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REGIONAL GEOTHERMAL GEOLOGY OF THE NGADA DISTRICT, CENTRAL FLORES, INDONESIA

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ABSTRACT

Geological investigations of geothermal resources in the Ngada District, Flores Island, Indonesia have been conducted as a part of a cooperative project. Subaerial volcanism started in the area about 4 Ma, reflecting the local collisional tectonics. Welas caldera appeared at about 2.5 Ma along the central axis of the island where 600 m of uplift has occurred since 2.5 Ma. On the southern coast, volcanism has continued until the present with Bajawa caldera appearing around 0.15 Ma. 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. 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. Four major geothermal systems in the study area, Mataloko, Nage, Wolo Bobo and Mengeruda derive their heat from the Bajawa caldera magma system.

1. I NTRODUCTION

A purpose of this study is to explore geothermal resources in Bajawa City and its surrounding areas, central Flores Island, Indonesia from the geological point of view, as a part of the Research Cooperation Project on the Exploration of Small-scale Geothermal Resources in the Eastern Part of Indonesia (Figure 1). The area has long been remarked from remote sensing imagery, because the imagery presents numerous spectacular volcanic craters (e.g., Hamilton, 1979; Silver et al., 1983; Muraoka, 1989; Urai et al., 1998). This part of Flores Island, in fact, consists not only of such numerous active volcanoes as Inerie, Inerika and Ebulobo, but also of such potential geothermal manifestations as Mataloko, Nage, Wolo Bobo and Mengeruda. This area could be one of the most prospective geothermal areas in Flores Island. However, because of the inaccessibility to the given area, volcanological and structural evolution of the area has not yet been fully investigated so far. Therefore, a study on volcanological and structural evolution is critically important for better understanding of the present geothermal activity in the area. This paper describes results of geological, chronological and petrological investigations, and then discusses the volcanological, structural and geothermal evolution of Bajawa City and its surrounding areas, central Flores Island.

2. 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. 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 the four areas, Mataloko, Nage, Wolo Bobo and Mengeruda (Figure 1). 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 to 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 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. 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. RECONNAISSANCE BY SATELLITE IMAGERY

Figure 1 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 1. 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 1). One of conspicuous examples is the north-south trending caldera 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 Inkerika 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 records of historic eruptions. Inerika and Wolo Bobo composite volcanoes are composed of numerous cinder cones, and they almost form a north-south single alignment (Figure 1). Alignment of cinder cones is also recognized as a northwest-southeast Mataloko crater chain (Figure 1). They suggest dike-shaped magma chambers beneath them.

4. GEOLOGY AND CHRONOLOGY

A geological map is shown in Figure 2. Lithology and stratigraphy are described with newly obtained chronological data. Most of volcanic rocks seem so young that ten samples taken from relatively older volcanic units were selected for K-Ar age measurements. Those results are shown in Table 1. Miocene strata are exposed near Ende but are not exposed in the study area. Pliocene volcanic rocks are the oldest unit exposed in the area. The Pliocene Series consists of the Wangka Andesite (Wn), Maumbawa Basalt (Mb), Welas Tuff (Wt), Aesesa Formation (Ae), Wolo Mere Basalt (Me) and Waebela Basalt (Wa) in ascending order. Quaternary System consists of the Wolo Sasa Andesite (Sa), Aimere Scoria Flow Deposits (As), Mataloko Andesite (Mk), Wolo Bobo Andesite (Bb), Inerika Andesite (Ik), Inerie Basalt (Ie), Lahar Deposits (Lh) and Alluvium (Qa) in ascending order.

Wangka Andesite (Wn)

The Wangka Andesite forms the rims of Welas caldera. The Wangka Andesite consists of lava flows of andesite, dacite and rhyolite in compositions, and silicic lava often contains biotite. The unit commonly shows sheared occurrence with zeolite and chlorite veins. Shear planes are developed in the north-south direction. Two K-Ar ages, 4.13 Ma and 2.96 Ma, were obtained (Table 1). This unit unconformably overlies the Miocene strata at the northern coast.

Maumbawa Basalt (Mb)

The Maumbawa Basalt is exposed on the road side of the way to Maumbawa. The unit consists of massive lava flows and commonly shows sheared occurrence. A K-Ar age, 3.37 Ma, was obtained at the eastern immediate border of the mapped area (Table 1). The unit is correlated to the Wangka Andesite.

Welas Tuff (Wt)

The Welas Tuff is a voluminous ash flow tuff related to the collapse of Welas caldera. The Welas Tuff contains not only abundant essential pumice but also abundant accidental lithic fragments. The tuff is tholeiitic in composition. This unit deposited as lacustrine tuff in the Aesesa Basin and probably as submarine tuff in the south of the Bajawa-Boawae ridge. In the former environment, this unit often contains siltstone lenses. In the latter environment, this unit was often altered to green tuff. The Welas Tuff consists, at least, of two cooling units. The maximum thickness of this unit may be 70 m. Three K-Ar ages, 2.73 Ma for a lithic fragment, 2.52 Ma and 1.66 Ma for pumice samples, were obtained (Table 1). A reasonable age for this unit may be 2.5 Ma. This unit uncomformably overlies the Wangka Andesite and the Maumbawa Basalt.

Aesesa Formation (Ae)

The Aesesa Formation is lacustrine sediments deposited in the Aesesa Basin. This unit consists of thin-laminated siltstone, sandstone, scoria-fall and pumice-fall deposits. Frequent intercalation of volcanic materials indicates that the volcanism has actively occurred during the sedimentation. The maximum thickness of the Aesesa Formation may be more than 100 m. The Aesesa Formation conformably overlies the Welas Tuff. The incipience age of deposition of the Aesesa Formation is 2.5 Ma, the age of the Welas Tuff, and the cessation age may be Early Pleistocene.

Wolo Mere Basalt (Me)

The post-caldera cones of Welas caldera form mesa-shaped lava domes, and are composed of basalt with plenty of plagioclase megacrysts of 1 or 2 cm in diameter named here Wolo Mere Basalt. This unit overlies the Welas Tuff and is intercalated with the Aesesa Formation.

Waebela Basalt (Wa)
The Waebela Basalt is exposed in the northwest and east of Inerie volcano, and the east of Mataloko. This unit consists of massive lava flows and their clinkers. Near the southern coast like Waebela, this unit occurs as submarine lava flows composed of massive lava, hyaloclastite and pillow lava and pillow robe. Two K-Ar ages, 2.40 Ma and 1.61 Ma, were obtained (Table 1). This unit may overlie the Welas Tuff.

Wolo Sasa Andesite (Sa)
The Wolo Sasa Andesite is widely distributed in the north and south of the Mataloko area. This unit forms cinder cones and has resemblance to the Mataloko, Wolo Bobo and Inerika Andesite described below. However, this unit exhibits more dissected edifices. Recently, it is found that magnetic polarities of lava flows of this unit belong to the Matsuyama Epoch older than 0.73 Ma. The unit is not only older than the Mataloko, Wolo Bobo and Inerika Andesite but also older than the Aimere Scoria Flow Deposits.

Aimere Scoria Flow Deposits (As)
The Aimere Scoria Flow Deposits are widely distributed in the surroundings of Bajawa caldera. This unit is mainly composed of scoria tuff and is sometimes intercalated with lava flows. Each tuff unit is only a few meters in thickness but piles of them form several tens meters of tall cliffs. Some of tuff units contain boulder-size scoria and others of them consist entirely of fine ash. The tuff deposited in the aerial environment. Scoria is not very porous and is occasionally similar to phreato-magmatic breccia. The tuff is dominant in essential materials rarely with accidental lithic fragments. This unit is andesitic and calc-alkaline. The maximum thickness is 100 m. The unit overlies the Waebela Basalt. Two K-Ar ages, both less than 0.15 Ma, were obtained (Table 1). However, considering a large gap between these ages and those of the Waebela Basalt, the lower part of this unit may be older than 0.15 Ma.

Mataloko Andesite (Mk)
The Mataloko Andesite forms a northwest-southeast alignment of cone volcanoes including Wolo Lele, Wolo Nawa, Wolo Sage, Wolo Bina and Wolo Bela. Each cone is composed of phreato-magmatic eruption materials. Each layer of single eruption materials ranges in thickness from a few tens centimeters to a several meters near eruption centers. Materials of each layer are less sorted in size, but generally show a weak normal grading. Larger breccia is sometimes a few meters in diameter, while smaller ash is very fine. Larger phreato-magmatic breccia often shows cooling cracks and quench rims, and are not porous. Lava flows are also important effusive components from those cone volcanoes, but are usually found a little away from the cone itself. In this paper, rocks of young cone volcanoes were classified into three groups, the Mataloko, Wolo Bobo and Inerika Andesite due to their spatial clustering.

Wolo Bobo Andesite (Bb)
The Wolo Bobo Andesite is distributed along a north-south alignment of cone volcanoes at the Wolo Bobo area. Lithology and stratigraphy are basically similar to the Mataloko and Inerika Andesite.

Inerika Andesite (Ik)
The Inerika Andesite is distributed along a north-south alignment of cone volcanoes at the Inerika volcano area. Lithology and stratigraphy are basically similar to the Mataloko and Wolo Bobo Andesite. The Inerika volcano has a historic record of phreatic eruption at 1905 but there is no fumarolic activty at present.

Inerie Basalt (Ie)
The Inerie Basalt forms Inerie strato-cone volcano. This unit is composed of lava flows, scoria-flow, scoria-fall and lahar deposits. An entire stratigraphic relation of this unit to the Wolo Bobo Andesite is not clear, but Inerie volcano is evaluated to be an active volcano.

Lahar Deposits (Lh)
The Lahar Deposits are distributed in the surroundings of Inerika volcano, Nage and other areas. This unit consists of boulder-size gravel and unsorted fine matrix that were derived from related volcanic edifices.

Alluvium (Qa)
Alluvium is distributed in the Mataloko, Waebela and other areas. This unit is composed of mud, sand and gravel.

5. 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 3 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 4 shows a Zr-Ba diagram. Their homogeneity is again found in such minor element diagrams.

6. 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 5. 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 5). Inerie volcano is a tholeiitic and basaltic post-caldera cone and may be isolated from the calc-alkaline magma chamber.

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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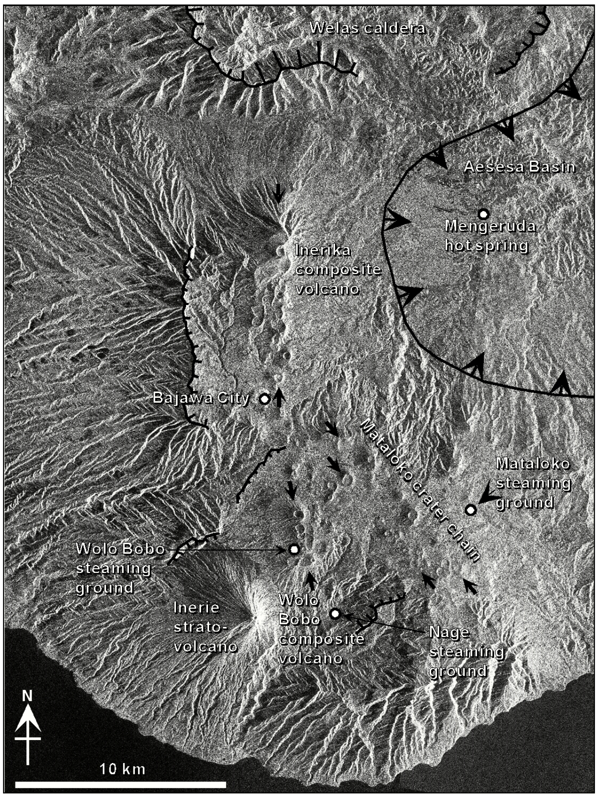

Figure 1. JERS-1 SAR imagery (Copyright MITI/NASDA, data provided by ERSDAC) and topographic frameworks of the southern Ngada District, Flores Island, Indonesia.

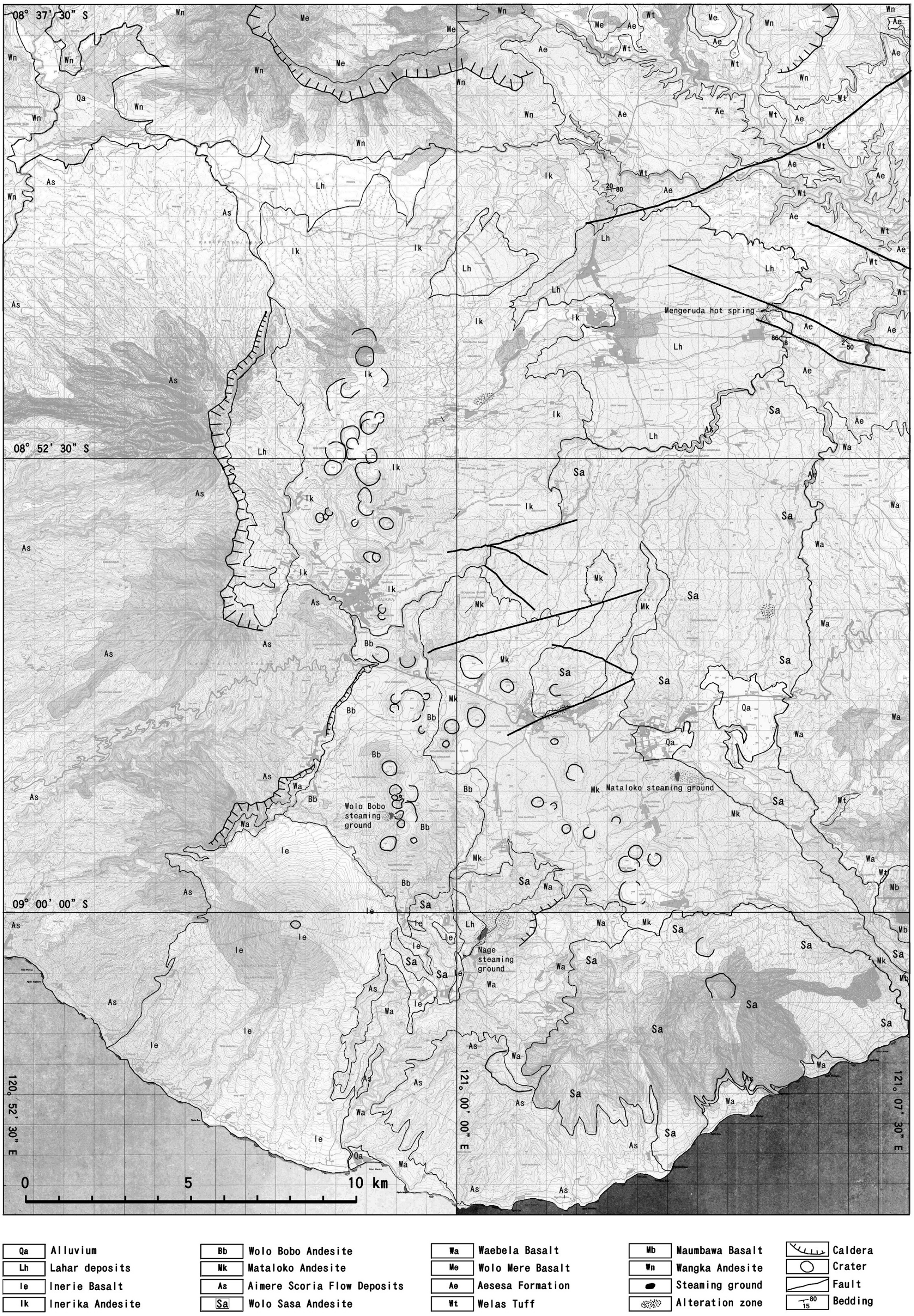

Figure 2. Geological map of the southern Ngada District, Flores Island, Indonesia.

Table 1. K-Ar ages of volcanic rocks in the southern Ngada District, Flores Island, Indonesia.

Sample no.	Rock type (Unit)	Analysis	Potassium (wt %)	Rad 40Ar ($10^{-5}cm^3/g$)	Air cont. (%)	Age ± 1σ (Ma)
980723-03	Andesite lava (Wn)	Whole rock	0.30	4.81±0.33	93.65	4.13±0.50
980723-04	Andesite lava (Wn)	Whole rock	1.47±0.04	16.92±0.74	89.64	2.96±0.16
980722-01	Basalt lava (Mb)	Whole rock	0.42±0.04	5.49±0.27	90.76	3.37±0.38
980726-03	Andesite lithic of pumice tuff (Wt)	Whole rock	1.06±0.03	11.25±0.40	87.61	2.73±0.13
980723-06	Pumice of pumice tuff (Wt)	Whole rock	0.42±0.04	4.12±0.26	90.75	2.52±0.30
980723-02	Pumice of pumice tuff (Wt)	Whole rock	1.37±0.04	8.81±0.51	92.47	1.66±0.11
980721-03	Basalt lava (Wa)	Whole rock	0.30±0.03	2.79±0.25	92.25	2.40±0.32
980727-01	Basalt pillow lava (Wa)	Whole rock	0.26±0.04	1.62±0.43	91.72	1.61±0.49
980718-04	Scoria of scoria tuff (As)	Whole rock	0.77±0.05	-0.91±1.39	100.22	<0.15
980722-04	Scoria of scoria tuff (As)	Whole rock	0.89±0.05	-0.95±0.36	100.85	<0.15
$\lambda\varepsilon=0.581 \times 10^{-10} yr^{-1}$; $\lambda\beta=4.962 \times 10^{-10} yr^{-1}$; $^{40}K/K=1.167 \times 10^{-4}$ mol/mol.						

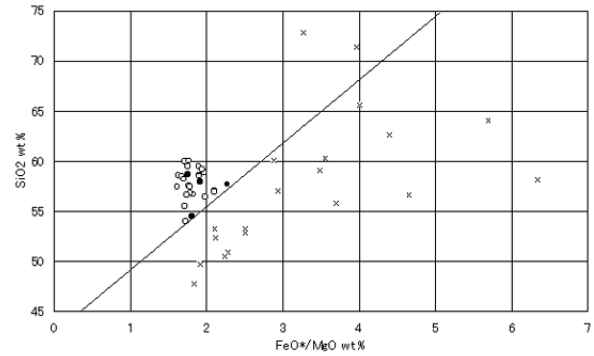

Figure 3. SiO2-FeO*/MgO diagram of 46 volcanic rock samples in the southern Ngada District. Closed circle; Aimere Scoria Flow Deposits, open circle; Mataloko, Wolo Bobo and Inerika Andesite, cross; other units.

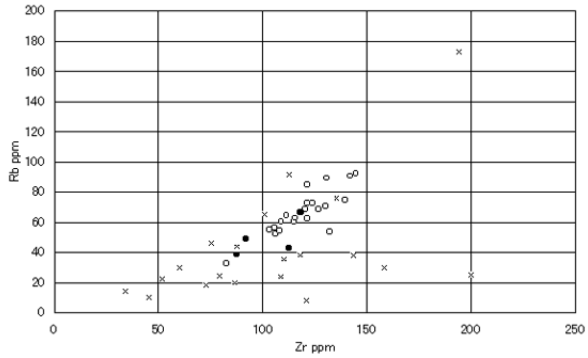

Figure 4. Rb-Zr diagrams of 46 volcanic rock samples in the southern Ngada District. Symbols are the same as Figure 3.

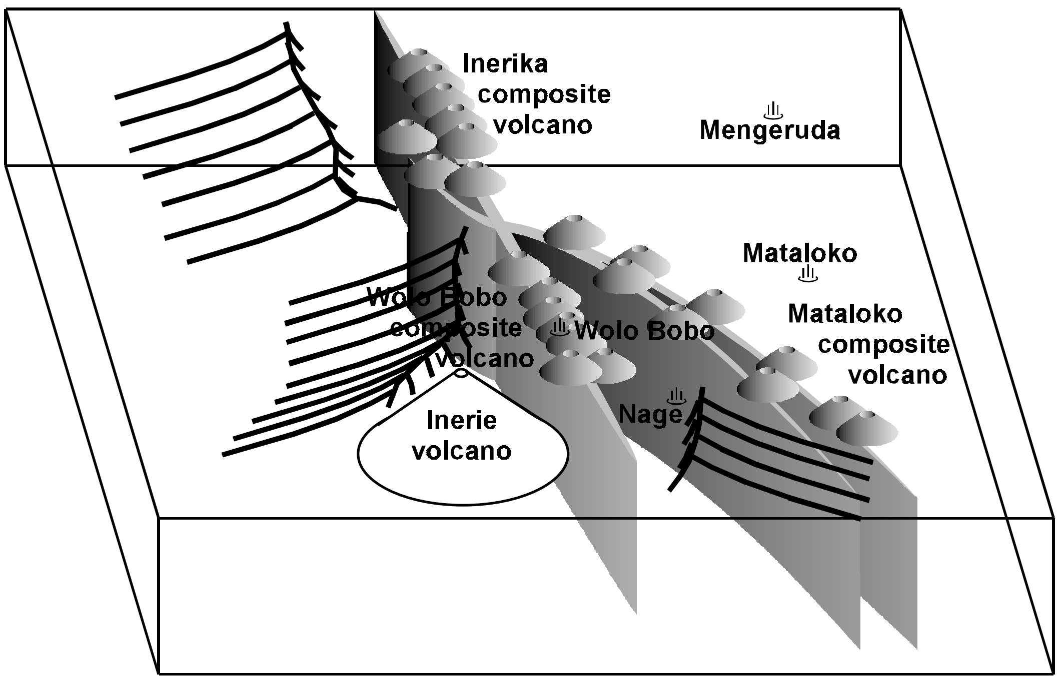

Figure 5. A model of radial dikes controlling volcano-tectonic and geothermal regimes in the Ngada District, Flores Island, Indonesia.