Characteristics of Geothermal manifestations in/around the Buyan-Bratan caldera, central Bali, Indonesia.

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ABSTRACT

Geothermal survey of hot springs and hydrothermal alteration were conducted in/around the Buyan-Bratan caldera, central part of Bali, Indonesia. The eight hot spring samples and three river water samples were collected mainly from the southern flank of the caldera, ranging from 320 m to 890 m in elevation. The measured temperature of hot springs is 37 to 52°C, and pH is almost neutral at 6.17 to 6.84. The hot springs are dominant in HCO_3 ranging from 480 to 2250 mg/L. On the southern flanks, the chemical composition of hot springs is systematically changing with decreasing elevations from SO_4-HCO_3 and HCO_3 to Cl-HCO_3 types. These waters are classified as immature waters on a Na-K-Mg diagram. Isotopic data of hot springs and river waters are plotted along the meteoric water line.

Hydrothermal altered zone in Teratai Bang is only the site of gas discharge in/around the Buyan-Bratan caldera, but it is cold and, composed of amorphous silica and/or cristobalite. These rocks are also sometimes associated with native sulfur. This means that at Teratai Bang silicification occurred with very low pH solutions. Probably once volcanic fluid had acted, and resulted in silicified rocks. Here is the only remnant of past high temperature solfatara activities in the Buyan-Bratan caldera.

1. INTRODUCTION

Indonesia has rich geothermal resources estimated to be 27,000 (National Geological Agency of Indonesia). There are more than 100 active volcanoes which are located along the volcanic belt (Sunda-Banda volcanic arc) in Indonesia, and most are distributed mainly in Java (Fig.1). Recent volcanological survey indicates that more than 300 areas show geothermal manifestations. Although there is a high potential of geothermal resources of Indonesia, actual electricity production is still only approximately 1,400MW (BP, 2014). It is therefore necessary to explore the geothermal characteristics and potential of undeveloped geothermal manifestations.

Hot springs and fumaroles are found in Bali, the small island to the east of Java. The studied geothermal area is located in/around the Buyan-Bratan Caldera near the center of the island. The thermal manifestations of the caldera are hot springs on the south and northwest flank of the caldera (B.Soetanri and Prijanto, 1982). A large, single geothermal system beneath the caldera, from which outflows of thermal fluids originate, supplies the hot springs on the flanks. In 1995, a joint operation contract (JOC) was signed and the exploration of Bedugul geothermal energy was indicated. In this project, three deep wells have been drilled for geothermal development (Mulyadi et al., 2005). In the central part of the caldera is a weak altered zone with cold solfatara (Teratai Bang Temple) (Soetanri and Prijanto, 1982). Unusual features of the prospect are the large distances over which the thermal fluids are transported (up to 20 km from the center of the caldera) and the limited active surface manifestations within the caldera. There was therefore great uncertainty as to existence of an economic geothermal reservoir beneath the caldera (Mulyadi, 1982).

This study aimed primarily to reveal the development of geothermal system beneath in/around Buyan-Bratan caldera using geochemical analysis of hot springs and altered rocks.

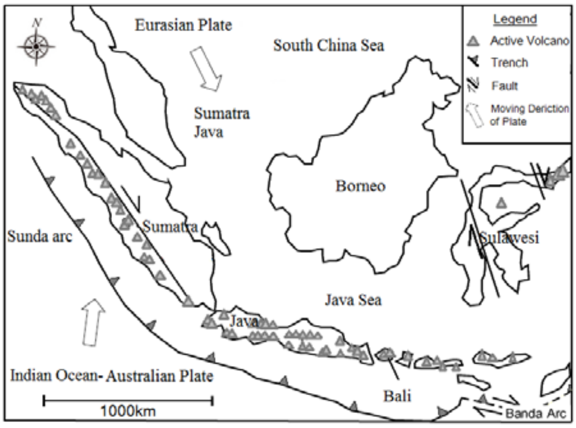

Figure 1: Location map of around Bali showing Sunda-Banda arc and volcanoes (filled triangles) (Katili, 1975).

2. GEOLOGICAL SETTING

2.1 Indonesia

The Sunda-Banda volcanic arc extends for 4,700km from the northern tip of Sumatra in to the small islands of eastern part of Sulawesi (Fig.1). This arc is the junction of three major plates, Australian plate, the Eurasian plate and the Pacific plate, and possibly also the Philippine sea plate (Katili, 1975). The Sunda-Banda arc is divided into two arcs in the southern part of Sulawesi, and the Sunda arc is the boundary between Indian Ocean–Australian plate and Eurasian plate. In Sumatra and western Java, volcanism may have been occurring since Triassic times but in the eastern part of the arc it seems to have begun only in the Middle to Late Miocene (Hamilton, 1979). The basement on which modern volcanism occurs changes progressively from the 20-30 km thick continental crust in Sumatra and Java, through intermediate-type crust near Bali and Lombok to the crust with oceanic thickness near Weter and Banda Islands (Curray et al., 1977; Purdy and Detrick, 1978).

2.2 Bali island

The oldest sedimentary rocks exposed in Bali are Late Miocene calcareous sandstones (Kadar, 1972). New K-Ar data (Wheller et al., 1987.) show that the oldest-known Balinese volcanic rocks are pillow basalts of Late Pliocene age. Most of the island is composed of subaerial volcanic sequences, which are mostly located in the eastern half of the island, are products from the extinct Quaternary volcanoes (Purbo-Hadiwidjojo, 1971). The southern part of Bali island was formed from upraised coral reefs of Pliocene-Pleistocene age (Kadar, 1977).

2.3 Buyan-Bratan caldera

Buyan-Bratan caldera is about 70 km^2 and surrounded with caldera rim except for a small part in the south. The southern rim is not visible because it is buried under the products of the post- caldera volcanic activity (Soetanti and Prijanto, 1982). The outer caldera rim lies between 200 and 400m above the level of three intra-caldera lakes (from west to east, Lake Tambligan, Lake Buyan and Lake Bratan). These lakes cover about one third of the floor part of caldera. Toward the south from the inside of caldera, there are several volcanoes such as Tapak, Pohen, Sengayang, Adeng and Batukaru. Those cones have crater at the top of the volcanoes indicating that each young volcanic cone inside the caldera has erupted at least once (Watanabe et al., 2010).

Bratan area is composed by basaltic to andesitic post caldera lavas and tephra, and the classification of these volcanic units has been established by Wheller and Varne (1986), Tanaka and Sunarta (1994), Yamanaka (2009), Watanabe et al., (2010), and Ryu (2012). Geothermal features are shown within the caldera (about 1,400-1,500 m above sea level) and the southern flanks (about 400-700 m above sea level) (Figure.2). Mulyadi and Hochstein (1982) indicated by resistivity survey that there is concealed lateral outflow of the system beneath Buyan-Bratan caldera, and a small flow of acid waters (near-surface condensates) is discharged in the dry season near the Teratai Bang Temple.

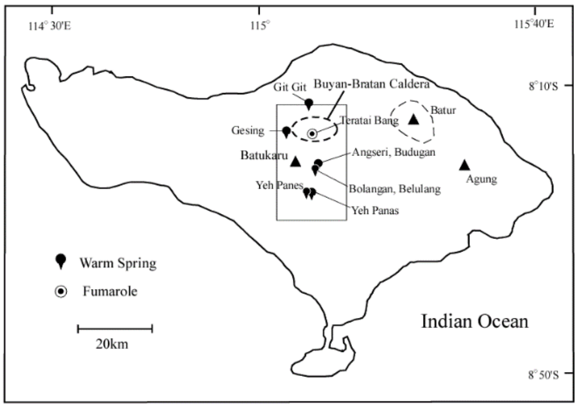

Figure 2: Map of Bali showing Buyan-Bratan caldera with hot springs and fumarole.

3. SAMPLES

The hot spring samples and river samples were collected in and around the caldera, mainly from the southern flank (Fig.2 and Fig.3). Geochemical characteristics of these samples are shown by hexa diagram in Figure 3. Git Git Hot Spring is located near waterfall site at the northern part of the caldera. The outflow of hot spring and gas are from the riverbed, and a volcanic sedimentary layer was found in the vicinity. Gesing Hot Spring, located in the west of Lesong volcano, is the location with the highest altitude where geothermal fluids could be collected in this study. Samples were also taken from hot springs 20 km to the south from the caldera. In Angseri (685 m above the sea level), hot

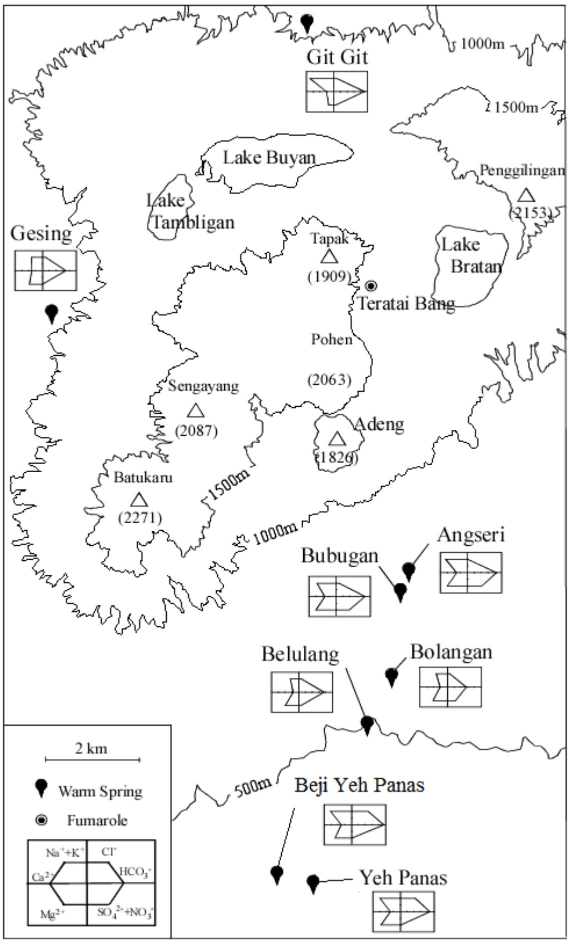

Figure 3: Sample location and chemical composition of hot springs shown by hexa-diagrams.

spring water was used as public bath from 2007. Mulyadi and Hochstein (1982) suggested that cold groundwater fraction in the Angseri springs lies between 0.53 and 0.83 corresponding to undiluted condensates with SiO2 temperature between 160℃ and 265℃, respectively. The thermal water in Bubugan flow out from a cliff along the river. The quantity of flow is estimated to be 40-50 L/min, and the temperature is the hottest in collected samples. Other hot springs are located in the river side, and weakly altered rock are partially developed along the river in Yeh Panas (330 m above the sea level) but the temperature of thermal water is less than 40°C.

The water samples were treated by filter papers which enable the filtration of particles up to 0.45μm, and the temperature and pH of discharged water were also measured on site. Concentration of HCO_3 was ditermined by titration method and other ions were analized by using ion-chromatography.

Some rock samples were also collected in and around these hot springs. Furthermore, the fumarole of cold gas exists in the center of Buyan-Bratan caldera at the Teratai Bang Temple. The gas is leaking at the base of a small constructions. In the Southwest west side flank of Teratai Bang temple, altered zone was confirmed and this feature was also found by previous reports (Mulyadi and Hochstein, 1981; Soetantri and Prijanto, 1982; Yamanaka, 2009; Watanabe et al., 2010). Samples were collected along the flank (From the upper part, E-D-C-B-A-F), then XRD and XRF were used to analyze these samples. When the preparation for XRF analysis, samples were heated for 4 hours with 100°C in order to prevent the sublimation of sulfur. Therefore, samples were measured without considering of LOI.

4. RESULTS

4.1 Geochemistry of hot springs

Hot spring waters around the caldera are almost neutral. The highest temperature is measured at Bubugan (52°C) and the lowest is at Yeh Panas (37°C). As shown in Figure 4, the chemical composition of these samples from southern flanks is dominantly bi-carbonate but can be classified into three types: SO_4-HCO_3, HCO_3 and Cl-HCO_3 type. Chloride contents increases (0.6% in Angseri to 23.9% in Beji Yeh Panas) and relative value of sulfate decreases (27.4% in Angseri to >0.1% in Beji Yeh Panas) with decreasing elevation. The surface phenomena as described above are very common in the geothermal fields in Indonesia, especially in Java (Soetantri and Prijanto, 1982). Johnstone (2005) indicates that spring pH is also dependent on these geographic factors. In fact, pH of the more distant spring from the caldera is slightly higher. Other cation contents

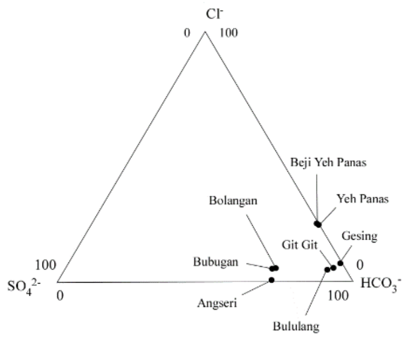

Figure 4: Ternary diagram of hot spring waters by Cl^{-}–SO_4^{2-}–HCO_3^{-}

except HCO_3^- and Mg^{2+} tend to follow the chloride (Li: ranging from 0.1 ppm to 0.3 ppm. Na: from 125 ppm to 330 ppm. Ca: from 60 ppm to 150 ppm). Characteristics of bi-carbonate and magnesium contents in hot springs is similar to that of chloride, but the concentration at an altitude of 480 m (Bululang) is the highest (2250 ppm of HCO_3 and 245 ppm of Mg). Johnstone (2005) indicates that spring pH is also dependent on these geographic factors. In fact, pH of the more distant spring from the caldera is slightly higher. These features were also observed by Mulyadi and Hochestein (1985). Hot spring at Git Git and Gesing samples are classified as HCO_3 type but that chemical composition seems to be different from the southern part of Buyan-Bratan caldera. In the Na-K-Mg ternary diagram (Giggerbach, 1988), it is revealed that the ratio of square root of Mg is dominant (>90%) in the hot springs. This result indicates that samples are plotted in the area of immature water. Furthermore, the result of oxygen-hydrogen isotopic ratio shows that the hot springs are plotted in a parallel to and above the meteoric water line (Fig.5).

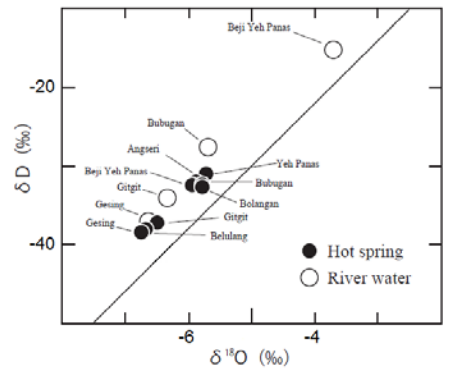

Figure 5: Oxygen-hydrogen isotopic ratio of hot spring waters. The line in the figure shows the meteoric water.

4.2 Chemical composition

Teratai Bang is the only site where altered rocks collected. Fresh rocks and altered rocks were mainly collected from the caldera and southern flank, and scoria were also collected in around Git Git and Angseri hot springs. Chemical composition of these shows that the SiO_2 concentration of fresh rocks ranges from 54.9 to 62.6 wt.% or from basaltic to andesitic. Rocks from caldera rim are characterized by high SiO_2 concentration from 65 to 72 wt.% or from dacitic to rhyolitic composition reported by Watanabe et al. (2010). Composition ratio of total alkali vs. SiO_2 follows MacDonald and Katsura (1964), who indicated that most of the rocks plot below the boundary of alkaline-subalkaline rock series. Furthermore, there are negative correlation with SiO_2 vs. CaO and MgO, but positive correlation with SiO_2 vs. Na_2O and K_2O. The Al_2O_3 is more scattered due to various extent of plagioclase accumulation in rocks (Ryu et al., 2013), and the major element signature in Bratan volcano is similar to that of Sunda-Banda island arc (Wheller et al., 1987). In the case of samples of Teratai Bang, the range of SiO_2 contents is from 53.1 to 81.9 wt.%. Al_2O_3 contents is from 0.4 to 1.2 wt.% (from 14.8 to 19.3 wt.% in fresh rock), and FeO contents is from 0.2 to 1.5 wt.% (from 6.7 to 8.9 wt% in fresh rocks). In several samples which was collected in Teratai Bang, sulfur is precipitated abundantly (12.5 wt.%).

Figure 6 shows the XRD analysis of altered rocks in Teratai Bang (ground level is the altitude of 1,400 m). Native sulfur is identified in the upper part of flank (Sample E and A), but cristobalite is clearly in the lower part (Sample G). As a result, it is revealed that amorphous silica is main component and there is a small amount of cristobalite. In other words, this is the remnant that the silicification was proceeding widely in Teratai Bang area.

5. CONCLUSION

Chemical composition of these hot springs are systematically changing with decrease the altitude as mentioned by Mulyadi and Hochstein (1981) and Soetanri and Prijanto (1982). Hot springs at Angseri, Bubugan and Bolangan are considered to be affected by gas which consist of H_2S. In this area, the occurrence of silicified rock is revealed with XRD analysis. Then, it is estimated that there was high temperature solfatara activities of volcanic fluid at Teratai Bang in the past. Hot springs at Yeh Panas and Beji Yeh Panas is classified into Cl-HCO_3 type. This feature is derived from a mixing of deeper chloride water and steam heated bi-carbonate water as indicated by Mulyadi and Hochstein (1981). HCO_3 dominant water is obtained around the altitude of 480 m (Bululang). Although the waters on southern flank of caldera is originated in meteoric water, HCO_3 contents in Bululang is significantly higher than the others. Probably the reservoir of hot bi-carbonate water is existed under the near surface around the altitude of 480m.

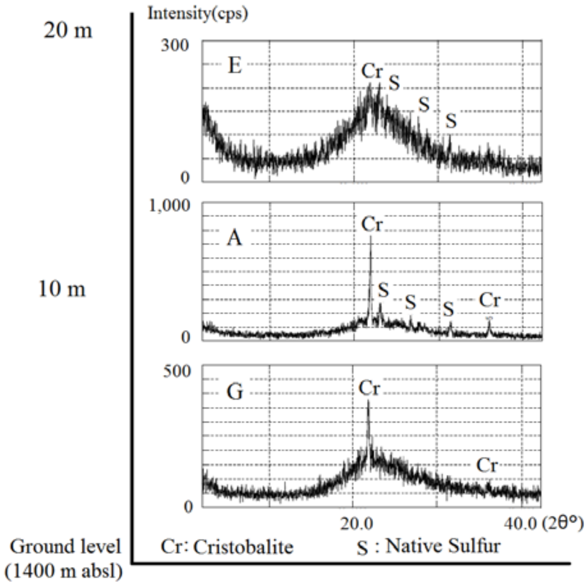

Figure 6: XRD identification of altered rocks from Teratai Bang Temple (central Buyan-Bratan caldera).

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