# GEOTHERMAL STRUCTURE AND FEATURE OF SULFIDE MINERALS OF THE MATALOKO GEOTHERMAL FIELD, FLORES ISLAND, INDONESIA

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**ABSTRACT**

The Bajawa geothermal area is located in the central part of Flores Island, one of the Nusa Tenggara Islands in eastern Indonesia. Many volcanoes are distributed on Flores and many hydrothermal alteration zones occur around the Bajawa area. The exploration wells MT-1 and MT-2 were drilled by the Japan-Indonesia Cooperation Research Program at the Mataloko geothermal field, one of the most active fields in the Bajawa area.

The Mataloko area is located along the southeast margin of the Bajawa Depression and has a suitable geological structure for geothermal reservoirs. Cinder cones are arranged in the Bajawa area, which extend in NW-SE and NE-SW directions. The heat source of this geothermal system is considered to be residual magma under the young volcanic cone. The Mataloko alteration zone is characterized by strong argillization, where many high temperature hot springs are distributed. A very low-resistivity layer distributes widely in this area. It is also considered that the alteration cap rock developed in this zone. The hot spring water of acid $SO_4$ type resulted from shallower ground water being heated by gases containing $H_2S$ and $CO_2$ and the ground water recharged from the surrounding area. Recharged meteoric water flows down to the deep. It changes to geothermal brine flows up toward the southeast and results in a geothermal reservoir.

According to the chemical composition, sulfur isotopic ratio of sulfide and previous explorations, the fluid system can be divided into two zones at about 160 - 180 m: the deeper fluid which comes from the steam-dominated reservoir is oxidized and rich in $CO_2$ and $H_2S$ and has temperatures between 230° - 250℃. This fluid led to the precipitation of wairakite and As- and Co-rich pyrite.

**Keywords**: Mataloko geothermal field, Flores Island, Indonesia, sulfide, sulfur isotope composition

## 1. INTRODUCTION

Bajawa area is located in the central part of Flores Island, eastern Indonesia. There are many Quaternary volcanoes on Flores Island, and intense geothermal activities occur around the Bajawa area. A five-year Indonesian-Japanese bilateral research cooperation program, named "Research Cooperation Project on the Exploration of Small-scale Geothermal Resources in the Eastern Part of Indonesia (ESSEI Project)", started in April 1997 and ended in March 2002. The Mataloko geothermal field is one of the most active fields in the Bajawa area (Fig. 1), where many indications for the existence of geothermal resources such as fumaroles, $SO_4$-type hot springs, and hydrothermal alteration zones at the surface are present. Two exploratory wells, MT-1 (depth 207.26 m) and MT-2 (depth 180.02 m) were drilled at the Mataloko geothermal field (Fig. 2). A proper discharge test was successfully carried out on the well MT-2 (Sueyoshi et al., 2002). Vigorous geological, geochemical, geophysical and remote sensing surveys were performed in this field.

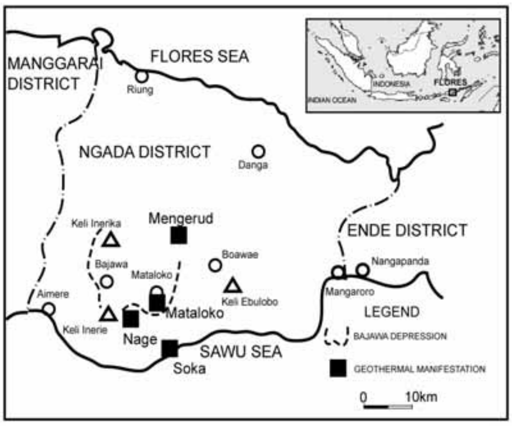


Fig.1 Locality map of the Mataloko Geothermal Field.

Recently, Two wells, MT-3 (depth 613.00m, 204℃at 540m depth) and MT-4 (depth756.47m, 205.5℃at 747m depth), were drilled by DGGMR within the prospect area (Kasbani et al.,2004).

## 2. GEOLOGICAL SETTING

The geologic structure of the Bajawa area is characterized by a depression called the "Bajawa Depression" (Figs. 1 and 2). The Bajawa Depression extends about 13-16 km east-west and more than 12 km north-south, and is characterized by intermittent steep cliffs, up to 300-400 m in height (Otake et al., 2002). Many lineament structures aligned in north-south, northwest-southeast and northeast-southwest directions are recognized in the Bajawa area (Fig. 2), and the margins of the depression are also included by the lineaments. Wae Luja fault is located in the Mataloko geothermal field, and fault control on the discharge of the Mataloko steaming ground is highly probable (Muraoka et al., 2002).

The Tertiary volcanic rocks, called “Green Tuff”, comprise the basement in the studied area. On the coast of Nangapanda (Fig. 1), in the eastern part of the studied area, the rocks consist of coarse-grained tuff, fine tuff, conglomerate and an alternation bed of silt and tuff. The rocks are assumed to distribute to a depth of about 2000 m or more at the drilling site because of the subsidence of the Bajawa Depression (Akasako et al., 2002).

The older volcanic rocks consist mainly of andesite lava, basalt lava, volcaniclastic rocks and minor lahar deposits. Andesite lava is a massive or partly foliated porphyritic rock containing phenocrysts of plagioclase, augite and hypersthene within the intersertal or intergranular groundmass lacking glass materials. Basalt lava is a very hard and massive porphyritic rock containing phenocrysts of plagioclase, augite and olivine within the intersertal or intergranular groundmass. K-Ar ages of 2.8 – 1.0 Ma were obtained for the older volcanic rocks (Otake et al., 2002).

The Bajawa volcanic rocks overlie unconformably the older volcanic rocks, and are composed of andesite lava and minor volcaniclastic rocks, which are interpreted as subareal volcanic products. The total thickness of the volcanic rocks is estimated to be at least 200 m at the Mataloko geothermal field according to the drill hole data. The andesite lava is a massive and hard, light grey to dark grey in color, porphyritic rock containing phenocrysts of plagioclase, augite and hypersthene. The volcaniclastic rocks, whose total thickness ranges from several tens to one hundred meters, are grey and greyish brown in color, soft and loose, and contain white pumice with no sedimentary structure.

The cinder cones are sporadically distributed within the Bajawa depressions (Fig. 3). The products of cinder cones are divided into two groups: older products (C1), e.g. Wolo Sasa (Mt. Sasa), and younger products (C2), e.g. Wolo Nawa, Wolo Bela and Wolo Bobo. They are all composed of andesite lavas and intercalation of andesitic volcaniclastic rocks. The andesite contains phenocrysts of plagioclase, augite, hypersthene and occasionally olivine. K-Ar ages for the C1 and C2 products are 0.51 Ma and <0.15Ma, respectively (Otake et al.,2002).

The Inerie volcano (Keli Inerie in Figs. 1 and 2) is the second highest active stratovolcano (2,245 m asl) on Flores Island. The last eruption was in 1988. The products of the Inerie volcano occupy the southern part of the study area and lie unconformably on underlying units (V1, Bv, C1 and C2). The rocks comprise andesite lava and volcaniclastic rocks with lahar deposits (Otake et al., 2002).

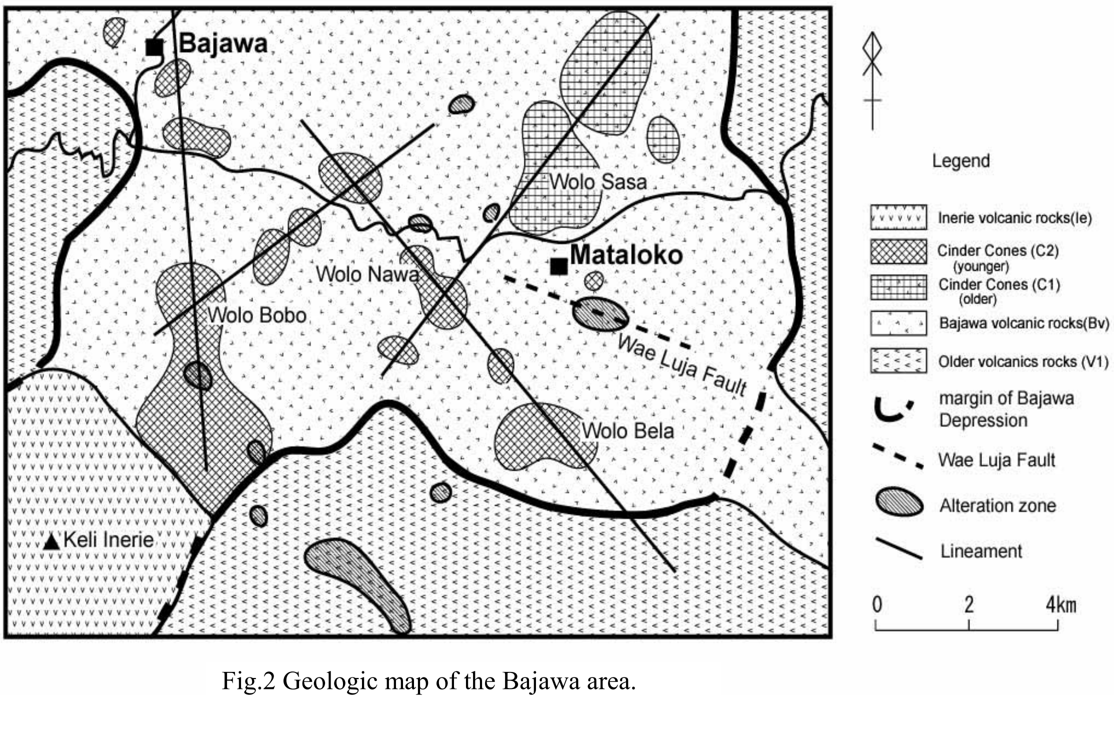


Fig.2 Geologic map of the Bajawa area.

## 3. GEOLOGY AND HYDROTHERMAL ALTERATION OF EXPLORATION WELL

The Bajawa volcanic rocks (Bv) are distributed throughout the drilling wells MT-1 and MT-2. They are composed mainly of tuff breccia in the uppermost part, andesite lavas in the middle part and tuff breccia in the deeper part (Fig. 3). The uppermost tuff breccia and andesite lava change color to white by alteration and are composed mainly of kaolinite and alunite (Sueyoshi et al., 2002). The middle lavas are composed of two-pyroxene andesite of ca. 120 m in thickness. A greenish alteration is characteristic for these lavas at depths of 50 – 140 m in the well MT-1 and 60 – 160 m in the well MT-2 and they are composed mainly of montmorillonite. The deeper pyroclastic rocks are composed of fine- to coarse-grained tuffs and tuff breccia, and change to chlorite/montmorillonite mixed-layer mineral and wairakite (Sueyoshi et al., 2002).

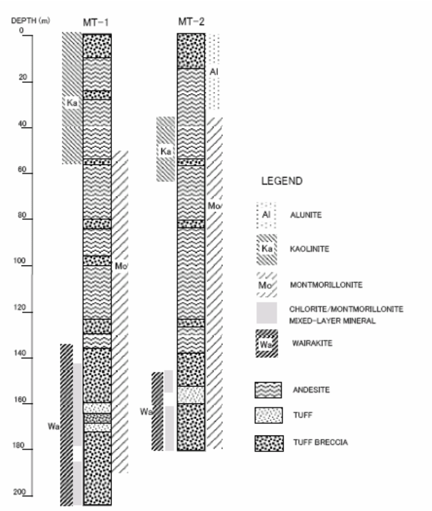


Fig.3 Geologic column and alteration minerals of wells MT-1 and MT-2.

## 4. CHEMICAL COMPOSITION OF SULFIDE MINERALS

Magnetite (hematite), pyrite, marcasite and sphalerite were recognized under the microscope and by EPMA (Koseki and Nakashima, 2006). Magnetite is the primary mineral of these volcanic rocks and other secondary minerals were formed by hydrothermal activity.

Pyrite occurs as small veinlets, thick veins composed of large euhedral to anhedral composite grains, euhedral to subhedral single grains and those altered from magnetite and mafic minerals. Very thin irregular pyrite veins are restricted in the upper zone samples, while the large ( >1000μm) discrete disseminated crystals become rich in the middle to lower zone samples. Magnetite remains even in some lower zone samples, and this means the hydrothermal solution was infiltered randomly into the volcanic rocks. When pyrite is made by alteration from magnetite, the core of the magnetite changes to goethite and the rim to pyrite though the crystal habit of the magnetite keeps its original form. Since the magnetite often alters to hematite or goethite along its rim, the alteration sequence is from magnetite through goethite/hematite to pyrite.

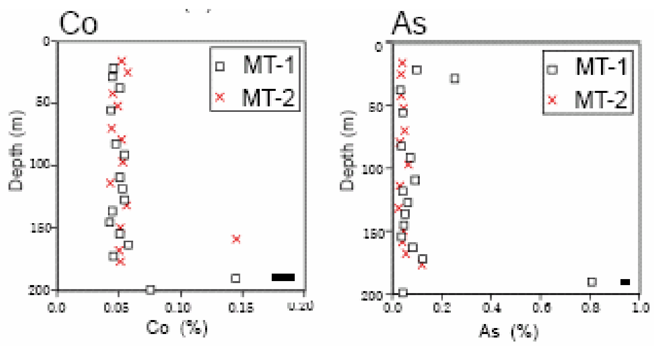


Fig.4 Average element compositions of pyrite vs. depth.

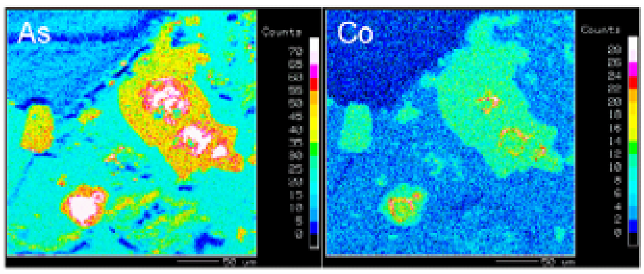


Fig.5 EPMA map analyses of As and Co in pyrite (MT-1,190-193m).

Pyrite contains up to 2.5 wt.% As, 0.8 wt.% Co, 0.9 wt.% Mn and 0.5 wt.% Cd . Arsenic and Co are rich in the lower zone samples (Fig.4), while Mn is enriched in the upper zone samples. Copper is enriched in some upper zone samples. Arsenic and Co anomalies are recognized occasionally in the cores of large euhedral to subhedral grains in deeper zone samples (Fig. 5). Other elements do not show a systematic variation with respect to depth.

## 5. SULFUR ISOTOPE COMPOSITION

The sulfur isotopes were measured by Koseki and Nakashima (2006). The$\delta^{34}S_{py}$ changes from -1.1 to -8.9 ‰ in the well MT-1 and from -3.6 to -11.1 ‰ in the well MT-2, centered around -5 ‰. The values from both wells show a constant tendency with respect to depth, though the $\delta^{34}S_{py}$ values of the well MT-1 was slightly heavier than those of the well MT-2. The following results are recognized. 1) The $\delta^{34}S_{py}$ of both wells is about -8 ‰ in the shallower zone and becoming heavier to about -2 ‰ in the deeper zone. 2) The $\delta^{34}S_{py}$ values abruptly change to about -10 ‰ in samples below 170 m in depth.

## 6. GEOTHERMAL SYSTEMS IN THE MATALOKO GEOTHERMAL FIELD

The Mataloko area is located along the southeast margin of the Bajawa Depression and has a suitable geological structure for geothermal reservoirs. Cinder cones are arranged in the zones, which extend in NW-SE and NE-SW directions. The heat source of this geothermal system is considered to be residual magma under the young volcanic cone. The Mataloko alteration zone is characterized by strong argillization, where many high temperature hot springs are distributed. A very low-resistivity layer distributes widely in this area. It is also considered that a clay cap rock developed in this zone. Geophysical exploration in the Mataloko area has revealed that a clay cap rock indicated by a low specific resistance zone is estimated to lie at a depth of 300 – 600 m (Tagomori et al., 2002). The hot spring water of acid $SO_4$ type resulted from shallower ground water being heated by gases containing $H_2S$ and $CO_2$ and the ground water being recharged from the surrounding area. Recharged meteoric water flows down to the deep. It changes to geothermal brine flows up toward the southeast and results in a geothermal reservoir. Temperatures estimated by chemical analyses of discharged gas from the well MT-2 range from 270 – 300℃ at levels of the reservoir (Fig.6 ). MT-3 and MT-4 were drilled within the prospect area and encountered temperatures of 200℃(Fig.7 ).

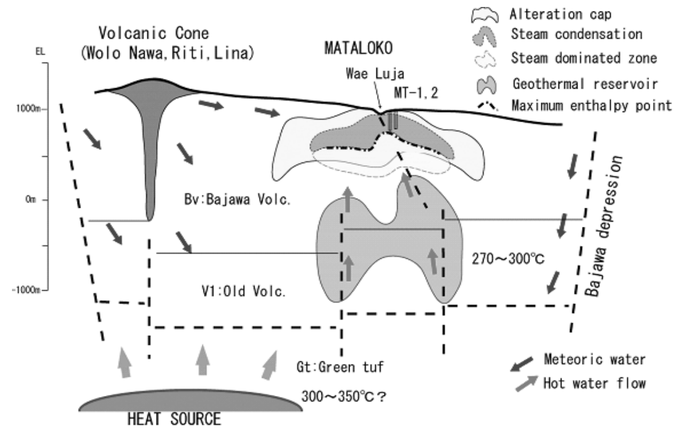


Fig.6 Schematic model of geothermal systems in the Mataloko

Chemical and isotopic compositions of sulfides from the wells MT-1 and MT-2 revealed that two different hydrothermal zones are present (Koseki and Nakashima, 2006). The zones are divided at a depth of 160 - 180 m, and mineralogical and sulfur isotopic characters of each zone are;

The upper zone:

1) Chemical composition of pyrite is close to pure pyrite.

2) As the depth become shallower, $\delta^{34}S_{py}$ changes from -2 to -10 ‰.

The lower zone:

1) Arsenic and Co anomalies are observed in the core of some large pyrite crystals.

2) $\delta^{34}S_{py}$ has values around -10 ‰.

Combined with the chemical and isotopic characters of pyrite and with the previous knowledge about geochemical and geophysical explorations in the Mataloko geothermal field, the following hydrothermal conditions have been deduced. The temperature of the lower zone reached 230 - 250 ℃ which exceeded the hydrostatic boiling point curve of pure water. The As- and Co- rich pyrite and high temperature hydrothermal alteration minerals such as wairakite were formed by this fluid. The composition of dissolved sulfur species in this lower zone might be $SO_4^{2-}$: $H_2S$ = 35 : 65 at 250℃. The upper zone is nearly saturated with liquid water derived largely from condensing steam rich in $CO_2$. Montmorillonite and kaolinite have been formed from the reaction of this $CO_2$-saturated condensate with rock silicates. The fluid is also characterized by $SO_4^{2-}$ which resulted from the reaction of $H_2S$ and water, and made acidic alteration minerals such as alunite. This fluid might have a sulfur composition of $SO_4^{2-}$: $H_2S$ = 15 : 85.

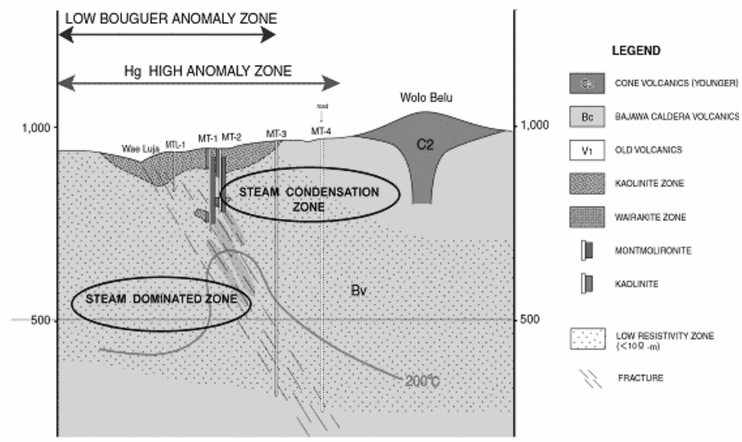


Fig.7 Schematic model of geothermal systems around the Wae Luja.

## 7. CONCLUSIONS

The Mataloko area is located along the southeast margin of the Bajawa Depression and has a suitable geological structure for geothermal reservoirs. The heat source of this geothermal system is considered to be residual magma under the young volcanic cone. A very low-resistivity layer distributes widely in this area. It is also considered that the alteration cap rock developed in this zone. The hot spring water of acid $SO_4$ type resulted from shallower ground water being heated by gases containing $H_2S$ and $CO_2$ and the ground water being recharged from the surrounding area. Recharged meteoric water flows down to the deep. According to chemical composition and sulfur isotopic ratio of sulfide, the fluid system can be divided into two zones at about 160 - 180 m: the deeper fluid which comes from the steam-dominated reservoir is oxidized and rich in $CO_2$ and $H_2S$ and has temperatures between 230° - 250℃. This fluid led to the precipitation of wairakite and As- and Co-rich pyrite. High temperature reservoir fluid retreated to deeper levels in the past and hydrothermal activity has declined now.

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