Proceedings of the 4th ITB Graduate School Conference
Innovation and Discovery for Sustainability
July 6, 2023

Geology and Fluid Geochemistry of the Mt. Rajabasa Geothermal System, Lampung

Eko Suwarno[1,4,*], Niniek Rina Herdianita[2,3], Wildan Mussofan [1,5] & Herwin Azis[5]

[1]Geological Engineering Master Study Program, Faculty of Earth Science and Technology, Institute of Technology Bandung, Jalan Ganesa No. 10, Bandung 40132, Indonesia
[2]Geological Engineering Study Program, Faculty of Earth Science and Technology, Institute of Technology Bandung, Jalan Ganesa No. 10, Bandung 40132, Indonesia
[3]Research Group of Petrology, Volcanology, and Geochemistry, Faculty of Earth Science and Technology, Institute of Technology Bandung, Jalan Ganesa No. 10, Bandung 40132, Indonesia
[4]Directorate of Geothermal, Directorate General of New Renewable Energy and Energy Conservation, Ministry of Energy and Mineral Resources (MEMR).
[5]PT. Supreme Energy, Menara Sentraya, Jakarta.
[*]Email: ekosuwarno19@gmail.com

Abstract. Mt. Rajabasa is a strato-volcano associated geothermal system located at the southern part of Lampung. This paper explains geology and fluid geochemistry of the Mt. Rajabasa geothermal system. The volcanic complex of Mt. Rajabasa consists of two volcanic edifices, i.e. Mt. Belirang and Mt. Rajabasa. Mt. Belirang is at south of the main complex and dominated by basaltic to andesitic volcanic product, while Mt. Rajabasa lies at the north and comprises andesitic to rhyolitic rocks. Surface manifestations occur at the north and southern flanks of Mt. Rajabasa. At south, surface manifestation occurs as fumaroles, steam vents, kaipohan, geyser, and hot springs. The north area consists of warm and hot springs. Chloride water discharge at Gunung Botak hot spring and mixed with 10-20% of seawater. Other springs i.e. at Pangkul, Way Merak, Kalianda, and Way Belerang are sulphate steam heated water. The Rajabasa geothermal system has four reservoirs i.e. Pangkul (south), Way Merak (south), Gunung Botak (south), and Kalianda (north). Based on Na-K liquid geothermometer calculation and the gas-grid diagram of H2-Ar and CO2-Ar, the temperature reservoirs were estimated, i.e. between 230 and 270±10°C at southern reservoir and 180±10°C at northern reservoir.

Keywords: *Rajabasa; mixing; manifestation; fluid; geology; geochemistry; model.*

1 Introduction

Rajabasa geothermal field is located at Lampung (**Figure 1**). The field is sited about 60 km southeast of Bandar Lampung City. This field is bounded by the sea both at the western side (Lampung Bay) and southern side (Sunda Strait). Rajabasa geothermal field is located at Mt. Rajabasa. Mt. Rajabasa is a type B composite stratovolcano with an elevation of about 1,281 meters above sea level [1–3]. The regional geology map shows Mt. Rajabasa is covered by Quaternary andesite products and structural geology is dominantly controlled by NW-SE, N-S, and NE-SW faults [4].

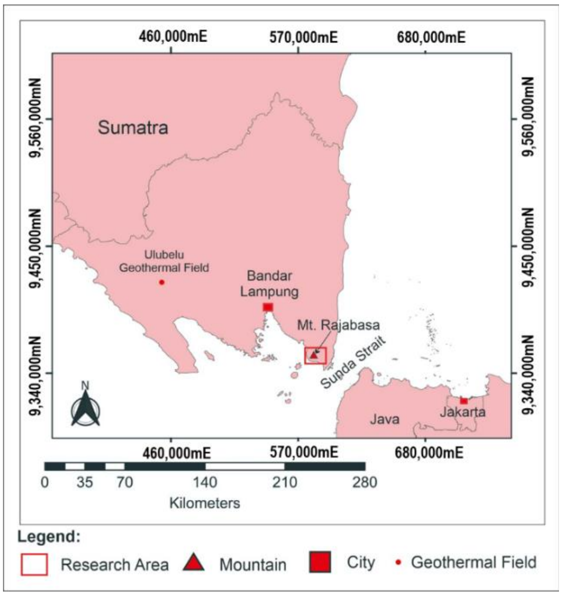


Figure 1 The location of the Mt. Rajabasa geothermal field.

The geothermal system in Rajabasa is interpreted to be associated with Mt. Rajabasa. The existence of a geothermal system in Mt. Rajabasa is indicated by surface thermal manifestations including fumarole, hot and warm springs, steaming ground, geyser, and kaipohan [5], [6]. Thermal manifestations discharge at the north and southern flanks of Mt. Rajabasa (**Figure 2**). This paper explains geology and fluid geochemistry of the geothermal system of Mt. Rajabasa. This paper aims to comprehensively understand the geology and fluid geochemistry of the Rajabasa geothermal system. The findings of this paper will be beneficial for the geological-geochemical concept of the Mt. Rajabasa geothermal system prior to conducting exploration drilling.

2 Data and Methodology

High resolution digital elevation model derived from LiDAR (data from [7], written communication, 2022) and surface geology mapping data [8], [9] were used to construct the geology map. Volcanic features including eruption center, circular feature, and volcanic product distribution delineated by LiDAR. Lithologic unit distribution and boundary confirming by field geology mapping data. The stratigraphy of Mt. Rajabasa is compiled based on the volcano stratigraphy concept. The succession of volcano stratigraphy developed based on the interpretation of superimpose topography.

The fluid chemistry data including water, gas, deuterium (δ^2H), and oxygen-18 ($\delta^{18}O$) stable isotope were used for geochemistry interpretation. The fluid chemistry data is based on the laboratory analysis of thermal manifestation samples. Water chemistry data is taken from hot and warm springs. Gas chemistry data is taken from fumaroles. Stable isotope data are taken from hot springs, steam condensate (from fumarole), and cold meteoric water.

Water chemistry analysis was conducted by a ternary plot diagram. Ternary plot diagram Cl-SO_4-HCO_3, Na-K-Mg, and Cl-Li-B respectively used for type and maturity of water and conservative elements for geoindicator that indicates a source of the reservoir [10–12]. The mass balance equation is used to evaluate the brine and seawater mixing model. Stable isotope ($\delta^{18}O$ and δ^2H) and gas geochemistry analysis of ternary plot diagram N_2-CO_2-Ar used to understand the origin of hydrothermal fluids [11–13]. Solute geothermometer calculation includes Na-K-Ca (with Mg correction), Quartz (adiabatic and conductive), and Na-K were used for predicting reservoir temperature [11,12,14]. The gas grid diagram of H_2-Ar and CO_2-Ar is used to evaluate reservoir temperature and equilibration condition of reservoir fluid [11].

3 Result and Discussion

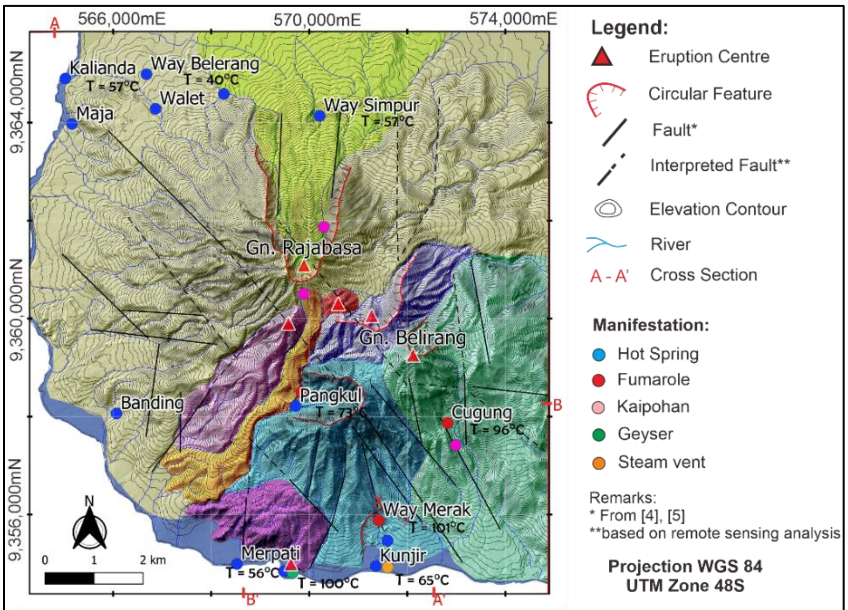
3.1 Volcanic Features

Based on LiDAR data interpretation, there are identified volcanic eruption centers i.e. Belirang, Rajabasa, and flank eruption i.e. Banding, Way Kalam, and Gunung Botak. Circular features were identified at Rajabasa Peak, Way Kalam, Pangkul, and Way Merak (Figure 2). Circular features are estimated as a boundary of the geothermal system and control of the manifestations.

3.2 Volcanostratigraphy

The volcanostratigraphy map of Rajabasa is carried out by LiDAR data and modification of the geological map by [8,9]. Based on volcanostratigraphy, there are two main products in Rajabasa, Belirang Crown in the south and Rajabasa Crown in the north (**Figure 2**). These two volcanic edifices separate the geothermal system in Rajabasa. Both of these units control the distribution of volcanic products in the study area. Belirang Crown (basaltic to andesitic) consist of Way Muli Hummock, Pangkul Hummock, Way Kalam Hummock, and Cugung Hummock. Rajabasa Crown (andesitic to rhyolitic) consists of Way

Simpur Hummock, Banding Hummock, as a flank eruption, and Way Simpur II Hummock (**Figure 2**).



AGE	STRATIGRAPHY UNIT		Eruption Centre	PRODUCT	
	Crown	Hummock		Symbol	Product
					Alluvial
QUARTERNARY	Rajabasa	Way Simpur	Centre		Way Simpur II Volcanic Product(breccia, tuff)
		Banding	Flank		Banding Andesitic Lava Banding Andesitic Lava Dome
		Way Simpur	Centre		Simpur Andesitic Lava Way Simpur Volcanic Product (breccia, andesitic lava, dasitic lava, tuff)
	Belirang	Cugung	Centre		Cugung Volcanic Product (breccia, andesitic lava, tuff)
		Way Kalam	Centre		Way Kalam Andesitic Lava
		Pangkul	Centre		Pangkul Volcanic Product (andesitic lava, breccia)
		Way Muli	Centre		Way Muli Volcanic Product (breccia, basaltic-andesitic lava)

Figure 2 Volcano stratigraphy of Mt. Rajabasa (modified from [8,9]). Mt. Rajabasa has two volcanic edifices, Belirang Crown (basaltic to andesitic) and Rajabasa Crown (andesitic to rhyolitic). These two volcanic edifices control the distribution of volcanic products and separate the Mt. Rajabasa geothermal system. Cross section A-A' is used to build the conceptual model later.

3.3 Water Type

The ternary plot diagram of Cl-SO_4-HCO_3 shows that Gunung Botak and Merpati samples are plotted at the Cl corner, indicating chloride water type (**Figure 3**). Kunjir sample is plotted in between Cl-HCO_3 corner that indicates chloride bicarbonate water type. Other manifestations including Way Merak, Pangkul, Way Simpur, Way Belirang, Way Curup, and Kalianda are plotted in the SO_4 corner that indicates sulphate water type. This water type originated from the steam-heated process of meteoric water heated by steam near the surface [12].

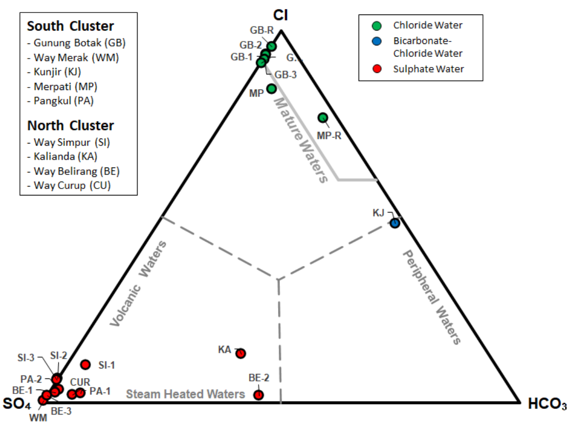


Figure 3 Ternary plot diagram of Cl-SO_4-HCO_3. Gunung Botak (GB) and Merpati (ME) samples indicated chloride water type. Kunjir (KJ) sample indicates chloride bicarbonate water type. Other manifestations are indicated by sulphate water type.

The location of Gunung Botak, Merpati, and Kunjir hot springs is quite close to the shoreline. The relatively high chloride concentration in the samples still becomes a question of whether it comes from brine geothermal fluid or seawater. Therefore, we evaluate this chloride water by mass balance equation.

3.4 The Evaluation of Reservoir and Sea Water Mixing

Hot springs from Gunung Botak and Merpati indicate that might be mixing with seawater. This was also indicated by the high magnesium (Mg) concentration in the samples (126 ppm). The mass balance equation is used to evaluate the reservoir and seawater mixing components. Based on the mass balance equation, it shows that the Gunung Botak chloride spring is mixed between 10-20% seawater and 80-90% geothermal brine fluid. Merpati hotspring is mixed between 13% seawater and 87% geothermal brine fluid. Based on this evaluation the composition of the Gunung Botak and Merpati samples is corrected by removing the seawater component in the sample.

3.5 Water Maturity

The ternary plot diagram of Na-K-Mg (**Figure 4**) is showing that only Gunung Botak samples are plotted in partial equilibrium. Pangkul, Kunjir, Merpati, Kalianda, Way Belirang, Way Simpur, and Way Curup the majority of samples are plotted as immature water. The Gunung Botak sample after correction (GB.R) is also plotted in partial equilibrium.

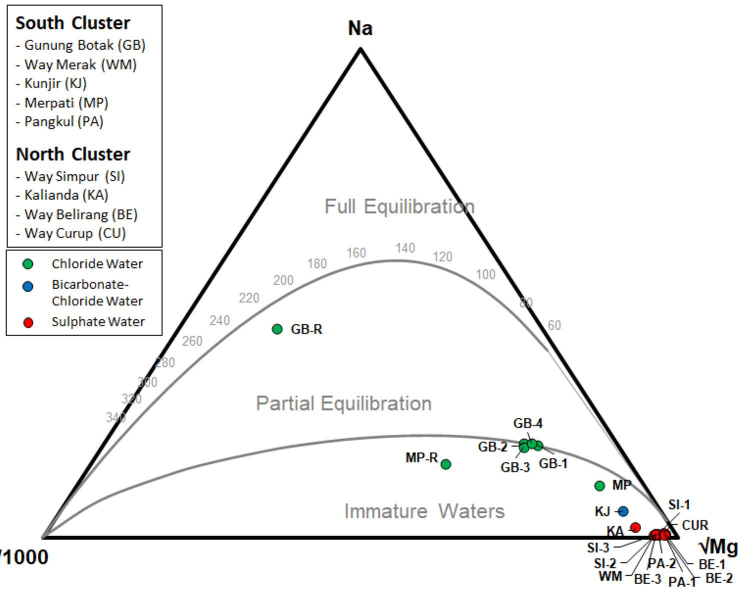


Figure 4 Ternary plot diagram of Na-K-Mg. The majority of samples are plotted as immature water. Only Gunung Botak (GB) samples are plotted in partial equilibrium.

3.6 Fluid Origin

The graphic plot of stable isotope $\delta^{18}O$ vs $\delta^{2}H$ is showing that all Rajabasa samples are plotted near global and local meteoric water lines (**Figure 5**). This result indicates that reservoir fluid in Rajabasa geothermal system originated from meteoric water. Gunung Botak (GB) and Merpati (ME) samples are shifting to Gunung Botak seawater.

The ternary plot diagram of gas N_2-CO_2-Ar is showing that Cugung and Pangkul samples originated from meteoric water with a little bit of potential magmatic gas component (**Figure 6**). Way Merak fumaroles are plotted near N_2/Ar=84 but with higher CO_2 gas representing a geothermal fluid. Gunung Botak, Kalianda, and Sumur Kumbang samples are plotted near N_2/Ar=38, showing meteoric origin.

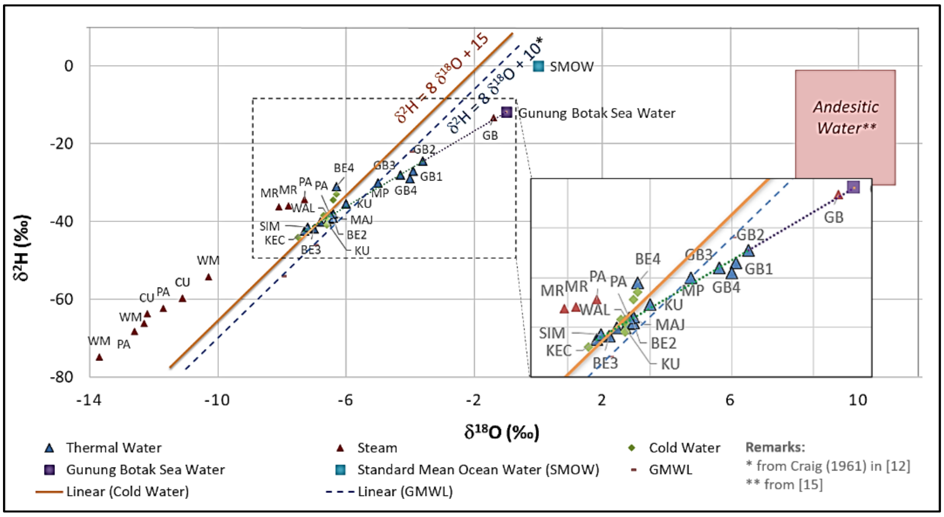


Figure 5 Graphic plot of stable isotope $\delta^{18}O$ vs $\delta^{2}H$. All Rajabasa samples are plotted near global and local meteoric water line indicating that reservoir fluid in Rajabasa geothermal system originated from meteoric water. Gunung Botak (GB) and Merpati (ME) samples are shifting to Gunung Botak seawater. Andesitic water from [15].

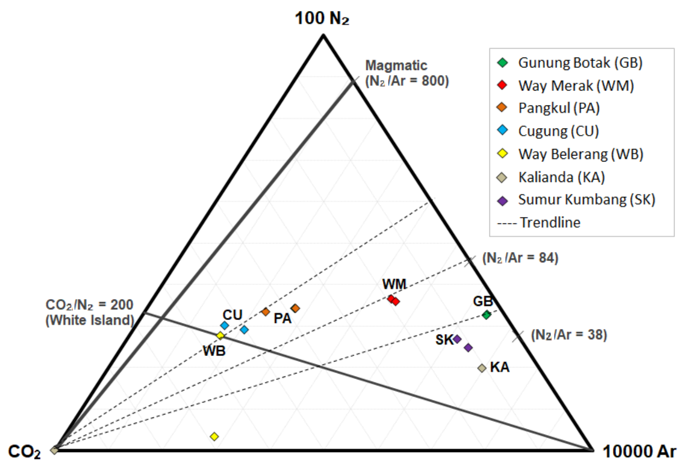


Figure 6 Ternary plot diagram of N_2-CO_2-Ar. Cugung (CU) and Pangkul (PA) samples originated from meteoric water and potential magmatic gas component. Gunung Botak (GB), Kalianda (KA), and Sumur Kumbang (SK) samples show meteoric origin.

3.7 Fluid Source

The ternary plot diagram of Cl-Li-B is showing that hot and warm springs in Rajabasa are plotted into some clusters (**Figure 7**). Hot springs from the southern cluster including Gunung Botak, Merpati, and Kunjir are plotted in one cluster which indicates these samples come from the same reservoir source. Other clusters include Kalianda, Way Belirang – Way Simpur, and Pangkul – Way Merak cluster. Based on the Cl-B ratio, Pangkul, Merak and Gunung Botak show different Cl-B ratios. It is noted that this ternary plot result needs to be considered because of the water type indicating steam heated SO_4 rich and immature water.

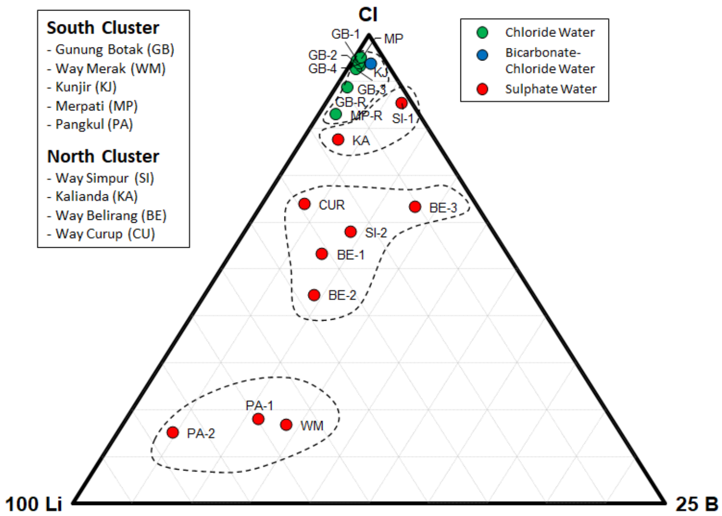


Figure 7 Ternary plot diagram of Cl-Li-B showing that hot and warm springs in Rajabasa are plotted into some clusters. Hot springs from Gunung Botak (GB), Merpati (ME), and Kunjir (KU) are plotted in one cluster. Other clusters include Kalianda (KA), Way Belirang (BE) – Way Simpur (SI), and Pangkul (PA) – Way Merak (WM) cluster.

3.8 Reservoir Temperature

The liquid geothermometer calculation can be applied to the Gunung Botak chloride spring sample. As mentioned before others steam heated waters origin are immature therefore geothermometer calculation cannot be applied. Based on Na-K Giggenbach liquid geothermometer calculation Gunung Botak sample has a temperature reservoir of 230±10°C. As a reference, Merpati has a reservoir temperature prediction of 210±10°C.

The reservoir temperature prediction of the upflow zone of the Rajabasa field is identified by gas geothermometry (**Figure 8**). Based on the gas-grid diagram of H_2-Ar and CO_2-Ar Pangkul has a temperature reservoir prediction of 270±10°C and Way Merak 260±10°C. Other samples are out of the grid. This gas grid diagram also shows Pangkul samples are slightly shifted toward equilibrated vapor which indicates two phases or steam cap may potentially exist beneath Pangkul area. This gas grid diagram also shows Gunung Botak has a reservoir temperature of 220±10ºC, the same range as the liquid geothermometry calculation result.

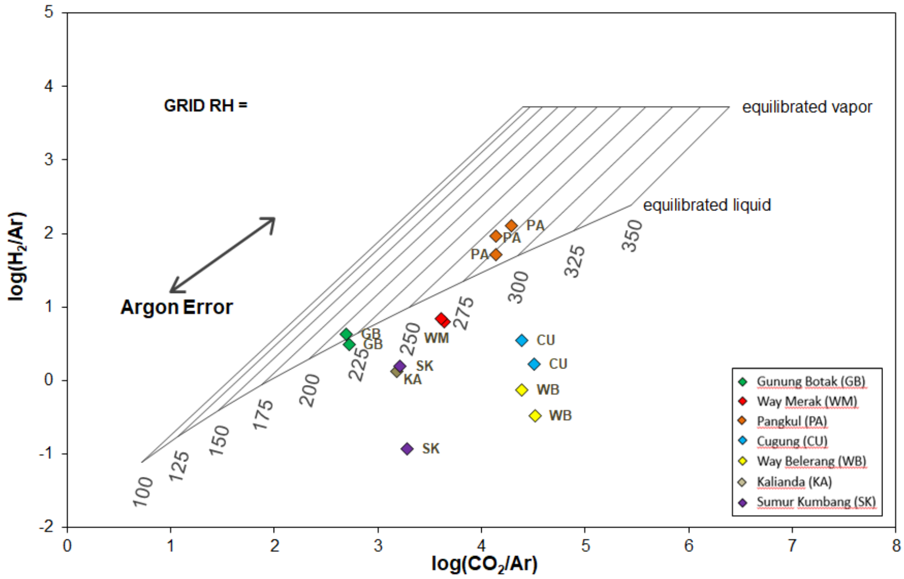


Figure 8 Gas-grid diagram of H_2-Ar and CO_2-Ar. Pangkul (PA) has a temperature reservoir prediction of 270±10ºC, Way Merak (WM) 260±10ºC, and Gunung Botak (GB) 220ºC±10ºC.

3.9 Depth of Reservoir

The determination of the reservoir depth has been conducted by magnetotelluric (MT) data [5]. Based on the presence of the MT base of conductor (BoC) layer, the reservoirs in Pangkul, Way Merak, Gunung Botak, and Kalianda have estimated depths of 700-900m, 500-700m, 300-500m, and 1000-1,300m respectively.

4 Geology-Geochemistry Model

The volcanic complex in Rajabasa is divided into Mt. Rajabasa in the north and Mt. Belirang in the south. These two volcanic edifices separate the geothermal system in Rajabasa (**Figure 9**). Mt. Belirang complex has several eruption centers interpreted as side eruptions including Way Kalam and Gunung Botak.

The distribution of manifestations is controlled by geological features and structures. A circular feature in Pangkul is open towards the west and serves as the boundary of the appearance of hot springs and fumaroles. The circular feature in Way Merak towards the south corresponds to the appearance of hot springs and fumaroles in Way Merak. At Gunung Botak, the presence of a younger flank eruption center has produced a separate system, indicated by the presence of hot springs and geysers that indicate an upflow zone. The system in the southern cluster is limited by a NNE-SSW oriented geological structure. The system in the northern cluster is a separate system due to the different volcanic products.

The presence of manifestations in Pangkul, Way Merak, and Gunung Botak, become key features in geochemical studies. Both Pangkul and Way Merak manifestations have fumaroles and hot springs, while Mount Botak has hot springs and geysers as key features. The presence of fumaroles in Pangkul and Way Merak indicates the occurrence of boiling beneath the surface. Some of the condensation and mixing fluids form sulphate hot springs in Pangkul and Way Merak. The Cl-Li-B diagram (**Figure 7**) shows the relationship between Pangkul-Way Merak-Botak. Botak is a separate cluster, while Merak and Pangkul are part of the same cluster. The Cl-B ratio shows four variations in the values between Pangkul, Merak, Gunung Botak, and Kalianda.

According to the geothermometer calculations, the Gunung Botak sample has a temperature reservoir of 230±10°C. Based on the gas-grid diagram of H_2-Ar and CO_2-Ar Pangkul has temperature reservoir prediction of 270±10°C and Way Merak 260±10ºC. At Gunung Botak, the fluids rise from the reservoir and undergo boiling, as well as mixing with 10-20% seawater, with a mixing temperature of around 120±10°C (using the K-Mg geothermometer). In the northern cluster, it is estimated that the fluids rise from the area around Rajabasa, but due to the thick and intensely altered products of Rajabasa, the condensed fluids mix with meteoric water to form sulphate-bicarbonate warm springs in Kalianda and Way Belirang. In Pangkul, fluids rise to the surface and boiling, producing fumaroles and sulphate hot springs. However, the emergence of manifestations in Pangkul is restricted by an open circular feature towards the west.

In Way Merak, fluids ascend to the surface and boiling, then discharge as fumaroles and sulphate hot springs. They are limited by an open circular feature towards the south. In Gunung Botak, fluids move from the reservoir and upflow, undergoing boiling before mixing with seawater (10-20%) and emerging as chloride hot springs and geysers. These fluids then flow to Merpati and Kunjir as outflow. In the northern part, fluids rise from the reservoir and flow towards Way Belirang and Kalianda. Due to the presence of thick overlying rock, the fluids undergo condensation and mixing with meteoric water, resulting in the emergence of neutral pH warm springs in Way Belirang and Kalianda. A schematic cross section of the geochemistry model of Rajabasa is shown in **Figure 9**.

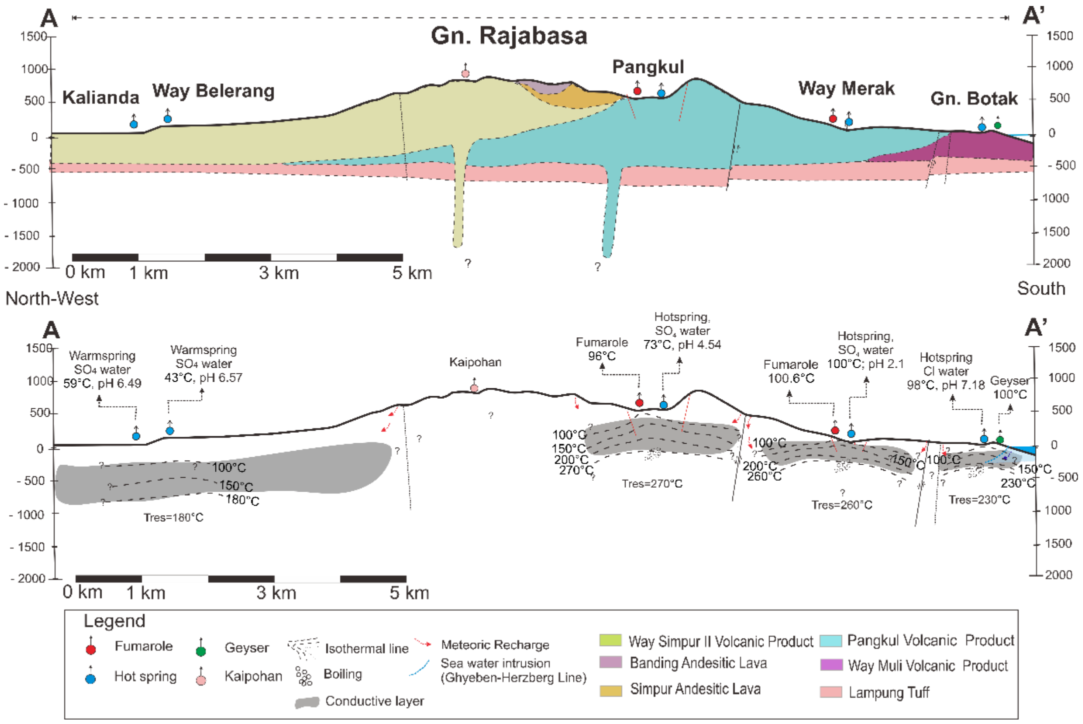


Figure 9 Schematic of the geology-geochemistry model of the Rajabasa geothermal system. The cross section line is shown in figure 2. There are four geothermal reservoirs in Mt. Rajabasa, Pangkul (270±10°C), Way Merak (260±10°C), and Gunung Botak (230±10°C) on the southern slopes, and Kalianda (180±10°C) on the northern slope. Direction of A-A' cross section is given in Figure 2.

5 Conclusion

Based on volcanostratigraphic studies, Mt. Rajabasa consists of Belirang Crown (basaltic to andesitic) and Rajabasa Crown (andesitic to rhyolitic). Both of these units control the distribution of volcanic products in the study area. Pangkul and Way Merak have circular features that control the presence of geothermal manifestations and systems. The appearance of geysers and the presence of a younger eruption center in Gunung Botak.

Based on the water and gas chemistry analysis, the type of water in the hot spring fields in Gunung Rajabasa, chloride water was only found in Gunung Botak and

Merpati, but there is a 10-20% component of seawater. Meanwhile, the Kunjir hot spring is characterized by bicarbonate-chloride water, and other water samples are of sulfate water type and immature. According to the geothermometer calculations, the Gunung Botak sample has a temperature reservoir of 230±10°C. Based on the gas-grid diagram of H_2-Ar and CO_2-Ar Pangkul has a temperature reservoir prediction 270±10°C and Way Merak 260±10°C.

There are four geothermal reservoirs in Gunung Rajabasa, namely Pangkul, Way Merak, and Gunung Botak on the southern slopes, as well as Kalianda on the northern slope. The system in the northern and southern parts is separated by Crown Rajabasa-Crown Belirang.

Acknowledgement

The authors thank PT. Supreme Energy for the permission to publish this work. This paper is part of the geology engineering master thesis project. We would like to thank the academic staff in the Department of Geology option Volcanology and Geothermal, Institute of Technology Bandung (ITB) for the insight. Thank the Directorate of Geothermal, Directorate General of New Renewable Energy and Energy Conservation, MEMR, and LPDP for permission and funding this master study. The overall knowledge of Rajabasa presented here has also benefited from many years of work by numerous scientists and engineers.

Disclaimer

The information presented in this paper is intended for academic purposes only and should not be considered as a recommendation. The authors do not assume any liability for any consequences arising from the use of the information contained herein.

References

[1] Bronto, S., Asmoro, P., Hartono, G., and Sulisiyono. Evolution of Rajabasa Volcano in Kalianda Area and Its Vicinity, South Lampung Regency. *Indonesian Journal of Geology*, **7**, 2012, pp. 11–25.

[2] Simkin, T. and Siebert, L. *Volcanoes of the World*. Geoscience Press, Arizona, 1994.

[3] van Padang, N. M. *Catalogue of the Active Volcanoes of the World Including Solfatara Field. Part I Indonesia*. Napoli, 1951.

[4] Mangga, A. S., Amiruddin, Suwarti, T., Gafoer, S., and Sidarto. *Peta Geologi Tanjungkarang, Sumatera Skala 1:250.000*. Bandung, 1993.

[5] Mussofan, W., Sutrisno, L., Ramadhan, I., and Aulia, N. Geological Aspects to Constrain Geothermal Conceptual Model: Gunung Rajabasa Case Study. *Proceedings The 5th Indonesia International Geothermal Convention and Exhibition*. 2016.

[6] Kusumasari, B. A. *Geologi Daerah Waymuli dan Sekitarnya serta Geokimia Fluida Panas Bumi di Gunung Rajabasa, Kabupaten Lampung Selatan, Provinsi Lampung*. Undergraduate thesis. Institut Teknologi Bandung, Bandung, 2011.

[7] PT Supreme Energy. LiDAR Data. 2022.

[8] LIPI. Structure Geology and Alteration of Rajabasa Geothermal Prospect South Lampung Sumatera. PT Supreme Energy. *unpublish*. 2008

[9] LAPI. Structural Mapping and Analysis at Rajabasa. PT Supreme Energy. *unpublish*. 2011

[10] Giggenbach, W. F., and Goguel, R. L. *Collection and Analysis of Geothermal and Volcanic Water and Gas Discharges*. New Zealand, 1989.

[11] Giggenbach, W. F. Chemical Techniques in Geothermal Exploration. In *Application of Geochemistry in Geothermal Reservoir Development* (F. D'Amore, ed.), UNITAR United Nations Institute for Training and Research, USA, 1992, pp. 119–142.

[12] Nicholson, K. *Geothermal Fluids Chemistry and Exploration Techniques*. Springer-Verlag, Germany, 1993.

[13] Nuti, S. Isotope Techniques in Geothermal Studies. In *Application of Geochemistry in Geothermal Reservoir Development* (F. D'Amore, ed.), UNITAR United Nations Institute for Training and Research, USA, 1992, pp. 215–250.

[14] Fournier, R. O. Water Geothermometers Applied to Geothermal Energy. In *Application of Geochemistry in Geothermal Reservoir Development* (F. D'Amore, ed.), UNITAR United Nations Institute for Training and Research, USA, 1992, pp. 37–66.

[15] Hoefs, J. and Hoefs, J. *Stable isotope geochemistry* (Vol. 201). Berlin: Springer. 1997.