Geothermal prospects of Flores Island in Indonesia viewed from their volcanism and hot water geochemistry

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Abstract: Lavas of the Flores volcanic arc have a range of compositions from basalt to dacite but mostly andesite, containing pigeonite and olivine in island arc tholeiitic series and amphibole and biotite in calc-alkaline series. Chemically, the rocks show a wide variety of SiO2 (51 - 67 wt.%), Al2O3 (14 - 20 wt.%), and low TiO2 (<1 wt.%), together with relatively high Rb, Sr and Ba. These K group elements represent an increase of SiO2 with increasing depth of the Benioff zone. Strontium isotope ratios of tholeiitic to calc-alkaline lavas are 0.7042 - 0.7045, assumed to be correlated with the depth of the subducted slab across the island. Flores geothermal prospects are situated in young volcanic terrains of andesite and basalt between 500 to 1000 m above sea level (a.s.l.) and associated with post volcanic fractures, faults and caldera structures. Hot water discharges represent a wide variety of chemical water types; sulfate, bicarbonate and chloride waters. Sulfate type is mostly associated with fumaroles and located on high volcanic terrains (700 - 1100 m a.s.l.), indicating the near-surface H2S oxidation (Ulumbu, Mataloko, Nage and Sokoria). Bicarbonate waters are located at the moderate slope of volcanics (400 - 700 m a.s.l.), shown by Langageda and Sokoria 2. Neutral chloride waters are located at the lower volcanic terrains approximately 5 - 600 m a.s.l., indicating an outflow from geothermal reservoirs with a temperature of 210 to 280 °C. Geothermal wells that were drilled at the Ulumbu and Mataloko prospects to a depth of 700 - 1800 m and 200 m, respectively have a subsurface temperature of 200 to 240 °C, indicating that the high sulfate concentration is associated with a vapor-dominated system. The same system probably occurs in the Sokoria field. While the geothermal prospects of high chloride water type are probably associated with hot-water or mixture system (Wai Sano, Wai Pesi, Jopu, Lesugolo and Oka).

1. Introduction

The Indonesian volcanic arcs represent a wide variety of volcanic rocks in compositions. The spatial and temporal variations of magma compositions are known of many island arcs (Gill, 1970). It is also known from the eastern Sunda arc (Whitford et al., 1979). Hatherton and Dickinson (1989) show that the potassium content of volcanic rocks or "K" value is positively correlated with increasing depth to the seismic plane or "h" beneath the arc. Flores forms a part of the eastern Sunda arc and represents a row of active and inactive volcanoes where some of them are associated with calderas. Compositions of these volcanic rocks will give information of the tectonic settings.

Some of active and inactive volcanoes in Flores exhibit fumaroles, solfataras and hot springs. Those geothermal manifestations are found along almost the entire island. Water and gas geochemistry in those areas provides a method to evaluate geothermal potential of the prospects. White et al. (1971) have studied characteristics of chemical elements of high temperature and high pressure fluid. Ellis and Mahon (1977) have classified geothermal prospects

Keywords: Flores, Indonesia, geothermal prospect, volcanism, volcano, petrology, rock series, hot spring, hot spring type, geochemistry

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based on water geochemistry and their volcanic activities. These methods will give geothermal information on potential areas to be promoted for geothermal developments.

This paper tries to inform the spatial variation of the volcanic rocks of active volcanoes and hot water geochemistry of geothermal prospects on Flores Island.

2. Tectonic frame work

Tectonically, Indonesian island arcs are the result of the interaction of the Eurasian, Pacific, Philippines and Indian-Australian Plates (Fig. 1). Most of these island arcs display micro-continental arc volcanism associated with an oceanic trench subduction zone (Cass and Wright, 1987). They can be divided into four arcs: the Sunda arc in the west, Banda arc in the east, two small Sangihe-North Sulawesi and Halmahera arcs situated north of the Banda arc.

The Flores volcanoes and geothermal prospects form a part of the eastern Sunda arc. The evolution of the volcanic arcs occurred from pre- to mid-Tertiary associated with the collision of the Australia Continent (Audly-Charles, 1975). This event might have caused active volcanisms and associated geothermal activity and resulted in a complicated differentiation in tectonic settings from west to east along the arc.

3. Volcanic activity

Flores Island has eight active volcanoes, the Anak Ranakah, Inerie, Inelika, Ebulo, Iya, Kelimutu, Egon, and Lewotobi (Fig. 2). Some of these volcanoes are associated with collapse calderas. The last volcanic eruptions occurred at Anak Ranakah in 1987, Lewotobi in 1992 and Inelika volcanoes in 2001, producing lava dome and pyroclastic products.

Petrographical data of volcanic rocks represent a variety of rock types as reflected by the phenocryst assemblages and rock chemistry. Figure 3 illustrates the distribution of rock types of lavas from each active volcano. In terms of SiO₂ contents, they are from 51 to 67 wt.% and span the range of basalt, basaltic andesite, andesite and dacite, but are predominantly basaltic andesite and andesite where dacite is relatively rare.

The volcanic products show a large variation in compositions even for a single centre of each active volcano. Tholeiitic series contain pigeonite, olivine and plagioclase phenocrysts, while calc-alkaline series contain hydrous minerals, amphibole and biotite, representing higher potassium contents. Rock nomenclature in this figure largely follows the chemical scheme of Le Bas et al. (1986; Fig. 3).

4. Chemistry of volcanic rocks

4.1 Major elements

Flores volcanic rocks of eastern Sunda arc are characterized by the wide variation of SiO₂ (51 - 67 wt.%), high contents of Al₂O₃ (14 - 20 wt.%), low contents of TiO₂ (below 1.0 wt.%), and relatively low MgO/FeO ratios. Except for Na₂O and K₂O, all major elements decrease in abundance with increasing SiO₂ in the Harker diagram (Fig. 4).

Representative major elements analyses of basalt, basaltic andesite, andesite and dacite of tholeiitic, calc-alkaline and high calc-alkaline suite are listed.
In relation between the depth of the subduction zone and geochemical association suggested by Jakes and Gill (1970), magma types of Flores volcanic rocks can be evaluated. The tholeiitic associations are found close to the trench over the Benioff zone with a depth ranging from 100 to 150 km. The calc-alkaline to high K calc-alkaline associations reflect increasing contents of K and related compatible elements within the apparently continuous spectrum of the compositions. These associations are more distant from the trench over the Benioff zone depth ranging from 150 to 250 km.

4.2 Trace elements
The trace element concentration of rocks from some volcanoes varies widely (Table 1) and is useful to identify mantle geochemical processes. The concentrations of Large Ion Lithophile (LIL) such as Rb, Ba and Sr show 12 - 60 ppm, 175 - 830 ppm and 244 - 481 ppm, respectively. These K group elements are positively correlated to each other, as shown by Rb vs. K or Sr vs. K. They increase with increasing silica from basalt, basaltic andesite to andesite, probably due to the fractionation of magma (Fig. 7). This is in harmony with the chemical variation across the island arc or LIL elements increase away from the trench.

Compatible element concentrations such as Ni, Sc, Co and V show <8 - 12.9 ppm, 25 - 30 ppm, 24 - 175 ppm and 166 - 209.87 ppm, respectively (Fig. 7). These low concentrations may be caused by fractionation and probably a few primary mantle-derived melts. In addition, the Y concentration falls into a range of 16 - 28 ppm, which are average values for orogenic andesite (Lambert and Holland,
Fig. 4  Harker diagram showing Na₂O and K₂O increase, and the other elements quantity decrease with increasing silica.
   ◆ Anak Ranakah; + Inelika; × Inerie; ◆ Ebulong; ▲ Iya; ■ Lewotobi Laki-Laki; □ Lewotobi Perempuan.

Table 1  Major and trace elements of volcanic rocks from active volcanoes in Flores (Lewotobi and Iya volcanoes).

| Sample Code | Na₂O | K₂O | MgO | Al₂O₃ | TiO₂ | SiO₂ | CaO | FeO⁺ | MnO | Zn | Sr | Y | Zr | Ba | Rb | Sr | Pb | Cu | Sn | Cd | Hg | Mg | Fe | Ca | Na | K |
|-------------|------|-----|-----|-------|------|------|-----|------|-----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
|             |      |     |     |       |      |      |     |      |     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |   |
| Lewotobi   |      |     |     |       |      |      |     |      |     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |   |
| Laki-Laki  |      |     |     |       |      |      |     |      |     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |   |
| Iya        |      |     |     |       |      |      |     |      |     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |   |

--- 90 ---
Table 1 (continued)  Major and trace elements of volcanic rocks from active volcanoes in Flores (Inerie, Inelika and Anak Ranakah volcanoes).

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</table>

Fig. 5  AFM (Na2O-K2O-FeO-MgO) diagram showing that most samples fall into the calc-alkaline suites. A boundary curve is quoted from that of pigeonite (tholeiitic) rock series and hypersthene (calc-alkaline) rock series by Kuno (1950). ◆ Anak Ranakah; + Inelika; × Inerie; ○ Eblobobo; Δ Iya; ■ Lewotobi Laki-Laki; □ Lewotobi Perempuan.

Fig. 6  MnO-TiO2-P2O5 diagram (Mullen, 1983) showing regions of calc-alkaline basalt, island arc tholeiite and others. ◆ Anak Ranakah; + Inelika; × Inerie; ○ Eblobobo; Δ Iya; ■ Lewotobi Laki-Laki; □ Lewotobi Perempuan.
1974). They have probably formed in the crust with a thickness less than 20 km.

5. Geothermal prospects of Flores

Geothermal prospects are mostly associated with post-volcanic activities and distributed on high-altitude volcanic terrains along the island. They are divided into three segments, the West Flores prospects, Central Flores prospects and East Flores prospects. Major geothermal prospects are Wai Sano, Ulumbu and Wai Pesi (West Flores), Mataloko, Bobo and Langageda (Central Flores), and Sokoria, Lesugolo, Jopu, Detusoko and Oka (East Flores) as shown on Table 2 and Fig. 2.

5.1 West Flores prospects

Wai Sano is a caldera lake, approximately 20 km west from the main Trans-Flores Road. Hot springs are situated in a fossil fumarole field at the southern side of the caldera lake and discharge high temperature and neutral pH water at a low flow rate with thick silica sinter.

Ulumbu is located at the southwestern boundary of the Poco Leok caldera. Hot springs are situated in a fumarolic field on the west slope of the Kokor River (700 m a.s.l.) approximately 11 km south of the main city, Ruteng. The high temperature and low pH water discharges at a relatively low flow rate. High amounts of steam flow from the fumarolic field are clearly seen from far away.

5.2 Central Flores prospects

Geothermal prospects are distributed in a volcanic complex of Wolo Bobo, Wolo Beo and Wolo Belah approximately 1000-1500 m above sea level. They are located ± 2 - 15 km south from the main Trans-Flores Road and easy to access. They are known as the Mataloko and Nage hot springs and fumaroles representing low to high flow rates of acid water (Table 2).

To the north of Bajawa (± 20 km), the hot
springs are distributed in several areas and closely associated to the Inelika volcanic complex represented by Mengeruda (± 300 m above sea level). They have a very high flow rate and are relatively acidic and low temperature, > 400 l/sec, pH 3 - 4 and 42 - 47 °C, respectively. The Mengeruda hot springs are known as a recreation area with small cottages and a nice natural warm pool.

**5.3 East Flores prospects**

Geothermal situations are indicated in a large area distributed from Ende to Larantuka (the eastern tip of Flores). Sokoria (± 600 - 1050 m a.s.l.) is a caldera complex associated with an active volcano to the north, known as a Kelimutu volcano (1690 m). The prospects are indicated by fumaroles and hot springs such as Sokoria, Detusoko and Jopu. They have low flow rates (0.5 - 5 l/sec), low pH and high water temperatures as shown on Table 2. The other hot spring discharges are located in relatively low land areas (5 - 600 m a.s.l.), Oka-Larantuka, Waigate, Lesugolo, Jopu and Detusoko (Fig. 2).

6. Water chemistry

Hot waters of Flores are classified into chloride
(Cl), sulfate (SO₄) and bicarbonate (HCO₃) type water.

6.1 Chloride water (Cl)
Wai Sano neutral hot springs represent a high concentration of Na, Cl, K, Ca and boron (B), 5946, 132900, 19456 and 418 ppm, respectively (Table 2). These show chloride type water, providing an indication of outflow water from a reservoir (Fig. 8). A ternary diagram of Na, K and Mg shows that the Wai Sano hot water is located in a “partial equilibrium” (Fig. 9), indicating a relatively small influence of surface water dilution. A high boron concentration is assumed to be the involvement of sedimentary materials in high temperature geothermal water, where boron is easily dissolved in high temperature water (Koga, 1981).

The other chloride water types are at the Wai Pesi, Detusoko, Jopu, Lesugolo, Oka and Kawalewu hot springs (Fig. 2), which are higher in the Na > Ca > Mg cation ratio and higher in the Cl/SO₄ ratio (Table 2). They are interpreted as an outflow water from an immature and partially equilibrated hydrothermal system that contains juvenile volcanic gases such as CO₂, H₂S and NH₃.

6.2 Bicarbonate water (HCO₃)
The bicarbonate waters are found at Sokoria and Langageda (Bajawa) on moderate topographical terrain (300 - 700 m above sea level). They show an average flow rate and neutral pH water (Table 2) indicating the neutral chloride water contains condensed CO₂ and H₂S in a shallow aquifer (Ellis and Mahon, 1977).

6.3 Sulfate water (SO₄)
Wai Kokor (Ulumbu), Mana-Mataloko, Nage, Sokoria and Detusoko hot springs are sulfate type water (Fig. 7) and are located on high volcanic terrain (Table 3). They represent a high concentration of SO₄, low flow rate and high water temperature (80 - 95 °C). The Cl/SO₄ ratio is relatively low, assumed to be an upflow of volcanic gasses (especially H₂S) oxidized on the way up to the surface with oxygen at a shallow water level. The hot springs plotted on a Na-K-Mg ternary diagram are located in an “immature water” and are interpreted that shallow meteoric water were much involved in hydrothermal processes near the surface (Fig. 9).

6.4 Subsurface temperature estimation
Chemical geothermometry using SiO₂, Na-K and Na-K-Ca-Mg components can be used for estimating the subsurface reservoir temperatures, especially for neutral pH water. Acid hot springs are better estimated by gas geothermometry. In general, neutral pH water of each Flores hot spring exhibits high Na/K and low Mg/Ca ratios, 4.96 and 0.016, respectively indicating a high reservoir temperature condition. The SiO₂ and Na/K or Na-K-Ca-Mg geothermometers show subsurface temperatures from 108 to 219 °C and 275 - 290 °C respectively as shown in Table 2. Therefore, high potentials are estimated in Flores in terms of the chemical geothermometry.

Ulumbu, Mana (Mataloko) or Nage and Sokoria are high temperature fumarolic fields showing subsurface temperature estimation from 240, 240 - 283

Fig. 8 Cl-SO₄-HCO₃ ternary diagram (Giggenbach, 1988) showing that Flores’s hot springs are mostly sulfate and chloride type waters.

Fig. 9 Na-K-Mg ternary diagram (Giggenbach, 1988) showing Flores’s hot springs located in a partial equilibrium indicating a possible subsurface hydrothermal system. A.P. means a hot spring in Indonesian.
Table 3 The distribution of geothermal manifestations from West, Central and East Flores.

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<td>Waniago</td>
<td>53.90</td>
<td>600-650</td>
<td>Associated with Waniago caldera’s</td>
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<tr>
<td>Ulumbu</td>
<td>76.94</td>
<td>700-1300</td>
<td>Associated with Portokal caldera’s at Sokor river</td>
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<td>Wai Pesi</td>
<td>80</td>
<td>100-150</td>
<td>Possibly associated with old volcanic dome (?)</td>
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<td>Central Flores</td>
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<tr>
<td>Mataloko</td>
<td>77.90</td>
<td>900-1020</td>
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<td>Nage</td>
<td>71.80</td>
<td>480-500</td>
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</table>

and 260 °C, respectively (Nasution et al., 2000). Therefore, there is a good correlation between water and gas geothermometry in assuming subsurface Mataloko and Sokoria geothermal fields.

Two drilling areas, Ulumbu and Mataloko have shown good geothermal prospects. Three wells (1800, 900 and 700 m) such as an exploration well, production well and injection well have been drilled in the Ulumbu geothermal field. The production well represents downhole temperatures approximately 230 - 245 °C with a vapor dominated system (Johnson, 1995 personal communication). The shallow Mataloko exploration drilling (200 m) has given subsurface temperature information of about 200 °C and has a vapor dominated system. These two areas have indicated good geothermal resources. Therefore, the SO₄ type water of Sokoria fumarolic field will probably have a similar system as the Ulumbu and Mataloko fields.

7. Discussion and conclusions

Geochemistry of Flores volcanic rock associations has characteristics of most island arcs. For more details, however, it is better to be volumetrically evaluated for the magmatic processes and genesis. The wide array of SiO₂ - K₂O trend of volcanic rocks of the Flores Island reflects variation in petrogenetic controls in the direction across the Flores volcanic arc. The tholeitic lavas of Flores have average values of ⁸⁷Sr/⁸⁶Sr = 0.7042 at the Benioff zone depth between 100 - 150 km. The high K calc-alkaline lavas have average values of ⁸⁷Sr/⁸⁶Sr = 0.7045 at the Benioff zone depth of 200 - 250 km (Whitford and Jezek, 1982). The source regions of isotopic values are correlated to the depth of the subducted slab, and the isotopic variation reflects the involvement of subducted materials (Whitford and Jezek, 1982). These data are supported by Ben Abraham and Emery (1973) that the depth of Benioff zone under Flores volcanic island is approximately 100 - 250 km.

Volcanologically, geothermal prospects of Flores are located in Quaternary volcanic areas, especially in volcanic caldera types. The hot springs are mostly associated with post-volcanic activities. The high temperature gasses (SO₂, HCl and toxic gasses such as CO) are mostly found in an active volcano and will probably not exist or will be very low concentration in geothermal fields. Therefore, the corrosive and toxic gases will probably be avoided.

In general, the high temperatures of sulfate type water are mostly obtained on a high topographic terrain, as shown by the Sokoria, Mana Mataloko and Ulumbu geothermal fields. They presumably represent the same system that volcanic gas tends to flow up through volcanic rock fractures to the surface (it is represented by an active volcano). In a lower topographic terrain, hot springs are mostly derived from neutral pH chloride water. They apparently tend to flow through low land and high porosity rocks (Wai Sano, Wai Pesi, Deteusoko, Lesugo and Oka).

Drilling of exploration-production wells in the Ulumbu geothermal field have been carried out by PLN (an Indonesian private company) and GENZL (New Zealand private company) and their producing steam capacity is approximately 12 MWe (Johnson, 1996, a personal communication). The shallow drilling in the Mataloko geothermal field gives a low
steam capacity of approximately 14 - 15 ton/hour, equivalent to 1.5 MWe. Therefore, young volcanoes contribute for the Flores geothermal heat source. Information on the post-volcanic activities provides useful data for detailed exploration of the geothermal prospects in Flores such as Wai Sano, Sokoria, Detusoko and Lesugolo.

Acknowledgement: This paper benefited from the thoughtful review by Dr. Shigeru Suto.

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火山活動および熱水化学組成からみたインドネシア・フローレス島の地熱有望地域

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要 旨

フローレス火山の溶岩類は玄武岩からデイサイトの組成範囲をもつが、ときに安山岩に卓越し、ソレイアイドゲート系ではピジョン輝石、カンラン石を、カルクアルカリ岩系では角閃石や黒雲母を斑晶として含む。化学的には、広い範囲の SiO2 (51−67 wt.% ) および Al2O3 (14−20 wt.% ) 含有と低い Ti O2 (<1 wt.% ) 含有を示し、比較的高い Rb、Sr および Ba 含量を示す。これら Kグループ元素はベニオフ帯の深度の増大につれて増加する。ソレイアイド系からカルクアルカリ溶岩にかけてのストロンチウム同位体比は 0.7042−0.7045 であり、これら島弧を横断して沈み込むスラブの深度に比例していると推定される。フローレス島の地熱有望地域は落石安山岩や玄武岩の火山地域に位置し、標高 500−1000 m にある火山活動後の断層と断層や、カルデラ構造に伴う、湧出熱水は広い化学的タイプを示し、硫酸塩型、塩素型、重炭酸塩型に分けられる。硫酸塩型は主に噴気を伴って、熱水地域（標高 700−1100 m）に位置し、表面における H2S の酸化を示す（Ulnumbu, Mataloko, Nage および Sokoria）、重炭酸塩型熱水は Langageda や Sokoria2 のように火山中腹（標高 400−700 m）に位置する。中性塩型熱水は低い火山地域（標高 5−600 m）に位置し、温度 210−280 °C の地熱蒸留層からのアウトフローを示す。地熱井戸は Ulnumbu と Mataloko 地熱有望地域でそれぞれ 700−1800 m と 200 m の深度まで掘削されているが、200 から 240 °C の地下温度を示し、その高い硫酸塩濃度が蒸気地化型に伴うことを示している。同様の型は Sokoria 地域にも期待される。他方、高塩素型の地熱有望地域はおそらく熱水卓越型か混在型を示すであろう（Wai Sano, Wai Pesi, Jopu, Lesugolo および Oka)。