

MAGMATIC HEAT SOURCE OF THE BAJAWA GEOTHERMAL FIELD, CENTRAL FLORES, INDONESIA

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ABSTRACT

Numerous cinder cone alignments are observed in the Bajawa geothermal field, central Flores Island, eastern Indonesia. They are considered as post caldera cones of the Bajawa caldera. Bajawa caldera is a sort of a small rift valley where fragmentary caldera walls are not closed and elongated north-south, indicating a dike-shaped magma chamber. This reflects left-lateral shear derived from the collision of the Australia continent. Four major geothermal systems in the study area, Mataloko, Nage, Wolo Bobo and Mengeruda derive their heat from the Bajawa caldera magma system. Although the majority of volcanic rocks in the study area are basaltic and tholeiitic, the Bajawa caldera magma system is andesitic and calc-alkaline. Chemical compositions of the caldera-forming tuff and post-caldera cones show little variation. This suggests a homogeneous, dike-shaped magma chamber beneath Bajawa caldera. Buoyancy of the calc-alkaline Bajawa caldera magma system may cause high-level intrusion. Petrology indicates that a depth of the magma genesis is also as shallow as 10 km.

1.0 INTRODUCTION

Geothermal heat sources of high temperature hydrothermal systems have long been ascribed to high-level magma chambers and their consolidated equivalents, because most high temperature hydrothermal systems occur in the vicinity of composite volcanoes that may mark long-lived magma chambers at shallow depths. Recent geothermal drillholes penetrating young intrusions in, and beneath hydrothermal reservoirs, have undoubtedly demonstrated such an idea (Lovelock et al., 1982; Thompson, 1989; Kato, Doi and Muramatsu, 1993; Muraoka et al., 1998). The

effect of the depth of magmatic heat sources is easily evaluated by a simple analysis as shown in Figure 1. Hydrothermal convection usually occurs at a depth less than 3 km. At a depth of 3 km, the diagram shows that the shallower magma chamber can raise the original temperature by more than 400°C through the entire cooling history whereas the deeper chamber can only raise the temperature by 30°C. It is clear that the former could be a potential geothermal heat source but never on the latter.

From a geothermal viewpoint, we shall consider the rise of magma to a high level in the crust. Magma may rise (a) in a diapir, (b) in an elastic dike disconnected from a magma source region or (c) in an elastic dike connected to the magma source region. There is a critical difference between magma in a diapir or a disconnected dike, which can rise if it is buoyant, and magma in a connected dike, which can rise

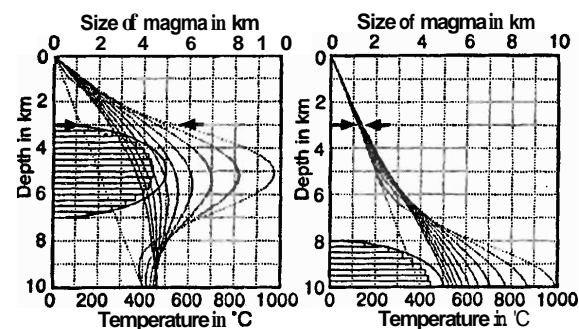


Figure 1. Effect of depth of magma bodies in thermal conduction calculated by the slab-stacked model of Muraoka and Matsubayashi (1994). Magma bodies are shown by the equivolume ellipsoids in a half section. Ten consecutive curves in both diagrams show thermal diffusions along axes of magma bodies from 20 Ka to 200 Ka with every 20 Ka increment after the intrusion of magma.

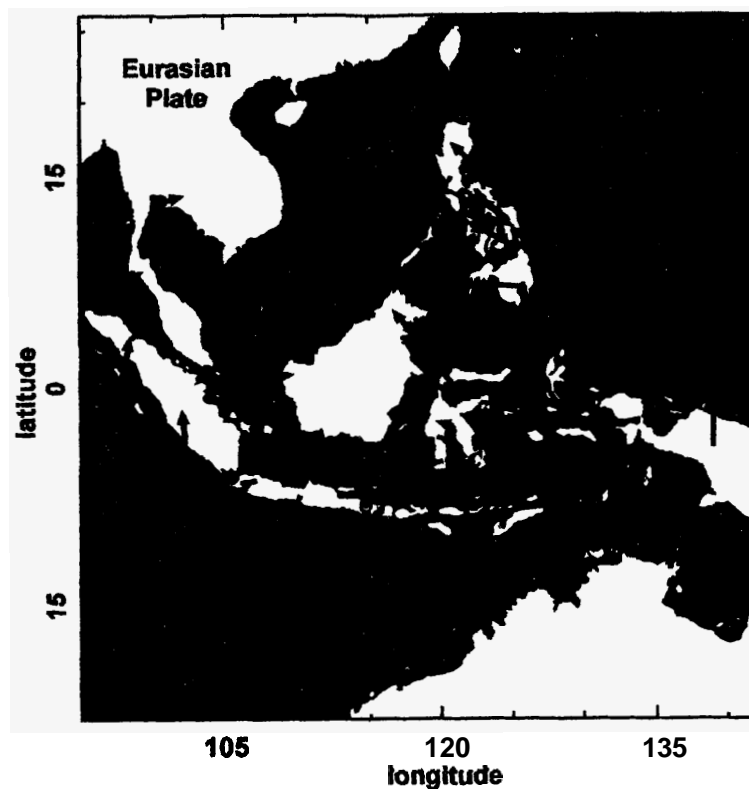


Figure 2. Velocity field derived from GPS observations of the 1994 and 1996 GEODYSSSEA measurement campaigns in the IRTF-94 reference frame (Wilson et al., 1998). Relative motions are shown when a Bali station is fixed. An abnormally high velocity at the north of Irian Jaya was due to 1.5 m displacement by the earthquake with M 8.2 on Feb. 17, 1996.

even when it is not buoyant if the source region has great enough over-pressure (Wilson et al., 1993).

The (c)-type is analyzed in terms of driving pressure, $P_d = P_m - \sigma_t$, where P_m is the magma pressure and σ_t is the tectonic compressive stress normal to the dike face (Rubin, 1990; Reches et al., 1993). Because the vertical (overburden) stress is a standard value to divide compressive or extensive stress and is almost equal to σ_1 in the extension tectonic fields, horizontal compressive tectonic stress σ_t is usually small or negative in the extension tectonic fields. Therefore, the driving force P_d is usually positive in the extension tectonic fields, allowing the magma to propagate to a shallow depth (Rubin, 1990; Reches et al., 1993). This explains a fundamental genesis of the rift-zone magmatism such as Iceland and Salton Trough where dike swarms are the most dominant geothermal heat sources (Muraoka and Yano, 1998).

The (a)- and (c)-types are exclusively constrained by the buoyancy of magma in the crust. The buoyancy is evaluated by the density contrast between the magma and the surrounding rocks (Muraoka, 1997). Therefore, we can evaluate the emplacement depth of magma from the densities of magma and rocks in the upper crust. Diapiric magma bodies of the (a)-type tend to form large-scale stocks and batholiths and are particularly important as long-lived magma chambers as well as potential geothermal heat sources. Muraoka and Yano (1998) have evaluated the emplacement depth of magma in terms of the density of rocks in the upper crust. Plutonic bodies recently penetrated by geothermal drillholes of 2-4 km have exclusively been reported from the contraction tectonic fields such as the Philippines, Northeast Japan and Kamchatka, and this is explained by the high density profiles of the shallower crust amplified by the tectonic-over stress in the contraction tectonic fields (Muraoka and Yano, 1998). Density of drillhole cores is actually

larger in the contraction tectonic fields than in the extension tectonic fields (Muraoka and Yano, 1998).

Muraoka (1997) has evaluated the emplacement depth of magma in terms of the density of magma. Methods to estimate magma density from petrochemical data are synthesized using Bottinga and Weill (1970) and Bottinga *et al.* (1982). Based on the methods, it is evaluated that emplacement depths are 8-2 km on the calc-alkaline magma and are around 10 km on the tholeiitic magma in the continental crust region. This suggests that calc-alkaline magma is potential geothermal heat sources in the continental crust region and tholeiitic magma can be only effective heat sources in ocean crust regions where crust is composed of denser materials of consolidated tholeiitic magma. This is well consistent with the fact that most of high temperature hydrothermal systems in Japan are associated with calc-alkaline volcanoes rather than tholeiitic volcanoes in the continental crust region.

However, this idea is still open to questions in other fields. Lesser Sunda-Banda Islands, eastern Indonesia, is an immature island arc where the continental crust is developing as thick as 5 km. We have an Indonesia-Japan bilateral cooperation project "the Research Cooperation Project on the Exploration of Small-scale Geothermal Resources in the Eastern Part of Indonesia" in Bajawa City, central Flores Island, since 1997. There are many geothermal manifestations in this area. Because of an immature island arc, most of volcanoes are tholeiitic in composition, but some calc-alkaline volcanoes started to appear in the area. Therefore, this area is adequate for the testing on the hypothesis described above. The purpose of this paper is to test the hypothesis whether calc-alkaline volcanoes are potential geothermal heat sources in this area.

20 TECTONIC AND GEOTHERMAL SETTINGS

The Lesser Sunda-Banda arc is an immature island arc system and has marginal seas of oceanic crust such as the Flores Sea and Banda Basin behind it. A subducted plate consists of the Australian continent, so that the buoyant lithosphere is subducted beneath less buoyant lithosphere, resulting in the colliding

subduction tectonics. Hamilton (1979) and Bowin *et al.* (1980) suggested that the leading edge of the Australian continental crust started to enter the Timor trough at 3 Ma. Silver *et al.* (1983) have described a significance of back arc thrust of the Lesser Sunda arc and a series of the NNE trending left-lateral faults from Flores to Wetar Islands. McCaffrey (1988) has shown that the rate of north-south shortening of the entire upper plate between the Seram and Timor troughs calculated from the seismic moments over the 22-year period is roughly 20 % of the predicted convergence rate between Australia and Southeast Asia. GPS observation by Wilson *et al.* (1998) has brought us important results as follows: (1) There exists a relatively rigid Sunda block in consistent with the Greater Sunda arc including the Bali Island. (2) On the contrary, the motions of Timor, eastern Flores, the adjacent islands to the east and Irian Jaya are currently accreting to the Australian Plate. This requires that there is a relatively sharp gap in the motions between the Sunda block and Lesser Sunda-Banda accretional block at somewhere from Sumbawa to western Flores. This gap in motion requires left-lateral shear in this area. Based on this work, we can also calculate relative convergence rates among tectonic blocks. For example, the northwestern Australia is moving north with 75 mm/y with respect to Bali, while Flores (Ende) is moving north with 50 mm/y. As a result, a relative convergence rate along the Timor trough is calculated to be 25 mm/y. Likewise, a shortening rate between Flores and Seram is calculated to be 10 mm/y. Whatever this is due to the back-arc thrusting (Silver *et al.* 1983) or entire upper plate contraction (McCaffrey, 1988), it is clear that Flores Island is subject to north-south contraction tectonics.

There are numerous hot springs in the study area, but major geothermal manifestations are in the four areas: Mataloko, Nage, Wolo Bobo and Mengeruda (Figures 3 and 4). The Mataloko manifestation is situated at the southern foot of a small cone volcano called Wolo Belu. The area of the steaming ground is about 150 m in diameter, but the acid alteration zone is to an extent 300 m by 1000 m elongated along rivers named Wae Belli and Wae Luja. One of candidates for heat source volcanoes is Wolo Belu volcano, but a northwest-southeast trending Mataloko crater chain including Wolo Lele, Wolo Nawa, Wolo Sage, Wolo Bina and Wolo Bela may be more promising in terms of

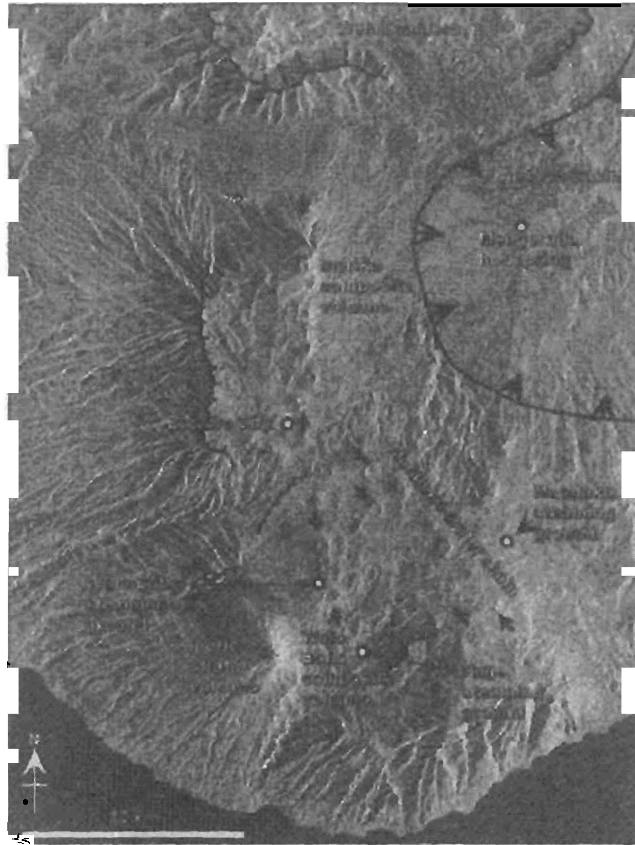


Figure 3. JERS-1 SAR imagery (Copyright MITI/NASDA, data provided by ERSDAC) and topographic frameworks of the southern Ngada District, Flores Island, Indonesia.

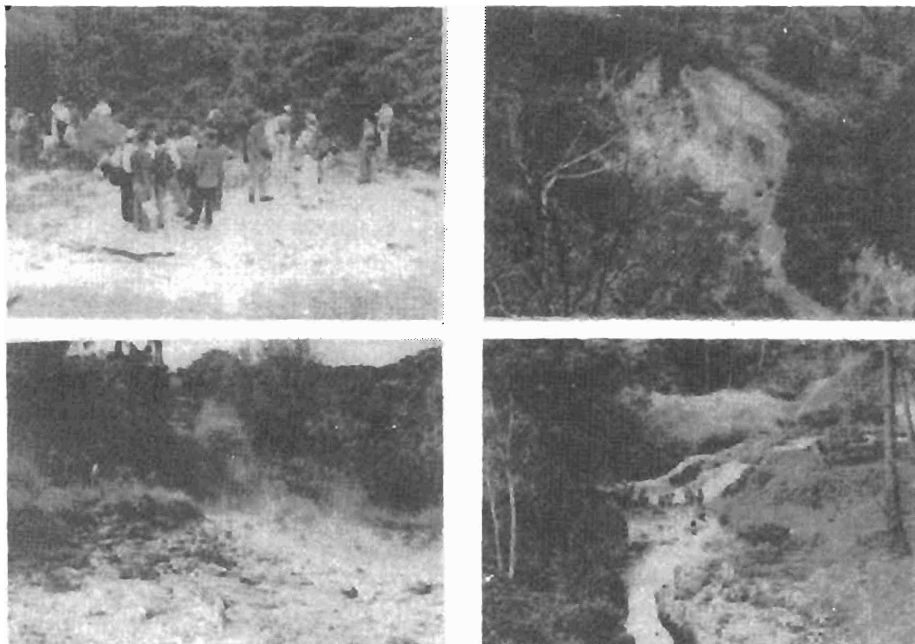


Figure 4. Photographs showing major geothermal areas in the Bajawa geothermal fields. Steaming grounds at Mataioko (upper left), Nage (lower left) and Woto Bobo (upper right) and a hot spring at Mengeruda (lower right).

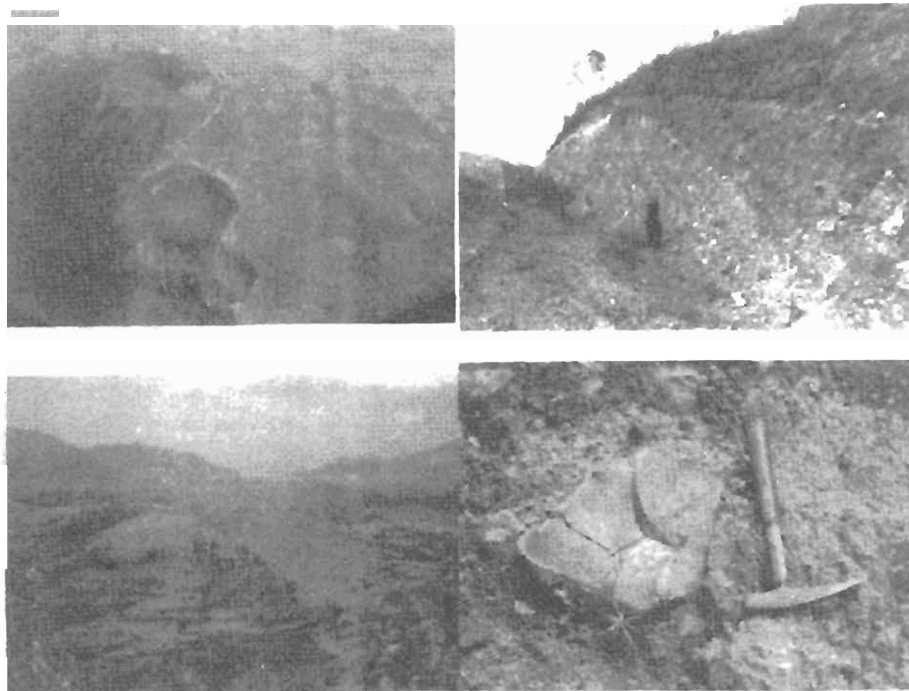


Figure 5. Photographs of configuration and outcrops of cinder cones at the Wolo Bobo area, the Bajawa geothermal fields.

the volume of a magma chamber. The Nage manifestation lies at the bottom of a small basin with 2 km in diameter. The steaming ground is to an extent of 200 m by 700 m elongated along a river named Wae Bana. The alteration zone is to an extent of 2 km in diameter, up to high walls of the basin to the Nio and Bea villages, 650 m and 900 m above the sea level, respectively. There is various possibility on the heat source volcano such as Wolo Bobo volcano and Bajawa caldera. The Wolo Bobo manifestation is situated at a western rim of one of cinder cones of Wolo Bobo composite volcano. The steaming ground seems a volcanic fumarole with 100 m in diameter. The alteration zone is 300 m in diameter and forms a landslide open to the west flank. The steaming ground is situated at 1400 m in altitude and may not be adequate for geothermal development. The heat source is, however, quite clear here, and must be Wolo Bobo volcano (Figure 5). The Mengeruda manifestation is a hot spring with a remarkably high discharge rate of hot water but has no steaming ground. The alteration zone is to an extent of 800 m in diameter. The silicified alteration zones are also sporadically found to the east along WNW-ESE trending faults. The heat source may be Inerika composite volcano. A fault that may control the Mengeruda hot spring discharge is actually found on the field.

3.0 RECONNAISSANCE BY SATELLITE IMAGERY

Figure 3 shows JERS-1 SAR imagery on the Ngada District (Urai et al., 1998). Broadly speaking, volcanoes are concentrated along two zones; a southern coast and a central axis in western Flores Island. The former is a volcanic front. This setting is similar to double volcanic belts in Northeast Japan, but is more obscured in Flores Island, probably due to the steeply dipping subduction regime. Between the two volcanic zones, Aesesa River forms an elliptical basin with 20 km (E-W) by 15 km (N-S) that contains Mengeruda and Gero as seen in Figure 3. We named it the Aesesa Basin where the lacustrine Aesesa Formation deposited during Pliocene to Pleistocene. Volcanoes in the central axis are represented by Welas caldera. The caldera collapse area is 15 km (E-W) by 8 km (N-S). The caldera rim is open to the southeast to the Aesesa Basin. Post-caldera cones are typically developed in the western caldera. We have tried to find hot springs in this caldera, but there are no hot springs because of old age of the caldera. In the area of clustered volcanoes at the southern coast, many fragmentary caldera walls are recognized on the satellite imagery (Figure 3). One of conspicuous examples is the north-south trending caldera

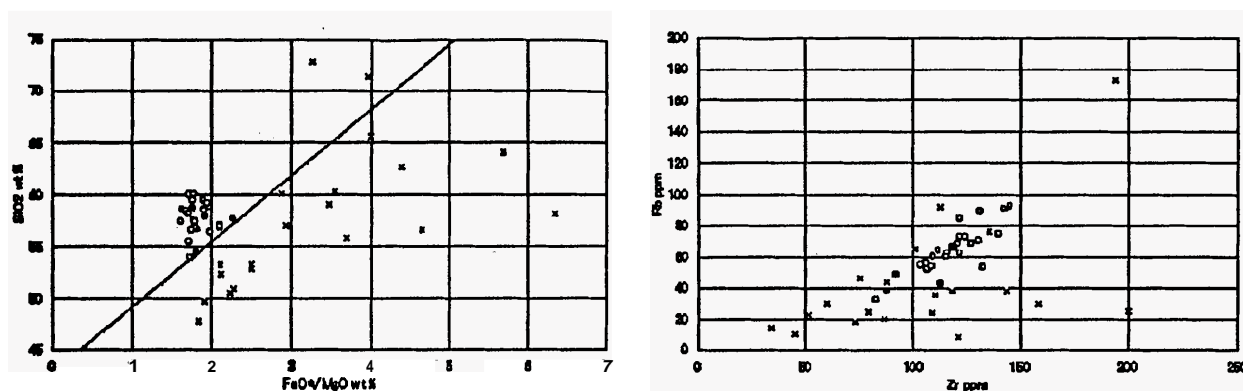


Figure 6. SiO_2 - FeO^*/MgO diagram (Left) and Rb-Zr diagram (Right) of 46 volcanic rock samples in the southern Ngada District. Closed circle; Aimere Scoria Flow Deposits, open circle; Mataloko, Wolo Bobo and Inerika Andesite, cross; other units.

wall at the west flank of the Inerika composite volcano. This is 10 km long, but there is no counter wall to the east of the Inerika volcano. Other examples are found around the Wolo Bobo composite volcano and the Inerie volcano. Many fragmentary caldera walls suggest that there exist many calderas in the vicinity of Bajawa city. Most of them seem to surround a complex of Inerie, Wolo Bobo and Inerika volcanoes. In this paper, all of those fragmentary caldera walls are collectively called the Bajawa caldera. The reasoning will be discussed below. Two active volcanoes are known in the study area; Inerie volcano at the south and Inerika volcano at the north. In addition, another active volcano, Ebulobo, lies at the east vicinity of the study area. Inerie volcano is a strato-volcano, while Inerika volcano is a composite volcano. Wolo Bobo volcano is also a young composite volcano that is similar to Inerika volcano, although this volcano has no record of historic eruptions. It should be noted that Inerika volcano has erupted at January 11, 2001. Inerika and Wolo Bobo composite volcanoes are composed of numerous cinder cones, and they almost form a north-south single alignment (Figures 3 and 4). Alignment of cinder cones is also recognized as a northwest-southeast Mataloko crater chain (Figure 3). They suggest dike-shaped magma chambers beneath them.

4.0 PETROLOGY

We have made multi-component chemical analyses for 46 rock samples taken from the study area, including minor and rare-earth elements. Some samples such as scoria or pumice, contain several percents of water

components due to devitrification. Therefore, when plotting them to diagrams, all the components are recalculated as an anhydrous basis even in minor elements. Figure 6 (left) shows a SiO_2 - FeO^*/MgO diagram (Miyashiro, 1974). Majority of rocks in the study area is plotted on the field of the tholeiitic rock series. Two exceptions are rhyolitic pumice-fall probably erupted from Ebulobo volcano and rhyolitic lava of the Wangka Andesite. A most important exception is, however, the rocks of the Aimere Scoria Flow Deposits and the rocks of cone volcanoes such as the Mataloko, Wolo Bobo and Inerika Andesite. All of them form a narrow cluster in the field of the calc-alkaline rock series. They range in a SiO_2 content only from 53.50 to 61.00 wt % and in a FeO^*/MgO ratio only from 1.50 to 2.30. An extent of their spatial distribution is quite large, nevertheless, their chemical nature is extremely homogeneous. This strongly suggests that they form a single and connected dike-shaped magma chamber. Figure 6 (right) shows a Zr-Ba diagram. Their homogeneity is again found in such minor element diagrams.

Plag-Di-SiOr pseudo-ternary diagram of 26 samples taken from the Inerika-Wolo Bobo cinder cone volcanoes suggests that the Bajawa dike system has been generated at a pressure between 2 kbar and 5 kbar (Figure 7). The magma has probably been generated from the partial fusion of basaltic and oceanic crust, at a depth as shallow as 3 kbar (ca. 10 km) below the continental crust. The homogeneity of the dike-shaped magma might be owing to the shallow-depth origin. The scale is very small but the mode has some resemblance to rift-type magmatism.

5.0 DISCUSSION AND CONCLUSIONS

Based on our survey, a scenario of volcanic evolution in the study area is drawn. About 4 million years ago, not only tholeiitic but also calc-alkaline volcanism started to occur along two volcanic belts along the present southern coast and the central axis. A lake named the Aesesa Basin appeared between the two volcanic belts. At about 2.5 Ma, a relatively large magma chamber caused a collapse of Welas caldera that produced the voluminous Welas Tuff. Most of the Welas Tuff deposited in the Aesesa Lake environment, but some flowed over the southern volcanic ridge, and entered the shallow marine environment, resulting in green tuff alteration. Next, volcanism occurred in the south such as pre-caldera volcanism of Bajawa caldera. The magmatism caused partial fusion of ocean crust and has generated a homogeneous, andesitic and calc-alkaline dike-shaped magma chamber beneath the Bajawa area as shown in Figure 8. This magma chamber may have formed north-south elongated radial dikes reflecting the maximum compressive stress axis, where the left-lateral shear stress between the Sunda block and Lesser Sunda-Banda accretional block may have caused the predominance in northwest-southeast trending radial dike elements. The dike-shaped magma chamber caused the collapse of Bajawa caldera and produced the voluminous Aimere Scoria Flow Deposits. The name 'Bajawa caldera' used in this paper is a collective name for many isolated fragments of caldera walls that are not necessarily closed and are elongated in the north-south direction. This may be explained by the shape of the magma chamber. Large dike intrusions may have formed a rift valley rather than a circular caldera, and have occasionally formed a half grabens as seen in one side wall in the Inerika area. Moreover, in the Bajawa caldera, many post-caldera cones have appeared above and along the dike-shaped magma chamber. Those post-caldera cones are the Mataloko, Wolo Bobo and Inerika Andesite. Though scattered over a wide area, they are, nevertheless, homogeneous in composition, because they share the same source (Figure 8). Recent eruption of Inerika volcano at January 11, 2001 indicates that the dike-shaped magma chamber is still active in part. Inerika volcano is a tholeiitic and basaltic post-caldera cone and may be isolated from the calc-alkaline magma chamber.

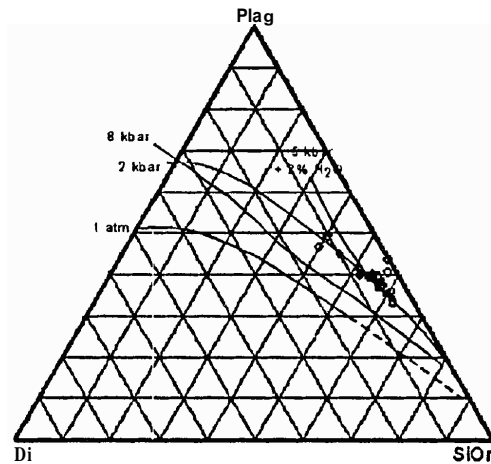


Figure 7. Pseudo-ternary diagrams of 26 samples from cinder cones in the Bajawa geothermal fields. Phase boundaries are quoted from Baker and Eggler (1983).

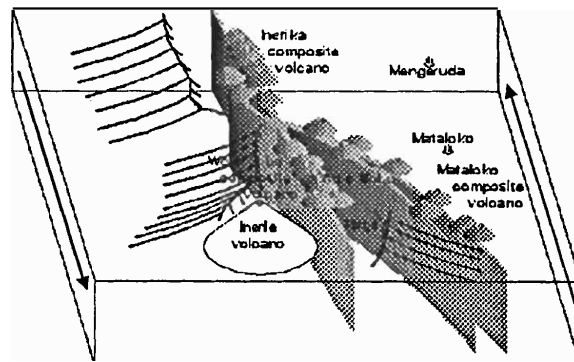


Figure 8. A model of radial dikes controlling volcano-tectonic and geothermal regimes in the Ngada District, Flores Island, Indonesia.

Calc-alkaline magma is important for geothermal heat sources in the continental crust region, because the buoyancy of the calc-alkaline magma tends to form shallow intrusions compared to the tholeiitic magma (Muraoka, 1997). Therefore, the Bajawa caldera magma system is a likely heat source in the study area. All the steaming grounds are, in fact, observed in close association with the Bajawa system as shown in the Wolo Bobo, Nage and Mataloko areas. The Mengeruda hot spring is relatively far from Inerika volcano, but the distribution of faults and alteration zones suggests that it is related. Relatively low temperature and high discharge rate in the Mengeruda hot spring indicate that the aquifer is derived from the Inerika volcano by the lateral out flow.

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