Characteristics of Geology, Geochemistry, Geophysics in Assessing the Geothermal Potential of the Bonjol Region, Pasaman, West Sumatra

Eddy Mulyadi[1], Arif Munandar[2]
[1]BRIN-Badan Riset dan Inovasi Nasional, Indonesia
[2]Pusat Sumber Daya Mineral Batubara dan Panas Bumi, Indonesia
Email edmul.1992@gmail.com

Abstract

The purpose of this study was to determine the Characteristics of Geology, Geochemistry, Geophysics in Assessing the Geothermal Potential of the Bonjol Region, Pasaman, West Sumatra. The Bonjol geothermal area is included in the Bonjol District, Pasaman Regency, West Sumatra Province. The rocks in the study area can be divided into 13 rock units, namely two sedimentary rock units, 10 volcanic rock units, and one surface sediment unit, while geothermal manifestations in the research area are scattered in the central part which is dominated by the emergence of hot springs in Padang Baru, Takis River, Limau River, and Langkuik/Kambahan River. In addition to hot springs, alteration rocks are also found around Ds. Blimbing and in the northwestern part of the research area are both past alterations.

Keywords: *Geothermal, Rock, Characteristics.*

– – – – – – – – – – ◆ – – – – – – – – – –

A. INTRODUCTION

Administratively, the Bonjol geothermal area belongs to the Bonjol District, Pasaman Regency, West Sumatra Province. The research area can be reached by using the Jakarta-Padang aircraft, then using a four-wheeled vehicle heading Padang-Bonjol (Location) or by road with the route Jakarta-Merak-Lampung-Padang-Bonjol (Location) through the Sumatran highway to the District Bonjol with a long trip spent about 2 days.

Several previous investigators who conducted investigations in the Bonjol area both directly and indirectly with geothermal investigations included: Van Bemmelen (1949) in his research on geology throughout Indonesia, Nikmatul Akbar (Directorate of Volcanology, 1972 and 1980) in the framework of inventory and preliminary investigation activities geothermal phenomena in the West Sumatra area which mentions the existence of several groups of hot springs that appeared in the Bonjol area, including the Padang Baru hot spring group, the Mudik hot spring group, the Sungai Limau hot spring group and the Air Putih hot spring group.

The Padang Baru hot spring group is located in Padang Baru Jorong Padang Baru Kenegarian Ganggo Hilir, located in the village. The coordinates of the hot springs are 100º 13' 14.2" E and 00º 00' 24.5" S, 1 km from Bonjol to the south. This location is located at an altitude of 190 meters above sea level. The hot water temperature is 430 C at an air temperature of 29.50 C, the hot spring discharge is 1 l/s

and pH = 7.6. Around the hot springs, sintered silica deposits were found covering an area of 1250 m^2.

Mudik group of hot springs, appears in Mudik Takis Jorong Sungai Hitam, Ganggo Mudiak District. The location coordinates are 1000 12" 02.2" and 00º 00' 18.5" N. The location of the hot springs is at an altitude of 250 meters above sea level, 4 km from Bonjol. The temperature of the hot water is between 41 – 730 C, the air temperature is 290 C, the debit of the hot spring is 2.5 l/s, the degree of acidity (pH) is between 5.8 – 7. Around the appearance of the hot spring, sintered silica deposits and there was a puff of water vapor accompanied by hissing and smelled of weak sulfur (Ebrahimi et al., 2019; Fauziyah & Daud, 2019).

The Limau river hot spring group appears in the upper reaches of the Limau river, Kenagarian Ganggo Mudiak. The location coordinates are 1000 12' 28.6" and 00º 00' 40.8" N. Hot springs appear through volcanic breccias at an altitude of 270 meters above sea level with a hot water temperature of 610 C at an air temperature of 290 C, hot water discharge of 1 l/s and pH = 7. The Air Putih/Kambahan hot spring group appears in the Kambahan Distance Ganggo Mudiak district. Hot springs appear at an altitude of 520 m above sea level with a hot water temperature of 52oC at an air temperature of 23oC with a discharge of 0.45 l/s.

There are many groups of hot springs in the Bonjol area as mentioned above, so it is interesting to do a research. Based on the background mentioned above, the authors through this research formulate two problem formulations, namely: 1) what are the characteristics of the Geology, Geochemistry, Geophysics of the Bonjol Region, Pasaman, West Sumatra; and 2) what are the types of rocks and geothermal systems in the Bonjol Region, Pasaman, West Sumatra?

B. METHOD

To see the distribution of low resistivity data that closes around the S. Limau and Takis hot springs, it was carried out using the results of the MT method. to see the age of the rock unit is done by fission track method. Meanwhile, for measuring logging temperatures, calculations are carried out using the Horner Plot method to obtain Initial Temperature (formation temperature) (Yamanlar et al., 2020; Marques et al., 2010). To measure the depth of the top reservoir layer, geoelectric and magnetotelluric methods are used. While geochemical methods are also applied to support the measurement of soil Hg content around the Takis and Padang Baru hot springs, and ground air CO2 in the prospect area.

C. RESULT AND DISCUSSION

1. Characteristics of Geology, Geochemistry, Geophysics of the Bonjol Region, Pasaman, West Sumatra

Characteristics of Geology, Geochemistry, Geophysics of the Bonjol Region, Pasaman, West Sumatra described in the following paragraphs:

a. Characteristics of Geology

The island of Sumatra is located on the southwest-south edge of the Eurasian Continental plate, which interacts with the Indian Ocean-Australian plate moving

north-northeast. The product of the interaction of these plates is affected by the magnitude of the interaction angle and the speed of the convergence of the plates. These movements have produced a combination of subduction and dextral faults that are steady but varied. The subduction that occurred during the Tertiary to Recent period under Sumatra Island resulted in the formation of a magma arc path, namely the Bukit Barisan Mountains. Subductions that form periodically have been released through transform faults that are parallel to the edge of the Plate (Fitch, 1972) and are concentrated along the Sumatran Fault System that extends along the island of Sumatra.

The current Tertiary and Quaternary geology of the Sumatran P. is a natural reflection of this movement. The magmatic arc and backarc basin cut along almost the entire length of Sumatra Island from North Sumatra to South Sumatra, is a dextral fault known as the Semangko fault or the great Sumatran fault. This fault is formed as a result of the interaction between the Indian-Australian plate and the oblique Sunda Microplate. This fault has an important tectonic position because it can be considered as the boundary between the Sunda microplate and the Indian-Australian plate to the west. Thus the Tertiary tectonic development of the part of Sumatra which is east of the Sumatran fault is also the Tertiary tectonic development of the Sunda microplate.

Regionally, the geology of the investigation area based on the Geological Map of the Lubuk Attitudeing Sheet (Rock, N.MS., et al., 1983) consists of sedimentary and metasedimentary rocks, volcanic rocks and intrusive rocks whose ages range from the Paleozoic to the Holocene. Furthermore, on the Geological Map of Sheet Padang (Kastowo, et al., 1996) it is stated that the rocks in the investigation area consist of surface deposits, sedimentary rocks, volcanic rocks, metamorphic rocks and intrusive rocks whose ages range from the Paleozoic to the Holocene.

Regionally, the geological structure of the study area is located in the Sumatra Fault System (SFS) zone, trending northwest – southeast, extending from Weh Island to Semangko Bay, Lampung. The length of this fault zone is 1650 km (Katili & Hehuwat 1967, Tjia 1970). At first the researchers thought that this fault system was a typical normal/terban fault, but later argued that this fault system was a collection of faults that are aligned parallel to different ages, some of these faults are of Middle Cretaceous age, while others are active in the Paleogene.

Tjia, 1977 states that there are at least 18 segments that make up this fault system, which are generally arranged in a right (dextral) en-echelon fault pattern. The movement of this fault is still active, as a result of the push of the Indian Ocean plate against the Eurasian Plate which forms a subduction zone along the west coast of Sumatra Island. As a result of the movement of this structural zone system, in several places depressions (grabens) occur, especially at the en-echelon intersection, as a result of the extension forces in this fault system (Faulds et al., 2015; Kurniawan et al., 2019). The investigation area is within this depression zone.

b. Geophysics Characteristics

Distribution of the Bouguer anomaly for the Bonjol geothermal area for a density of 2.65 gr/cm3. The Bouguer anomaly lineation pattern shows a general

northwest-southeast direction, and in several places, such as in the central, east, west, and south, there is deflection and polarization of low and high anomalies. The direction of the regional pattern corresponds to the direction of the geological structure which stretches from northwest to southeast.

The distribution of the high Bouguer anomaly in the northwest, which widens west to southwest, is interpreted as a response from rocks dominated by fresh and massive lava. The low Bouguer anomaly seen to the west of the Padang Baru hot spring is interpreted as a response to rock intrusion that forms Binuang Hill, while the low Bouguer anomaly to the northeast of the Padang Baru hot spring is interpreted as a response to rock that has undergone alteration.

From the distribution of the Bouguer Residual anomaly, it shows that the gravity alignments trending southwest-northeast, and northwest-southeast which are clearly visible in the western, central, and eastern parts of the investigation area are very compatible with the presence of identifiable geological structures on the surface and from the lineaments topographical contours (Abetsinghe et al., 2020; Hinz et al., 2020). The complexity of the lineaments in the central and eastern areas cannot be recognized from the surface geology probably due to the strong erosion rates in these areas. In addition, it also shows polarization of positive anomalies and negative anomalies with density and sharp contour deflections. This condition indicates the existence of dominant fault structures trending southwest-northeast and northwest-southeast in the direction of the main structure of Sumatra Island.

The distribution of total magnetic anomaly values varies from low to high. The high and low anomaly to the west of the Padang Baru hot springs are interpreted as a response to the intrusion that formed Bukit Binuang. The high anomaly in the north is interpreted as a response from old volcanic rocks, while the low anomaly in the south is interpreted as a response from the boundaries of volcanic rocks and sedimentary rocks.

The distribution of apparent resistivity over a stretch of AB/2 = 800 meters (Figure 8), generally decreases to the northeast and is interpreted as a resistive rock that appears to form the Bukit Binuang intrusion. The moderate apparent resistivity which is spread almost to dominate the Bonjol area is thought to be associated with pyroclastic flows or sedimentary rocks, while the low apparent resistivity seen to the east is thought to be the response of altered rocks or the response of sedimentary rocks (Hasbi et al., 2020; Siahaan et al., 2023).

The distribution of apparent resistivity over a stretch of AB/2 = 1000 m (Figure 9), is generally dominated by moderate apparent resistivity which is interpreted as a response from sedimentary rocks and pyroclastic flows. The high apparent resistivity seen to the west of the Padang Baru hot spring is interpreted as an intrusion that forms Binuang Hill, while the low apparent resistivity which forms a closed contour between the Padang Baru hot spring and the Sungai Limau hot spring and the Takis hot spring is interpreted in response to altered rocks and sedimentary rocks.

c. Magnetotelluric Characteristics

The distribution of apparent resistance from the MT survey shows that there is a pattern of distribution of resistivity that extends from south to north past the Padang Baru hot springs and the Sungai Limau hot springs. The pattern of distribution of apparent resistivity can be seen in the 0.1 second period and the 1 second period. This apparent resistivity value is interpreted as altered rock. This pattern of distribution of low apparent resistivity is not visible in the 5 second period, it is estimated that in the 5 second period it has crossed the boundary of altered rock (Jolie et al., 2019; Jolie et al., 2021).

In the east and west of the investigation area, there is a medium to high distribution of pseudo-type prisoners. The distribution of this apparent resistivity tends to continue to increase up to a period of 5 seconds. The distribution of apparent resistivity is interpreted as a response from the Malintang lava. In the 5 second period, there is a high contour pattern that tends to close around Bukit Binuang. This contour pattern is interpreted as a response to the intrusion of Bukit Binuang.

From the resistivity map of the MT survey results, it can be seen that there is a distribution of low resistivity which at a depth of 0 m asl almost dominates the investigation area. In general, the area of distribution of this low resistivity gets smaller at a depth of 500 m asl, even at a depth of 1000 m asl it tends to be invisible. This low resistivity is interpreted as an altered rock which in the Bonjol geothermal system functions as a cap rock. At a depth of 1000 m asl, around the Padang Baru hot springs, there is a distribution of moderate resistivity, this medium resistivity is interpreted as the top of the geothermal reservoir. Based on these data, geothermal cap rocks are visible to depths above 500 m asl and the top geothermal reservoirs are between 500 and 1000 m asl depths, which are around the Padang Baru hot springs.

2. Temperature Slope Drilling

The BJL-1 temperature gradient well is located at coordinates 100◎12'44.64" E and 0◎0'6.90" N or 634920 mE and 0000212 mN with an elevation of 236 m above sea level. The rocks that make up the BJL-1 temperature slope well from the surface to a depth of 41.26 m are composed of depression/lake deposits and old (ancient) river deposits that have not been affected by hydrothermal alteration, only on the surface of the rocks experiencing exogenic processes in the form of low-intensity weathering currently. The existence of these old river deposits can be seen clearly from the rock samples obtained and from the drill parameters, where the rock samples consist of various rock components (polymic) and loose rock, making it difficult to penetrate and the holes often collapse during drilling (Rera et al., 2021; Neuraliee et a., 2021). Furthermore, at a depth of 41.26 m to the final depth (250.80 m) found altered rocks at that depth interval. The intensity of the changes varies from weak to very strong (SM/TM = 15 – 85 %). The results of rock analysis in the BJL-1 well provide the following altered minerals: montmorillonite/smectite, kaolinite, secondary quartz, opal, calcite, iron oxide, pyrite, gypsum, chlorite and secondary biotite. Clay minerals predominate at almost every depth in the BJL-1 well.

In general, the alteration process that occurred in the BJL-1 well until the final depth still shows a low degree of change which is characterized by changes in the results of argilitization, silification, oxidation processes, with/without pyritization, carbonatization and chloritization. These altered minerals are grouped into the argillic type which functions as a clay cap. Based on the results of PIMA analysis and petrography, a secondary biotite mineral was found as a result of alteration of the hornblende mineral in the BJL1 well, which is known to have a relatively high formation temperature, namely > 260◎C, this is suspected to be a remnant of past changes or as an alteration fossil, this is very possible because the location of the BJL-1 well is not far from the Tertiary age mineralization route with old volcanic rock types, namely in the northwest (around the S. Takis hot spring) and Malintang Hill in the east-southeast.

The presence of altered clay minerals in the BJL-1 well to its final depth supports the previous integrated survey data, which indicated the presence of low resistivity rock layers to a depth of 800 m. This ensures that the low resistivity is not caused by sedimentary rocks, but by the presence of hydrothermal altered clay layers in the Bonjol geothermal system.

Based on the formation temperature of the altered minerals present in the JL-1 slope well, it can be estimated that in general the BJL-1 well to its final depth (250.80 m) has a temperature of around 90°C. The estimated temperature is in line with the results of logging temperature calculations which give a temperature of 66.2°C at a depth of 200 m.

In the BJL-1 temperature gradient well, there were at least two partial loss circulations, namely at depth intervals of 30.80 – 39.45 m and 227 m, respectively of 5 – 10 lpm and 30 lpm . The first PLC that occurred at a depth interval of 30.80 – 39.45 m was thought to be caused by the presence of cavities between rock components in ancient river sediment units, while at a depth of 227 m PLC occurred due to the presence of joints in the rocks at that depth.

In measuring temperature logging, a calculation is carried out using the Horner Plot method to obtain the Initial Temperature (formation temperature). Based on the calculation results, the formation temperature value is 66.2 oC Horner Plot at a depth of 200 meters. Based on the formation temperature at a depth of 200 m, a temperature gradient of 18.97 oC/100 meters is obtained, or more than six (6) times the earth's average gradient (± 3◎C per 100 m). Furthermore, if the estimated top reservoir in the Bonjol geothermal area is at a depth of about 1000 m (results of an integrated survey, 2006) and the gradient is assumed to be linear in the BJL-1 well, then the temperature at that depth is around 218 ^{o}C.

3. Rock Types and Geothermal Systems

Rock Types and Geothermal Systems described in the following paragraphs:

a. Rock Type

The rocks in the study area can be divided into 13 rock units, namely two sedimentary rock units, 10 volcanic rock units, and one surface sediment unit

(aluvium). Volcanic rocks are thought to have originated from seven different eruption points, namely: Bukit Malintang, Bukit Gajah, Maninjau, Bukit Tinggi, Mount Beringin, Bukit Simarabun, and Bukit Binuang and one rock unit whose source of eruption is unknown. Sedimentary rocks in the investigation area consist of sedimentary deposits from the Sihapas Formation and lake sediments, while surface deposits consist of loose material which is included in the alluvium rock unit.

The sequence of rock units from old to young is Sihapas Formation Sediment Unit (Tms), Bukit Malintang Lava, Old Lava, Mount Beringin Lava-1, Mount Beringin Lava-2, Old Sediment, Maninjau Pyroclastic Flow, Bukit Gajah Lava, Bukit Tinggi Lava, Lava-1 Bukit Simarabun, Lava-2 Bukit Simarabun, Bukit Binuang Lava, and Alluvium Deposits. The dialup investigation area has five fault structures, namely: 1) Malintang Fault This fault structure is trending relatively northwest-southeast. This fault is a normal type of fault; 2) The Bonjol fault is trending northwest-southeast and is a normal fault; 3) Dead Alahan Fault.

This fault is in the southwestern part of the research area which has a northwest-southeast direction in the form of a normal fault 4). The Padang Baru fault, a fault structure trending northwest-southeast, is in the center of the investigation area. This fault is a normal fault 5). The Takis fault is trending southwest-northeast. This fault structure is called the Takis fault, which is a normal fault.

b. Heat Source

Heat sources are the main components in a geothermal system, there are several geological formations that can be sources of heat, first in the form of residual heat from magma chambers associated with young volcanic cones, secondly in the form of young intrusive rock bodies. Geologically there are several areas in the investigation area that are likely to become sources of heat, namely Binuang Hill which is 1.3 ± 0.1 million years old (Plistocene) with andesitic rock products and still has the possibility of storing residual heat from its magma chamber and the results of gravity measurements indicating the presence of a body. intrusion (laccolith ?) under the hot water of S. Takis and its surroundings, which is thought to be of Quaternary (Plistocene) age. The location of the two hot sources is in a depression zone that forms a graben, this is a natural thing where Binuang Hill is the last volcanic phase in a large volcanic activity. Furthermore, the existence of geological structures in the investigation area is a medium for the release of hot water to the surface.

c. Reservoir

The geothermal reservoir layer by definition is a subsurface container that is nested and has the ability to pass through fluids, can store hot fluids and has the temperature and pressure of the geothermal system. Based on geophysical investigations, especially with geoelectric and magnetotelluric methods, the depth of the top reservoir layer is estimated to be > 800 meters with a resistivity value of > 40 Ohm-m. The reservoir is thought to be old volcanic rock (old lava units and lava units from Malintang Hill products) which are rich in fractures or which are permeable.

d. Cap Rock

Cap rock (Batuan Penudung) has the property of not passing water or impermeable so that the hydrothermal fluid contained in the reservoir layer below it can be retained. The rock suspected as the cap in the investigation area varies, at a depth of about 500 m to 800 m, with a resistivity value of around 10 - 15 ohm-meters. This considerable difference in depth is due to the relatively thicker cover layer towards the south. The combination of the geothermal system components above (heat source, reservoir, and cap) forms a geothermal system in the research area. This geothermal system is spread along the graben/depression structure which is part of the Sumatran fault system.

e. Geothermal Prospect Area

The results of a compilation of geology, geochemistry and geophysics, obtained that the prospect area is located in a depression area bounded by the Takis fault in the northwest, the G. Malintang fault in the northeast and the Padang Baru fault in the northwest. Airpanas appears to be controlled by the three structures above and the prospect area is also limited by low resistivity (< 15 Ohm-m) and MT data that extends from the Takis hot spring, Sungai Limau to Padang Baru hot spring, with a prospect area of 23 km² (supposedly) and 16 km2 (hypothetical).

The results of the geochemical method also support the prospect area with high soil Hg content around the Takis and Padang Baru hot springs, and ground air CO_2 in the prospect area. Based on the results of gravity it is known that there is a high density around the Takis hot spring which is assumed to be the source of heat from intrusions that do not surface.

4. Geothermal Energy Resource Potential

The distribution of low resistivity data from the MT method closes around the S. Limau and Takis hot springs and is still open to the southeast, indicating that this resistivity is associated with geothermal activity in the form of a clay cap and reservoir of sedimentary rock which is a prospect area that has a large area. about 23 km² (supposed) and 16 km2 (hypothetical). Estimated reserve potential is calculated based on the formula, assuming a reservoir thickness of 1.5 km, estimating subsurface temperature based on thermal gradient results data is 200 °C with a cut-off temperature of 150°C. Recovery factor of 50% is then obtained:

Q = 0.11585 x 23 x (200-150) Mwe x 1.5 = 200 MWe (unexpected backup) and

Q = 0.11585 x 16 x (200-150) Mwe x1.5 = 140 MWe (hypothetical resource)

So the estimated geothermal potential in this area is 200 Mwe and the hypothetical resource is 140 Mwe.

D. CONCLUSION

The rocks in the study area can be divided into 13 rock units, namely two sedimentary rock units, 10 volcanic rock units, and one surface sediment unit (aluvium). Volcanic rocks are thought to have originated from seven different eruption points, namely: Bukit Malintang, Bukit Gajah, Maninjau, Bukit Tinggi,

Mount Beringin, Bukit Simarabun, and Bukit Binuang and one rock unit whose source of eruption is unknown. Sedimentary rocks in the investigation area consist of sedimentary deposits of the Sihapas Formation and lake sediments, while surface deposits consist of loose material which is included in the alluvium rock unit. The sequence of rock units from old to young is Sihapas Formation Sediment Unit (Tms), Bukit Malintang Lava, Old Lava, Mount Beringin Lava-1, Mount Beringin Lava-2, Old Sediment, Maninjau Pyroclastic Flow, Bukit Gajah Lava, Bukit Tinggi Lava, Lava-1 Bukit Simarabun, Lava-2 Bukit Simarabun, Lava Bukit Binuang, and Alluvium Deposits.

Geothermal manifestations in the study area are scattered in the central part which is dominated by the emergence of hot springs in Padang Baru, Sungai Limau Takis River, and Langkuik/Kambahan River. In addition to hot springs, alteration rocks are also found around Ds. Blimbing and in the northwestern part of the research area, both of which are past alterations (alteration fossils). The results of plotting the chemical composition of the hot springs on the triangle diagram Cl - SO_4 -HCO_3, Na-K-Mg, and Cl-Li-B referring to Giggenbach (1988) stated Takis hot water, Sungai Limau hot water, hot water Additions and Padang Baru hot springs, located in the chloride position. If the chloride concentration is higher than the SO_4 or HCO3 concentration, this hot water may be an indication of deep water. The hot steam fluid, associated with geothermal sources, interacts with the surrounding rocks, mixing with surface water forms the appearance of neutral hot springs (pH = 6.50-7.50).

Geothermal manifestations in the study area are scattered in the central part which is dominated by the emergence of hot springs in Padang Baru, Sungai Limau Takis River, and Langkuik/Kambahan River. In addition to hot springs, alteration rocks are also found around Ds. Blimbing and in the northwestern part of the research area, both of which are past alterations (alteration fossils). The results of plotting the chemical composition of the hot springs on the triangle diagram Cl - SO_4 -HCO_3, Na-K-Mg, and Cl-Li-B referring to Giggenbach (1988) stated Takis hot water, Sungai Limau hot water, hot water Additions and Padang Baru hot springs, located in the chloride position. If the chloride concentration is higher than the SO_4 or HCO_3 concentration, this hot water may be an indication of deep water. The hot steam fluid, associated with geothermal sources, interacts with the surrounding rocks, mixing with surface water forms the appearance of neutral hot springs (pH = 6.50-7.50).

REFERENCES

1. Abeysinghe, A. M. A. M., Thilakarathna, M. P., Dissanayake, C. B., & Subasinghe, N. D. (2020). Application of Geological, Geochemical, and Geophysical Techniques in Geothermal Explorations of Sri Lanka-A review.
2. Akbar, N. (1972). Inventarisasi dan penyelidikan pendahuluan gejala panas bumi di daerah Sumatra Barat, bagian Proyek Survei Energi Geothermal. *Dinas Vulkanologi, Direktorat Geologi, Bandung*.
3. Bemmelen, van R. W. (1949). *The Geology of Indonesia*. Vol. I A. The Hague. Netherlands.

4. Distamben Kabupaten Pasaman. (2006). Potensi Energi Panas Bumi (Geothermal) Kabupaten Pasaman, Sumatera Barat.
5. Ebrahimi, D., Nouraliee, J., & Dashti, A. (2019). Assessing the Geothermal Potential of the Shahin Dezh Region, Based on the Geological, Geochemical and Geophysical Evidence. *Journal of African Earth Sciences*, *152*, 84-94.
6. Faulds, J., Hinz, N., Coolbaugh, M., dePolo, C., Siler, D., Shevenell, L., ... & Queen, J. (2015, September). Discovering geothermal systems in the Great Basin region: An integrated geologic, geochemical, and geophysical approach for establishing geothermal play fairways. In *PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering* (No. DOE-UNR-06731-06). Nevada Bureau of Mines and Geology, University of Nevada, Reno.
7. Fauziyah, Y. H., & Daud, Y. (2019, October). Reconstruction of conceptual model in Mataloko geothermal field (Nusa Tenggara Timur). In *Journal of Physics: Conference Series* (Vol. 1341, No. 8, p. 082042). IOP Publishing.
8. Fournier, R.O. (1981). *Application of Water Geochemistry Geothermal Exploration and Reservoir Engineering, "Geothermal System: Principles and Case Histories"*. John Willey & Sons. New York.
9. Giggenbach, W. F. (1988). *Geothermal Solute Equilibria Deviation of Na-K-Mg-Ca Geo-Indicators.* Geochemica Acta 52. pp. 2749 – 2765.
10. Giggenbach, W. F., & Goguel. (1988). *Methods for the Collection and Analysis of Geothermal and Volcanic Water and Gas Samples*. Petone New Zealand.
11. Hasbi, H. G. F., Hamdani, M. R., Prasetyo, A. B. T., Khrisna, W. A. R., Lampuasa, M. J., Pratama, H. B., & Prabata, T. W. (2020). Application of numerical simulation to update conceptual model and resource assessment of Songa-Wayaua geothermal field. In *IOP Conference Series: Earth and Environmental Science* (Vol. 417, No. 1, p. 012014). IOP Publishing.
12. Hinz, N. H., Faulds, J. E., Coolbaugh, M. F., Hardwick, C., Gwynn, M., Queen, J., & Ayling, B. (2021). Play Fairway Analysis of Steptoe Valley, Nevada: Integrating Geology, Geochemistry, Geophysics, and Heat Flow Modeling in the Search for Blind Resources.
13. Jolie, E., Hutchison, W., Driba, D. L., Jentsch, A., & Gizaw, B. (2019). Pinpointing Deep Geothermal Upflow in zones of Complex Tectono-Volcanic degassing: New insights from Aluto volcano, Main Ethiopian Rift. *Geochemistry, Geophysics, Geosystems*, *20*(8), 4146-4161.
14. Jolie, E., Scott, S., Faulds, J., Chambefort, I., Axelsson, G., Gutiérrez-Negrín, L. C., ... & Zemedkun, M. T. (2021). Geological Controls on Geothermal Resources for Power Generation. *Nature Reviews Earth & Environment*, *2*(5), 324-339.
15. Kastowo, G. W. L. (1996). *Peta Geologi Lembar Padang, Sumatera Barat, Pusat Penelitian dan Pengembangan Geologi, Bandung*.
16. Kurniawan, I., Pratama, H. B., & Adiprana, R. (2019, April). A Natural State Model and Resource Assessment of Ulumbu Geothermal field. In *IOP Conference Series: Earth and Environmental Science* (Vol. 254, No. 1, p. 012017). IOP Publishing.

17. Lawless, J. (1995). Guidebook: An Introduction to Geothermal System. *Short course. Unocal Ltd. Jakarta*.
18. Marques, J. M., Carreira, P. M., Marques, J. E., Chaminé, H. I., Fonseca, P. E., Santos, F. M., ... & Teixeira, J. (2010). The Role of Geosciences in the Assessment of Low-Temperature Geothermal Resources (N-Portugal): A Review. *Geosciences Journal*, *14*, 423-442.
19. National Standardization Body, 1998, SNI 13-5012-1998, Classification of Potential Geothermal Energy in Indonesia.
20. Nicholson, K. (2012). *Geothermal Fluids: Chemistry and Exploration Techniques*. Springer Science & Business Media.
21. Nouraliee, J., Ebrahimi, D., Dashti, A., Gholami Korzani, M., & Sangin, S. (2021). Appraising Mahallat Geothermal Region using Thermal Surveying Data Accompanied by the Geological, Geochemical and Gravity Analyses. *Scientific Reports*, *11*(1), 1-14.
22. Rera, G. F., Pratama, H. B., & Saptadji, N. M. (2021, April). Approach for Pre-Feasibility Study of Medium Enthalpy Geothermal Field, Case Study: Danau Ranau, Indonesia. In *IOP Conference Series: Earth and Environmental Science* (Vol. 732, No. 1, p. 012021). IOP Publishing.
23. Rock, N. M. S., Aldiss, D. T., Aspden, J. A., Clarke, M. C. G., Djunuddin, A., Kartawa, W., ... & Whandoyo, R. (1983). Peta Geologi Lembar Lubuksikaping skala 1: 250.000. *Sumatra, Puslitbang Geologi*.
24. Siahaan, M. F., Purba, D., Septiani, G. A., & Paripurna, A. (2023). Preparing Technical and Commercial Documents for Geothermal Exploration Project Financing in Indonesia. In *Proceedings*.
25. Van Kooten, G. K. (1987). Geothermal Exploration using Surface Mercury Geochemistry. *Journal of Volcanology and Geothermal Research*, *31*(3-4), 269-280.
26. Yamanlar, S., Korkmaz, E. D., & Serpen, U. (2020). Assessment of Geothermal Power Potential in Buyuk Menderes Basin, Turkey. *Geothermics*, *88*, 101912.