in the area. Therefore, advocating for a large-scale geological study that incorporates all available geological data related to geothermal springs is essential. Such a study would not only rectify this mapping deficiency but also contribute to emphasising the structural and geological relationships among these hot springs, providing a more holistic understanding of these geothermal systems. Although there is a lack of studies examining the influence of radiogenic heat generation on the geothermal potential of West Malaysia, [138] evaluated certain outcomes to draw parallels with their research conducted on Bangka Island, Indonesia. Nevertheless, uncertainties remain because of the quantity of samples and the uneven distribution in regarding to the granite belts and other lithologies. Their investigation established a relationship between radiogenic heat production and the geothermal system of Bangka Island, with minimal comparisons drawn to the Malaysian geothermal framework. While the researchers utilized heat flow data from the offshore region of East Malaysia, they omitted specific measurements for terrestrial sites in West Malaysia, particularly in relation to the locations of thermal springs. This deficiency in knowledge underscores the imperative for further research to determine the extent to which radiogenic heat influences geothermal activity in Malaysia. Furthermore, integrating geological surveys with other relevant methodologies could enhance the accuracy and efficiency of mapping and characterization efforts, and future research endeavours should extend beyond exploring geotourism potential, emphasising the importance of sustainable management and conservation practices, thus yielding more comprehensive insights into the geological setting and distribution of hot springs in Peninsula Malaysia.

Moreover, the geochemical exploration, although informative, and endeavours have enriched our understanding of various facets of hot springs, significant knowledge gaps persist, underscoring the necessity for more extensive research. Isotopic analyses, including oxygen-18 (18O), deuterium (2H), and tritium (3H), have illuminated the recharge zones and origin of hot spring waters, suggesting a likely distant and higher-elevation origin, as witnessed in the study by [78] at Ulu Slim. However, it is imperative to conduct a comprehensive examination of stable isotope compositions and the interaction among hot springs, surface water, and groundwater. This study may encompass the analysis of radon gas, a subject that has been investigated in various global regions. These studies provide useful insights that can be referenced, such as the study conducted by [139], which is essential to deciphering the intricate dynamics of these systems. The exploration of the hydrothermal cycle, mineral saturation indices, and unclassified thermal water analyses can lead to a deeper comprehension of their origin, water-rock correlation, mineral properties, and even health benefits, particularly in balneotherapy practices. By leveraging stable isotope and geochemistry analyses, we can shed light on the unique hydrothermal dynamics and mineral compositions contributing to the therapeutic qualities of hot spring waters. Moreover, whilst multiple studies have evaluated the water quality and its compliance with established criteria, there is a need for strong and uniform evaluation methodologies to guarantee the safety and appropriateness of spring water for varied uses. Specific concerns such as the presence of odors from hydrogen sulfide and the risk of seawater contamination in springs require thorough investigation and the development of mitigation strategies. Furthermore, the examination conducted by [103] on the viability of harnessing energy from abandoned oil wells raises questions regarding its cost-effectiveness within the given context. These gaps in research along with the nature of hot spring systems highlight the importance of scientific efforts to unlock Peninsular Malaysia's distinctive geothermal resources scientific, economic and touristic potential. An important observation in recent studies, as emphasised by [140, 141], is the acknowledgement of geothermal waters as a large reservoir of lithium. Although their lithium contents are lower than those of brines, these waters are plentiful and can be accessed using current geothermal infrastructure, making them an appealing choice for lithium extraction. This highlights the diverse possibilities of geothermal resources.

In geophysical studies, it is crucial to tackle challenges related to depth penetration and accuracy particularly when precise techniques for exploring subsurface areas are lacking. Moreover, there are mounting worries about the viability of extracting energy as well as potential environmental and community impacts emphasizing the necessity for further exploration and mitigation plans. The geological similarities between Malaysia and Thailand enhance the significance of the geothermal exploration achievements in Thailand. Over the ten years Thailand's integration of the MT technique to explore and develop geothermal as detailed by [142] has significantly advanced its geothermal energy research mitigated risks and pushed forward exploration efforts. To expedite their efforts in utilizing geothermal energy for national development, local research, and industry can gain valuable insights from Thailand's experiences, particularly its effective use of the MT technique.

The assessment of geothermal potential in West Malaysia, emphasizing the substantial role played by geological faults in influencing the accessibility of geothermal resources, as highlighted by [43], and considering geological factors such as Curie Point depth, thermal structure, and crustal thickness beneath Peninsular Malaysia, according to studies by [130, 131], points to encouraging and promising possibilities. To effectively utilize Malaysia's resources, a comprehensive interdisciplinary approach is essential. This approach should include depth analysis, exploration beyond hot spring areas to identify suitable hot rock sources for geothermal energy extraction, economic feasibility assessments, environmental considerations, community involvement, and the exploration of alternative geothermal strategies. These elements contribute to promoting responsible energy development practices in the region.

7. A Geothermal System Model for Peninsular Malaysia

After examining research, a general agreement has been reached on the source and composition of geothermal springs in Malaysia. Researchers widely agree that these hot springs are primarily formed when rainwater percolates through deep fractures within the highly fractured thrust zone, ultimately resurfacing or remaining near the surface to create these thermal features. Rainwater, originating from higher-elevation areas, plays a crucial role in replenishing this geothermal system by gradually absorbing heat from the underlying geothermal source during its underground percolation (Figure 18). However, intriguing variations can be observed in some locations where both hot springs and lakes coexist in proximity to one another or the sea, such as Ayer Hangat Langkawi. These anomalies may be attributed to temperature fluctuations or heightened salinity conditions, which arise due to the coexistence of deep and shallow-level fractures in the same area. Although certain studies indicate that hot spring replenishment primarily takes place in remote and higher-altitude areas of the geothermal system, the intricate interaction between geothermal features and their surroundings, along with the underlying hydrogeological and geological conditions, can result in localised fluctuations in temperature. As a result, a thorough research effort is required to enhance our knowledge of the geological factors involved which can offer insights, for effectively utilizing and managing these distinct geothermal systems. In the field of studies, sophisticated methods like surveys, gravity measurements and remote sensing tools have been actively utilized. However, the lack of comparisons and dependence on methods highlight the crucial need to implement more direct approaches, such as borehole data for validating research outcomes. Despite explorations into geochemical and geophysical aspects, there remains a lack of integrated research with most studies predominantly concentrating on only one or two techniques. This gap emphasizes the necessity for models and a broader research outlook that goes beyond the origins and flow patterns of springs to facilitate a more comprehensive comprehension of the remarkable geothermal systems in Malaysia.

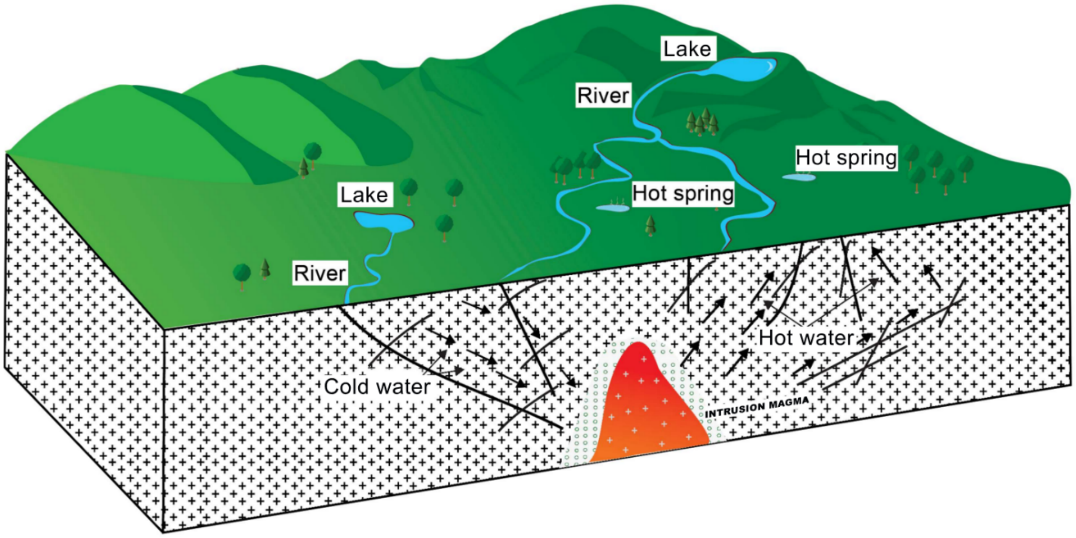


Figure 18. Chart showing the formation of hot springs in peninsular Malaysia.

8. Conclusions and Future Directions

8.1. Conclusions

In essence, the studies were carried out on springs, in Peninsular Malaysia. Encompassing geological, geochemical, and geophysical analyses. This has led to important discoveries regarding their distribution and characteristics. However, it's worth noting that there are still gaps in our knowledge. Geological surveys mostly focus on surface features. For an understanding of geothermal resources creating an up-to-date geothermal map and conducting in-depth investigations integrating subsurface data are essential. While geochemical studies offer insights they have limitations in terms of analyses and water quality assessments. Geophysical methods require enhancements to improve their ability to penetrate layers accurately. Leveraging lessons from neighboring countries could accelerate Malaysia's progress in developing energy resources. This highlights the importance of research, for ensuring responsible energy development. By adopting an approach Malaysia can fully utilize its potential to advance scientific knowledge boost economic growth and promote tourism. Furthermore, this strategy will significantly contribute to understanding geothermal energy knowledge.

8.2. Future Directions

Malaysia currently finds itself in the early to intermediate stages of geothermal exploration. While various studies have highlighted prospective geothermal resources, particularly within Peninsular Malaysia, the nation has yet to make significant strides toward extensive geothermal energy production. To move forward, Malaysia ought to develop a thorough and up-to-date geological map that integrates data on thermal springs, granite formations, and fault systems. Comprehensive and in-depth geophysical studies play a role in improving our understanding of intricate underground structures especially through magnetotelluric (MT) research. The establishment of a systematic program to evaluate radiogenic heat generation in granite formations will aid in identifying potential hot dry rock (HDR) resources A thorough investigation of the chemical composition and isotopic properties of hot springs is crucial for understanding their origins, their interactions with nearby rocks, and their potential for extracting lithium. It is imperative to consider environmental implications and community effects through comprehensive assessments. The process of well drilling for geothermal exploration is fundamental for assessing subsurface conditions and resource viability. Evaluating the feasibility of energy extraction from decommissioned oil wells, alongside examining Thailand's successful geothermal exploration strategies, will promote the sustainable development of Malaysia's geothermal resources, while factoring in economic, environmental, and social dimensions.

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اکتشاف منابع زمین گرمایی در شبه جزیره مالزی: مروری بر تکنیک‌های زمین شناسی، ژئوشیمیایی و ژئوفیزیک

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چکیده:

بیش از شصت چشمه آب گرم در سراسر شبه جزیره مالزی شناسایی شده است که حدود ۷۵ درصد آنها به راحتی در مناطقی با دسترسی آسان قرار دارند. پتانسیل رشد انرژی حرارتی در چهار محل چشمه آب گرم شناسایی شده است: Lojing، Dusun Tua، Ulu Slim و Sungai Klah. این مقاله تحقیقات زمین شناسی، ژئوشیمیایی و ژئوفیزیکی توسعه زمین گرمایی شبه جزیره مالزی را برای ارزیابی مناسب بودن و عملکرد آن تحلیل می کند. داده های زمین شناسی بینش هایی را در مورد ویژگی های ساختاری و توزیع فضایی چشمه های حرارتی در منطقه مورد مطالعه ارائه می دهد. مطالعات ژئوشیمیایی دمای مخزن را اندازه گیری می کند و نشان می دهد که بالاترین دمای ثبت شده بیش از ۱۸۹ درجه سانتی گراد است. این بررسی نشان می‌دهد که چشمه‌های آب گرم از یک منطقه تغذیه مرتبط با توپوگرافی ارتفاع بالا مشتق شده‌اند که منبع آنها آب شهاب‌سنگ است. چندین تکنیک ژئوفیزیکی مانند مغناطیس الکترومغناطیس گذرا (TEM)، گرانش، زمین و ماهواره مغناطیسی، رادار نفوذ زمین (GPR)، لرزه، مقاومت و قطبش القایی (IP)، برای بررسی سیستم زمین گرمایی در مالزی به کار گرفته شده است. بررسی تنها مگنوتتلوریک (MT) در Ulu Slim از این الگو منحرف است. منبع عدم اطمینان در مورد دقت مربوط به فاصله ایستگاه را نشان می دهد و این نگرانی ها را برجسته می کند. اکثر مطالعات نشان می دهد که نفوذ ماگما محتمل ترین منبع گرما است. برای ارائه درک جامعی از پتانسیل زمین گرمایی شبه جزیره مالزی، این مطالعه تحقیقات قبلی را مرور می‌کند و یک مدل عملی ارائه می‌کند که تمام حقایق فعلی را در بر می‌گیرد.

کلمات کلیدی: منابع زمین گرمایی، زمین شناسی، ژئوشیمی، ژئوفیزیک، شبه جزیره مالزی.
