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Geochemistry Monitoring of Surface Thermal Manifestation in Sibayak, North Sumatra, Indonesia

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ABSTRACT

Sibayak was the first geothermal power plant where operated in Sumatra Island, Indonesia. This two-phase geothermal field has been produced 12 MW electricity since 1994 from 10 wells. During the exploitation stage, a geochemical study on geothermal surface manifestation conducted to monitor the effect of reservoir production and injection to the surface manifestation. The geothermal surface manifestation found in the crater and the flank of Mt. Sibayak and Barus, North Sumatra, Indonesia. The Sibayak manifestation is located near Sibayak geothermal power plant, and it consists of solfatara, kaipohan, hot spring, and warm spring. The hot spring in Sibayak mainly as steam-heated water, acid sulfate fluid. In Barus, most of the thermal manifestation consists of neutral bicarbonate water which located on 12 km east to Mt. Sibayak. Based on the Cl vs. B diagram, it can be concluded that geothermal water from Sibayak and Barus came from different heat sources. Geochemistry data monitoring acquired based on sampling data in 2011 and 2018 during exploitation stage of Sibayak geothermal field. The data showed the change of temperature, pH, and some geothermal geochemistry of ion and cations from water and shifting in gas geochemistry diagram. Nevertheless, the variation of data from 2011 and 2018 did not show the effect of reservoir exploitation, while the weather condition might be as the main cause of the change of water geochemistry.

1. INTRODUCTION

Sibayak geothermal field is located at about 65 km to the southwest of Medan in the North Sumatera Province, Indonesia. Since 1989, Sibayak field has been investigated by various geoscience methods, then continued by drilling of 10 wells, which is consist of 7 production wells and 3 injection wells. The exploration results suggested that the Sibayak area is a high potential geothermal field. Recently, 1 unit mono-block with the capacity of 2 MW and 2 units PLTP with 2x5 MW have been installed. Total installed capacity at this time is 12 MW (Siregar, 2004). The geology of Sibayak geothermal field is located in the Singkut caldera, consists of altered volcanic rocks in the shallow zone from the surface down to about 1150 m depth and meta-sedimentary rocks in the deeper zone (Atmojo et al., 2000).

This study aims to assess the changes in water and gas compositions related to the changes in reservoir conditions based on sampling data in 2011 and 2018 during the exploitation stage. The surface area of active thermal manifestation in the Sibayak field covers a small area along the Mt. Sibayak crater and the southern side of the Mt. Sibayak, and also Barus complex manifestation in the eastern part of Mt. Sibayak. The surface thermal manifestation consisted of solfatara, kaipohan, hot spring, and warm spring.

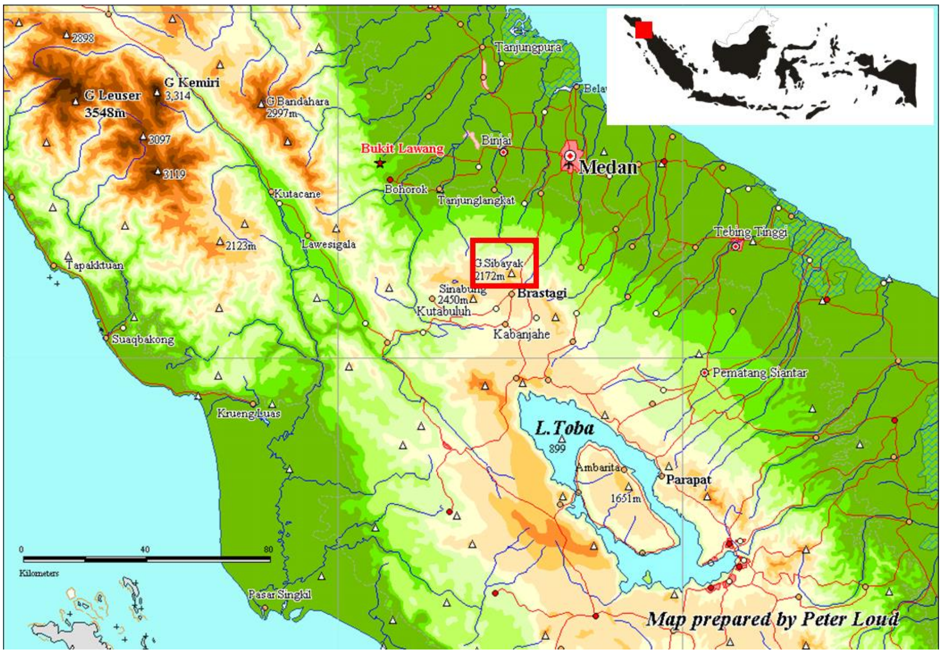

Figure 1: The map of Sibayak geothermal field location in North Sumatra, Indonesia

2. METHOD OF SAMPLING AND LABORATORY ANALYSIS

The geochemistry data was derived from water and gas surveys and sampling. The water chemistry acquired from water samples coming from both natural hot spring and artificial hot spring pool made by people living in the area of Sibayak. Some of the hot spring in Sibayak already built as a touristic place and hot spring bath pool. The water sample was taken from the main source of hot spring pool and collected to the polypropylene (PP) plastic bottle and added with the HNO_3 acid solution as a preservative. The temperature, pH measurement and and physical properties of surface wanifestation were also conducted, to see the physical change of surface manifestation. The gas chemistry acquired from surface gas manifestation such as fumarole and solfatara. The gas coming out from the vent was connected to the apparatus and stopcock gas bottle to take the gas sample. After the field sampling, detailed analyses of water and gas chemistry are carried out in the laboratories. Water chemical analysis of dissolved ion is determined using atomic absorption spectroscopy - flame (AAS Flame) refers to APHA 3111 B (for Na, K, Mg, Fe, Li, Mn) and APHA 3111 D (for Ca, SiO_2, As, Sr). Both Al and Ba chemical analyses are determined using atomic absorption spectroscopy - graphite tube atomizers (AAS-GTA) refer to APHA 3111 D. The HCO_3, H_2S in water, and Cl, analysis is determined using titration method. The B and SO_4 are analyzed using the spectrophotometer method, while the F analysis is determined by ion meter. The gas analysis was carried out to determine the water vapor content, CO_2, H_2S, NH_3, Ar, N, CH_4, and H_2 using gas chromatography method.

3. GEOTHERMAL SURFACE MANIFESTATION

The geothermal surface manifestation found in the crater and the flank of Mt. Sibayak as Sibayak Complex Manifestation and Barus Complex Manifestation which is located 12 km apart to the eastern side of Mt. Sibayak.

3.1 Sibayak Complex Manifestation

3.1.1 Kawah Sibayak (SBY1F, SBY2F, SBY1M)

This manifestation is located in the crater of Mt. Sibayak, which consists of gas manifestations, solfatara, labeled as SBY1F and SBY2F, and also manifestations of crater water (SBY1M). At the peak of Mt. Sibayak it was found a crater structure with up to 70 meters of massive and brecciated andesite lava, mostly fresh rock, but partially altered. Around the solfatara, it can be seen tiny crystals of sulfur, indicated with the yellowish color. At the bottom of the crater, there is a crater lake that appears like a mud plain that dries during the dry season. The crater is filled by clayey mud rocks, cold-acidic water (temperature: 20°C, pH 1.8). The temperature of solfatara is 97.5 °C with a pH of condensate is 4.5.

3.1.2 Kawah Silangge-langge (SLG1 and SLG2)

The Kawah Silangge-langge manifestation is located 900 meters from the Dizamatra power plant, on the slopes of G. Sibayak at the southeast side. The lithology consists of an alteration of volcanic rocks, tuff, and tuff breccia to andesite breccia with high alteration intensity. Solfatara is coming out of holes with diameters varying from 2 cm to 15 cm, with the presence of abundant sulfur crystals. Gas manifestation has low pressure. The temperature of the gas discharge is 94.4 ° C and the pH of condensate is 4.5.

3.1.3 Pancur Pitu (PCP)

The location of the manifestation of Pancur Pitu is near Pancur Enam (PCE) hot spring, with the lithology of andesite and tuff boulder. Hot springs with clear water, with some gas bubble. This hot spring is rich in silica and sulfur deposits. Based on measurements, the temperature of hot water in PCP is equal to 51.9 °C, and pH 6.1.

3.1.4 Pancur Enam (PCE)

The location of the manifestation of Pancur Enam is near the Sibayak A well pad, which is a hot spring that has now dried up, and decreased discharge (compared from 2011 to 2018). The location is adjacent to the Pancur Pitu (PCP) hot spring. Formerly, this is a source of hot springs, but not yet discharged since 2-3 years ago. Around the location of the manifestation, there are still white silica deposits (silica sinter).

3.1.5 Ladang Kangkung (LDK)

The manifestation is located in valleys filled with alluvial deposits, clay with andesite breccia - tuff breccia boulder. It also found deposits of silica and greenish-white algae around the manifestation. Hot spring complex that emerges from the gap of alluvial deposits in a valley surrounded by swampy area. LDK hot springs can be found in the form of ponds with a size of 1 x 1 meter, clear water, the temperature at 62.1 °C and pH 6.4.

3.1.6 Probo (PRB)

Probo hot spring is located in the alluvial plain paddy field area and surrounded by silica sinter and sulfur. Hot springs are found in the cracks of the hollows on the banks of small creeks, low discharge, clear water, slightly smelling sulfur, and sulfur deposits on the river bed. 15 cm thick sinter deposits are found on the banks of the river. The temperature of the water is 63.4 ° C, and pH 6.5.

3.1.7 Ginting (GTG)

The manifestation location is in the form of hot water baths that have been built with cement/concrete by the local people, so that lithology or alteration is not known around the hot springs. The Ginting hot spring is near PGE Sibayak's office, about 500 m away. Hot springs are enclosed in pond buildings, greenish waters with sulfur odor, and sulfur deposits on the surface of the water. The measured temperature in the hot spring pool is 52.7 °C and pH 6.3.

3.1.8 Alam Sibayak (ASB)

The location of the hot spring is 300 meters from PGE Sibayak office, no rock outcrops are found because the hot springs have been cemented and made for bathing facilities. Alam Sibayak hot spring is bluish water, with the temperature of the hot spring pool is 48.1 °C and pH of 6.5.

3.1.9 Karona (KRN)

The Karona hot spring is located 1.3 km from the Sibayak A well pad and PGE office, near Sibayak C well pad. The spring pool is clear bluish water with some gas bubble, clean water surface without deposits, and mineral accumulation. The hot water pool is a concrete pool with a size of 2.5 m x 2.5 m. The water has a temperature of 47 °C and pH 6.7.

3.1.10 Lau Sidebu-debu (LSD)

Lau Sidebu-debu is a manifestation of hot water in the form of a hot spring bath, located near the Bandar Baru - Berastagi highway. The location of the manifestation is 3.6 km from the well pad A. The main pool is the source of the spring, clear turquoise, foamy, clean water surface without deposits and mineral accumulation. The temperature of the hot spring pool is 34.3 °C and pH 6.4.

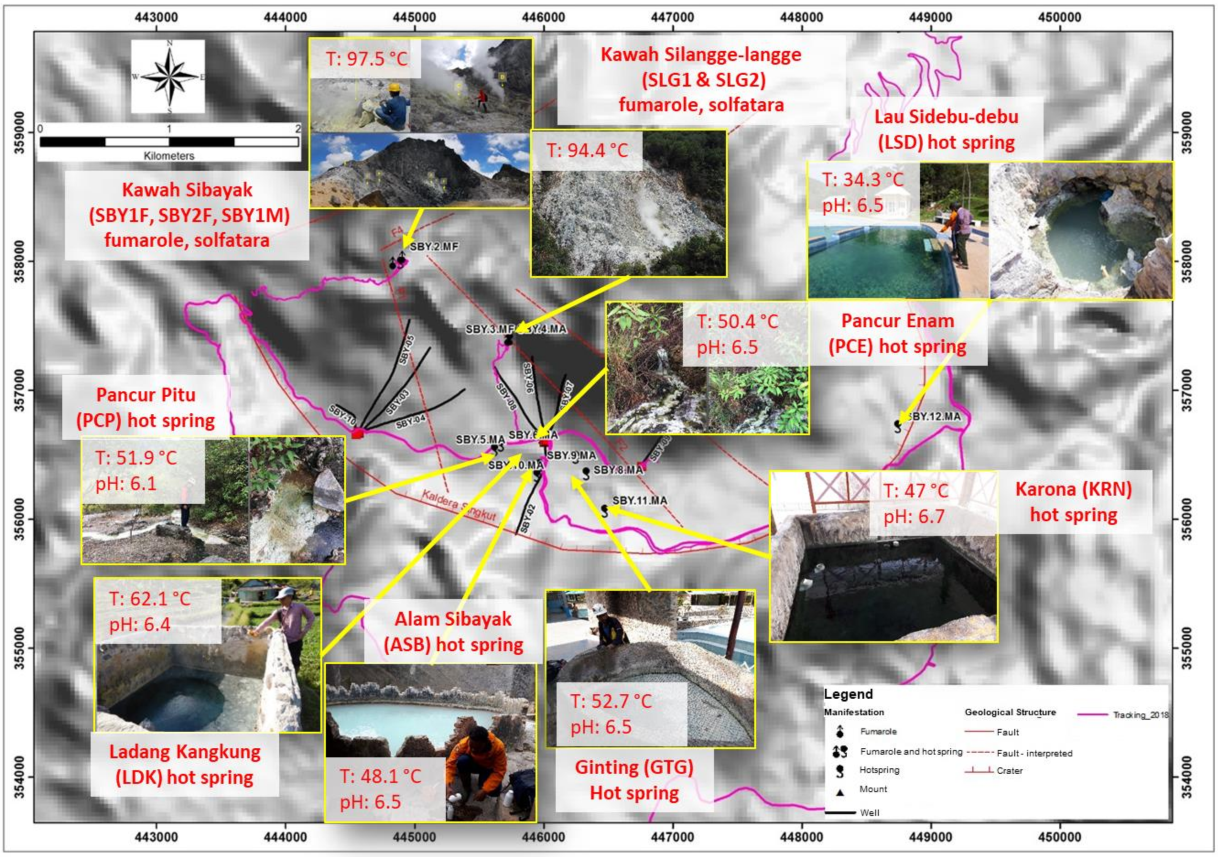

Figure 2: Sibayak Complex Manifestation

3.2 Barus Complex Manifestation

Barus Complex Manifestation is located about 12 km eastern part of Mt. Sibayak, including Bandar Baru manifestation and Penen hot spring.

3.2.1 Bandar Baru (BBR)

The Bandar Baru manifestation is located in the river valley which is located 300 meters from the Bandar Baru - Berastagi highway. The lithology is composed of unaltered andesite and volcanic breccia, rounded-subrounded shape, and some white color clay. Kaipohan of Bandar Baru has 1-1.5 meters length of the diameter. Water temperature is 20 °C, pH 4.0, and is characterized by sulfur gas that comes out from cracks and in the rocks. There is a small discharge of water out of manifestation, but it emits a very strong smell of sulfur.

3.2.2 Barus 1 (BRS1 and BRS1A)

The manifestation of hot water is founded in the form of a water pool, with clay alteration, weathered tuff, and algae deposit. It also found conglomerate boulder diorite fragments, andesite and andesite breccia in the riverbed. The hot spring water is clear blue with the temperature of 50 °C and pH 7.8, emerged from the rock in the east side of the river wall, showing a gas bubble, mixed with the flow of cold water from the river in the upstream.

3.2.3 Barus 2 (BRS2)

The manifestations are found in the river flow, located between the andesite-diorite weathered rocks, carbonate travertine crystal. This river is a mixture of cold water from upstream which is colorless and clear, meets hot springs which are bluish and milky white-colored, giving a contrast in colors on the river's body The BRS2 location is about 50 meters from BRS1A. The water temperature is 71 °C and pH 7.0.

3.2.4 Barus 3 (BRS3)

The location of the BRS3 manifestations is about 10 meters from BRS2. BRS3 hot springs emerge from the crevice of rocks on the banks of the river, showing gas bubble. The water is clear blue, with the smell of sulfur odor. BRS3 hot spring has a temperature of 75 ° C, pH and pH 7.2.

3.2.5 Barus 4 (BRS4)

BRS4 is a small hot spring that is used by local people, flowing through the river. It is a hot spring mixed with cold water from upstream. The water is clear, the temperature is 50 ° C, and pH 8.0.

3.2.6 Barus 5 (BRS5)

The location of this manifestation is on the embankment wall of rice fields in the Barus hill, composed of alluvial deposit, strongly weathered rocks, with some vegetation around the hot spring. Hot spring with a low discharge that flows into a pool isolated by vegetation. BRS5 hot spring has a temperature of 55.0 ° C, and pH 6.5.

3.2.7 Barus 6 (BRS6)

The location of this BRS6 manifestation is on the embankment wall of the rice fields in the Barus hill, composed of alluvial material, strongly weathered rocks, with some vegetation around the hot spring. It a circle-shaped pool with about 50 cm diameter, cloudy dark green color, weak sulfur smell, temperature 75 °C, and pH 7.1.

3.2.8 Penen (BRS7)

The Penen manifestation (BRS7) is surrounded by alluvial clay deposits, the soil is very soft and easy to collapse. Hot spring pools with 15 m x 4 m in size, cloudy dark green color, and several layers of white algae deposits and silica sinter. Hot spring with temperature 53 °C, and pH 7.0, and also a strong smell of sulfur.

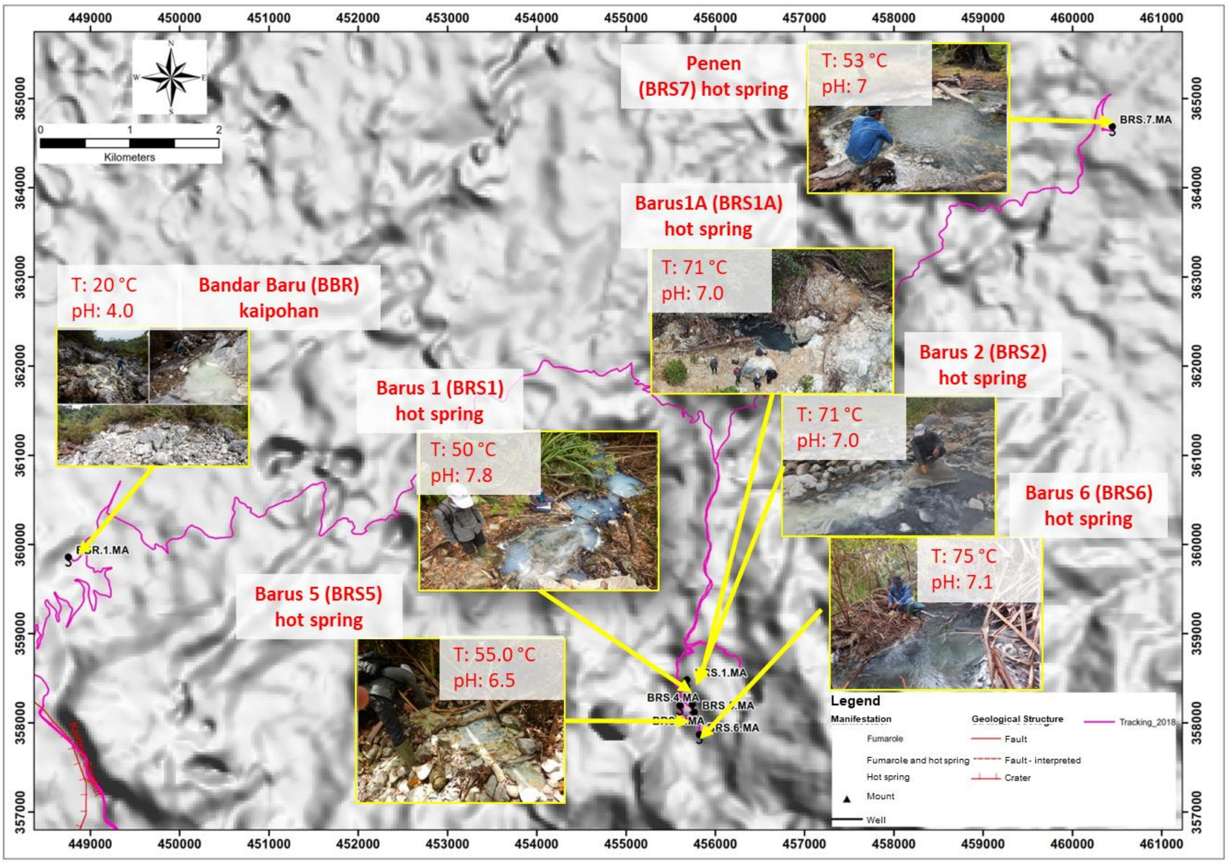

Figure 3: Barus Complex Manifestation

Table 1: Sibayak geothermal surface manifestation

No	Sample Code	Location	Type of Manifestation	Coordinate (UTM 47N)		Elevation (masl)	Temp (°C)	pH
				N	E			
1	SBY1F	Kawah G.Sibayak	Fumarole/Solfatara	357989	444859	1959	97.5	4.5 (SCS)
3	SBY2F	Kawah G.Sibayak	Fumarole/Solfatara	358035	444904	1995	95.4	4.5 (SCS)
4	SLG1	Kawah Silangge-langge	Fumarole/Solfatara	357396	445720	1553	94.4	4.5 (SCS)
5	SLG2	Kawah Silangge-langge	Hot Spring	357397	445734	1552	79.8	3.0
6	PCP	Pancur Pitu	Hot Spring	356539	445619	1420	51.9	6.5
7	PCE	Pancur Enam	Hot Spring	356575	445669	1423	50.4	6.5
8	LDK	Ladang Kangkung	Hot Spring	356479	446246	1368	62.1	6.4
9	PRB	Probo	Hot Spring	356352	446329	1363	63.4	6.5
10	GTG	Ginting	Hot Spring	356415	445966	1382	52.7	6.3
11	ASB	Alam Sibayak	Hot Spring	356341	445948	1377	48.1	6.5
12	KRN	Karona	Hot Spring	356064	446474	1345	47.0	6.7
13	LSD	Lau Sidebu-debu	Hot Spring	356719	448743	1286	34.3	6.4
14	BBR	Bandar Baru	Kaipohan	359824	448750	974	20.0	4.0
15	BRS1	Barus 1	Hot Spring	358450	455680	656	50.0	7.8
16	BRS1A	Barus 1	Hot Spring	358158	455602	646	71.0	7.0
17	BRS2	Barus 2	Hot Spring	358158	455602	646	72.0	7.0
18	BRS3	Barus 3	Hot Spring	358158	455600	646	75.0	7.2
19	BRS4	Barus 4	Hot Spring	358170	455739	672	50.0	8.0
20	BRS5	Barus 5	Hot Spring	358086	455763	667	55.0	6.5
21	BRS6	Barus 6	Hot Spring	357837	455820	673	75.0	7.1
22	BRS7	Penen	Hot Spring	364654	460445	401	53.0	7.0

3. GEOCHEMISTRY ANALYSIS OF SURFACE THERMAL MANIFESTATION

3.1 Type of Fluid and Fluid Equilibrium

Fluid manifestations around Mt. Sibayak (SLG2, PCP, PCE, LDK, PRB, GTG, ASB, KRN, and BBR1) are found as sulfate water. Meanwhile, bicarbonate water is common in Barus manifestation (BRS1, BRS3, BRS4, BRS5, BRS6, and BRS7), see Figure 4. Magnesium concentrations in reservoir fluids in mature geothermal systems range from 0.01-0.1 ppm (Nicholson, 1993). Hot springs in Mount Sibayak and Barus are adjacent to the apex of magnesium (with magnesium values 1.4 to 82 ppm), indicate as immature water condition. Fluid characters from SBY-3, SBY-4, and SBY-5 wells are in partial equilibrium to immature water conditions (Figure 4). The high concentration of magnesium might be caused by the presence of dominant surface water contamination of these manifestations. It might also be cause by the process of leaching from surrounding rocks (Nicholson, 1993).

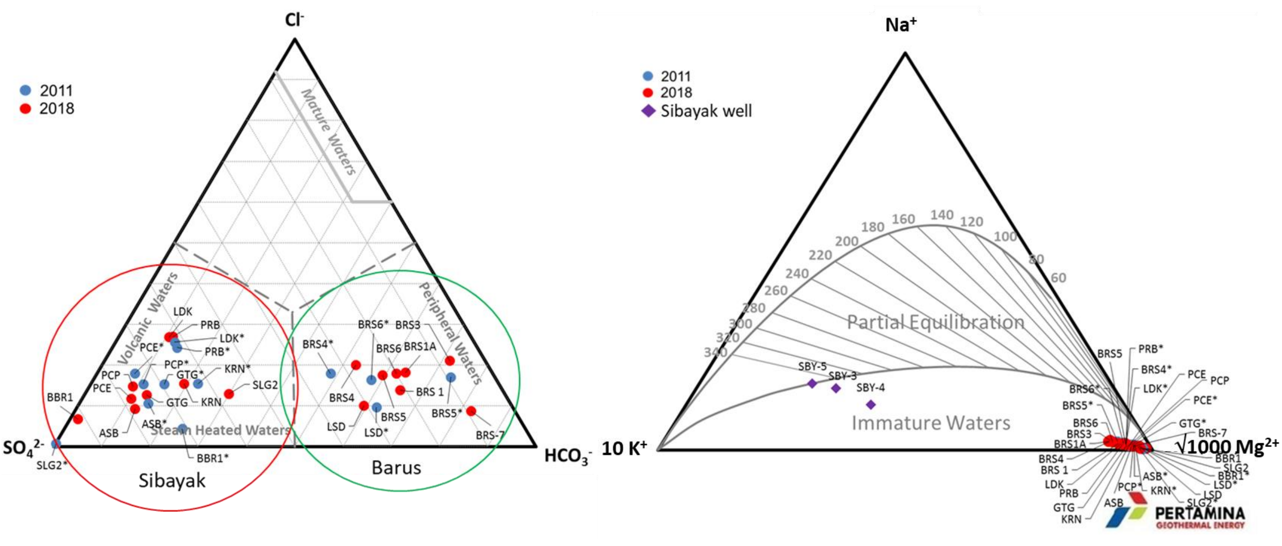

Figure 4: The trilinear diagram of Cl-SO_4-HCO_3 (Giggenbach and Goguel, 1989) and the trilinear diagram of Na-K-Mg (Giggenbach, 1991)

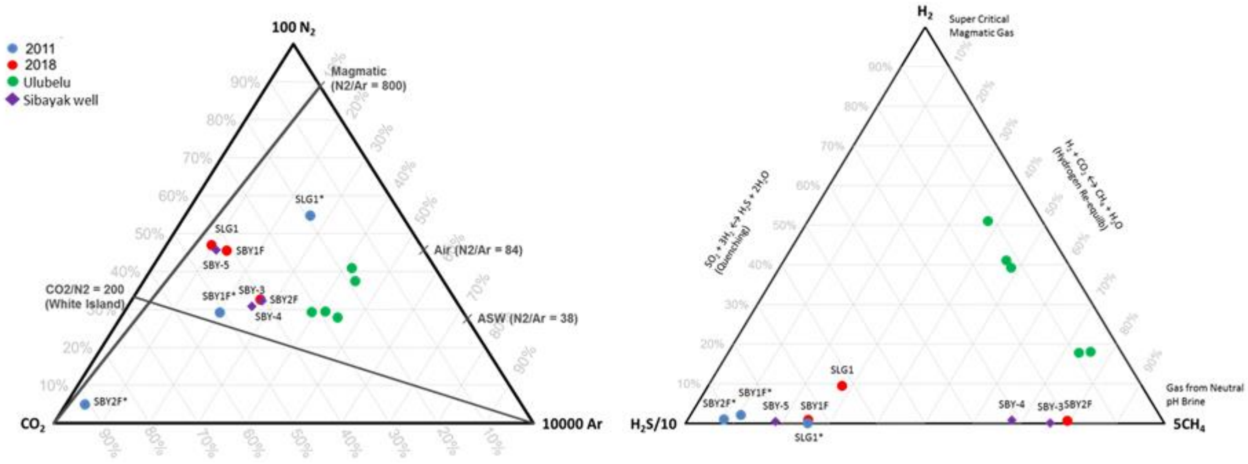

Figure 5: The trilinear diagram of N_2-CO_2-Ar (Giggenbach, 1992) and the trilinear diagram of H_2-H_2S-CH_4 (Giggenbach and Glover, 1992)

The fluid from the SLG1 and SBY1F approaches the magmatic line with an N_2/Ar ratio of 800 (Figure 5). It indicates that the fluid of the two manifestations has the dominant magmatic volatile contribution (Figure 5). The fluid character of these two manifestations is similar to the fluid from the SBY-5 well. Fluid from SBY2F manifestations adjacent to White Island line with a CO_2/N_2 ratio of 200 (Figure 5, left). It also indicates that the contribution of magmatic volatiles is dominant compared to meteoric fluids. Fluid characters from SBY2F manifestations are similar to fluids in SBY-3 and SBY-4 wells. Although the fluid from SBY1F and SBY2F manifestation has the dominant contribution of magmatic volatiles, there are differences in the results of plotting in the N_2-CO_2-Ar trilinear diagram caused by differences in the concentration of argon. SBY1F has an argon concentration of 0.00281 % mol, while SBY2F is 0.00587 % mol. Contribution of the concentration of argon to a geothermal fluid is related to a meteoric fluid (Nicholson, 1993). So, it can be decided that the difference in argon concentration is due to the different sampling methods taken. A gas sampling of SBY1F manifestation uses a funnel, while in SBY2F use tubing to catch the gas from solfatara.

Based on the comparison of fluid characteristic of Ulubelu (Lampung, Indonesia) and Sibayak wells and surface manifestation, it can be seen that the fluid from the Ulubelu wells and manifestation originates from a meteoric fluid which is heated by a heat source, indicate by the fluid adjacent to apex of argon (Figure 5, left). On the other hand, fluid from Sibayak wells and manifestations have dominant magmatic volatile contributions. It shows that the geothermal system in the Sibayak field is younger than the Ulubelu field.

Based on the trilinear diagram of H_2-H_2S-CH_4 it can be seen that the fluid from the manifestations of SBY1F and SLG1 has a quenching process from magmatic gases (Equation 1). This fluid of SBY-5 well is also in the same condition.

$$SO_2 + 3H_2 \leftrightarrow H_2S + 2H_2O \quad (1)$$

Equation 1 shows the composition of magmatic gases with high H_2 concentrations at high temperatures also become H_2S at a lower temperature (Bogie and Lovelock, 1999). On the other hand, fluid from SBY2F, which is similar to fluid in SBY-3 and SBY-4 wells are adjacent to the apex of methane (CH_4), which indicates the neutralization process (Figure 5). This neutralization process shows that the gases that are owned by fluid from both SBY-2F and SBY-3 and SBY-4 wells come from brine with a neutral degree of acidity (pH).

Besides that, there are differences in fluid characters from the manifestations and wells in Ulubelu or Sibayak on the trilinear H_2-H_2S-CH_4 diagram (Figure 5). The fluid from the Ulubelu wells and manifestations leads to the apex of methane, which indicates the presence of a hydrogen re-equilibrium process. Meanwhile, the fluid from Sibayak wells and manifestations and comes from the process of quenching magmatic gases. Based on the trilinear diagram, it can be affirmed the hypothesis of the geothermal system at Sibayak field is younger than Ulubelu.

3.7 Soluble Gas

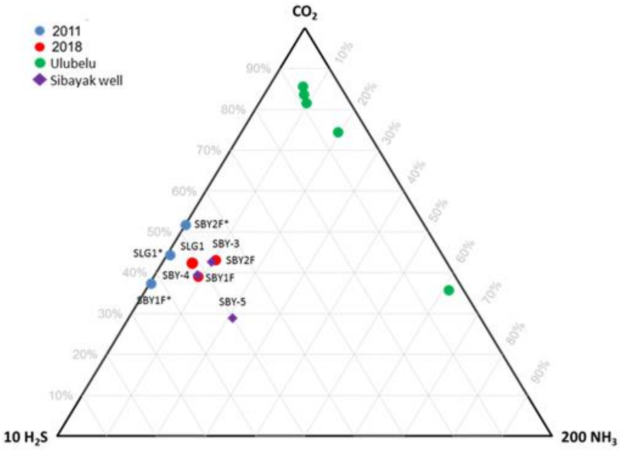

Figure 6: The trilinear diagram of CO_2-H_2S-NH_3

The solubility of the gas in the liquid phase in this reservoir fluid can be determined based on the fractionation of the gas in the vapor phase. The following is a sequence of geothermal gases that have low to high solubility: $N_2 < O_2 < H_2 < CH_4 < CO_2 < H_2S < NH_3$ (Nicholson, 1993).

The trilinear diagram of CO_2-H_2S-NH_3 (Figure 6) shows the contribution of gas in SBY1F, SBY2F, and SLG1 fluids. These three manifestations have higher H_2S concentrations compared to the manifestations in Ulubelu. The high concentration of H_2S is a result of the quenching process of magmatic gases.

3.8 Origin of Fluids

Based on the chloride vs. boron diagram (Figure 7), it can figure out that there are two different patterns between fluids originating from the manifestations of Sibayak and Barus (Ellis, 1970). This is an indication of different source of reservoir fluid between several manifestations in Mount Sibayak (SLG2, BBR1, LSD, ASB, GTG, PCE, KRN, PCP, PRB, and LDK) and Barus (BRS1, BRS1A, BRS3, BRS4, BRS5, BRS7)

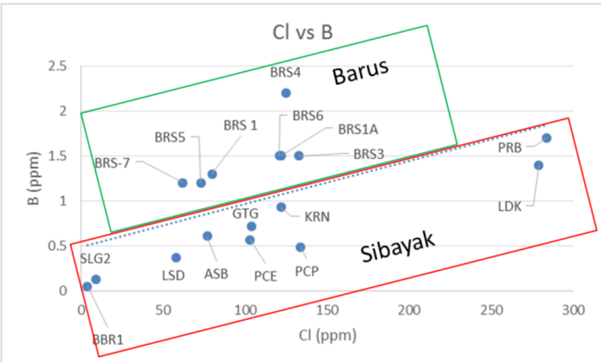

Figure 7: Cl vs. B diagram of Sibayak and Barus

4. GEOCHEMISTRY MONITORING OF SURFACE THERMAL MANIFESTATION IN SIBAYAK

4.1 pH and Temperature

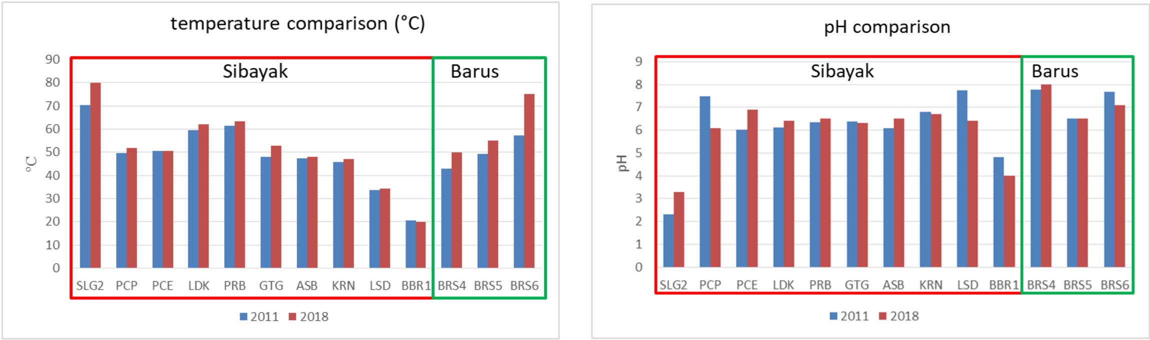

Figure 8: The pH and temperature comparison in Sibayak and Barus at 2011 to 2018 period

The pH and temperature comparison shows no significant change from 2011 to 2018 period. An increase in temperature of 10°C only occurs in the manifestations of SLG2 located on Mount Sibayak. Whereas in other manifestations there is no change in temperature. Increasing pH from 2 to 3 only occurs in fluid from SLG2 manifestation. Fluid from PCP and LSD manifestations in Sibayak Mountain has decreased pH from 7.5 to 6.0 and fluid at BBR-1 has decreased pH from 5.0 to 4.0 in the 2011 to 2018 period.

4.2 Gas Geothermometer

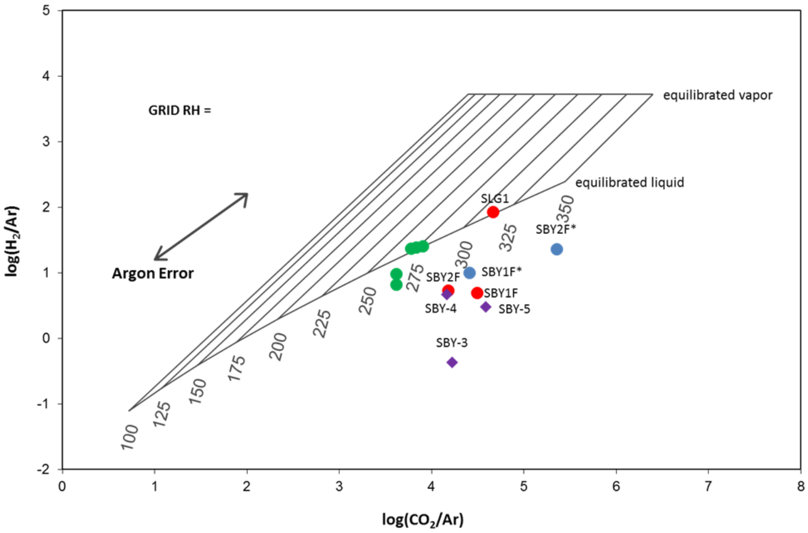

Figure 9: The CAR-HAR geothermometer (Giggenbach and Glover, 1992)

The reservoir temperature of SBY2F manifestation is 275 °C based on the CAR-HAR geothermometer (Figure 9). The temperature value is similar to SBY-3 and SBY-4 wells. The manifestations of SBY1F and SLG1 have a higher temperature, which is equal to 300 °C. The temperature value of the reservoir is similar to the SBY-5 well. Whereas, the Ulubelu manifestation has a lower temperature, 250 - 275 °C. Both of Sibayak and Ulubelu manifestations are in an equilibrated liquid system (Figure 9).

4.3 Geochemistry Monitoring

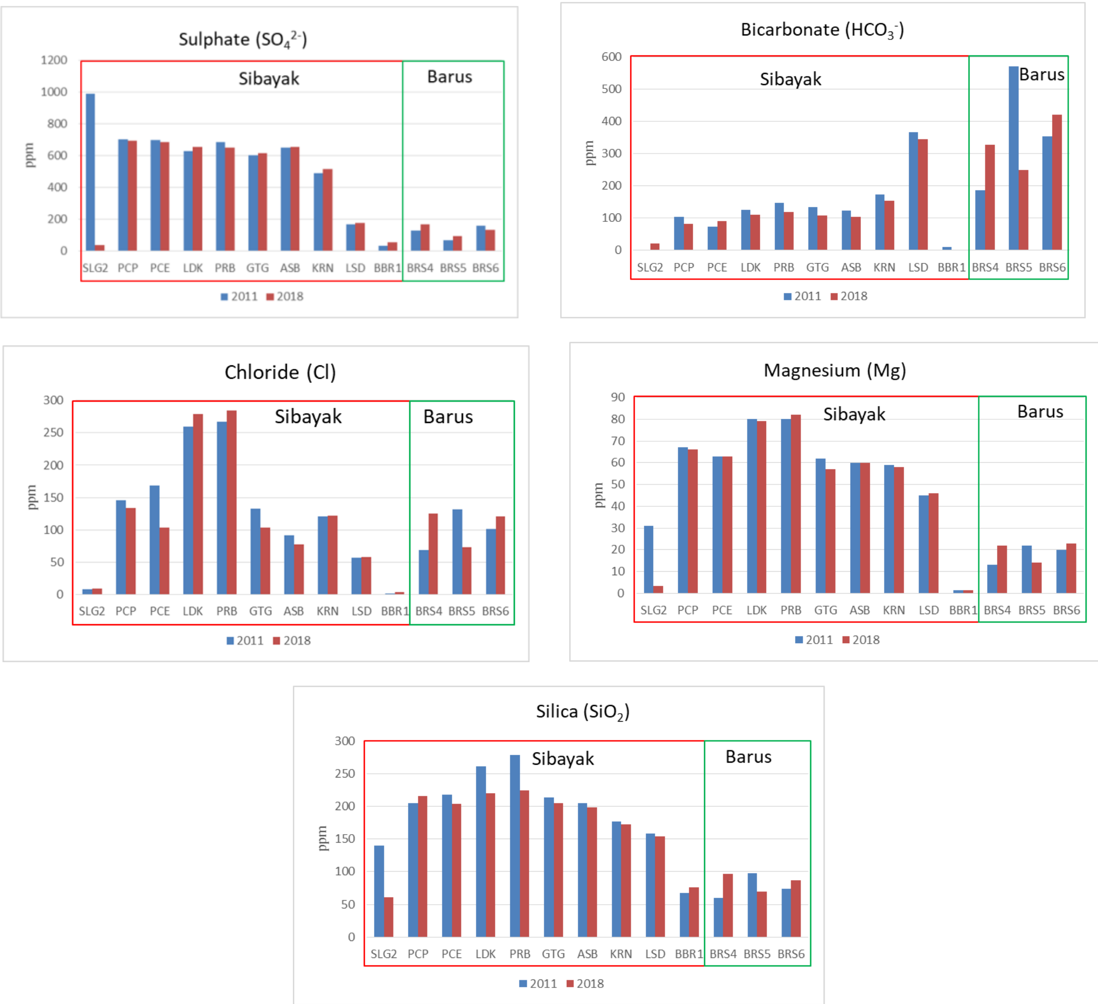

Figure 10: The dissolved element comparison in Sibayak and Barus through 2011 to 2018 period

Geochemical monitoring is carried out in hot spring manifestations located in Sibayak, (SLG2, PCP, PCE, LDK, PRB, GTG, ASB, KRN, LSD, BBR1) and Barus (BRS4, BRS5, BRS6) from 2011 to 2018. When sampling for monitoring manifestations in 2018, the weather conditions are dry season and low intensity of rainfall, and it caused the hot springs might be quite dry. Sampling in Barus is only a comparison and will not be discussed further because it is outside the PGE's geothermal working area.

PCE and GTG are manifestations of Mount Sibayak. These two manifestations have a decrease in chloride concentration (Figure 10) from 2011 to 2018 which led to the results of plotting in the trilateral diagram of Cl-SO_4-HCO_3 (Figure 4) shifting towards the apex of sulfate. SLG2 manifestation is located on Mount Sibayak undergoes a shift away from the apex of sulfate in the trilinear diagram Cl-SO_4-HCO_3 (Figure 4). This condition is caused by a significant decrease in sulfate concentration (Figure 10).

$$H_2S + O_2 \leftrightarrow SO_4 + H_2O \quad (2)$$

Based on Equation 2, it can be seen that the decrease in sulfate concentration is influenced by a decrease in oxygen concentration from the oxidation process with meteoric fluid.

In addition, a decrease in magnesium and silica concentration (Figure 10) also occur in SLG2 manifestations accompanied by an increase in acidity (Figure 8). This indicates a decrease in the contribution of meteoric fluid so that the process of leaching due to the presence of water-rock interaction has not occurred intensively.

5. CONCLUSION

Based on the geochemical evaluation of the manifestations in Sibayak, it can be seen that the manifestations in Sibayak are steam-heated sulfate water, while the manifestations in Barus are bicarbonate water. This difference in the type of water in Sibayak and Barus is due to the difference in reservoir source (based on the diagram of chloride vs. boron).

There are few changes in manifestation characters based on geochemical manifestation monitoring from 2011 to 2018: the manifestations of SLG2 in Sibayak have increased acidity (pH) and bicarbonate accompanied by a decrease in sulfate, magnesium and silica concentrations. This indicates that there is a decrease in the contribution of meteoric fluids due to dry weather factors (low rain fall intensity) compared to reservoir fluids so that the leaching process is not too intensive. Geochemistry monitoring based on data from 2011 and 2018 does not show the significant effect of reservoir exploitation, while the possible change in the geochemistry of water might be caused by variation of weather condition.

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