Geochemical Exploration of Geothermal Manifestations: Study Case of Bajawa Volcanic Complex, Flores Island, East Nusa Tenggara Province.

H H Herzhegovina¹, M Abdurrachman², M Hafidh¹ and M Divi¹

¹ Department of Geology, Indonesian College of Mineral and Technology, Bandung 40263, Indonesia.
² Department of Geology, Bandung of Institute of Technology, Bandung 40132, Indonesia.

* Corresponding Author: geo.herzhegovina@gmail.com (Helmy Hizkya Herzhegovina)

Abstract. Currently Indonesia occupy third place in the World demand of geothermal energy with using of 1375 Mwe (Mega Watt electrical). Energy utilization is only used around 4 – 5% of geothermal energy capacity owned by Indonesia. Surely, this fact encourages many researcher to develop geothermal field with multidisciplinary sciences. One of potential geothermal areas is Nagegeothermal field located in Bajawa City, Ngada District, East Nusa Tenggara Province. Four hot springs and fumarole were founded in the area. The Exploration using geochemical analysis in the form of descriptive method and analysis of geothermal fluid data. Based on regional geology, Bajawa volcanic complex composed of three periods of volcanic, first is old volcanic that formed Nage Caldera and Old Inierie volcanoes, then formed Bajawa Cinder Cone unit with North – South and North East – Southwest alignment, this alignment surely controlled as a linear eruptions. And the last is Inierie unit, this unit is active stratovolcano. The results of data obtained from one fumarole and four hot springs sample were taken from Wolo puti fumarole, Bena hotspring, Keli hotspring, Nage I hotspring and Nage II hotspring. Based on the relationship of chemical element ratio and plotting of triangular Giggenbach diagram shows that Keli and Bena hot springs are sulphate type, this hotspring controlled by Wolo puti fumarole as upflow of the geothermal system then Keli and Bena hot springs are in the outflow zone, which has mixed by meteoric water. Nage I and Nage II hot springs are chloride type, which has different geothermal system from Keli and Bena hot springs. Based on the geothermometer calculation of the Na-K-Mg diagram, the temperature of reservoir is 220° - 340° C, which is included of high enthalpy geothermal system.

1. Introduction
One way to improve national energy security is by exploring renewable energy. One of the renewable energies that is clean, sustainable and eco-friendly is geothermal energy. Indonesia became the third most populous country to use geothermal energy as a power generator worldwide after Mexico. Indonesia has the potential of 40% geothermal resources because it contains the largest geothermal reserves in the world located on the surface of the country of Indonesia. However, Indonesia uses only 5% of its reserves as most of these sources are only developed in western part of Indonesia such as Java and Sumatera Islands. Surely, this fact encourages many researchers to develop the potential of geothermal energy reserves and discover a new field in eastern Indonesia. As we know the development
of geothermal energy in eastern part of Indonesia that has been producing is PLTP Lahendong which is
located in Tomohon City, North Celebes Province. One of potential geothermal areas in Eastern part of
Indonesia is Bajawa geothermal field located in Bajawa City, Ngada District, East Nusa Tenggara
Province. Based on regional geology, Bajawa is surrounded by volcanoes [1-3] that composed of three
periods of volcanic, first is old volcanic that formed Nage Caldera and Old Inierie volcanoes, then
formed Bajawa Cinder Cone unit with North – South and North East – Southwest alignment, this
alignment surely controlled as a linear eruptions. And the last is Inierie unit, this unit is active
stratovolcano.

![Figure 1](Image)

Figure 1 Location of Bajawa city, Ngada district, East Nusa Tenggara Province. Red square location
of Bajawa Geothermal Field.

2. Data and Method
The geothermal manifestations that appear in this field are hot springs and fumaroles. There are 4 hot
springs and 1 fumarole which can be observed, that is Bena Hot springs, Keli Hot springs, Nage-1 Hot
springs, Nage-2 Hot springs and Wolo Puti Fumarole (Figure 2). The method used in this research is:

2.1. Field Observations
Direct observations of the hot springs and fumaroles manifestations were documented and some physical
properties (Table 1) were directly measured in the field including surface and water temperature. Water
sampling based on procedure according to [4]. Sample taken by filtered using a 0.45μm Nicholson pore
filter. Water samples from each sampling point are then divided into two different containers with
different treatments. Water samples for cation and anion major analysis using Ion Chromatography
methods such as Na, K, Ca, SO4, Cl, etc., were placed on a 100 ml HDPE plastic bottle. Water samples cultivated have no contact with free air is too long to avoid reaction with air. This is done so that errors during laboratory analysis can be minimized. As for the water samples to be used for the analysis of SiO2 and trace ions such as Rb, Cs, As, etc. using ICP-AES method, acidification was done using 2 mL of HNO3 acid.

2.2. Laboratory Analysis

The process of geochemical data analysis is processed by 3 methods, namely titration, ion chromatography, and ICP-AES. The titration method was used to determine the concentration of HCO3 in hot water samples, ion chromatography was used to measure the concentration of major ions, while ICP-AES was used to measure trace ion concentration.

After water samples are processed in the laboratory to investigate chemical properties (Table 2) the result of Laboratory analysis then calculated with error analysis or ionic balance which signifies the balance of concentration between positive and negative ions in solution (sample). Positive results showed higher cation concentrations, whereas negative results indicated more dominant anions. A result close to 0<5 means that the equilibrium of cation and anion has been achieved [4] and the quality sample is good to further analyzed (Table 3).

Based on ion equilibrium calculations, Nage-1 and Nage-2 water samples have poor quality due to the value of anions of too high chloride (Cl-) and too low a Ph value that affects the cation value of hydrogen (H+).

3. Results and Discussions

After the data of the laboratory analysis results are considered valid, then the analysis can be processed. First, geothermal analysis is using Cl-SO4-HCO3 element.

![Figure 3. HCO3-CI-SO4 triangle diagram according to [5] for determination of fluid type and maturity.](image)

Based on the result of plotting on SO4-CI-HCO3 triangle diagram for the determination of fluid type according to [5] (Figure 3), it can be seen that there are 4 types of water based on the concentration ratio of HCO3, Cl and SO4. The samples from the Nage-1 and Nage-2 hot springs including into the chloride type. While other samples of Keli and bena included into the type of sulfate springs which is mixing with meteoric water rich in HCO3.
Plotting Triangular diagram of Na / 1000-K / 100 shown [5] is a method is used for estimating reservoir temperatures and for knowing that water reaches a balance in lithology. From the data and calculation of the percentage content of the three elements, a plotting of the Na / 1000-K / 100-Mg½ triangle diagram (Figure 4) is performed for each hot springs sample.

**Figure 4.** The Na-K-Mg triangle diagram [5,6] for estimating the temperature of the geothermal reservoir and determination of fluid maturity

Based on the calculation of the relative content of Na / 1000-K / 100-Mg½ and after plotting of the value of the triangle Na-K-Mg, hot springs Nage-1, Nage-2, Keli and Bena lies in immature water. Geothermometer calculation of the Na-K-Mg diagram, the temperature of reservoir is 220° - 340° C, which is included of high enthalpy geothermal system [7].

The Cl-Li-B triangle diagram is used to evaluate the boiling and dilution processes on the basis of the alternate concentrations of Cl / 100, Li, and B / 4 which have been changed in the triangular Cl / 100 diagram for each hot-water sample.
Based on the result of triangle diagrams Li-B-Cl [5] to determine the different geothermal systems, the presence of two groups can be separated. The first group is the Nage-1 and Nage-2 hot springs that have a low B / Cl ratio value as well as the second group of Keli and Bena hot springs that have the same B / Cl ratio value. So it can be interpreted that the value of B / Cl ratio as the system age difference. The older system generally has a low B / Cl ratio value [5] this is due to the boron ion which tends to be released at the beginning of the heating stage as well as the elements of As, Hg and Sb. So it can be interpreted that the geothermal system of Nage-1 and Nage-2 hot springs is older than Keli and Bena hot springs. This is supported by the geographical and geological position of the region where the hot water of Nage-1 and Nage-2 is located on the nage caldera which is the oldest volcanism located in the volcanic complex of bajawa.

Based on the type of hot springs water present in the research area, the four manifestations of the hot springs are in the outflow zone. Sulphate type shows that the reservoir fluid has been mixed with surface water. In (Figure 5), it shows that hot springs water in the study area has high Cl values compared to B and Li. This indicates that hot springs are affected by volcanomagmatic activity.

Based on [7], the manifestations present in geothermal systems that are volcanomagmatic are strongly influenced by the relief and topography of volcanoes. At the top, the manifestations may be fumaroles containing vapors and gases such as wolo puti fumaroles. In addition, the present manifestation is sulfate spring which is the result of condensation of vapor mixed with shallow meteoric water so that H2S is oxidized to H2SO4. Chloride-type water is deeper than sulfate-type water due to topography and hydrologic gradients, the chloride type hot springs usually found far from the source of heat and the main reservoir up to several kilometers away. so geothermal system with steep relief in the form of volcanoes.

Most of discharges water from Nage-1 hot springs, Nage-2 hot springs, Keli hot springs and Bena hot springs have inequilibrated fluids which is extensive interactions with rocks cause that fluids are controlled by dissolution rocks or rather than mineral-solution equilibrium (Figure 6)

**Figure 5.** The Cl-Li-B triangle diagram [5] for estimating source of geothermal fluid.
Figure 6. Plot of $\frac{10K}{10K+Na}$ versus $\frac{10Mg}{10Mg+Ca}$, Ci in mg/kg or Na-K/Mg-Ca Diagram [5]

The point marked “rock dissolution” in (Figure 6) with $x=0.8$ and $y=0.8$ is based on several averages of $x=\frac{10K}{10K+Na}$ and $y=\frac{10Mg}{10Mg+Ca}$ ratios for mean x and y ratio of dissolved volcanic rocks.

4. Conclusions

The geothermal system that formed in the Bajawa region is estimated to be associated with a volcanomagmatic environment consisting of 2 types of springs ie sulfate and chloride with an estimated Na-K geothermometer of $220^\circ - 340^\circ$ C, which is included of high enthalpy geothermal system. Based on the water source diagram, there are two distinct sources, in which the Nage-1 and Nag-2 hot springs belong to a hot spring type with a small B / Cl ratio, thus indicating the older geothermal heat system versus springs hot Keli and Bena, this is supported by regional geology and geographical position of the hot springs that reside in old volcanic that has a relative age early Pliocene. Then, based on ternary diagram analysis, Nage-1, Nage-2, Keli and Bena hot springs are immature water which mixed meteoric water resulted from rock dissolution.

The results of this study are needed for further research in order to develop geothermal model systems for geothermal exploration with other geochemical explorations such as soil sampling and multidisciplinary science such as geological and geophysical exploration.

5. Acknowledgements

The authors are grateful to Center of Coal and Geothermal Mineral Resources (PSDMBP), especially to Mr. Dedi Kusnadi, Mr. Chandra, Mr. Dudi Hermawan and Mrs. Sukaesih who has guided the conduct of this research, Mr. Taat and Mrs. Rita who have helped to chemical analysis of water sample and Visuvius, Rijon and Hanis who have helped in the activities of field observations.
References

[1] Muraoka, H., Nasution, A., Urai, M., Takhashi, M., and Takashima, I. 1999. Geology, Geochemistry and Geochronology of the Bajawa area. Interim report of Geological Survey of Japan Research, Cooperation Project on the Exploration of Small-scale Geothermal Resources in Eastern part of Indonesia (ESSEI).

[2] Muraoka, H., Nasution, A., Urai, M., Takahashi, M., Takashima, I., Simajuntak, J., Sundhoro, H., Aswin, D., Nahlohy, F., Sitorus, K., Takahashi, H., and Koseki. 2002. Tectonic, Volcanic and Stratigraphic geology of the Bajawa geothermal field, Central Flores, Indonesia, Bulletin of Geological Survey of Japan, 53, 109-138 p.

[3] Nicholson, K, 1993. Geothermal fluids: Chemistry and exploration techniques, Springer-Verlag, 263 p.

[4] Muraoka, H., Nasution, A., Urai, M., Takhashi, M., and Takashima, I. 1999. Regional geothermal geology of the Ngada district, central Flores, Indonesia. Interim report of Geological Survey of Japan Research, Cooperation Project on the Exploration of Small-scale Geothermal Resources in Eastern part of Indonesia (ESSEI), 17-46p.

[5] Giggenbach, W.F. 1997, The origin and evolution of fluids in magmatic-hydrothermal systems,” in Geochemistry of Hydrothermal Ore Deposits 3rd edition, H.L. Barnes ed., John Wiley and Sons, NY, June 1997.

[6] Giggenbach, W.F., 1988. Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geo indicators. Geochemica et Cosmochimica Acta Vol. 52, p. 2749-2765

[7] Hochstein, Manfred P and Patrick R.L. Browne. 2000. Surface Manifestations of Systems with Volcanic Heat Sources Encyclopedia of Volcanoes. Academic Press.
Appendix

Figure 2. Manifestations Map of Bajawa Volcanic Complex
| Number | Manifestations       | Code    | Location (Coordinate) | Elevation | Temperature | Surface Temperature | Ph          | Debit | Electric   | Conductivity (EC) | Informations                                                                 |
|--------|----------------------|---------|------------------------|-----------|-------------|--------------------|------------|-------|------------|-------------------|-----------------------------------------------------------------------------|
| 1      | Bena Hot springs     | APB     | S 08°52'39.715" E 120°59'3.22" | 827 Masl  | 35.63°C     | 24.97°C            | 6.36       | 3     | 880        |                   | Located in Leko Laka River, Tiworiwu, Jerebuu district. Strong sulphur smells and Sulphur deposit and Altered rocks. |
| 2      | Keli Hot springs     | APK     | S 08°52'44.076" E 120°59'24.71" | 801 Masl  | 67.32°C     | 33.23°C            | 6.05       | 0.1   |            |                   | Strong sulphur smells, Sulphur deposit, Silica sinter and Altered rocks.    |
| 3      | Nage-1 Hot springs   | APN-1   | S 08°52'36.382" E 121°0'41.091" | 552 Masl  | 79.99°C     | 29.83°C            | 2.03       | 5     | 1213       | 3550              | Located in Wae Kadhu River, Tiworiwu, Jerebuu district.                      |
| 4      | Nage-2 Hot springs   | APN-2   | S 8°52'12.8892" E 121.0'32.52" | 518 Masl  | 73.14°C     | 25.79°C            | 2.04       | 1     |            | 4000              | Strong sulphur smells, Sulphur deposit, Silica sinter and Altered rocks.    |
| 5      | Wolo Puti Fumarole   | FM WP   | S -8°50'54.5172" E 120°58'55.6752" | 1435 Masl | 98.72°C     | 30.5°C             | -          | -     | -          | -                 | Altered rocks and Sulphur sublimation. Located in Beja, West Golewa district. |

**Table 1. Physical Properties of Geothermal Manifestations**
Table 2. Chemical Properties of Hot springs Geothermal Manifestations

| Number | Manifestations       | Code | Smells       | Taste | EC (µS/cm) | Ph | Water Hardness | Ca²⁺ (mg/L) | Mg²⁺ (mg/L) | Fe³⁺ (mg/L) | Mn²⁺ (mg/L) | K⁺ (mg/L) | Na⁺ (mg/L) | Li⁺ (mg/L) | NH₄⁺ (mg/L) | CO₃²⁻ (mg/L) | HCO₃⁻ (mg/L) | Cl⁻ (mg/L) | SO₄²⁻ (mg/L) | NO₂⁻ (mg/L) | NO₃⁻ (mg/L) | SiO₂ (mg/L) | B (mg/L) | F (mg/L) | As (mg/L) | TDS (mg/L) |
|--------|----------------------|------|--------------|-------|------------|----|---------------|-------------|-------------|-------------|-------------|----------|-----------|-----------|------------|-------------|-------------|-----------|-------------|----------|-----------|-----------|---------|-------|---------|----------|
| 1      | Bena Hot springs     | APB  | None         | None  | 111.5/40= | 6.56| 519           | 1172        | 57/24.30    | 0/55.84     | 0/54.93     | 16.5/39.09| 51.6/22.98| 0.3/6.94  | 0/18       | 0           | 290.5      | 35.9      | 303        | 0.06      | 6.1       | 116.1     | 0.25    | 0        | 0.52     | 784      |
| 2      | Keli Hot springs     | APK  | Sulphur      | Acid  | 1897       | 6.77| 713.6         | 328.6       | 62          | 0.3         | 0.6         | 40.2      | 85.6      | 0         | 0.9        | 0           | 158.8      | 102.2     | 585        | 0.07      | 0.1       | 211.95    | 0.6      | 1        | 0.4      | 1268     |
| 3      | Nage-1 Hot springs   | APN-1| Strong sulphur| Strong Acid | 4600       | 2.41| 328.6         | 82.2        | 29.1        | 9.75        | 1.56        | 32        | 131.8     | 0.3       | 1.6        | 0           | 0         | 399.7     | 142.3     | 0.16      | 0         | 93.90     | 2.60    | 1        | 0.76     | 3068     |
| 4      | Nage-2 Hot springs   | APN-2| Strong sulphur| Strong Acid | 4349       | 2.53| 316.1         | 82.2        | 26.5        | 10.08       | 0.06        | 34        | 115.1     | 4         | 3.2        | 0           | 0         | 392.8     | 68        | 0.01      | 0         | 91.17     | 3        | 1        | 0.71     | 2900     |
Table 3. Ion Balance Calculation

| Code | Cation | Anion | Cation + Anion | Kation – Anion | Ion Balance | Sample Quality |
|------|--------|-------|----------------|----------------|-------------|----------------|
| APB  | 12.96  | 12.08 | 25.04          | 0.88           | 0.3%        | Good           |
| APK  | 18.99  | 17.72 | 36.71          | 1.27           | 0.3%        | Good           |
| APN-1| 17.39  | 14.29 | 31.68          | 3.10           | 9%          | Bad            |
| APN-2| 16.20  | 12.55 | 28.75          | 3.65           | 12%         | Bad            |