Cl/B ratio of geothermal fluid around Slamet Volcano, Jawa Tengah, Indonesia

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Abstract. Geothermal manifestations occurred in four areas surrounding Slamet Volcano, such as Guci, Baturraden, Paguyangan, and Bantarkawung. These areas are located of about 7.5 km, 8 km, 25 km and 33 km from the summit of Slamet volcano, respectively. We analyzed the chemical composition of cold and hot hater in order to understand the genesis and hydrological the relationship of the hot springs. The plot on HCO3-Cl-SO4 ternary diagram classified the hot water into four water types i.e. chloride-bicarbonate water (Bantarkawung), chloride water (Paguyangan), sulfate-chloride water (Baturraden), and bicarbonate water (Guci). The Cl/B ratio values indicate that the southern part of the Slamet volcano (Baturaden) hot springs have high Cl/B ratio compared to that of the northern hot springs (Guci area). While the hot springs in the western part (Paguyangan and Bantarkawung) are classified into high and low Cl/B ratio. This indicates that the hot springs in Paguyangan and Bantarkawung are the outflow of Baturraden and Guci.

1. Introduction

The occurrence of geothermal system beneath Slamet volcano is featured by hot springs discharged in four areas (Baturraden, Guci, Paguyangan and Bantarkawung) surrounding the Slamet volcano (figure 1). The Baturraden area is located about 8 km from the summit at southern flank, while the Guci area is located about 7.5 km away from the summit at northern flank of Slamet volcano. The Paguyangan and Bantarkawung both are located at western area at the distance about 25 and 33 km from the summit, respectively. The hot springs in Paguyangan and Bantarkawung discharge from the fracture of sedimentary rock (figure 2).

The Government of Indonesia divides the geothermal prospect surrounding Slamet volcano into two Geothermal Working Areas (WKP) of Baturraden and Guci (figure 1). The hot springs in Paguyangan and Bantarkawung are located out of those WKP. Until now, those two WKP’s are still in exploration stage. For further exploration therefore it is important to understand the characteristic of the geothermal fluid of Baturraden and Guci hot springs. In addition it also important to understand the relation of hot springs in Paguyangan and Bantarkawung to the geothermal system surrounding Slamet volcano based on its chemical composition especially chloride and boron concentration.

Chloride and boron content of geothermal fluids have been commonly used to interpret the origin of the fluid [1]. Besides, it may give a hint to evaluate the degree of geothermal water mixing and to assess other characteristics of geothermal systems [1][2][3][4][5][6].

2. Geology of Study Area

Slamet volcano can be divided into two stages, the old Slamet and young Slamet [7]. Slamet Volcano stands on tertiary sedimentary rocks as its basement, consists of Rambatan, Halang, and Tapak Formation [8] shown in figure 2. The composition of Rambatan Formation is quite similar in Bantarkawung and Paguyangan compared with that around Slamet Volcano. It is composed mainly by shale, marl, calcareous sandstone and conglomerate [8][9]. Around Slamet Volcano, Halang Formation is slightly affected by volcanic product, shown in the composition of andesitic sandstone, tuffaceous conglomerate and marl which is interbedded with sandstone [8], while around Bantarkawung Halang Formation consists of sedimentary rocks show typical structure of turbidite product. The appearance of several oil seepages around Slamet volcano [10][11] can be the evidence for the existence of organic-rich sedimentary rocks and probably formation water. Even though, the exact formation which contains those organic-rich rocks are still uncertain.
Generally, in the western part of Slamet Volcano is dominated by normal fault trending NW-SE and NE-SW surroundings this volcano, while in the eastern part strike-slip fault can be found [7]. Further to the west of Slamet Volcano where the lithology is dominated by tertiary sedimentary rocks, the geological structure changes into fold and thrust fault trending NE-SW and gradually change into NW-SE [9], indicating the change of physiographical zone into Bogor Zone.

3. Samples and Laboratories Analytical Method
The water samples were collected from hot springs, cold springs, river, and dug well. Water sampling procedure follow the procedure described by Nicholson [12]. The sampling applied water filtration using 0.45 μm pore size of cellulose membrane. The acid treatment was applied for the samples used for cation and silica analysis.

Laboratory analyses were conducted in Department of Earth Resources Engineering, Kyushu University. Three methods were used to determine cation-anion and neutral components, which are titration, ion chromatography (using Dionex ICS-90 instrument) and Inductively Coupled Plasma - Atomic Emission Spectrometry (ICP-AES) of Optima 5300 DV series.

3.1. Water Type
The type of geothermal water is defined based on the main anions concentration of Cl\(^-\), SO\(_4\)^2- and HCO\(_3\)- [14]. Plot on the ternary diagram of those anion (figure 3) reveals that the type of geothermal waters discharged surrounding Slamet volcano are different. The hot springs from Baturaden are classified into chloride-sulfate water, while hot springs from Guci are bicarbonate water. The hot springs in Bantarkawung are chloride-bicarbonate water. The Paguyangan hot spring is classified as chloride water. All of the cold waters collected from all the areas are classified as bicarbonate water. The cold waters have bit high chloride and sulfate concentration. The Bantarkawung cold waters, Guci and Baturaden hot springs seem having a mixing trend of bicarbonate and chloride-sulfate waters.

The high sulfate and chloride concentration in hot waters may be produced due to condensation of volcanic steam. Therefore the Baturaden hot springs can be interpreted as a result from mixing of surface water with volcanic condensate water. Possibly, there is a condensate of volcanic steam flowing from the summit to the southern flank of Slamet volcano. In the passage of flowing the condensate mixed with the surface water forming hot spring in Baturaden.
Figure 2. Regional geology map of Slamet Volcano and surrounding area [8][9][17].
Figure 3. SO$_4$-Cl-HCO$_3$ ternary diagram plot for hot springs and meteoric water samples from research area.

Figure 4. Na-K-Mg ternary diagram plot for hot springs and meteoric water samples from research area.
The Paguyangan hot spring is exceptional among others hot springs as it is classified as chloride water. The Bantarkawung hot springs are chloride-bicarbonate waters. Though, the chloride concentration of the Paguyangan and Bantarkawung is low (414 ppm and <120 ppm). Moreover, this hot spring is included as partially equilibrium water based on concentration of Na, K and Mg (figure 4). Based on the graphical estimation of the Na-K geothermometer in Fig.4 the temperature of the reservoir is about 120°C. This temperature is too low for the volcanic hosted geothermal system. The Na/K estimation of the Na-K geothermometer in Fig.4 is partially equilibrium water based on concentration of Na, K and Mg (figure 4).

The Paguyangan and Bantarkawung are low Cl/B ratio. Moreover, this hot spring is included as Bantarkawung hot springs (Cilakar hot springs) are classified as high Cl/B ratio while the other two hot springs (Paguyangan and Baturaden) are chloride-bicarbonate waters. Though, the chloride concentration of the Paguyangan hot spring has high Cl/B ratio and is plotted close to the Baturraden hot springs. Two of the other hot springs (Karangpari and Cipanas) are low Cl/B ratio. This plot revealed that geothermal system in Baturraden is different from the geothermal system in Guci. Paguyangan hot spring is probably the outflow of the Baturraden geothermal system.

Table 1. Geochemistry data of hot spring, cold spring, and other water samples from research area

| Location        | Source          | T (°C) | pH  | Cl-  | SO₄²⁻ | HCO₃⁻ | Li⁺  | Na⁺  | K⁺   | Mg²⁺ | SiO₂ | B     | Ionic Balance |
|-----------------|-----------------|--------|-----|------|-------|-------|------|------|------|------|------|-------|---------------|
| Bantarkawung    | River           | 27.4   | 6   | 5.07 | 28.6  | 197.64| 0    | 11.56| 0.92 | 6.90 | 17.85| 0.34  | -1.0          |
| Bantarkawung    | Rain            | 28.1   | 5   | 1.39 | 5.95  | 2.24  | 0    | 0.62 | 0.30 | 0.30 | 0.00 | 0.28  | -12.4         |
| Bantarkawung    | Ground water    | 27.8   | 7   | 31.8 | 60.2  | 409.19| 0    | 32.4 | 16.81| 15.95| 30.18| 0.42  | -2.4          |
| Bantarkawung    | Cold Spring     | 27.4   | 8   | 3.96 | 11.23 | 201.30| 0    | 7.96 | 0.69 | 5.31 | 24.69| 0.35  | -2.5          |
| Bantarkawung    |                | 26.7   | 7   | 1.2  | 6.16  | 185.85| 0    | 27.52| 0.26 | 9.11 | 93.57| 0.33  | -1.6          |
| Baturaden        |                | 21     | 6   | 13.36| 14.68 | 70.15 | 0.01| 12.48| 4.29 | 7.07 | 48.02| 0.37  | -2.3          |
| Bantarkawung (Cipanas) |            | 43     | 6   | 43.7 | 3.59  | 54.90 | 0.01| 50.9 | 0.32 | 0.04 | 38.29| 3.37  | 1.7           |
| Bantarkawung (Cilakar) |            | 42.6   | 7   | 113  | 2.39  | 140.30| 0.01| 89   | 0.56 | 2.48 | 42.38| 1.48  | -1.5          |
| Bantarkawung (Cilakar) |            | 43.1   | 7   | 120  | 1.20  | 132.17| 0.01| 94.9 | 0.59 | 1.86 | 44.15| 1.64  | -0.7          |
| Bantarkawung (Karangpari) |            | 56     | 8   | 105  | 8.48  | 56.93 | 0.01| 86.2 | 0.69 | 0.05 | 51.70| 7.40  | -2.1          |
| Baturaden (Pancuran 7) |                 | 50     | 7   | 754  | 609  | 687.27 | 0.67| 389  | 76  | 185 | 169.14| 4.40  | -1.5          |
| Baturaden (Pancuran 3) |            | 46     | 6   | 724  | 609  | 695.40 | 0.58| 377  | 76  | 185 | 163.75| 3.97  | -1.0          |
| Guci (Pancuran 13) |                 | 40.5   | 8   | 17.3 | 32.5  | 345.67 | 0.02| 57.3 | 24.35| 29.8| 121.33| 2.84  | 0.6           |
| Guci (Pengasihan) |                 | 50.4   | 8   | 44.2 | 89    | 549.00 | 0.06| 129  | 36.3 | 46.1| 134.83| 6.87  | 0.7           |
| Paguyangan      |                 | 72     | 7   | 414  | 8.51  | 20.33 | 0.16| 193  | 2.92 | 0.23 | 57.67| 3.72  | -2.1          |

3.2. Hot springs relationship

The plot on the ternary diagram of Cl-B-Li indicates that hot springs in Baturaden are different from the hot springs in Guci (figure 5). The Guci hot springs have lower Cl/B ratio than that of Baturraden hot springs. Paguyangan hot spring has high Cl/B ratio and is plotted close to the Baturraden hot springs. Two of the Bantarkawung hot springs (Cilakar hot springs) are classified as high Cl/B ratio while the other two hot springs (Karangpari and Cipanas) are low Cl/B ratio. This plot revealed that geothermal system in Baturaden is different from the geothermal system in Guci. Paguyangan hot spring is probably the outflow of the Baturraden geothermal system.

Referring to the regional geology map, marine sedimentary rocks such as Rambatan Formation and Halang Formation crop out surrounding the Slamet Volcano. Those sedimentary formation may extend beneath Slamet Volcano and become the bed rocks of the volcano. The occurrence of oil seepages near Slamet volcano as reported by Tjahjono [10] and Tobing [11] indicate the petroleum system containing formation water. There may be influence of the marine sedimentary rocks and/or the formation water to the geothermal water composition surrounding Slamet volcano.

The binary diagram of Cl and B (figure 6) shows that all of the cold waters have similar B concentration, but their Cl concentration varies. The Cl/B ratio is represented by the gradient of the trend in that diagram. As
the Cl/B ratio value is relatively constant therefore we may use the Cl/B ratio to differentiate the hot springs into two groups. The first is group of Guci trend. This trend includes hot springs in Guci, Cipanas and Karangpari (both are in Bantarkawung), and Cilimus cold spring. Those hot springs and cold spring are distributed at the northern part of Bantarkawung area. The second group is Baturraden group that includes Baturraden hot springs, Paguyangan hot spring, Cilakar hot springs, Baturraden cold spring, dug well water in Bantarkawung, and Warudoyong cold spring. The Baturraden group is distributed in the southern part of the Bantarkawung area.

Both the Guci and Baturraden groups have similar Cl/B ratio value. The Baturraden group has higher intercept on Cl concentration. Therefore it is interpreted that the thermal water that feed the Baturraden group have been mixed with high Cl fluid possibly formation water from the marine sedimentary rocks. It is estimated based on the extension of the trend line of Baturraden group that crosses the mixing line of condensate water and seawater (figure 6).

![Figure 5. Cl-Li-B ternary diagram plot for hot springs and meteoric water samples from research area](image)

4. Conclusions
Hot springs surrounding Slamet volcano are the out flow of the geothermal system beneath Slamet volcano. The Baturraden hot springs is a result of the mixing of volcanic water and surface water. Cl/B ratio value can distinguish two geothermal system beneath Slamet. The first is the geothermal system related to Guci hot springs and is purely volcanic related geothermal system. The other geothermal system is feeding Baturraden hot springs that have contribution of the formation water. Both geothermal system flow laterally to the west until Bantarkawung area. The Baturraden system is situated in the southern area while the Guci system flows in the northern area.

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Figure 6. Cl vs B binary diagram plot for hot springs, meteoric water samples from research area, sea water [16] and condensate fumarole from Slamet crater [17].

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