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Characteristics of Reservoir Fluid Chemistry from Preliminary Survey and Exploration Assigment Areas in Sumatra Island, Indonesia

Solikhatun Yuniasih[1], Agri Saputra[2], Rokhimi Utami[3]

Directorate of Geothermal, Ministry of Energy and Mineral Resources[123]

s.yuniasih@gmail.com[1], agri.saputra@esdm.go.id[2], rokhimi.utami@esdm.go.id[3]

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ABSTRACT

According to Indonesia's Geological Agency (2018), Indonesia has geothermal resources of 25.3 GW which are spread along the volcanic pathways, ranging from Sumatera, Java, Bali, Nusa Tenggara, Sulawesi, Moluccas, to Papua. One of the government's efforts to accelerate the development of geothermal energy is by granting Geothermal Preliminary Survey and Exploration Assignments (abbreviated as PSPE in Indonesian) to business entities. Until now, the government has established 11 areas, most of which are in Sumatera island, i.e. Mount Geureudong (Aceh Province), Simbolon-Samosir (North Sumatera Province), Cubadak and Bonjol (West Sumatera Province), Graho Nyabu (Jambi Province), Tanjung Sakti (South Sumatera and Bengkulu Province), and South Sekincau (Lampung Province). This study analyzes and interprets geochemical properties as observed from water, gas, and isotope samples taken from the surface manifestations in PSPE areas through a comparison between ternary diagrams (which consist of Cl-HCO_3-SO_4, Cl-Li-B, Na-K-Mg, N_2-He-Ar), the diagram of deuterium-^{18}O isotope, and the mixing diagrams of enthalpy vs. chloride. The results will be used to determine the chemical characteristics of reservoir fluids, which include fluid type, fluid origin, fluid chemical properties, fluid processes, reservoir systems, enthalpy, pH, and reservoir temperature estimation.

1. GEOTHERMAL IN INDONESIA AND THE ROLE OF GEOCHEMISTRY

Indonesia has an abundance of volcanoes which have geothermal energy potential. According to data from the Geological Agency (2018), the potential of Indonesia's geothermal resources amounts to 25.3 GW and is spread over 349 points, starting from Sumatra, Java, Bali, Nusa Tenggara, Sulawesi, Moluccas, North Moluccas, to Papua. The abundant geothermal energy can be used as a power plant by extracting steam or hot water from the Earth through drilling activities at a depth of about 1,500 meters, and can also be used directly for heating plantation products, such as sugar, mushrooms, coffee, and copra, and also for bathing.

Despite the ample geothermal resources in Indonesia, the utilization has not been optimized. Power plants from geothermal energy only reached 1948.5 MW (8%). To accelerate geothermal development in Indonesia, the government, among other ways, has been assigning business entities to carry out Geothermal Preliminary Survey and Exploration (abbreviated as PSPE in Indonesian) activities, as regulated in the Minister of Energy and Mineral Resources' Regulation No. 36 of 2017 concerning Procedures for Geothermal Preliminary Survey Assignments and Preliminary Survey and Exploration Assignments. For a period of three years (which can be extended at most two times each year), business entities are given a PSPE to obtain geoscience data about a geothermal area which has been studied in prior preliminary surveys or in an open area, and subsequently required to drill a minimum of one exploration well and calculate geothermal reserves.

PSPE activities are divided into Preliminary Surveys and Exploration. Preliminary Surveys refer to the collection, analysis, and presentation of data on geological, geophysical, and geochemical conditions, as well as a temperature gradient survey aimed at estimating the location and presence or absence of geothermal resources. Meanwhile, Exploration is a series of activities involving geological, geophysical, geochemical, and drilling tests, and exploration well drilling. Currently, the Indonesian government has established 11 (eleven) geothermal PSPE areas, and 7 (seven) of them are located in Sumatra Island, including Mount Geureudong (Aceh Province), Simbolon-Samosir (North Sumatra Province), Cubadak and Bonjol (West Sumatra Province), Tanjung Sakti (Bengkulu Province and South Sumatra Province), Graho Nyabu (Jambi Province), and South Sekincau (Lampung Province) (Figure 1).

All processes occurring in a geothermal system are closely related to the chemical conditions and equilibrium of the circulating fluid and the medium it passes. Therefore, the chemical composition of fluid flowing to the surface can inform geothermal resources in the reservoir. As such, geochemistry plays a very important role in geothermal exploration activities, for example, the sampling of water and gas manifestations and a laboratory analysis to determine chemical composition of the fluid to represent the characteristics of a geothermal reservoir system, including fluid type, fluid origin, fluid chemistry, fluid process, enthalpy, pH, and reservoir temperature estimation.

In this study, the results of the laboratory analysis on the water and gas samples which were carried out by business entity as PSPE's or PSP's holder and Geological Agency were interpreted to find out the characteristics of reservoir fluid chemistry. The interpretation used ternary diagrams (Gigganbach) comparing the content of Cl-HCO_3-SO_4, Cl-Li-B, Na-K-Mg, deuterium and ^{18}O isotopes, mixing models of enthalpy vs. chloride, and calculating geothermometers.

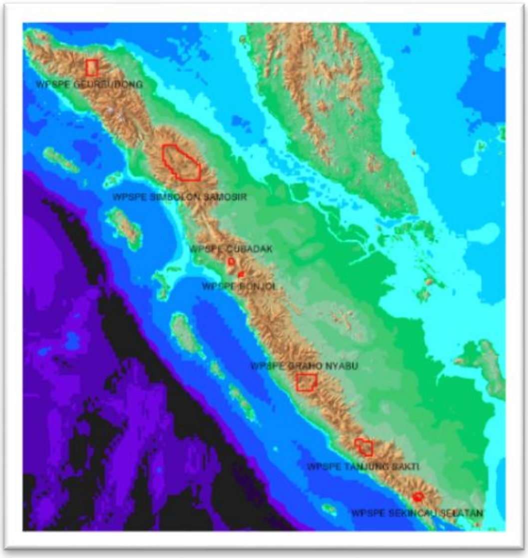


Figure 1: PSPE Geothermal Areas in Sumatra Island

2. GEOLOGICAL CONDITIONS AND ANALYSIS OF GEOCHEMISTRY IN PSPE AREAS

2.1. Mount Geureudong PSPE Area

Geureudong area is located in Bener Meriah Regency, Central Aceh Regency, and North Aceh Regency in Aceh Province. This area was carried out Preliminary Survey by PT Jasa Daya Chevron (2013) and now the PSPE was given to PT Hitay Bumi Energy based on the Head of Investment Coordinating Board's Decree No. 2/1/PSPB/PMA/2018 dated August 6, 2018.

2.1.1. Geology

The stratigraphy of Geureudong area can be classified into two major lithology groups, namely quarternary volcanic rocks and older basement rock. The geological map in Appendix Figure 1(a) shows the overall distribution with basement rocks outcropping nearby the western, southern, and southeastern margins of the area. Appendix Figure 1(b) displays the stratigraphy column of Geureudong area. Appendix Figure 1(c) portrays NE-SW geology cross section.

Basement rocks comprise paleozoic, mesozoic, and tertiary rocks as shown in Appendix 1(b). Paleozoic rocks consist of Kluet Formation (low-grade metasediment-slate, phyllite, and sandstone), Tawar Formation (metalimestone), Biden Granite, and Bergang granite. Mesozoic rocks consist of Penarun Formation (low-grade metamorphic rocks-slate, phyllite, and quartzite). Tertiary rocks consist of Bampo Formation (interbedded siltstone and sandstone). Meanwhile, quarternary volcanic rocks are classified into five main groups, encompassing Silih Nara, Geureudong, Lampahan, Pepanji, and Burni Telong, as ordered from the oldest to the youngest. Regarding geological structure in Geureudong area, based on field data, satellite images and DEM (Digital Elevation Model) point to three important fault systems, namely Northwest-Southeast, North-South, and East-West faults. These faults are assumed to be formed by the large fault in the southwest of the area and are likely to contribute to the formation of geothermal reservoir permeability.

2.1.2. Geochemistry

Surface thermal manifestations in Mount Geureudong area are characterized by the distribution of hot springs (in Wih Pesam, Pepanji, Uning Bertih, and Wih Porak), and a cold gas seep (kaipohan). All hot springs in this area are neutral fluids with pH of 5-7 and temperature ranging from 36 to 68^{o}C. Wih Pesam Hot Spring has a higher concentration of Li, Na, K, Ca, Mg, SiO_2, B, and Cl than others. The type of thermal water was assessed by comparing the relative concentration of anion Cl, SO_4, and HCO_3 (see Figure 2 (a)). Based on the ternary diagram, Wih Pesam is considered chloride fluid and located in mature water zone. This thermal fluid indicates geothermal reservoir conditions and may originate directly from the reservoir. High chloride content (7.336 mg/kg) is a type of liquid geothermal system and a neutral outflow, while high Li and B content shows thermal fluid reaction with sedimentary rocks at depth.

In comparison, hot springs in Pepanji, Uning Bertih, and Wih Porak contain bicarbonate water. This type of water is not derived from geothermal reservoir but near the surface due to the condensation of steam in groundwater or surface water. Moreover, those springs have high concentrations of Cl, HCO_3, and Mg, which indicate that these diluted springs are highly mixed liquids and cooled by various processes and characterize peripheral water rather than a mature geothermal system. The high Mg content shown in Na-K-Mg diagram (Figure 2 (c)) demonstrates that the springs are in immature water zone and have been mixed with groundwater. Overall, this peripheral fluid is a feature of an outflow from a geothermal system.

Ternary diagrams of Li-Cl-B (Figure 2 (b)) can be used to determine reservoir source. In the diagram, Pepanji, Uning Bertih, Wih Porak, and Wih Pesam hot springs are in one group, suggesting that they are from the same reservoir. These springs have relatively high Cl concentration, which indicates that the thermal water is influenced by vulcano-magmatic activities. Meanwhile, water Geothermometer calculation could not be done because all of the water samples from the hot springs are the results of dilution processes. The ternary diagram of Na-K-Mg (Figure 2 (c)) shows that Wih Pesam is in partial equilibrium zone, with a temperature maximum equilibrium of 240 ^{o}C. Furthermore, the amount of stable isotop of ^{18}O and D can also be used to interpret the origin of thermal fluid. The diagram in Figure 2 (d) shows that Pepanji, Uning Bertih, and Wih Porak fluids are near local meteoric water line, indicating that the reservoir fluid is affected by meteoric water. Differently, Wih Pesam has enrichment of ^{18}O, which shows the possibility of thermal fluid interacting with surrounding rocks.

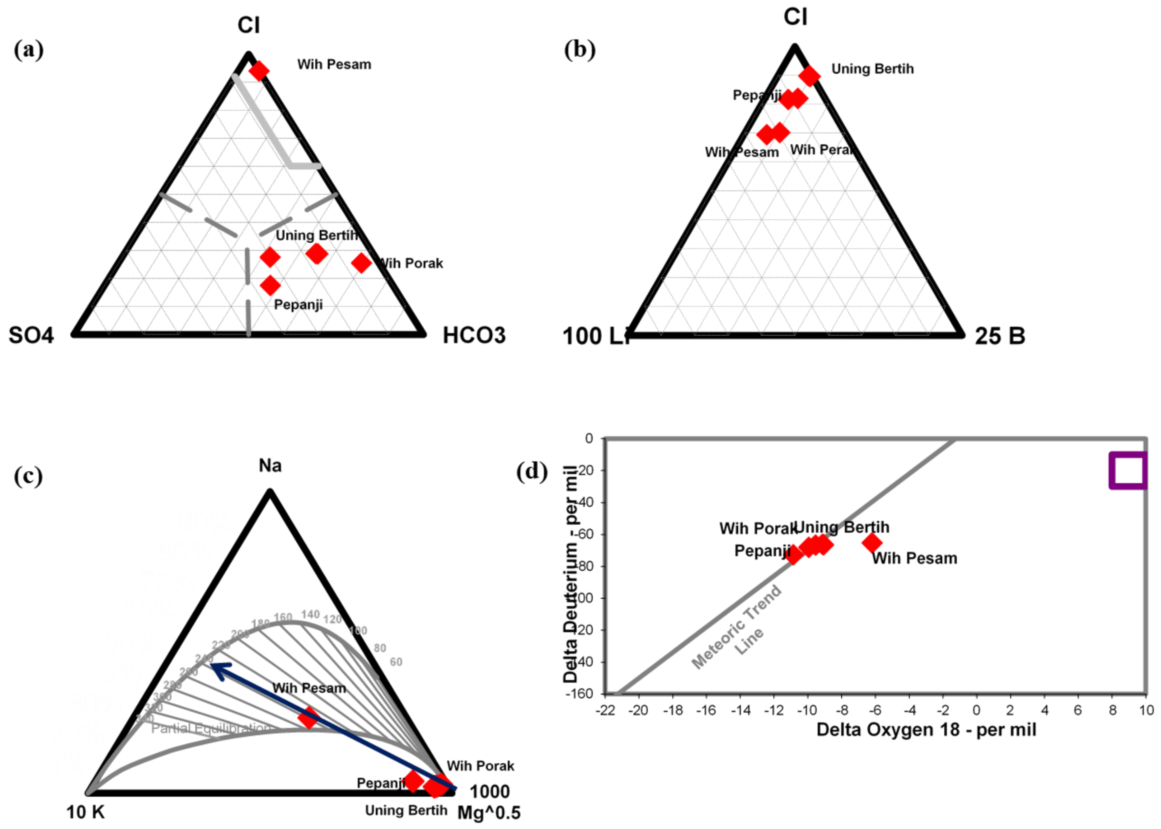


Figure 2 (a) Ternary Diagram Cl-HCO3-SO4 (b) Ternary Diagram Cl-Li-B (c) Ternary Diagram Na-K-Mg (d) Deuterium-^{18}O Diagram

2.2. Simbolon-Samosir PSPE Area

Simbolon-Samosir geothermal Area is located in Dairi Regency, Samosir Regency, Humbang Hasundutan Regency, North Tapanuli Regency, Toba Samosir Regency, Asahan Regency, Simalungun Regency, and Karo Regency in North Sumatra Province. This area was carried out Preliminary Survey by PT Optima Nusantara Energi (PT ONE) in 2011 and now the PSPE was given to PT ONE based on the Minister of Energy and Mineral Resources' (MEMR's) Decree No. 1867 K/30/MEM/2018 dated June 21, 2018.

2.2.1. Geology

Provided the shape of the caldera wall morphology, lithology type, and the pattern of rock distribution, the Toba Pre-Caldera volcano is estimated as "a giant volcanic cone", characterized by a cycle of effusive eruptions. The characteristics of the volcanic eruption of the Toba Post-Caldera are dominated by side eruptions which form a lava cone, cinder cones, and minor lava eruption slits. Considering that G. Pusuk Bukit fertilizes several lava flows, G. Pusuk Bukit is considered the youngest central eruption of the Toba Post-Caldera.

Based on the period of vulcanism, the stratigraphy arrangement of the Simbolon Geothermal Area - Samosir, North Sumatra Province is divided into five stratigraphic groups, including, as ordered from the oldest to the youngest, Pre-Toba Caldera, First Caldera Porsea (Toba 1), Second Caldera Haranggaol (Toba 2), Third Caldera Sibandung (Toba 3), and Pusuk Bukit (Appendix Figure 2(a) and (b)). The surface erosion process produces colovial deposits as the youngest deposits. The Pusuk Bukit stratigraphy group is volcanism post the Third Caldera Sibandung that formed its own volcanic murmur in the Toba region (PT. ONE's Report, 2011).

2.2.2. Geochemistry

Surface thermal manifestations in Simbolon-Samosir area are characterized by hot springs, hot pools, hot mud pools, steaming ground, solfatara, fumaroles and altered rocks, which are spread out in five regional groups, including Tanduk Benua (Tongging), G. Pusuk Bukit, Rianiate-Sigaol, Pagaran (Siborong-borong), and Siregar-Sibadihon (the east side of Lake Toba). The results of this study are as follows:

a. The manifestations in Tanduk Benua area are only alteration rocks.
b. The manifestations in G. Pusuk Bukit area are characterized by hot springs, namely Rumah Holi and Pusuk Bukit. Rumah Holi hot spring have varied temperature of 40-62°C with relatively neutral water (pH=6.2). Differently, the temperature in G. Pusuk

Bukit is higher, at 55-92^oC, and the water is acidic (pH=2) and contains high SO_4 concentration, as indicated by very strong sulfur odor.

c. The manifestations in Rianite-Sigaol area are Rianite, Sigaol and Janji Nauli hot springs. Rianite-1 and Rianite-2 springs have temperature of 41-45^oC and are acidic (pH=1.5-2), whereas Rianite-3 has a higher temperature of 91^oC and is relatively neutral. Sigaol is characterized by two very different groups, namely acidic hot spring group (temperature of <50^oC) and neutral hot spring group (pH=7) with relatively high temperature (74^oC). Lastly, Janji Mauli has a temperature of 44^oC and neutral pH (pH=6.5-7).
d. The manifestations in Pagaran area are hot pools in Pagaran, Sigondang, and Pea. The temperature is quite various, ranging from 38^oC to 71^oC and having neutral pH (pH=6.5-7).
e. The manifestation in Siregar-Sibadihon area is a hot spring with a temperature of 36-43^oC and pH of 7.0-7.83. Sibadihon hot spring has a temperature of 26^oC and nearly neutral pH (pH=6.5).

The ternary diagram of Cl-HCO_3-SO_4 (Figure 3 (a)) was used to determine the type of geothermal fluid. It shows that hot springs in Simbolon-Samosir area contain steam-heated water (acid sulphate water) and bicarbonate water, and there is no chloride water found. Steam-heated water groups, namely Pusuk Bukit and Rianite-Sigaol hot springs, have low or acid pH (pH=2), with dominant SO_4 (891-1679 mg/kg) compared to Cl (1-5 mg/kg) and HCO_3 (1 mg/kg) concentrations. They also have a high NH_4 concentration, which points out that the fluid flowing from the reservoir has had a reaction with sedimentary rocks at depth. These springs cannot be used in the calculation of the geothermometer to determine reservoir temperature estimation. Differently, hot springs groups in Pagaran, Siregar-Sibadihon, Janji Mauli, and Rumah Holi contain bicarbonate water.

Acid sulfate water is formed through the process of condensing gases from geothermal fluid vapor with oxygen-rich groundwater near the surface. Gases, along with steam and other volatile elements, are initially dissolved in geothermal fluids at depth, then released from the liquid phase of hot fluids after a boiling process. The gases then migrate towards the shallower part (above groundwater level), so that condensation occurs and sulphate water is formed. The presence of acid sulfate water manifestations indicate the presence of a permeable zone which serves as a container of chloride (boiling) water under the surface of Mount Pusuk and Rianiate-Sigaol. Bicarbonate water is formed through the condensation of vapor and gases into oxygen-poor subsurface groundwater. Bicarbonate water usually indicates the margin/outflow of a geothermal system due to lateral migration.

Based on the ternary diagram of Cl-HCO_3-SO_4, it was concluded that there was no sample of water that could be used in calculating an accurate geothermometer to determine the reservoir temperature. Thus, the determination of reservoir temperature was by calculating gas geothermometers taken from solfatara around Pusuk Bukit and Rianiate. Next, to find out the relationship between sub-systems in a deeper zone, more conservative elements, such as Cl, Li and B, were used. The ternary diagram of Cl-Li-B (Figure 3 (b)) was used to analyze the source of geothermal fluid reservoir. Based on a significant B/Cl and Li/B ratio, the manifestations of warm and hot springs in Simbolon-Samosir Area can be grouped into three classes:

a. Low B/Cl ratio, which is between 0.04 and 0.07 with low Li/B ratio <0.5 (Rianite-1, Rianite-2, Rianite-4, Sigaol-1, Sigaol-2, Pagaran-1, Pagaran-3, Pagaran-5, Sibadihon, and Sigondang-3), showing that springs may originate from one reservoir source. The value differences between B and Cl (different ratio values) are caused by variations in B proportion, which is dissolved from sedimentary rocks when the thermal fluid passes through sedimentary rocks. Low B/Cl content can also be formed due to a dilution process of chloride water when flowing to the surface.
b. High B/Cl ratio, which is between 0.12 and 1.10 with low Li/B ratio of 50.5 (Rianite-3, Pusuk Bukit-1, Pusuk Bukit-2, and Rumah Holi), indicating a steam absorption process from thermal fluid. A relatively high proportion of B, compared to Cl, signals the absorption of steam into liquid phase. The high value of B in Rianite-3 is assumed to be due to a steam absorption process with a high B/Cl content.
c. High B/Cl ratio (0.12) and high Li/B ratio (0.6-0.9) (Sigaol-3 and Pagaran-2).

The geological conditions of Simbolon-Samosir area indicate an association with volcano-magmatic activities (from Caldera Toba). Also, there are fluid interactions with sedimentary rocks around it. Hot springs are predicted to originate from the same reservoir source at depth, then migrate and undergo evolutions through different processes of dilution and absorption of Cl/B in their interaction with sedimentary rocks. The ternary diagram of Na-K-Mg (Figure 3 (c)) shows that all the hot springs are in immature water zone, suggesting a mix between reservoir fluid and surface water in the process of forming hot spring manifestations. Next, an isotope analysis was carried out on the eight samples of hot springs manifestations in Pusuk Bukit (Pusuk Bukit-1 and Rumah Holi), Rianite-1, Rianite-3, Sigaol-1 and Sigaol-3, Pagaran and Siregar-Sibadihon. The results of plotting between ^{18}O and deuterium (Figure 3 (d)) show that the ^{18}O isotope position from Pusuk Bukit-1 and Rianite-1 is shifting quite significantly (close to the magmatic zone), which may be caused by the mixture of reservoir fluid and meteoric water which enriches ^{18}O content of meteoric fluid. Meanwhile, Rianite-3, Sigaol-1, and Sigaol-3 are near meteoric water lines, and this indicates that the fluid is originated from meteoric water.

A gas chemical analysis was also conducted by taking six samples of bubble gas and solfatara. The six samples contain high CO_2 gas, which is typical in various geothermal regions with high temperature in the world. In addition, their H_2S content is also high, which can occur due to an alteration of reservoir rocks or magmatic contribution. He/Ar and N_2/Ar ratios in the diagram of He-N_2-Ar (Figure 3 (e)) show the presence of magmatic components in gas samples from Sigaol-2. Although NH_3 gas is not present, the presence of N_2 gas, which is quite dominant, and CH_4 gas, which is quite significant, in Sigaol-2 is interpreted as the result of reaction between thermal fluid and sedimentary rock at depth. This is supported by a B-content analysis in Simbolon-Samosir geothermal system which is associated with subsurface sedimentary rocks. The results of gas geothermometer calculation using the Nehring-D'Armore (1981) and Arnorsson Gunlaugsson (1985) methods provide representative results, namely quite high reservoir temperatures ranging between 222 and 258^oC for Pusuk Bukit area and 157-263^oC for Rianite area. Simbolon-Samosir geothermal upflow area is estimated to be around Pusuk Bukit and Rianite-Sigaol, with temperature reservoirs ranging between 222 and 263^oC.

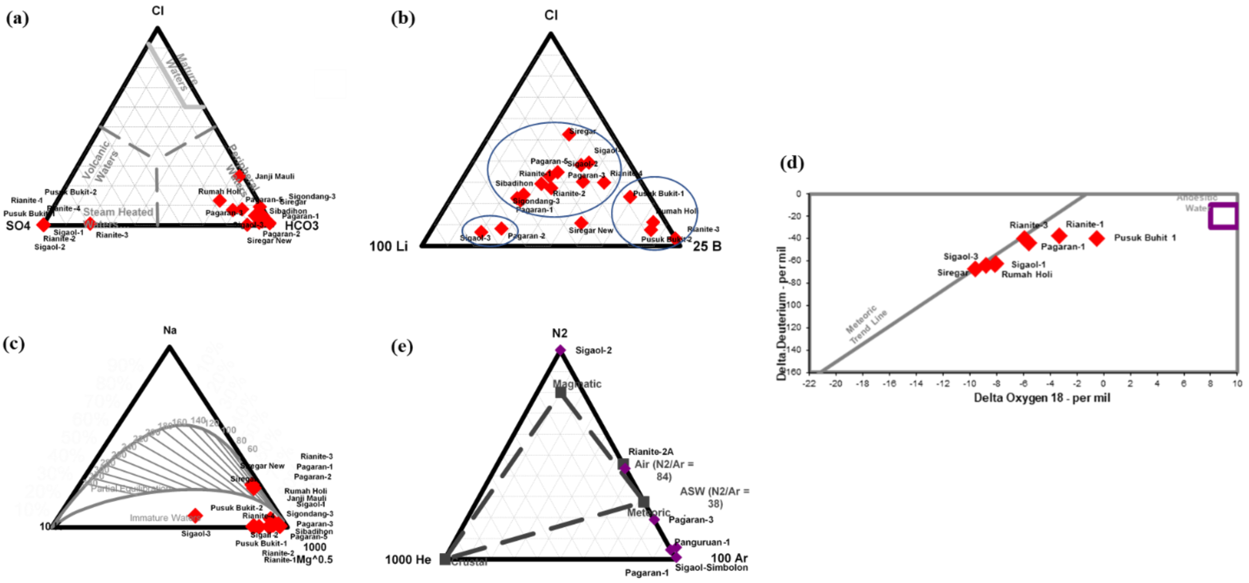


Figure 3 (a) Ternary Diagram Cl-HCO_3-SO_4 (b) Ternary Diagram Cl-Li-B (c) Ternary Diagram Na-K-Mg (d) Deuterium-^{18}O Diagram (e) Ternary Diagram He-N_2-Ar

2.3. Bonjol PSPE Area

Administratively, Bonjol geothermal area is located in Bonjol District, Pasaman Regency, West Sumatra Province. This area was carried out Preliminary Survey by Geological Agency in 2007 and now the PSPE was given to PT Medco Power Indonesia based on the Head of Investment Coordinating Board's Decree No. 1/1/PSPB/PMDN/2019 dated February 8, 2019.

2.3.1. Geology

The morphology of Bonjol area is categorized based on the shape of landscape and the level of the slopes, such as steep morphological hillsides, medium sloping hills, and plain morphology. The rock units in Bonjol region, as ordered from the oldest to the youngest (Appendix Figure 3), are Sedimentary Sihapas Formation (Tms), Bukit Malintang Lava (Tmlm), Old Lava (Tmv), Mount Beringin Lava-1 (Ql1br), Lava-2 Mountain Banyan (Ql2br), Old Sediment (Qs), Maninjau Piroklastika (Qapm), Bukit Gajah Lava (Qlg), Bukit tinggi Lava (Qlbt), Bukit Lava-1 Simarabun (Ql1s), Lava-2 Bukit Simarabun (Ql2s), Bukit Binuang Lava (Qlb), and Alluvium Deposits (Qa). The rock units which play an important role in the formation of Bonjol geothermal system are units of young volcanic rocks, which form the youngest volcanic cone of Bukit Binuang, aged 1.3 ± 0.1 million years old (Kala Plistosen). The heat source is estimated to be beneath the Binuang cone which originates from the residual of magma chamber underneath at an unknown depth.

Bonjol area is located in Great Sumatra Fault (GSF) zone, which lies in the direction of northwest - southeast. This is evidenced by the results of an investigation by Geological Agency which shows that the structures developed in the field are dominated by normal faults trending northwest - southeast (Padang Baru fault, Alahan Mati fault, Bonjol fault, and Malintang fault) and southwest - northeast (Takis fault). The New Padang Fault and Takis fault are structures that control the appearance of hot springs in Bonjol area.

2.3.2. Geochemistry

Geothermal manifestations in Bonjol area consist of hot springs in Takis, Sungai Limau, Padang Baru, and Kambahan areas, and also cold spring in Batu Ampa. Hot and cold springs are relatively neutral (pH=6.5-7.5). The highest temperature is in Takis spring, at 87.9 ^oC, while Sungai Limau and Kambahan have temperatures of around 73 ^oC. These springs have dominant Cl concentration (1118.1-1512.12 mg/kg), compared to HCO_3 (98.83-127.14 mg/kg) and SO_4 (61.73-213.57 mg/kg). The ternary diagram of Cl-SO_4-CO_3 (Figure 4(a)) shows that those springs contain chloride water, indicating deep water. The thermal fluid associated with geothermal sources then interacts with the surrounding rock and is mixed with the surface water, forming a neutral spring. The relatively high B content indicates that the thermal fluid interacts with sedimentary rocks at depth. Also, those springs are located in mature water, which are supposed to originate directly from the deep reservoir, so they provide better pictures of reservoir fluid conditions.

As a comparison, Padang Baru hot spring has a lower temperature than that of Takis, Sungai Limau and Kambahan, which is 49.7^{o}C, and has the type of chloride-bicarbonate fluid. This hot spring is indicated to have been mixed with surface water. Based on the ternary diagram of Na-K-Mg (Figure 4(c)), the positions of Takis, Sungai Limau, and Padang Baru hot spring are in partial equilibrium, signaling that the manifestations appearing on the surface are influenced by interactions between fluid and rocks in thermal conditions before mixing with surface water. Meanwhile, Kambahan hot spring is located in immature water zone. The estimated reservoir temperature based on the diagram of Na-K-Mg is 180^{o}C (medium temperature).

Furthermore, the ternary diagram of Cl-Li-B (Figure 4(b)) illustrates that all hot springs come from the same reservoir and are located more towards the middle position of the diagram below Cl. The concentrations of ^{18}O and deuterium isotopes in four hot spring samples and one cold spring sample show ^{18}O isotope values ranging from -9.22 to -7.06 o/oo and D isotope ranging from -61 to -53 o/oo. The graph of ^{18}O vs. D (Figure 4(d)) points out that the hot spring samples are located on the right of meteoric water line, indicating enrichment to oxygen 18 from the hot spring due to the oxygen 18 substitution reaction between rock and oxygen from thermal fluid when it interacts with rocks at depth before appearing on the surface. Finally, Batu Ampa is located in meteoric water line, as indicated by surface water.

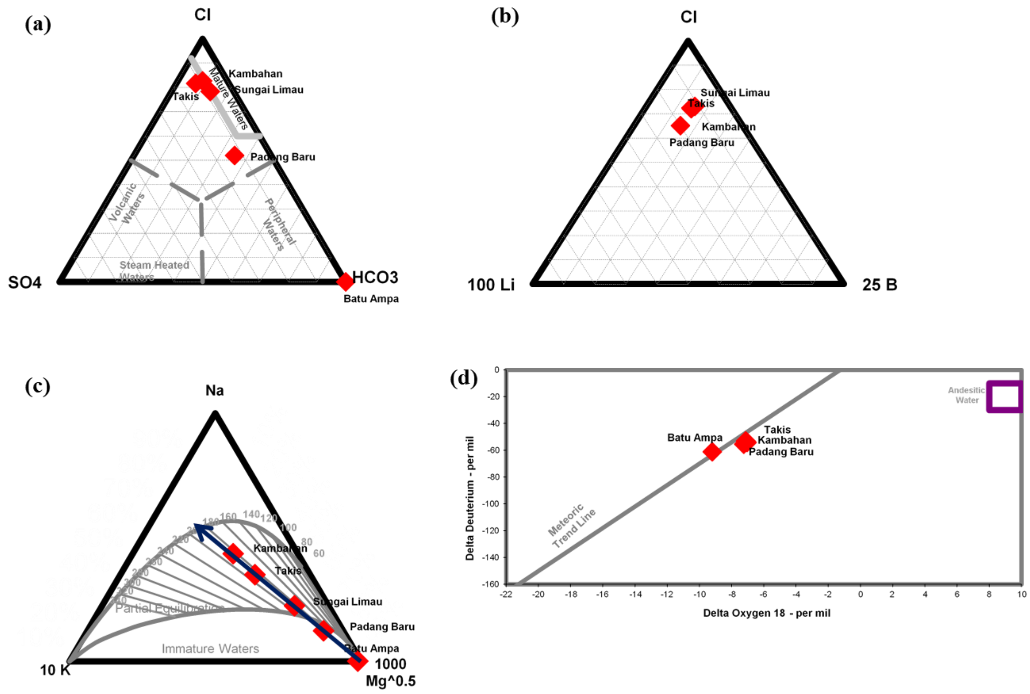


Figure 4 (a) Ternary Diagram Cl-HCO_3-SO_4 (b) Ternary Diagram Cl-Li-B (c) Ternary Diagram Na-K-Mg (d) Deuterium-^{18}O Diagram

2.4. Cubadak PSPE Area

Administratively, Cubadak geothermal area is located in Duo Koto District, Pasaman Regency, West Sumatra Province. This area was carried out Preliminary Survey by Geological Agency in 2008.

2.4.1. Geology

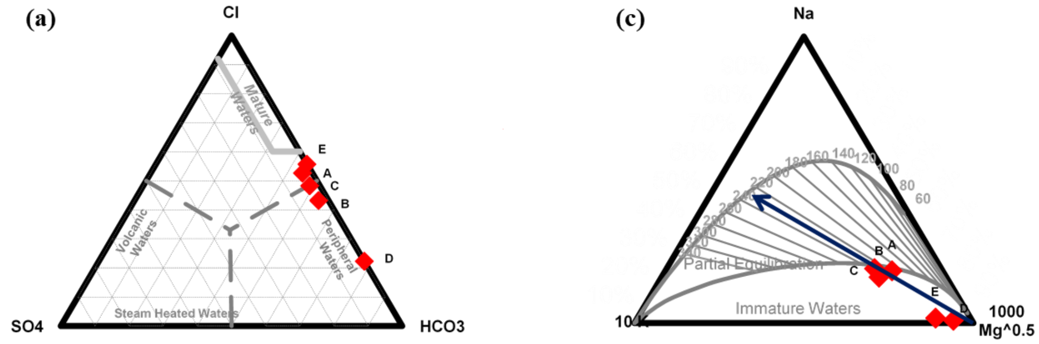
The morphology of Cubadak area is categorized based on the shape of landscape and the level of the slopes, such as steep hills, bumpy hills, gentle slopes and plains. The rock units in Cubadak region, as ordered from the oldest to the youngest, include Batusabak (Pbs), Meta Andesit (Pma), Meta Limestone (Pmg), Kristalin Limestone (Pgk), Rao Hill Intrusion (Tir), Cubadak Pyroclastic Flow (Qpc), Bukit Godang Lava (Qlg), Bukit Godombong Lava (Qlgd), Bangkok Hill Lava (Qlb), Bukit Tampatbulakan (Qlt) Lava, Lava Bukit Tombangpinang (Qltp), Bukit Lava (Qls), Lake Deposition (Qed), and Aluvium (Qal) (Appendix Figure 4). The rock units which play an important role in the formation of Cubadak geothermal system are volcanic rock units consisting of pyroclastic flows and lava products from fissure eruption activities that are 1.2 ± 0.2 million years old (Kala Plistosen). The heat source is estimated to be in the form of residual heat from magma chamber associated with volcanic eruptive eruptions (fissure eruption).

Cubadak area is located in the Great Sumatran Fault (GSF) zone, in the northwest-southeast direction. This is evidenced by the results of an investigation by Geological Agency which shows that the structures developed in the field are dominated by normal faults in the direction of northwest-southeast (Cubadak fault, Andilan fault, and Rantaupanjang fault), normal faults in the direction of southwest-northeast (Botung fault, Batuampar fault, and Kuraba fault), and a horizontal fault in the direction of southwest-northeast. Cubadak and Botung faults are fault structures that control the appearance of hot springs in Cubadak area.

2.4.2. Geochemistry

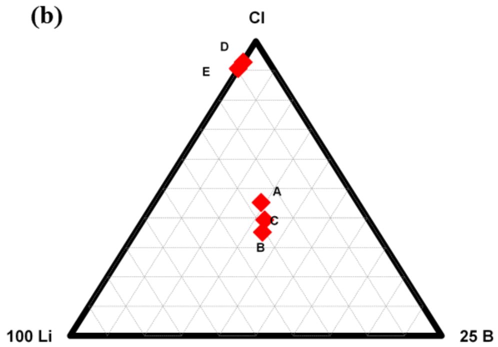
Geothermal manifestations in this area consist of hot springs spread out in Cubadak and Sawah Mudik. Hot springs in Cubadak area (Cubadak-1, Cubadak-2, and Cubadak-3) have temperatures varying from 68.4 to 74.8 °C and near-to-normal pH (pH=6.4-6.8). These springs have high concentrations of Li, Na, K, Ca, Mg, SiO_2, and B compared to the hot spring in Mudik Sawah. The concentrations of Cl (391.99-452.27 mg/kg) and HCO_3 (381.57-496.38 mg/kg) are more dominant than SO_4 (25-30 mg/kg). The ternary diagram of Cl-HCO_3-SO_4 (Figure 5(a)) shows that those springs are categorized as the type of chloride-bicarbonate fluid. Meanwhile, the hot spring in Sawah Mudik has a lower temperature than those in Cubadak area, which is at 37.1 °C, and is relatively normal (pH=7.7). This spring similarly contains chloride-bicarbonate fluid. Chloride-bicarbonate fluid is formed through a condensation process of vapors and gases of thermal fluids from inside (reservoir) into underground oxygen-poor groundwater. The level of B, which is relatively high in hot springs in Cubadak area, can inform the possibility of high temperature fluid interacting with sedimentary rocks when flowing to the surface.

The ploting in the ternary diagram of Na-K-Mg (Figure 5(c)) shows that hot springs of Cubadak (Cibadak-1, Cubadak-2 and Cubadak-3) lie in the border line between partial equilibrium and immature water. This illustrates that the hot springs are likely to come directly from a depth with a fairly high temperature and shows relatively little meteoric water dilution, whereas the hot spring in Mudik Sawah is in the immature water zone and is likely to be heated surface water or influenced by dominant meteoric water. The plotting in ternary diagram of Cl-Li-B (Figure 5(b)) shows that all of the hot springs are positioned in the middle and head towards Cl-B, indicating that the thermal fluid comes out between sediment and volcanic rocks. This is in accordance with the high B concentration in the area (11.52-16.36 mg/kg). The estimation of reservoir temperature in Cubadak area used: 1) SiO2 geothermometer (conductive cooling), resulting in 148-161ºC, which is categorized as medium entalphy; and, 2) Na/K Giggenbach geothermometer, capturing a range of 218-250ºC, which shows a relatively high temperature (Figure 5(d)).



(d)

Sample Name	Quartz cond	Na/K (Giggenbach)
Cubadak-1	148	218
Cubadak-2	157	250
Cubadak-3	161	235



Hot Spring:
A : Cubadak-1
B : Cubadak-2
C : Cubadak-3
D : Sawah Mudik
Cold Spring:
E : Cubadak

Figure 5 (a) Ternary Diagram Cl-HCO3-SO4 (b) Ternary Diagram Cl-Li-B (c) Ternary Diagram Na-K-Mg (d) Results of Geothermometer Calculation

2.5. Tanjung Sakti PSPE Area

Administratively, Tanjung Sakti area covers two provinces (South Sumatra and Bengkulu) and five districts/cities (Empat Lawang, Lahat, Pagaralam City, South Bengkulu, and Seluma).This area was carried out Preliminary Survey by PT Hitay Tanjungsakti Energy (PT THE) and and now the PSPE was given to PT THE based on MEMR's Decree No. 1868 K/30/MEM/2018 dated June 21, 2018.

2.5.1. Geology

The morphology of Tanjung Sakti can be grouped into several main morphological units, namely Mount Dempo, undulation, and lowland. Based on regional and field geological data, rocks found in the prospective area are volcanic rocks, such as andesitic lava, tuff, and lava, while the oldest rocks include Lingsing, Saling, Talangakar, Gumai, and Kikim formations in the form of meta-sediment and volcanic rocks. Old-aged rocks are also found, which are likely to be basements from the southern Sumatra region. Tanjung Sakti is controlled by the Great Sumatra Fault (GSF) and its companion faults, which produce a depressive structure trending northwest-southeast. In the area of depression there are volcanic activities of quaternary age, with Mount Dempo as the latest product (Appendix Figure 5).

Geothermal manifestations in the form of fumarole and alteration on the surface are commonly found near the summit of Mt. Dempo, but in the south foot of Mt. Dempo, some alterations are also identified by remote sensing and field data. In the northern part of the study area, further away to the southwest, other than rock alterations in some locations, other manifestations are found in the form of hot springs and warm springs. The geology in this case indicates that the most obvious geothermal activity (indicated by the emergence of fumarole) is estimated to be controlled by heat source connected to the volcanic depression of Mt. Dempo. The manifestation of fumaroles near the summit of Mount Dempo requires a high temperature geothermal system (reaching 99ºC).

2.5.2. Geochemistry

Surface manifestations found in Tanjung Sakti geothermal area consist of fumaroles, hot springs, warm springs, cold springs, rivers, and crater lakes. The types of geothermal fluids analyzed from water samples are grouped into (Figure 6(a)) :

a. Acid sulfate and volcanic water, namely Dempo Air Bayau spring, which has a low temperature (22ºC) and acid pH (pH=3). This spring has high concentrations of Na, K, Ca, Mg, SiO_2, SO_4, and F.
b. Sulfate-chloride water, including Dempo Air Klinsar, Dempo Tanjungsakti, Tanjungsakti Beringin Dempo, and Dempo Tanjungsakti Pamindaian, with a low temperature (22ºC) and alkali pH (pH=8).
c. Chloride bicarbonate fluid, namely Tanjung Alam 2 HS, Tanjung Alam 1 Dempo HS, Dempo Tanjung Raman 1 and 2, with a temperature of 44-45ºC and more alkaline pH (pH=9).

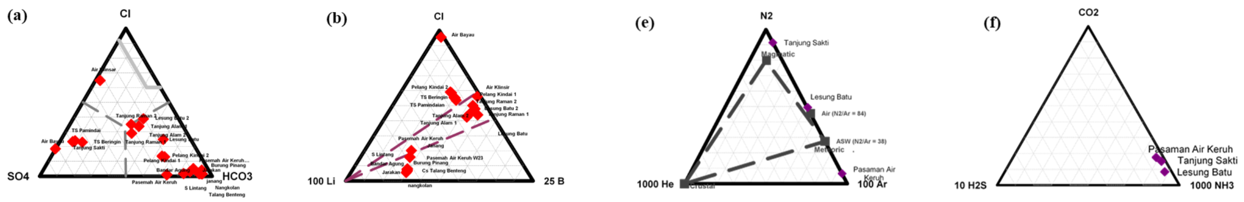
d. Bicarbonate fluid with a lower temperature (22°C) and near-to-neutral pH. This spring is indicated as an outflow of geothermal system in Tanjung Sakti area.

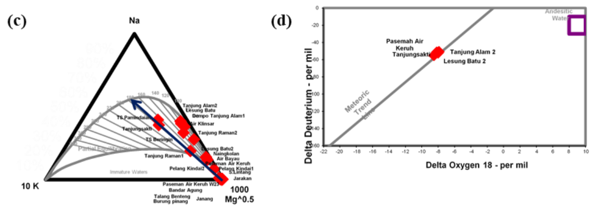
The comparison of Li-Cl-B concentrations (Figure 6(b)) can be used as an indication of reservoir fluid origin. The ternary diagram displays three separate groups: 1) the northern block, including Pelang Kindai 2, Tanjungsakti Beringin, and Tanjungsakti Pamindaian springs; 2) the middle block, including Turbid Water, Janang, W23 Turbid Water Pasemah, Pinai Bird, CS Talang Benteng, Nangkolan, Jarakan, Bandar Agung, and S. Lintang springs; and, 3) the southern block, including Klinsir, Pelang Kindai 1, Tanjung Raman 1, Tanjung Raman 2, Lesung Batu 2, Tanjung Alam 1, and Tanjung Alam 2 springs. Meanwhile, the comparison of Na-K-Mg concentration (Figure 6(c)) can indicate the balance process between reservoir fluid and rock. Tanjungsakti, Tanjungsakti Pamindaian, Lesung Batu, Tanjung Alam 1, Klinsar Water, Tanjungsakti Beringin, Tanjung Raman 2, and Tanjung Raman 1 are located in partial equilibrium zone, suggesting that the fluids have experienced a partial equilibrium after reacting with the surroundings they pass. On the other hand, the other springs are in immature water zone, characterized by a high concentration of Mg, and have been mixed with surface water or groundwater.

The manifestation of hot springs samples in Tanjung Sakti geothermal area could not be effectively used in geothermometers to calculate reservoir temperature estimation because the fluids have been mixed with surface water or groundwater. Furthermore, an isotope analysis was only carried out on four fluid samples taken from manifestations in Pasemah Air Tanah, Tanjung Sakti, Lesung Batu 2, and Tanjung Alam 2. The availability of the low deuterium and ^{18}O isotopes could not be used to analyze the mixing relationship between samples. The D vs. ^{18}O isotope comparison diagram (Figure 6(d)) shows that hot water manifestation samples are near meteoric trend line, which indicates that geothermal reservoir fluid is from meteoric water.

The temperature calculation results of Na-K (Gigganbach) geothermometer from hot spring samples show that reservoir in the southern cluster has a temperature of 113°C, the one in the middle cluster has a temperature of 340°C, and the one in the northern cluster has a temperature of 140°C. The results of gas geothermometer calculation reveal the temperature manifestation of Tanjung Sakti at 220°C, Pasaman Air Keruh at 227°C, and Lesung Batu at 273°C (Figure 6(g)).

Next, the chemical gas content in Tanjung Sakti geothermal manifestation is low in CO_2, H_2S, NH_3, and H_2. However, Tanjung Sakti and Lesung Batu have a high concentration of N_2 compared to Pasaman Air Keruh and the lowest Ar content is in Tanjung Sakti. The ternary diagram of He-N_2-Ar (Figure 6(e)) shows the presence of potentially acidic magmatic heat source in Tanjung Sakti gas. The high N_2/Ar ratio in Tanjung Sakti is likely due to the addition of N_2 resulting from thermal decomposition of organic material in subducted sediment rock. This finding also supported by the high NH_3 concentration which showed in the ternary diagram of H_2S-CO_2-NH_3 (Figure 6(f)).





(g)

GEOTERMOMETER							
Gas Sample	T_{DAP} (°C)	T_{H2S} (°C)	T_{CO2} (°C)	$T_{H2/Ar}$ (°C)	$T_{CO2/H2}$ (°C)	$T_{H2S/H2}$	$T_{CH4/CO2}$
Lesung Batu	281	94	-12	95	310	326	174
Pasaman Air Keruh	195	89	37	33	239	285	188
Tanjung Sakti	186	101	98	117	242	292	166

Figure 6 (a) Ternary Diagram Cl-HCO_3-SO_4 (b) Ternary Diagram Cl-Li-B (c) Ternary Diagram Na-K-Mg (d) Deuterium-^{18}O Diagram (e) Ternary Diagram N_2-He-Ar (f) Ternary Diagram H_2S-CO_2-NH_3 (g) Results of Gas Geothermometer

2.6. Graho Nyabu PSPE Area

Graho Nyabu Geothermal PSPE area is located in Merangin Regency, Kerinci Regency, Jambi Province and Muko Muko Regency, Bengkulu Province. This area was carried out Preliminary Survey by PT EDC Indonesia and and now the PSPE was given to PT EDC Indonesia based on MEMR's Decree No. 1866 K/30/MEM/2018 dated June 21, 2018.

2.6.1. Geology

The stratigraphy in Graho Nyabu area was previously mapped as part of the 1:250,000 Geological Map of the Sungai Penuh and Ketaun Quadrangle, Sumatra (Kusmana et al., 1993). Based on this geological map, the lithology of the survey area consists of tertiary to quaternary igneous rocks that can be classified into several lithological units, namely Hulusimpang Formation (Tomh), Langkup Granodiorite (Tpgd), Rhyo Andesite Volcanic Unit (QTv), Volcanic Breccia, and Tuff (Qhv). The conclusion of the structural synthesis by investigators was that the area was dominated by the Great Sumatra Fault (GSF), specifically the Little Fault segment. Data on the measurement of the joint and the fault indicate that the direction of the structure that develops northwest - southeast and extensional structures is relatively dominated by faults trending northeast-southwest.

Geothermal manifestations in Graho Nyabu area are closely associated with the structure (Appendix Figure 6), located in the northern central part of the study area which is bordered by the Sumatran Fault in the west, the edge of the Lubuk Mentilin caldera in the south, and the young structures of Mount Hulunilo, Mount Sumbing, and Mount Atapijuk/Hutapanjang in the northwest. The most important part of these thermal manifestations is the Graho Sakti hot spring with neutral pH and acid fumaroles from Graho Solar/Graho Kunyit and Graho Gas located around Mt. Kunyit at a higher altitude. In Mt. Sumbing, only steam fields are observed, but it should also be noted that there are historic hydrothermal eruptions in several areas. Graho Sakti is located along the intersection between northwest-southeast direction faults and the eastern-western synthetic dextral transtensional faults. Meanwhile, the Graho Solar complex is considered to be controlled by a hidden north-south Riedel sinistral antithetis transtensional fault.

2.6.2. Geochemistry

The hot spring manifestations in Graho Solar, Graho Ngoa, Graho Gas, and Graho Kunyit have high temperatures of 92-94°C and acid fluid with pH of 4. These springs have a high concentration of SO_4 (68-382 mg/kg), very low Cl (2-4 mg/kg), and HCO_3 (0.99 mg/kg) content, and are included in the type of sulfate acid (steam heated) water, which is formed by H_2S gas oxidation process of sulfate fluid from the reservoir and reacts with surface water or groundwater, and this is indicated as an upflow of Graho Nyabu geothermal system. Sipurak and Serampas springs have a neutral pH, relatively low temperatures (42-63 °C), low SO_4 (11-83 mg/kg), and high HCO_3 (60-259 mg/kg) and Cl (129-181 mg/kg) concentration, and are classified as bicarbonate-chloride water. Graho Ngabu spring has the lowest temperature compared to other springs (39°C), neutral pH, and dominant HCO_3 (117 mg/kg) content compared to Cl (3 mg/kg) and SO4 (4.99 mg/kg) content. This spring is the type of bicarbonate fluid and indicates the outflow/margin of Graho Nyabu geothermal system. Graho Sakti spring has the highest temperature approaching boiling, which is 98.1°C, and Graho Matahari has a temperature of 87.1°C. Both springs have a pH that tends to be alkaline, which is equal to pH 8-9, high Cl content (574-714 mg/kg), low HCO_3 (36-47 mg/kg), and SO_4 (65-77 mg/kg). These springs contain chloride fluid and are located in mature water zone. The alkaline pH is thought to be due to a slight mixing with surface water that is rich in bicarbonate and formed from relatively high gas content from deep reservoir. Graho Inum spring also belongs to the chloride fluid type (Cl 722 mg/kg) and is located in mature water zone but has a lower temperature (64°C) and a neutral pH of 7). The hot spring manifestation in mature water zone is indicated as reservoir fluid and can be used in calculating reservoir fluid temperature using a geothermometer calculation. Graho Nyabu reservoir fluid has a neutral pH (pH=7) (Figure 7(a)).

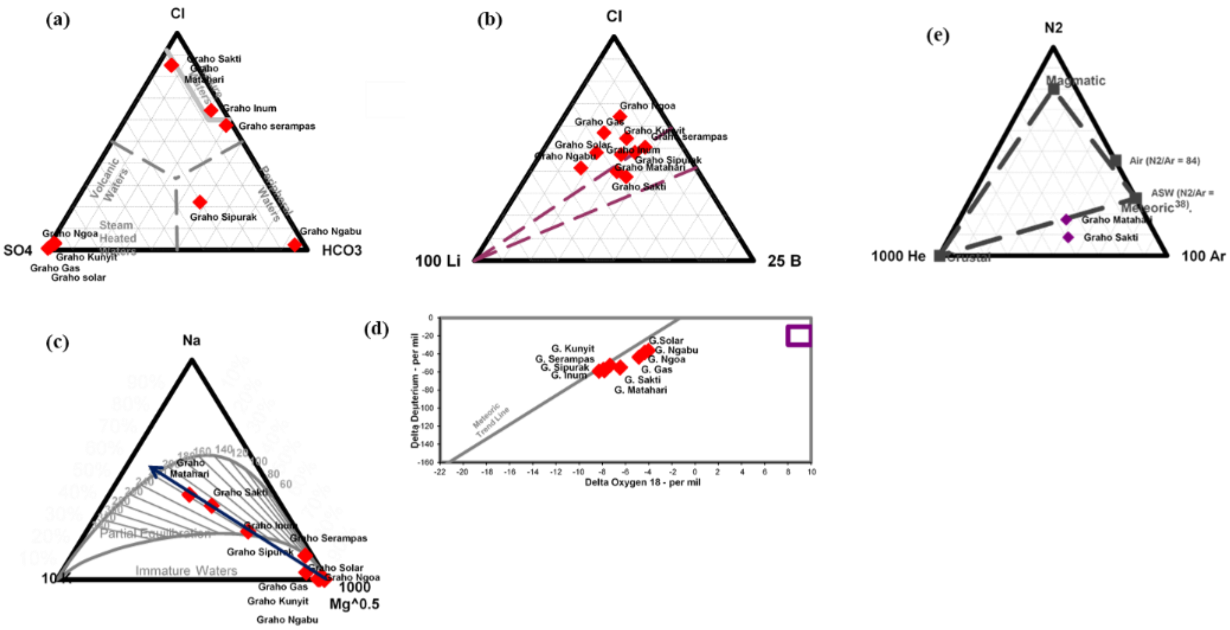


Figure 7 (a) Ternary Diagram Cl-HCO$_3$-SO$_4$ (b) Ternary Diagram Cl-Li-B (c) Ternary Diagram Na-K-Mg (d) Deuterium-^{18}O Diagram (e) Ternary Diagram N$_2$-He-Ar

The Cl/B ratio (Figure 7(b)) was used to determine the homogeneity of thermal fluid, whether or not it comes from one source reservoir. The ternary diagram indicates that all of the hot springs are from the same reservoir. However, the content of B varies across all hot springs due to various degrees of B adsorption in rocks in the area. Next, the estimation of reservoir temperature based on the diagram of Na, K, and Mg shows 212 °C (Figure 7(c)). The origin of reservoir fluid is indicated to be influenced by meteoric water as shown by the comparison isotop diagram of D and ^{18}O (Figure 7(d)), which shows that the hot springs samples are near meteoric water line. Finally, as for gas samples from Graho Matahari fumarole, they have higher content of CO_2, H_2S, Ar, N_2, CH_4, H_2, and He than in Graho Sakti. Gas samples from surface vapor released in Graho Sakti and Graho Solar were also analyzed to find out the reservoir fluid origin. The ternary diagram of N_2-He-Ar (Figure 7(e)) shows that the gas in Graho Nyabu is from meteoric water inside circulation. Gas geothermometer calculations provide a higher estimate of reservoir temperature than the calculation of water geothermometers, which is at 250 - 272°C.

2.7. South Sekincau PSPE Area

Administratively, South Sekincau Geothermal PSPE area is in West Lampung Regency, Lampung Province. This area was carried out Preliminary Survey by PT Star Energy Geothermal Suoh Sekincau (PT SEGSS) and now the PSPE was given to PT SEGSS based on the MEMR's Decree No. 1870 K/30/MEM/2018 dated June 21, 2018.

2.7.1. Geology

South Sekincau PSPE area is in the volcanic mountains of Bukit Barisan, adjacent to the Great Sumatra Fault (GSF). Dextral movement on the large Sumatran fault produces a downward movement and forms the Suoh sedimentary basin. Mount Sekincau is an inactive andesitic volcanic complex, about 15 km to the north of the Suoh basin, with a large crater/caldera containing younger dome and intermediate silicic composition. This volcanic complex is mostly pleistocene with an andesitic to dacitic composition (Appendix Figure 7(a)).

The stratigraphy of the study area (Appendix Figure 7(b)) can be classified into four main rock groups: 1) volcanic rocks and basin fill rocks with quaternary age; 2) local tertiary volcanic rocks that are mapped in the study area; 3) regional tertiary volcanic rocks and sediments interpreted under local rock units; and, 4) older pre-tertiary basement rocks. Of the four rock groups, only the first two units are mapped on the surface of the preliminary survey area. Two other units are interpreted under the unit (PT SEGSS's Report, 2015). The main fault system in this area is the Great Sumatra Fault (GSF) with a northwest-southeast direction which is a horizontal sliding fault stretching along Sumatra. This fault has several segments, and one of the major steps is found in the Suoh area, and between the two segments of this fault, the lowlands of Suoh have decreased and formed sedimentary basins. The research area, regionally, consists of low grade meta sedimentary rocks (slate, phyllite, and quartzite) and granite intrusion.

2.7.2. Geochemistry

Thermal manifestations in South Sekincau geothermal area consist of fumaroles, kaipohans, mud pools, and hot springs. The hot springs manifestations in South Sekincau area have high temperature ranging from 80 to 100^oC with varying fluid pH, including acidic (pH=1-3), near-to-normal pH (pH=6-7), and alkaline (pH=8) with details as follows (Figure 8 (a)):

a. Acid sulfate fluid (steam heated water) type, namely Purunan, Danau Tapir, Belirang, Umbul Jeruk, Kawah Putri, Becingut, Gajah Mati AS, Talang Minggu, and Onje Springs. This fluid is characterized by acidic pH (pH=1.4-3.59) and high SO_4 (52.85-1434.99 mg/kg) compared to Cl (0.51-1.57 mg/kg) and HCO3 (2 mg/kg) concentrations. Sulfate fluid comes from oxidation of H_2S gas which accompanies the condensation process when steam rises to the surface. These springs are indicated as upflows of South Sekincau geothermal system.
b. Chloride fluid, including Way Haru, Kalibata, Keramikan, and Sukamarga springs. This fluid is characterized by high temperatures (approaching boiling water) and pH tending to be alkaline (pH=8). In addition, this fluid has high content of Li, Na, K, Ca, SiO_2, B, and Cl. Way Haru hot spring has the highest chloride concentration of 1900 mg/kg. This spring is also in mature water zone, which is good for geothermometer calculation to estimate reservoir temperature.
c. Bicarbonate fluid, namely Gajah Mati HS spring, which has a near-to-boiling temperature (98^oC), nearly-normal pH (pH=6.74), and high HCO_3 (269.98 mg/kg) compared to Cl (1.22 mg/kg) and SO4 (8.73 mg/kg) content. Bicarbonate spring are a result of CO_2 gas in steam that reacts and mixes with water near the surface. This fluid is indicated as an outflow of South Sekincau geothermal system.

Giggenbach Na-K-Mg diagram (Figure 8 (c)) was used to determine fluid equilibrium at depth. Kalibata and Keramikan springs are in full equilibrium zone with geothermometer temperature of 260^oC, while Way Haru spring is in partial equilibrium zone with a temperature of 200-220^oC. This spring may be affected by deposition of Mg-rich minerals when the fluid flows leave the reservoir. Low reservoir temperature and low Mg content in Way Haru constitute the characteristics of geothermal outflow areas. Equilibrium conditions of calibration and noise samples indicate a direct flow from geothermal reservoir. This spring is good to be used in water geothermometer calculation to estimate the temperature South Sekincau geothermal reservoir, which is 260^oC. Stable isotope plots show (Figure 8 (e)) that most hot spring samples are positioned near meteoric water line, which indicates typical geothermal fluid when mixed with meteoric water. Meanwhile, Keramikan and Talang Minggu springs appear to be located away from meteoric water line, showing the possibility of hot fluids experiencing interactions with the surrounding rocks.

Fumaroles in West Sekincau (Danau Tapir, Umbul Jeruk, and Kawah Sekincau) have moderate NCG levels and low H_2S concentration. Kaipohan in Umbul Jeruk area also has low H_2S concentration. Meanwhile, fumaroles in Northern Sekincau (Mount Loreng, Belirang, Kawah Putri, and Kawah Puncak) have high NCG content (>1wt%), relative to fumaroles in Southern Sekincau, and also have high H_2S concentration and high composition of CO_2 and N_2 relative to Ar (Figure 8 (f)). This indicates that the fumaroles may be associated with parts of hydrothermal system which are more magmatic with little influence from meteoric water. In Suoh Area, these characteristics are possessed only by fumaroles in Mount Loreng, while in East Sekincau, several fumaroles in Belirang sector share those characteristics. The gases are estimated to originate from immature water with acid fluid risk or high gas content. Conversely, samples taken from Southern part (Becingut sector) and South Suoh have lower NCG and H_2S content.

The comparison diagram of log H_2/Ar and log CO_2/Ar shows (Figure 8(g)) that the gas samples from fumaroles are in the zone between equilibrated liquid and equilibrated vapor, signaling that the reservoir fluid is of type 2 phase, with the highest temperature of around 250-275^oC. This is consistent with the calculation of water geothermometer from the equilibrium diagram of Na-K-Mg, which is 260^oC.

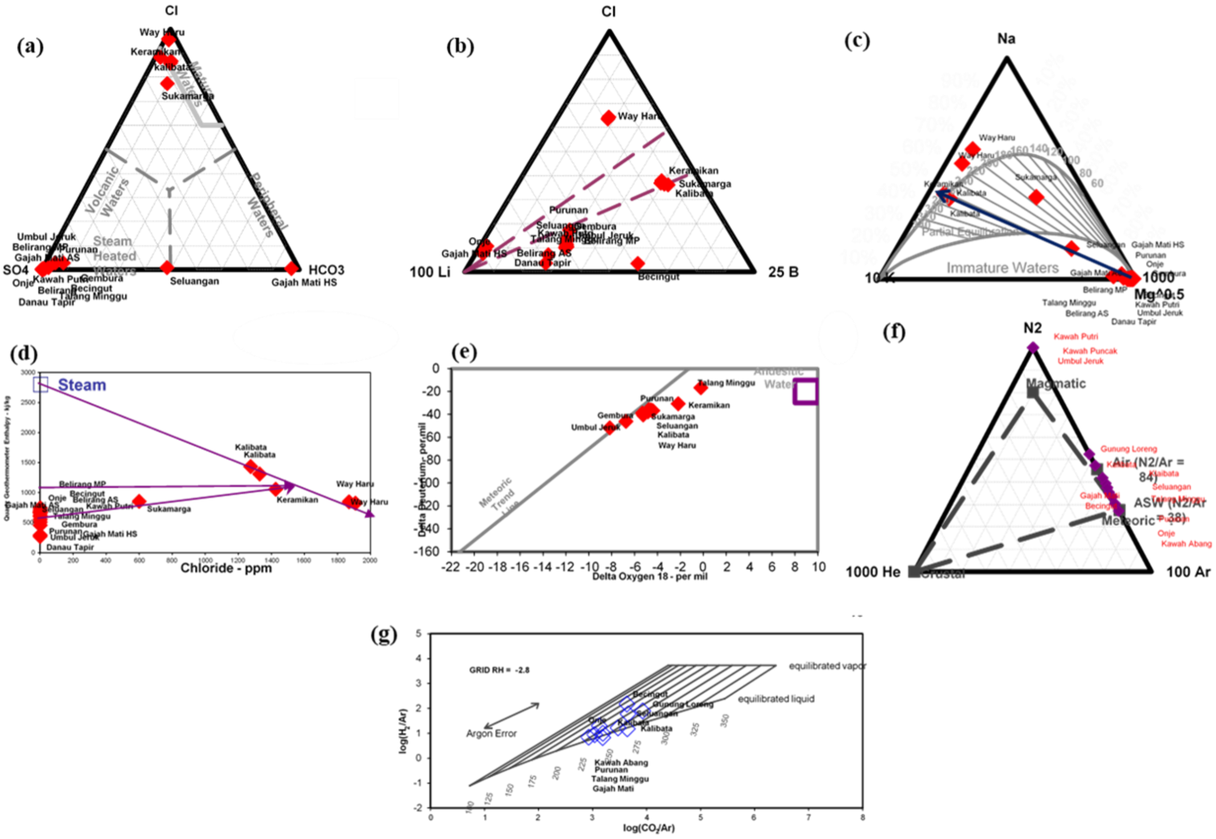


Figure 8 (a) Ternary Diagram Cl-HCO3-SO4 (b) Ternary Diagram Cl-Li-B (c) Ternary Diagram Na-K-Mg (d) Deuterium-18O Diagram (e) Ternary Diagram N_2-He-Ar

3. CONCLUSION

Characteristic of fluid chemistry in each PSPE's areas are as follow:

1. All hot springs in Mount Geureudong area are neutral fluids with pH of 5-7 with temperature ranging from 36 to 68°C. Wih Pesam hot spring is considered chloride fluid and located in mature water zone. Hot springs in Pepanji, Uning Bertih, and Wih Porak contain bicarbonate water. Deuterium and ^{18}O isotope analysis indicate that the origin fluid of the reservoir is meteoric water. The best indication of a high temperature geothermal resource is from Wih Pesam thermal area, with geochemical indication of 240°C liquid dominated system.
2. Hot springs in Simbolon-Samosir area contain steam-heated water (acid sulphate water) and bicarbonate water, and there is no chloride water found. The geological conditions of Simbolon-Samosir area indicate an association with volcano-magmatic activities (from Caldera Toba). Also, there are fluid interactions with sedimentary rocks around it. The results of plotting between ^{18}O and deuterium show that the ^{18}O isotope position from Pusuk Bukit-1 and Rianite-1 is shifting quite significantly (close to the magmatic zone). Meanwhile, Rianite-3, Sigaol-1, and Sigaol-3 indicates that the fluid is originated from meteoric water. Gas analysis show that the presence of magmatic components in gas samples from Sigaol-2. Simbolon-Samosir geothermal area is classified into the steam-dominated system (steam-heated reservoir) with the upflow area is estimated to be around Pusuk Bukit with an estimated temperature of 220-250°C (high enthalpy).
3. All hot springs in Bonjol area contain chloride fluid and are in partial equilibrium, as indicated by the liquid-dominated system with estimated an reservoir temperature of 180°C (medium enthalpy).
4. Cubadak hot springs point to the type of chloride-bicarbonate water and comes out between sediment and volcanic rocks. Based on Na-K Giggenbach geothermometer, the estimated geothermal reservoir temperature of Cubadak area is a range of 218-250°C (high enthalpy).
5. The ternary diagram of He-N_2-Ar shows the presence of potentially acidic magmatic heat source in Tanjung Sakti gas. The high N_2/Ar ratio in Tanjung Sakti is likely due to the addition of N_2 resulting from thermal decomposition of organic material in subducted sediment rock. The temperature calculation results of gas geothermometer reveal the estimation of reservoir temperature manifestation in Tanjung Sakti area is ranging 220-273°C.
6. Based on isotop and gas analyses, the fluid in Graho Nyabu reservoir may originate from meteoric water circulated in deep depth and heated by hot rocks. The estimated reservoir temperature according to a gas geothermometer calculation is 250 - 272 °C and is classified as a high-temperature system.
7. The interpreted prospective areas with the potential of high-temperature geothermal resources in South Sekincau area are in Western Sekincau, Eastern Sekincau, and Kalibata. Sekincau geothermal reservoir fluid belongs to the type of 2 phase system with an estimated temperature of 260°C (high temperature system) based on the gas geothermometer and liquid geothermometer.

Based on the geochemistry interpretation, the seven PSPE's areas show that each area has their-own characteristic although they are located in same Great Sumatra Fault structure. This conclusion may be resulted from aged rock, rock type, and local geological structure in each area. The extensive exploration data from drilling activities may confirm about the characteristic of reservoir fluid.

REFERENCES

Giggenbach and Goguel: Collection and Analysis of Geothermal and Volcanic Water and Gas Discharges, Petone, New Zealand (1989)

Nicholson, K.: Geothermal Fluids Chemistry and Exploration Techniques, Springer-Verlag, Berlin, Heildelberg (1993)

PT Jasa Daya Chevron: Preliminary Survey Assginment of Mount Geureudong Central Aceh Regency, Bener Meriah Regency, North Aceh Regency-Nanggroe Aceh Darussalam Province (2014)

PT Optima Nusantara Energi: Final Report Integrated Geothermal Preliminary Survey in Simbolon-Samosir Area, North Sumatra Province (2010)

Integrated Survey Team: Integrated Geological, Geochemical and Geophysical Survey of Cubadak Geothermal Area, Pasaman Regency, West Sumatra Province, Center for Geological Resources, Geological Agency (2008)

Integrated Survey Team: Integrated Survey of the Bonjol Geothermal Region of Pasaman Regency, Province of West Sumatra, Center for Geological Resources, Geological Agency (2007)

PT Hitay Tanjung Sakti Energy: Final Report Assignment of Preliminary Survey of Tanjung Sakti Geothermal Prospects, South Sumatra. (2015)

PT EDC Indonesia: Graho Nyabu Geothermal Prospect Geoscientific Assessment, Jambi Province Sumatera. (2014)

PT Chevron Geothermal Suoh Sekincau: Report of Geothermal Preliminary Survey Assignment in South Sekincau, West Lampung Regency, Lampung Province (2015)

APPENDIX

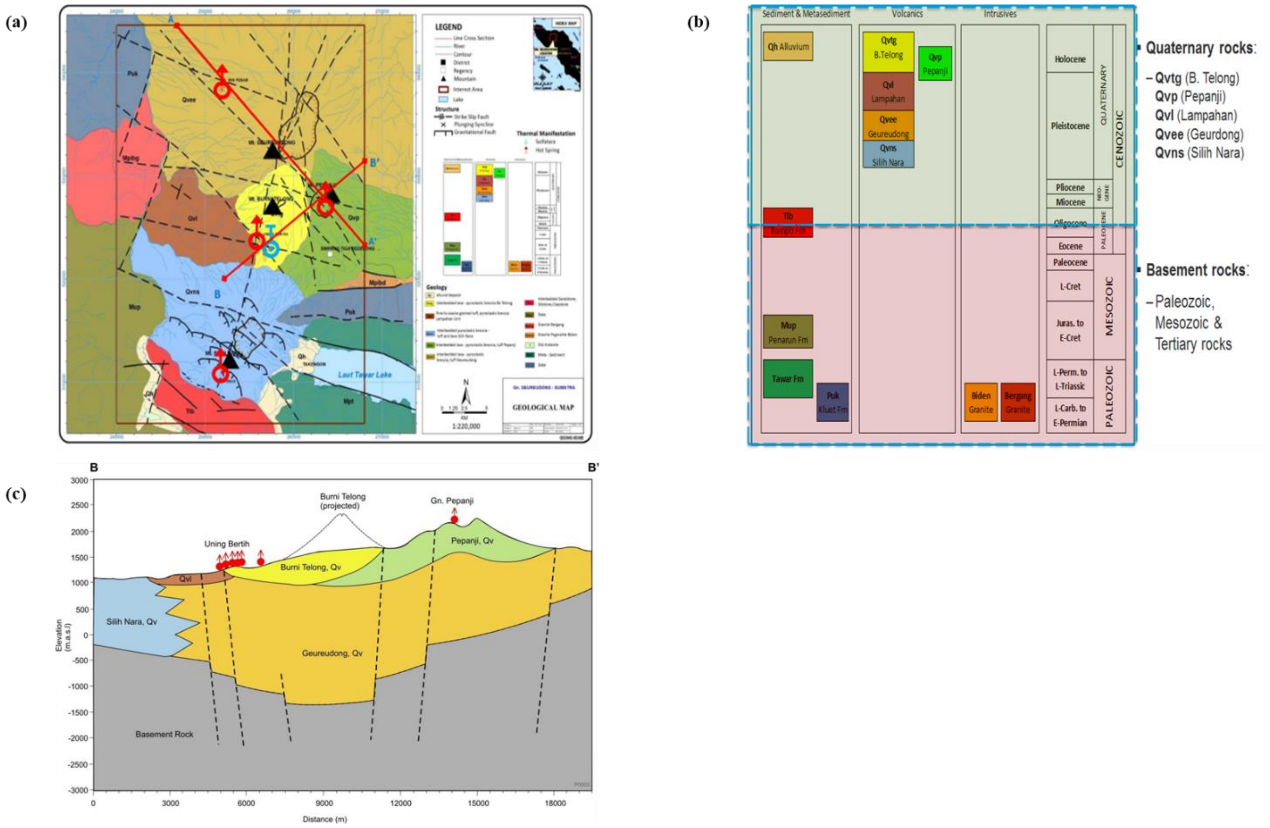


Figure 1 (a) Geological Map of Mount Geureudong Area (b) Stratigraphic Column of Mount Geureudong Area (c) Cross Section Map of Mount Geureudong Area (PT Jasa Daya Chevron, 2014)

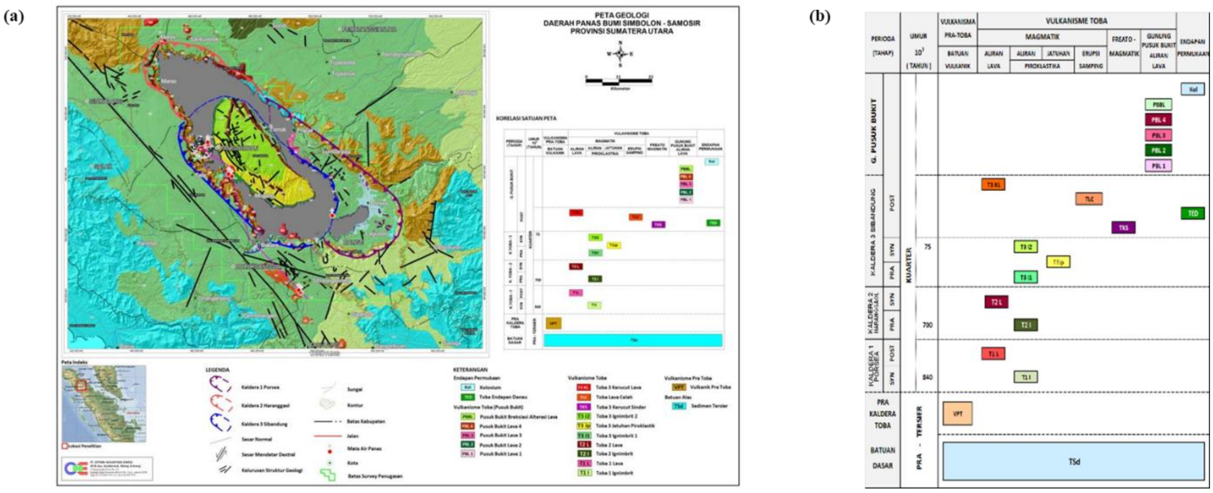


Figure 2 (a) Geological Map of Simbolon Samosir Area (b) Stratigraphic Column of Simbolon Samosir Area (PT Optima Nusantara Energi, 2010)

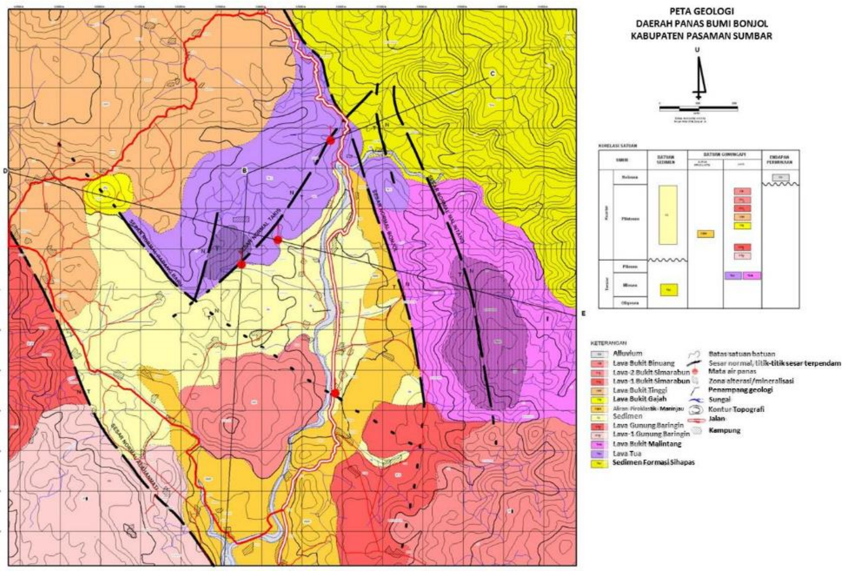


Figure 3 Geological Map of Bonjol Area (Geological Agency, 2007)

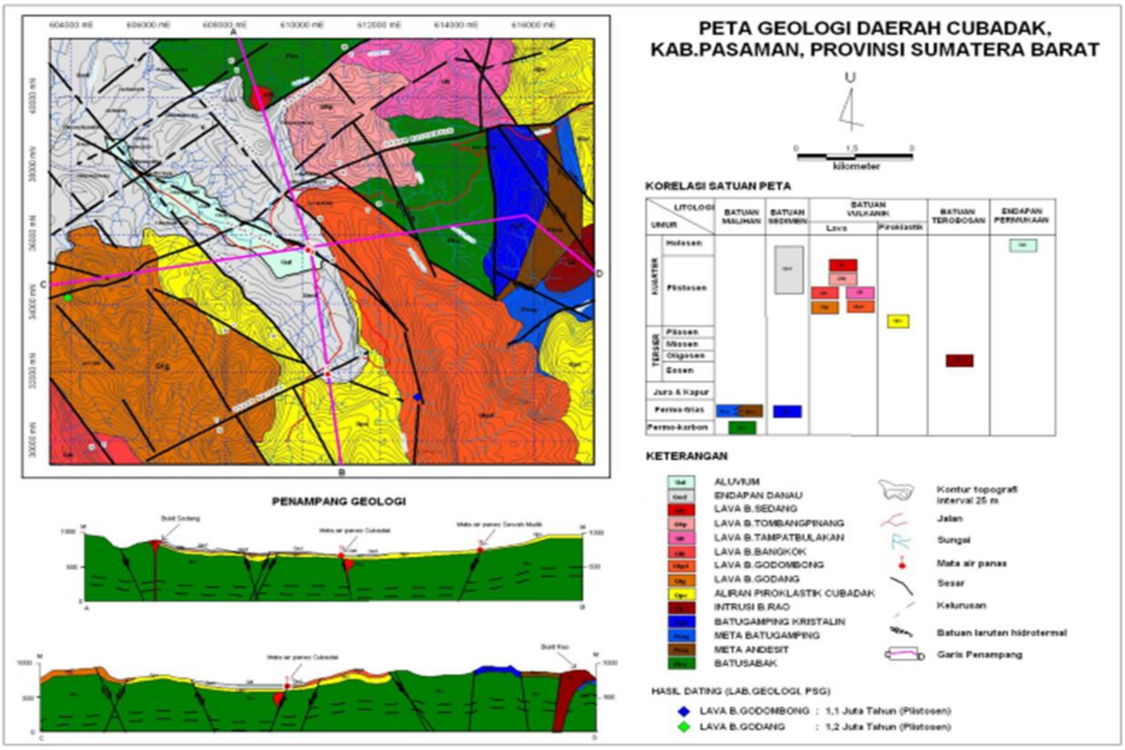


Figure 4 Geological Map of Cubadak Area (Geological Agency, 2008)

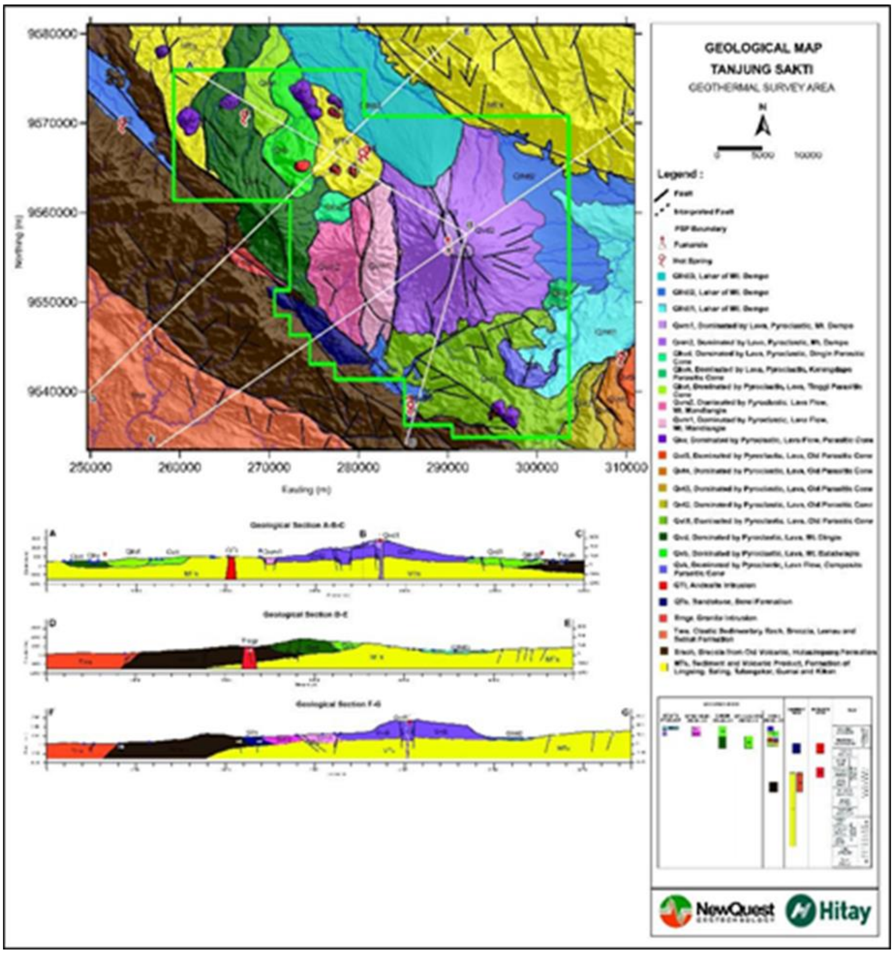


Figure 5 Tanjung Sakti Geological Map (Hitay, 2015)

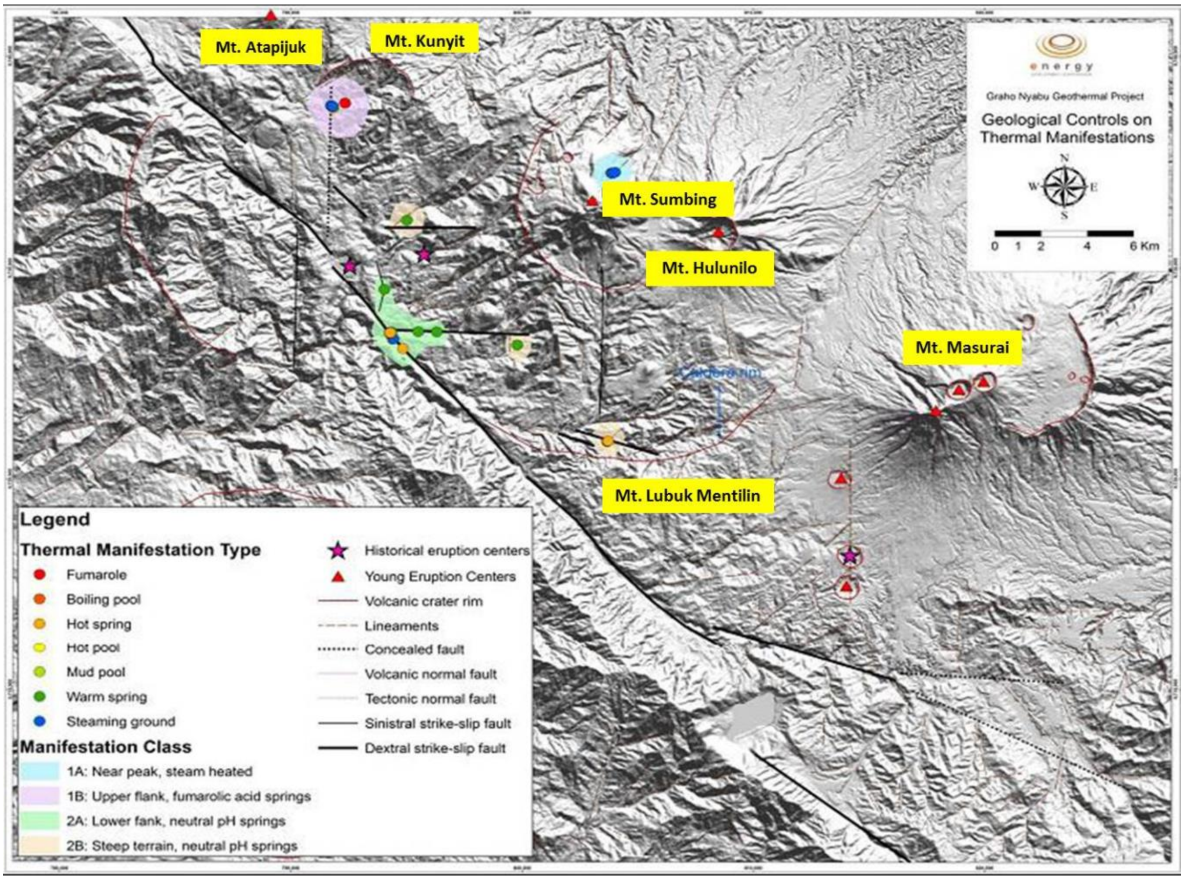


Figure 6. The Map Shows Structural Control of Heat Manifestations in Graho Nyabu Area (PT EDC Indonesia, 2014)

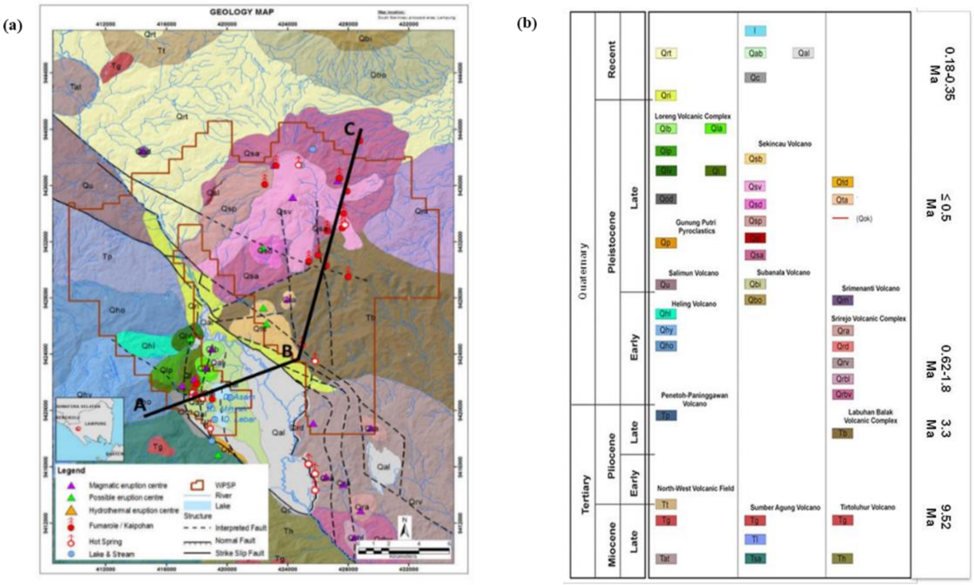


Figure 7 (a) Geological Map of South Sekincau Area (b) Stratigraphic Column of South Sekincau Area (PT SEGSS, 2015)

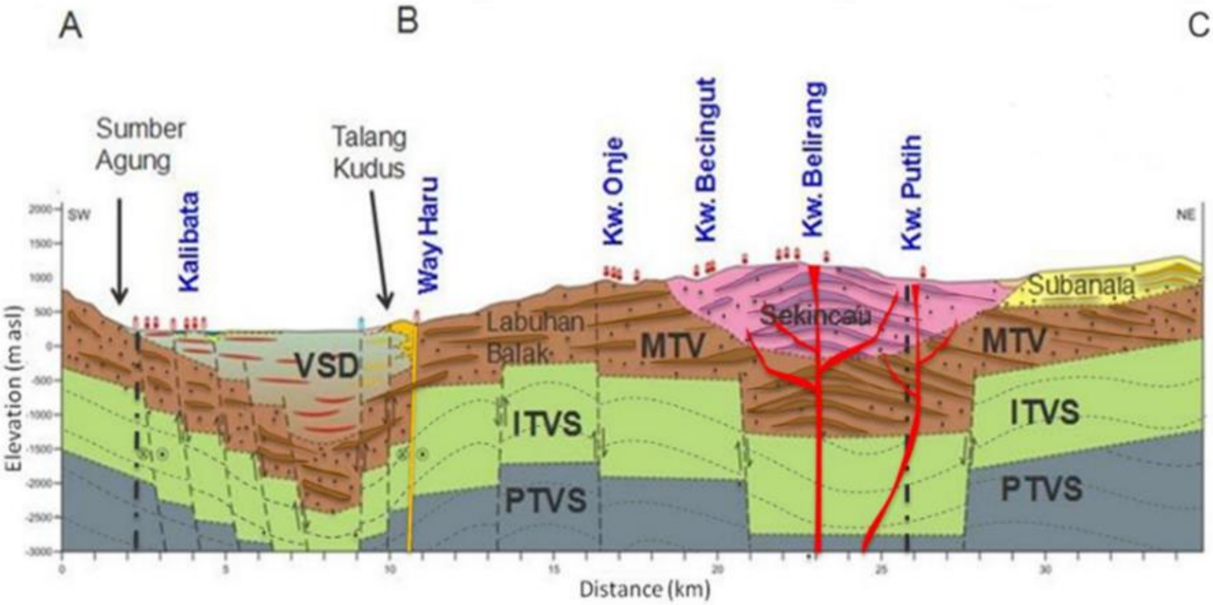


Figure 8 Cross Section Map of Sekincau Selatan (PT SEGSS, 2015).