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An overview on controls for geothermal resource exploration

PHAM Bao Ngoc[1*], HO Trong Long[1], BUI Viet Dung[2], TRAN Thi Oanh[1], DO Thi Thuy Linh[1]

1) PetroVietnam University, Ho Chi Minh City, Vietnam
2) Department of Geophysics, Institute of Earth Sciences, Hanoi, Vietnam
** Corresponding author: ngocpb@pvu.edu.vn*

Abstract: *Geothermal energy is a renewable resource that harnesses heat from the Earth's interior, offering one of sustainable alternatives to fossil fuels. The effectiveness of geothermal energy exploration is heavily influenced by geological controls (including tectonic settings, geological formation, and geologic structures), geochemical, and geophysical characteristics. This review examines the interplay between these geological factors and their implications for geothermal resource potential. Key lithological formations, such as volcanic rocks and sedimentary basins, significantly influence heat retention and fluid movement. Variations in the geothermal gradient across different tectonic settings, including rift zones and subduction zones, dictate the temperature and pressure conditions favorable for geothermal systems. By integrating geological settings, geologic structures, geophysical data, and geochemical analyses, this paper aims to enhance the understanding of geothermal systems and optimize exploration strategies. This underscores the necessity of a multidisciplinary approach in evaluating geothermal resources, promoting sustainable energy development in high potential regions of geothermal energy.*

Keywords: *geothermal energy, geological controls, geothermal surface manifestations, geothermal resource exploration*

1. Introduction

As the world grapples with the pressing challenges of climate change, energy security, and sustainable development, the importance of renewable energy sources has never been clearer. Among natural sources, geothermal energy stands out due to its reliability, low environmental impact, and vast potential. It is necessary to discuss the significance of developing geothermal resources, exploring its benefits, challenges, and future prospects. Geothermal has significant contributions to economic development as well as environmental protection. It is clear that geothermal energy produces less greenhouse gas emissions than fossil fuels. In terms of economy and enegy security, geothermal resources are already used as a reliable energy source for heat and/or electricity in 90 countries [1, 2]. Despite its benefits, the development of geothermal resources currently faces several challenges, such as high initial costs, geographic limitations, and technological hurgles.

One of the most important step is understanding geothermal resources, how to explore and exploit this energy. Geothermal energy is derived from the Earth's internal heat, which can be found in the form of steam, hot water, or hot rock. This energy can be harnessed for various applications, including electricity generation, direct heating, and even in industrial processes. The potential of geothermal energy is immense, with estimates suggesting that it could provide a significant portion of the world's energy needs. Besides that, the future of geothermal energy looks promising, driven by advancements in technology and a growing global emphasis on sustainable energy solutions. Increased investment in research and development can unlock new geothermal resources, making it possible to harness energy in areas previously considered unviable. Moreover, as countries strive to meet their climate goals, geothermal energy can play a crucial role in transitioning to a low-carbon economy. Governments and private sectors must work together to create supportive policies, incentives, and funding mechanisms to accelerate geothermal development.

Exploring geothermal resources involves a series of systematic steps to identify and assess viable geothermal system. It is crucial to research and evaluate heat flow, permeability, and fluid flow patterns, which dircectly influence the geothermal potential. In order to analyze these features we need to integrate geological, geophysical and geochemical data in a particular region.

2. Geological Characteristics

2.1. Geological settings

Typically, the geothermal gradient within depths of less than 5 km in continental crust areas ranges between 2.5–3.0°C per 100 m, depending on the physical properties of rock structures in particular regions.

The geothermal gradient is higher in areas with active tectonic or magmatic processes. These regions are associated with geological settings such as volcanic island arcs, hotspots, pull-apart basins, rift zones, and offshore hydrothermal vents (Figure 1) [3, 4]. Volcanic island arcs worldwide include the Andean Volcanic Belt; Sunda Arc in Indonesia; Philippine Arc; Taupo Volcanic Zone in New Zealand; and the Japanese volcanic arc system. Major global hotspots are Yellowstone in the continental crust and Hawaii in oceanic crust. Regarding to pull-apart basins, it is notice that Salton Trough in California and the Dead Sea-Jordan Rift Valley are high potential regions for geothermal exploration. Besides that, large-scale rift zones, such as the East African Rift and mid-ocean ridges in Atlantic Ocean and Pacific Ocean, have active tectonic structures which are favourable for geothermal resources.

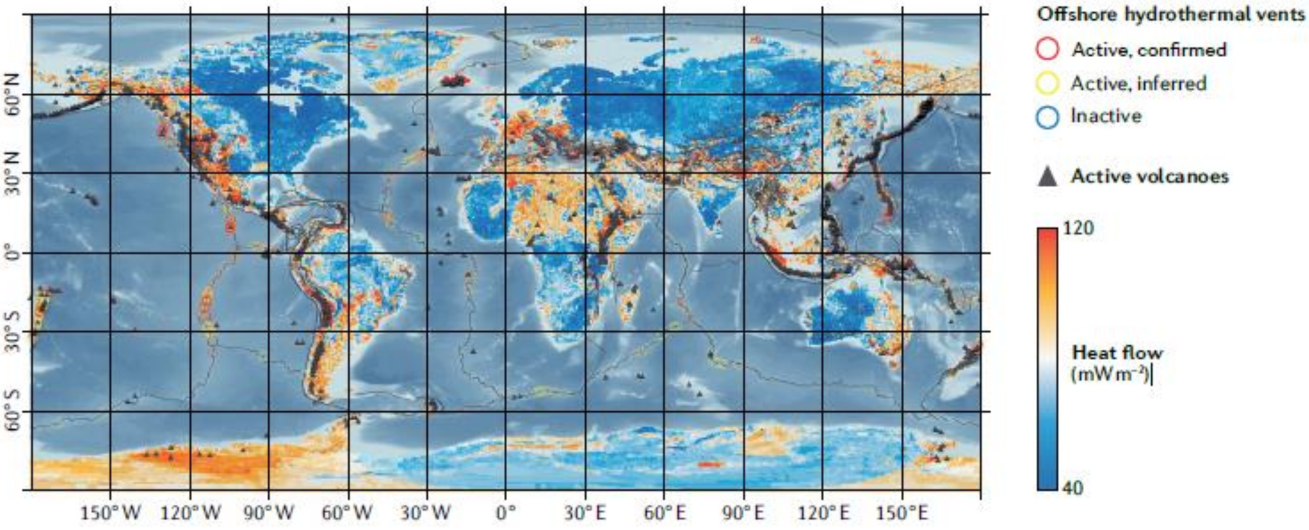

Fig. 1. Global distribution of geothermal resources related to tectonic activities [3, 4]

Volcanic island arc regions, such as Taupo in New Zealand and Iceland, are often directly linked to magmatic intrusions, volcanic eruptions, and crustal extension. These areas are characterized by heat flow values as high as 600–800 mWm^{-2} [5, 6, 7]. Amagmatic extension regions also have high geothermal potential, though their heat flow is lower than that of magmatic rift zones. For instance, the Basin and Range Province of the western North America and the Aegean extensional province in western Turkey have measured heat flows of approximately 85 mWm^{-2} [8, 9, 10].

In volcanic areas, three types of geothermal systems correspond to three volcanic system types: andesitic arc systems (e.g., Awibengkok, Indonesia), silicic volcanic systems (e.g., Taupo, New Zealand, and Kyushu, Japan), and mafic volcanic systems (e.g., Iceland and the East African Rift) [11]. Globally, most geothermal resources exploited for electricity production are associated with volcanic island arc systems.

Vietnam has experienced tectonic activities that are influenced by the overall tectonic regime of Southeast Asia (Figure 2) [12]. The onshore region features several significant fault systems, including the Red River fault zone (which accommodates left-lateral shear from the India-Eurasia collision and contributes to regional tectonic deformation), Son La fault, Ma River fault, Da River fault, Dien Bien Phu fault, Quang Nam – Da Nang fault zone, Tam Ky – Phuoc Son fault, Dong Nai fault zone. These fault systems cause to Vietnam's complex tectonic framework that contributes to diverse geological formations and significant geothermal resource potential (Figures 3, 4) [13, 14]. The sedimentary basins in the continental shelf are also the potential areas for geothermal. Through fault system analysis, magmatic activity assessment, and geophysical data evaluation from petroleum production wells, isogeothermal gradient maps in some blocks of Cuu Long and Nam Con Son basin are generated as in Figure 5 [15]. Based on the isogeothermal gradient curves, the geothermal potential areas are shown in the red areas. In general, in the sedimentary basins of offshore Vietnam at the depth from 500-4,000m, minumum temperatures varies from 44.1 to 115.0 degree celsius, maxium temperature from 54.1 to 185.0 degree celsius, and the averate temperature from 49.0 to 151.0 degree celsius [16].

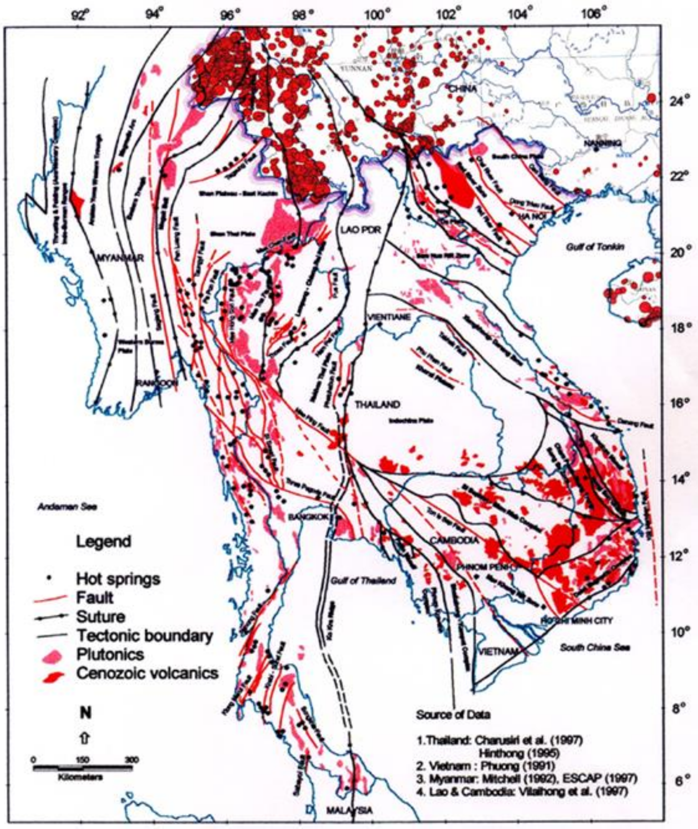

Fig. 2. Simplified tectonic map of SE Asia showing hot springs and potential geothermal areas in onshore Vietnam [12]

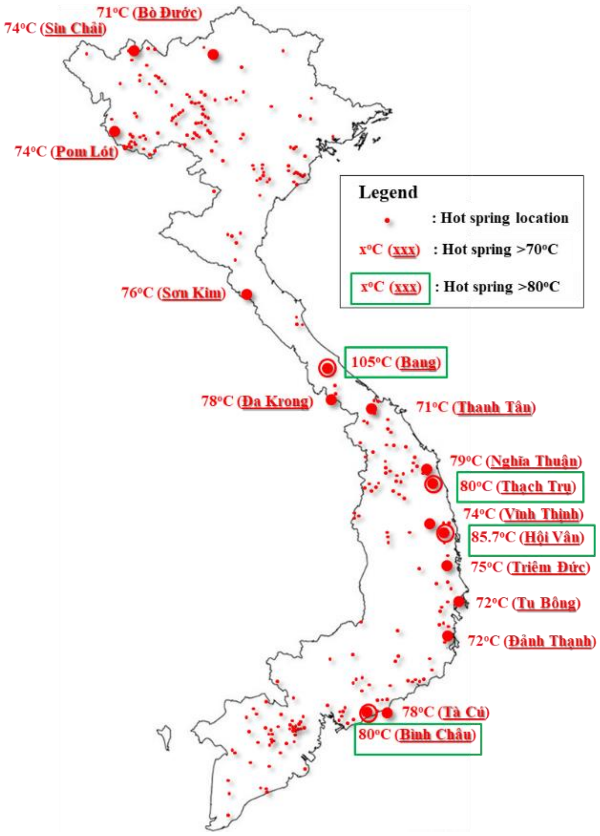

Fig. 3. Hot springs location map in Vietnam [13]

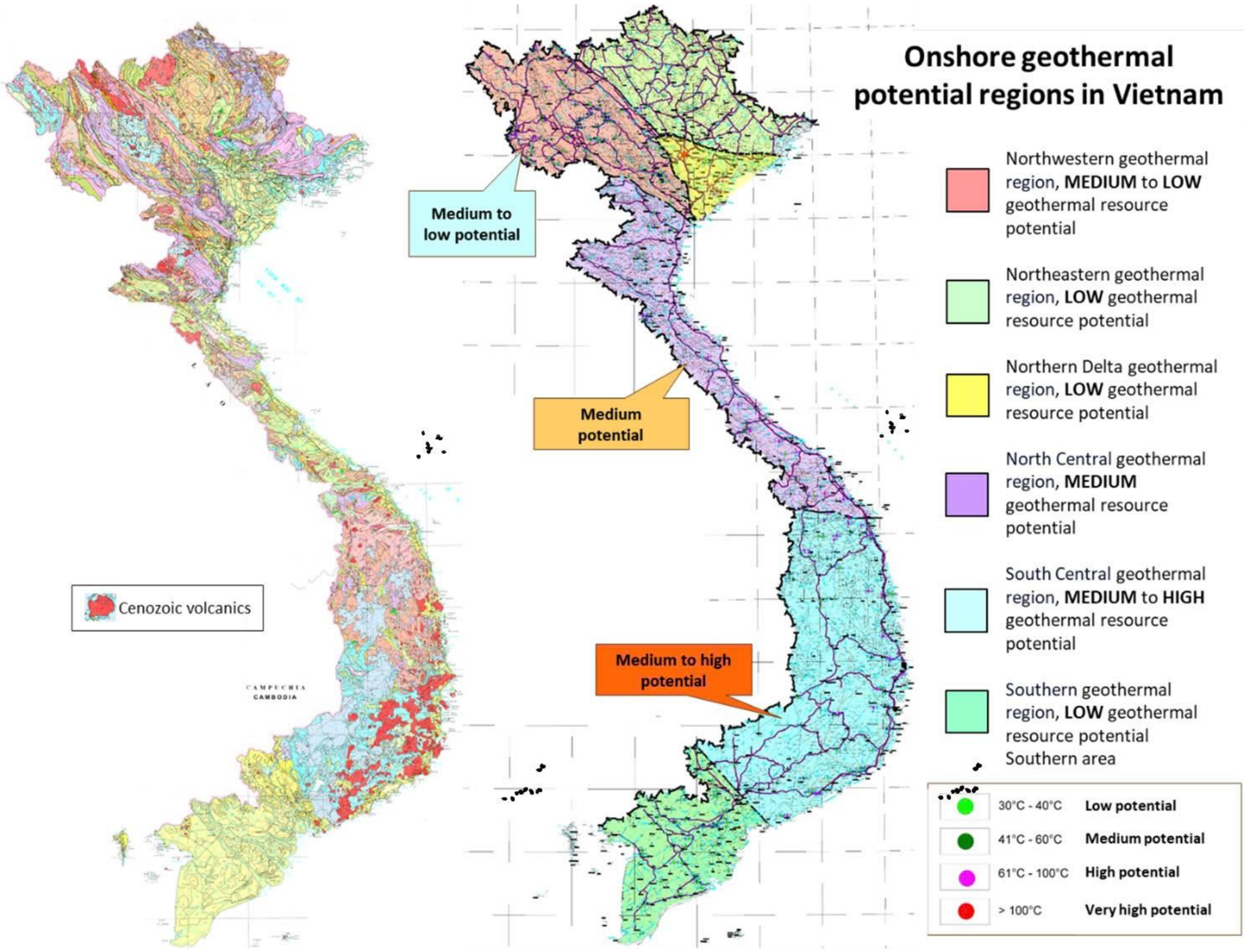

Fig. 4. Onshore geothermal potential regions in Vietnam and their correlation to intrusive magma rocks areas in geological map [14]

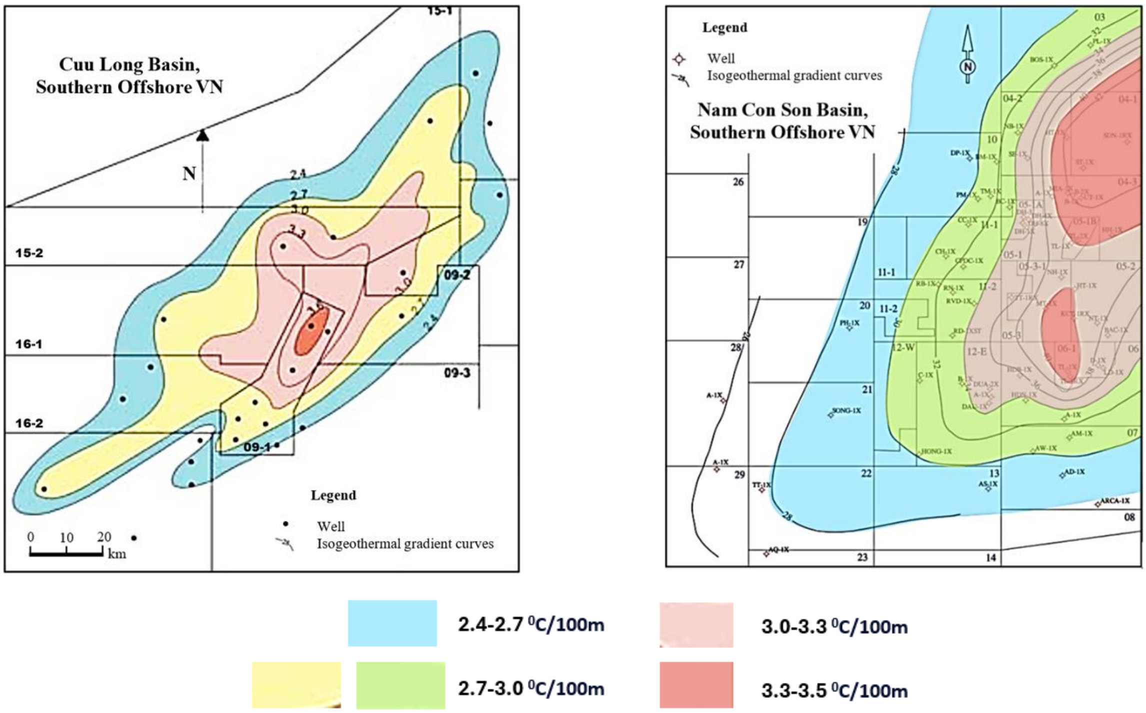

Fig. 5. Isogeothermal gradient maps in Cuu Long and Nam Con Son basin [15]

2.2. Geological formation

Geological formations with geothermal potential exhibit diverse lithological types, depending on the geological context. For example, in regions with active volcanism, geothermal reservoirs primarily consist of magmatic formations, including rhyolite, andesite, and basalt, as well as metamorphic basement rocks. In continental crust areas or amagmatic rift settings, reservoirs can include carbonates, metamorphic rocks (such as marble, schist, and quartzite), volcanic rocks (like basalt and basaltic andesite), and sedimentary rocks (including volcanic clastic deposits).

The lithological characteristics of these reservoirs and the temperature distribution with depth play a critical role in determining the location and volume of high-temperature fluid flow. Porosity and permeability are key parameters in evaluating the fluid storage capacity of these reservoirs (Figure 6). These parameters are influenced by lithology, depth, stress regimes, and hydrothermal alterations. Generally, both porosity and permeability decrease with depth due to burial and compaction. However, some rocks retain high primary porosity and permeability. For instance, sandstone can have primary porosity up to 30%, pumice up to 70%, and permeability ranging from 10^{-14} to 10^{-16} m², seen in volcanic breccias and clastic formations like sandstone and limestone [17, 18].

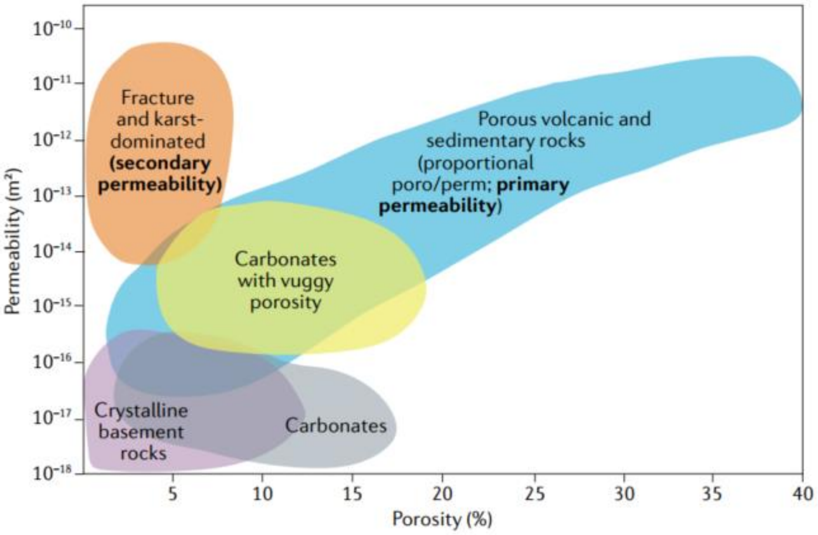

Fig. 6. The relationship between porosity and permeability in geothermal reservoirs [3]

Volcanic formations have wide-ranging primary permeability, from 10^{-19} to 10^{-11} m², making them noteworthy geothermal reservoirs. Secondary permeability, however, is often more critical in geothermal systems. It results from geological processes after the rocks were formed, such as tectonic activity creating fault and fracture systems or mineral dissolution in carbonates [19, 20]. This secondary permeability occurs in various rock types, including intrusive igneous, metamorphic, and carbonate sedimentary rocks, enhancing geothermal systems when primary permeability is insufficient. Therefore, detailed studies of geological processes affecting porosity and permeability are essential in geothermal research.

In formations with geothermal potential and fluid movement, interactions between rocks and fluids, as well as hydrothermal alterations, can lead to the dissolution of primary minerals and the deposition of secondary minerals in cracks or voids. This process may increase or decrease porosity and permeability, altering the physical properties of the geological formations. Additionally, the replacement of primary matrix minerals or the formation of clay minerals like illite, smectite, and kaolinite can reduce porosity and permeability. Fractures and voids can also lose porosity and permeability due to mineral precipitation during secondary alteration processes.

2.3. Geological structure

In addition to tectonic settings and geological formations, geological structures are crucial in assessing a region's geothermal potential. The formation of geological structures is directly linked to the tectonic regime of the area. Faults and fracture systems are not only critical for creating reservoirs with high secondary permeability but also serve as channels for high-temperature fluids to rise from deeper depths and for meteoric water from near-surface aquifers to recharge deeper layers. This process is vital for maintaining convective geothermal systems. Therefore, a primary task in geothermal exploration and exploitation is to identify geological structures with high permeability and fluid mobility.

Most medium-temperature (>125°C) to high-temperature (>225°C) geothermal systems are distributed along normal faults in complex fault interaction zones. These include fault terminations, fault intersections, relay ramps, accommodation zones, displacement transfer zones, and transtensional pull-aparts [3, 17, 21]. These structural types and their associated geothermal systems are detailed in Figure 7, both in map view and cross-section.

For fault terminations, faults are typically closely spaced and converge in a horsetail pattern; geothermal systems are likely to be located in these convergence areas (Figure 7a). Relay ramp structures are characterized by dense networks of minor faults connecting branches of the main fault system, making geothermal systems possible within these fractured zones (Figure 7b). Accommodation zones consist of fault systems dipping in opposite directions, creating multiple fault convergence or intersection points (Figure 7d). Displacement transfer zones are found in extensional tectonic settings, with a series of normal faults converging with a major strike-slip fault (Figure 7e).

Overall, geothermal-prone geological structures share common features of densely fractured and complexly interacting fault systems, creating highly permeable fractured zones. This high permeability is essential for fluid flow, supporting geothermal resource exploitation. Therefore, exploration and production wells should ideally be located in areas with dense fault networks and at fault intersection points.

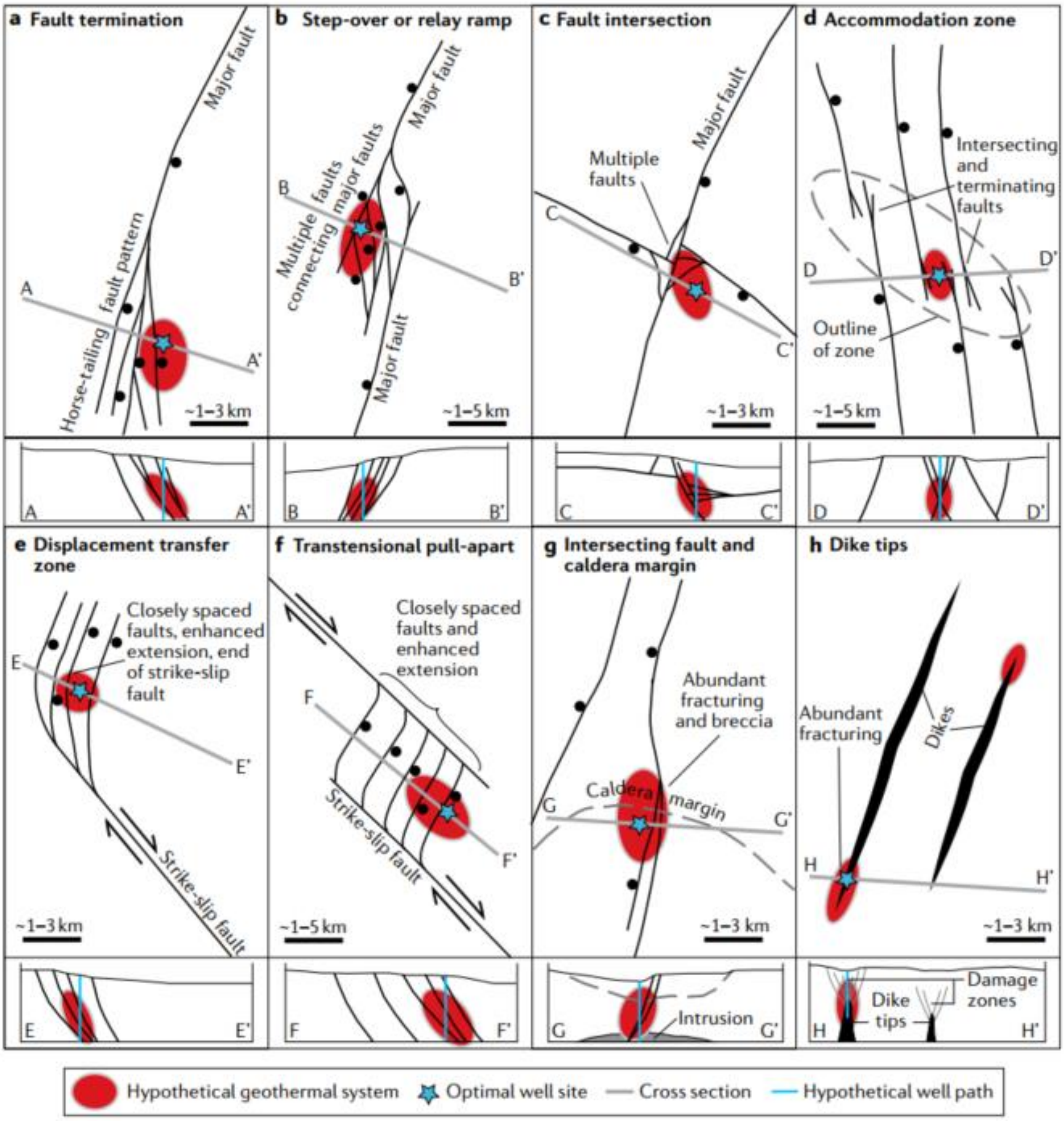

Fig. 7. Favourable structures supporting for geothermal exploration and exploitation [3, 21]

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In fact, potential geothermal systems often have complex geological structures that integrate more than one type of geological feature. For example, in the Basin and Range Province, USA, and the Taupo Volcanic Zone, New Zealand, most geothermal systems in operation are structured by a combination of accommodation zones, fault terminations, and fault intersections [22, 23, 24, 25, 26]. In the Basin and Range Province, the flow rate in geothermal wells within these complex structural zones ranges from 10 to over 300 liters per second, averaging about 100 liters per second more than single-structure zones [3]. Such complex structural zones are also common in nearly 75% of geothermal systems associated with volcanic regions, especially in extensional or compressional areas along strike-slip faults [21].

3. Geophysical Characteristics

Geophysical exploration of geothermal resources deals with measurements on the physical properties of the Earth. The emphasis is mainly on parameters that are sensitive to temperature, good porosity/permeable zones and fluid content of the rocks, or on parameters that may reveal structures that influence the properties of the geothermal system (Figure 8).

Exploration work in geothermal areas is mostly aimed at delineating geometry of geothermal reservoirs where upflow zones cause surface thermal manifestations or geologic structures associate with surface thermal activities. However, deeper geothermal systems sometimes exist without any upflow zones and surface manifestations.

The thermal state of the fluid in the reservoir adds further complications. The physical properties of porous rocks, such as resistivity and density, are different in rocks filled with steam from those filled with hot water.

Various classifications of the geophysical methods used in geothermal exploration have been suggested. The methods can be classified according to the depth range for which they are particularly suited. They can also be classified as direct and indirect methods. Direct methods include thermal exploration techniques which aim at mapping anomalous thermal zones geometrically. Indirect methods include techniques for investigating geological structures that may control the movement of geothermal fluids. The direct methods include logging method, thermal methods, electrical (resistivity) methods and self-potential (SP), while the indirect methods include magnetic measurements, gravity measurements, and seismic methods and others method like remote sensing and gamma ray spectrometry.

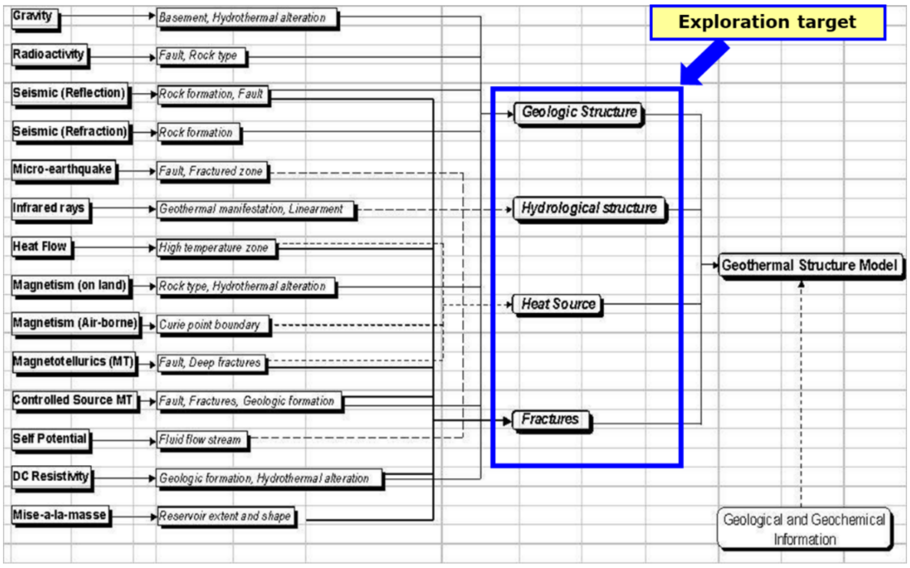


Fig. 8. Geophysical methods and those objectives for geothermal exploration [27]

The important physical parameters in a geothermal system are temperature, porosity, permeability, chemical content of fluid (salinity), and pressure [28]. Most of these parameters cannot be measured directly through conventional geophysical methods applied on the surface of Earth. On the other hand, there are other interesting parameters that can be measured which are linked with the parameters above and may thus give important information on the geothermal system. Among these parameters are temperature (°C), electrical resistivity (Ωm), magnetisation (Vs/m^2 or T), density (kg/m^3), seismic velocity (km/s), seismic activity, thermal conductivity (W/mK), and streaming potential (V).

The geophysical data interpretation for geothermal exploration is based on geophysical characteristics of geothermal keys elements (Figure 9). An example of geophysical survey for Bang geothermal project is displayed in Figure 10 [13].

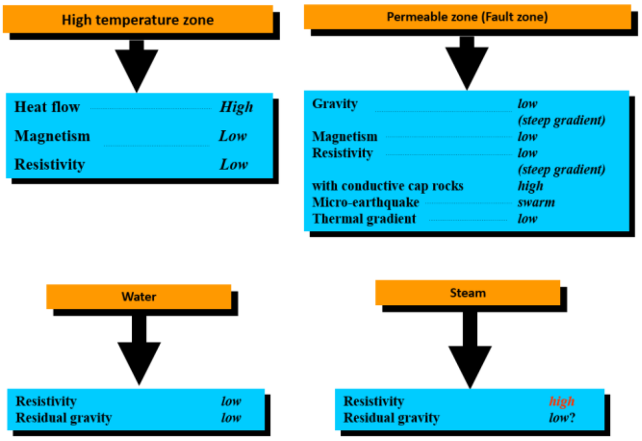


Fig. 9. Geophysical characteristics of geothermal keys elements [27]

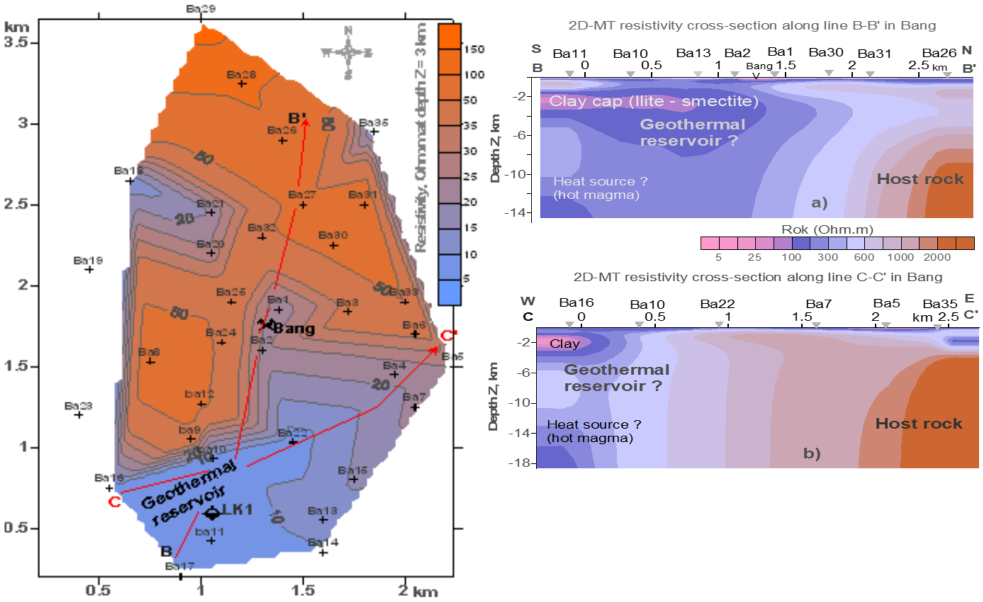


Fig. 10. Geophysical Magnetotellurics (MT) survey showing location and structure of geothermal system in Bang geothermal project, Quang Binh province, Vietnam [13]

4. Geochemical Characteristics

The integration of geochemical data into geothermal studies is essential for a comprehensive understanding of geothermal systems. Key areas where geochemical data contribute include reservoir characterization, fluid-rock interaction, resource assessment, environmental considerations; and exploration and monitering.

Regarding to reservoir characterization, the chemical analysis of geothermal fluids reveals crucial information about the nature of the reservoir. The major ions and trace elements detected can indicate the types of rocks in the reservoir, the temperature, and the potential for scaling and corrosion. Isotopic studies are also important for tracing the origin of the fluids, their interaction with geological formations, and understanding the fluid pathways. Utilizing chemical geothermometers, such as silica and Na/K ratios, allows scientists to estimate subsurface temperatures, which is critical for assessing the viability of a geothermal resource.

In order to evaluate geothermal systems, fluid-rock interaction is one of the most important features. Mineral saturation indices are essential for assessing whether geothermal fluids are in equilibrium with surrounding minerals, helping identify potential issues like scaling or corrosion. Additionally, the study of alteration minerals provides valuable insights into past and ongoing fluid-rock interactions, offering information on the temperature and pressure conditions within the reservoir. Geochemical data play a key role in assessing geothermal resource size and sustainability, aiding models that predict reservoir longevity, which is vital for long-term energy production. Identifying recharge sources and fluid mixing processes enhances understanding of how the geothermal system is replenished, supporting resource sustainability.

Understanding fluid geochemistry help to predict and mitigate scaling and corrosion, which can affect the efficiency and longevity of geothermal installations. Monitoring geochemical data aids in assessing environmental impacts, such as emissions and groundwater contamination, ensuring environmental safety and regulatory compliance. Geochemical surveys, including soil gas analysis and hot spring sampling, are vital in the early stages of geothermal exploration to locate potential reservoirs. Continuous monitoring of geochemical parameters is also essential for tracking the dynamics of the geothermal system, supporting its sustainable management and resource exploitation.

Take one example of the Bang geothermal project in Quang Binh Province, Vietnam, this project exemplifies the essential role of geochemical data in geothermal exploration and assessment. By conducting geochemical surveys and thermometry, scientists have been able to estimate subsurface temperatures, offering valuable information on the geothermal potential of the area (Figure 11). These temperature calculations, derived from geochemical thermometers, suggest the likely productivity and sustainability of the geothermal resource, guiding further exploration and development. Moreover, the composition of water samples collected from the Bang geothermal site reveals critical details about fluid-rock interactions, mineral saturation, and the influence of recharge sources. This analysis provides a snapshot of the geochemical processes within the reservoir, helping to predict potential challenges like scaling or corrosion, which can impact operational efficiency (Table 1, Figure 12).

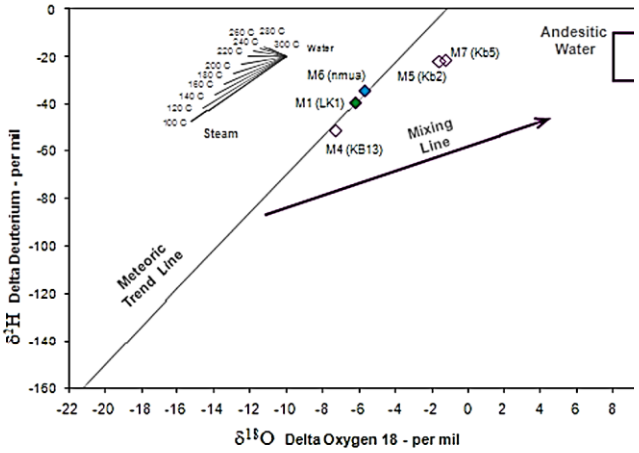


Fig. 11. Geochemical survey by thermometer in Bang geothermal project, Quang Binh province, Vietnam [13]

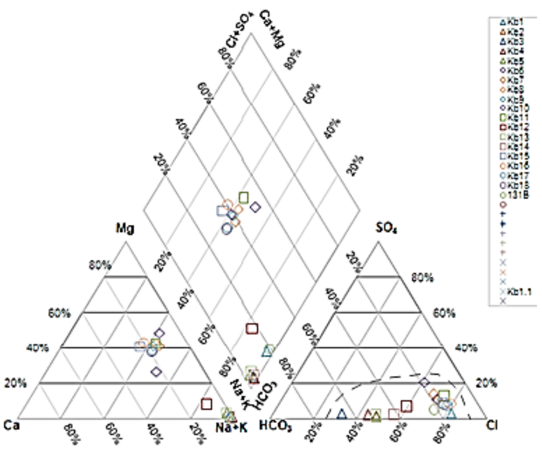
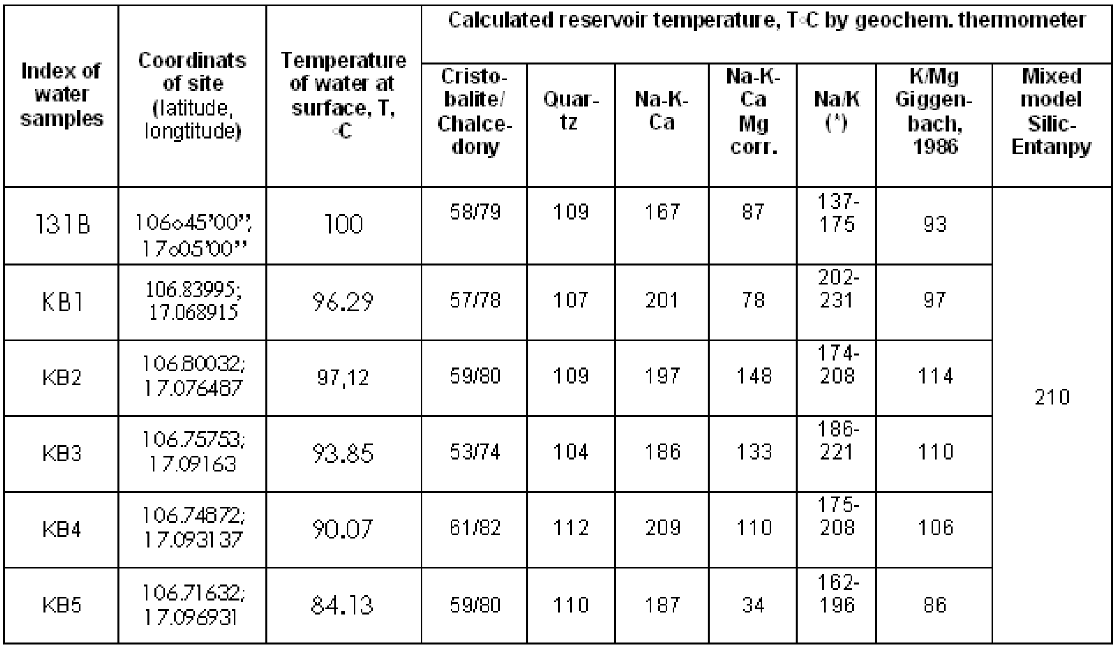


Fig. 12. Water samples composition in Bang geothermal project, Quang Binh province, Vietnam [13]

Tab. 1. Calculated reservoir temperature by geochemical thermometer in Bang geothermal project, Quang Binh province, Vietnam [13]



Index of water samples	Coordinats of site (latitude, longtitude)	Temperature of water at surface, T, °C	Calculated reservoir temperature, T°C by geochem. thermometer						
			Cristobalite/ Chalcedony	Quartz	Na-K-Ca	Na-K-Ca Mg corr.	Na/K (*)	K/Mg Giggenbach, 1986	Mixed model Silic-Entanpy
131B	106°45'00"; 17°05'00"	100	58/79	109	167	87	137-175	93	210
KB1	106.83995; 17.068915	96.29	57/78	107	201	78	202-231	97	
KB2	106.80032; 17.076487	97,12	59/80	109	197	148	174-208	114	
KB3	106.75753; 17.09163	93.85	53/74	104	186	133	186-221	110	
KB4	106.74872; 17.093137	90.07	61/82	112	209	110	175-208	106	
KB5	106.71632; 17.096931	84.13	59/80	110	187	34	162-196	86	

5. Discussion

A multidisciplinary approach in evaluating geothermal resources is essential when considering the controls from geology, geophysics, and geochemistry data. Each discipline provides unique and complementary insights that are critical for comprehensive understanding the characteristics and complexity of geothermal systems. Firstly, geological controls are needed to examine the foundational knowledge of the geothermal potential in a particular region. The must-be geological characteristics include geological setting, geological formation, and geological structures. Geological studies help identify the location of geothermal resources, characterize the subsurface geology, and assess the reservoir's potential for heat extraction. Geologists will provide information on tectonic activity, fault lines, and porosity / permeability, which are essential for determining the system's capacity to store and transmit heat. Understanding the rock formations and their interaction with fluids is crucial for predicting how geothermal reservoirs will behave over time and for identifying areas that are most likely to be productive.

Based on geophysical characteristic evaluation, the emphasis is mainly put on parameters that are sensitive to temperature, good porosity/permeable zones and fluid content of the rocks, or on parameters that may reveal structures that influence the properties of the geothermal system. It was obvious that, the most successful methods are aimed at parameters that are directly influenced by the geothermal activity, such as geophysical well logs, self-potential, geoelectrical and thermal methods, and are usually referred as direct methods. Other methods explore the physical parameters of the host rock, including magnetic properties, density and seismic velocity, and are usually referred as in direct or structural methods. It appears that, direct methods give information on parameters that are influenced by the geothermal activity, while the structural methods give information on geological parameters which may reveal structures or geological bodies that are important for the understanding of the geothermal system.

Geochemistry method also plays a crucial role in understanding fluid-rock interactions within geothermal systems. By analyzing the chemical composition of geothermal fluids, geochemists can determine the temperature, pressure, and potential for scaling or corrosion, which impact the operational efficiency of geothermal power plants. Geochemistry also helps assessing the recharge and sustainability of geothermal resources by tracking the movement and mixing of fluids. Additionally, it provides essential data on the environmental impacts of geothermal energy production, such as emissions or groundwater contamination, ensuring that the resource is developed and managed responsibly.

Therefore, integrating these disciplines allows for a more comprehensive evaluation of geothermal resources. Geologists can identify potential reservoir sites, geophysicists can map their structure and dynamics, and geochemists can monitor fluid behavior and assess environmental risks. The combination of geological, geophysical, and geochemical data provides a holistic understanding of geothermal systems, enabling better decision-making regarding exploration, resource assessment, and sustainable management. This multidisciplinary approach helps maximize resource efficiency, minimize risks, and ensure the long-term viability of geothermal energy as a clean and renewable energy source.

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