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Tectonic, volcanic and stratigraphic geology of the Bajawa geothermal field, central Flores, Indonesia

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Abstract: Regional geological investigation has been carried out since 1998 to evaluate geothermal resources in the Bajawa City and its surrounding areas of Flores Island as a part of the Research Cooperation Project on the Exploration of Small-scale Geothermal Resources in the Eastern Part of Indonesia (ESSEI Project). Since 4 Ma, volcanic activity occurred in two volcanic terrains: the central area and southern coast. Both of terrains form an element of the en echelon island structure characteristic from Flores to Alor Islands. An 800 m uplift occurred in the two terrains during the past 2.5 million years. In the central area, the Welas caldera formed at about 2.5 Ma. After its post-caldera volcanism, the volcanic activity has been almost extinct. On the southern coast, volcanic activity has continued from 4 Ma to the present. The most conspicuous event was the appearance of the Bajawa rift zone that was related to the north-south left-lateral shear stress accommodated between the north moving Australian accretion block in the east and relatively fixed Sundaland block in the west. The Bajawa rift zone was initiated by the formation of a NNW-SSE elongated volcano probably during 0.8−0.2 Ma. It was followed by the collapse of the eastern flanks from its crest. The collapsed area produced the Bajawa Cinder Cone Complex that consists of more than 60 cinder cones aligned 20 km along the NNW-SSE trending rift zone. Although the majority of volcanic rocks in the study area is basaltic and tholeiitic, all the effusive rocks from the Bajawa rift zone including the volcanic rocks of the elongated volcano and Bajawa Cinder Cones Complex are andesitic, calc-alkaline and very homogenous in composition. This suggests a connected dike swarm magma chamber beneath alignments of numerous cones of the Bajawa Cinder Cone Complex. Three steaming grounds and several high temperature hot springs in the study area are closely associated with the Bajawa rift zone magma system as a heat source.

1. Introduction

The purpose of this study is to give geological backgrounds for assessment of geothermal resources in Bajawa City and its surrounding areas, central Flores Island, Indonesia. The assessment area of this study is defined as the onshore zone transecting central Flores Island from north to south that are bounded by 120° 52' 30" E −121° 07'30" E and 8° 22' 30" S −8° 58' 00" S (Fig. 1). The study area covers a western half of the Ngada District. The southern half of the study area has been noticed for a long time from the viewpoint of geologic remote sensing because the remote sensor imagery presents numerous spectacular volcanic craters resembling the surface of the moon (e.g., Hamilton, 1979; Silver

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Keywords: geology, tectonics, volcanology, stratigraphy, chronology, geothermal resources, eastern Indonesia, Flores Island, Bajawa, Mataloko

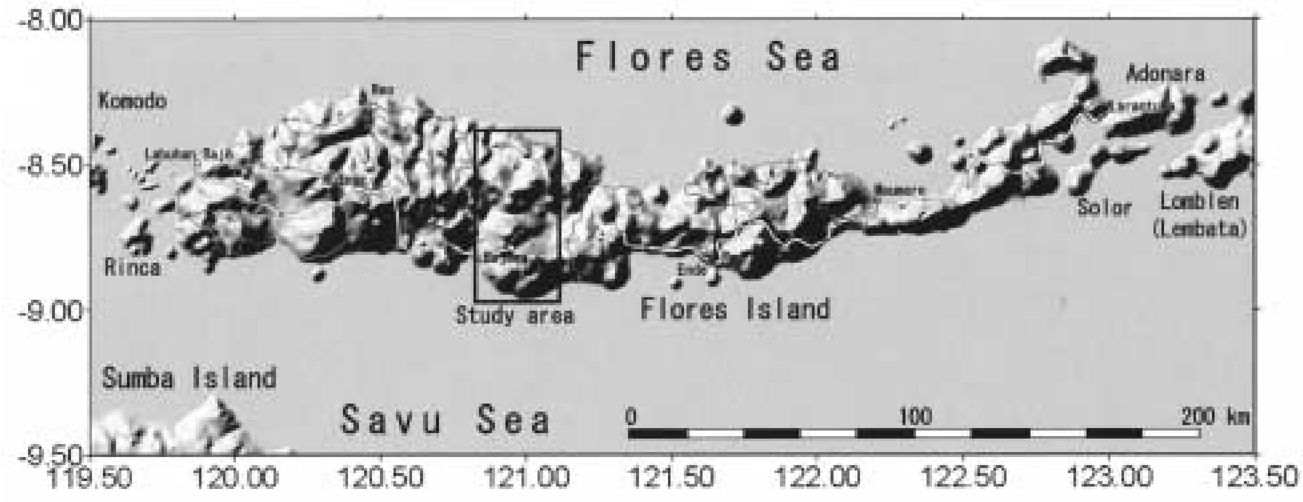


Fig. 1 Shaded relief map of Flores Island and the study area. The source DEM data are GTOPO30 released from USGS EROS Data Center and were shaded by Masao Komazawa. A rectangle in central Flores shows the study area.

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 and Inie Lika but also potential geothermal manifestations as Mataloko, Nage, Bobo and Mengeruda. This area could be one of the most prospective geothermal areas on Flores Island. However, volcanological and structural evolution of the area is complicated due to the overlying young and voluminous effusive rocks, and it has not yet been fully investigated. A geological map on a scale of 1: 250,000 has been published from the Geological Research and Development Centre, Indonesia (Koesoemadinata *et al.*, 1994). This map covers the entire western half of Flores Island, but the scale is not necessarily large enough for the evaluation of local geothermal resources. Recently, the Volcanological Survey of Indonesia has published geological maps of the Inerie volcano with a scale of 1: 25,000 (Munandar *et al.*, 1997) and Inie Lika volcano with a scale of 1: 25,000 (Pribadi *et al.*, 2000). These maps are detailed enough but cover only a limited part of the study area. Therefore, a further study on volcanological and structural evolution is critically important for a better understanding of the present geothermal activity in the area.

We have carried out field investigations of the study area during one or two weeks every dry season in fiscal years 1998 to 2001, as a part of the Research Cooperation Project on the Exploration of Small-scale Geothermal Resources in the Eastern Part of Indonesia (ESSEI Project; Muraoka and Uchida, 2002). We have often published part of the results (Muraoka and Uchida, 1999, 2000; Muraoka *et al.*, 1998, 1999a, 1999b, 2000a, 2000b, 2000c, 2001). However, most results were in preliminary publications as Interim Reports for the rapid information exchange among the participating organizations on this project. This paper describes the tectonic and geologic background of the Bajawa geothermal field, central Flores, Indonesia, including regional tectonics and details of the field observations.

We first review the tectonic setting of the Sunda-Banda arc and describe physiography of the area. A major part of this paper is spent on the field observations on stratigraphy and structure and results of chronological analyses of rock samples. We finally discuss stratigraphy and volcanological and structural evolution of the area.

2. Regional tectonic setting

The Sunda-Banda arc spans 4,300 km from Sumatra Island in the west through Kai Islands in the east to Buru Island in the north. This arc is broadly divided into two contrasting sectors: the Greater Sunda sector in the west and Lesser Sunda-Banda sector in the east as shown in Fig. 2. The Greater Sunda sector is said to be an active continental margin because the arc is situated at the southern front of a broad continent called "Sundaland" mainly concealed under shallow seawater that contains the Indochina Peninsula, Malay Peninsula, Sumatra Island, Sunda Shelf, Java Island, Java Sea and Borneo Island. A subducting plate basically consists of the oceanic crust in the Greater Sunda sector. This combination allows a stable subduction regime in the sector. The Lesser Sunda-Banda sector is an immature island arc with marginal seas of oceanic crust behind it such as the Flores Sea and Banda Sea as shown in Fig. 2. A subducting plate consists of the Australia continent in the Lesser Sunda-Banda arc so that the buoyant lithosphere is underplating less buoyant lithosphere resulting in unstable subduction or collision tectonics.

Eastern Indonesia is a place of interactions between

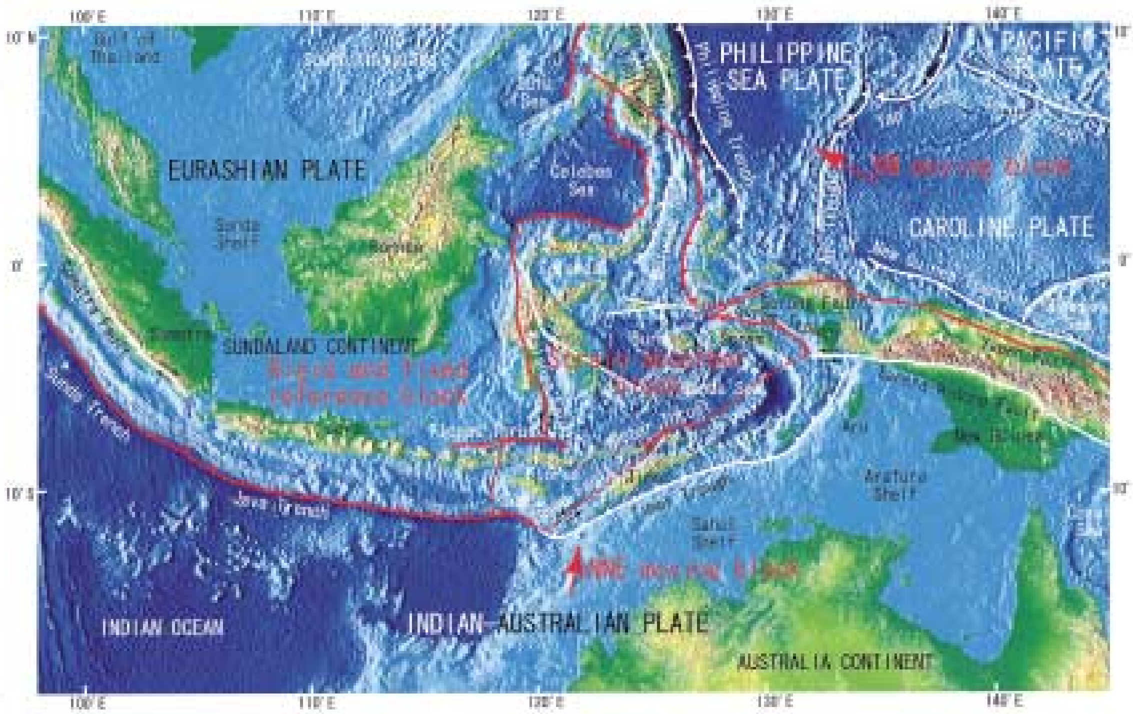


Fig. 2 Tectonic map of Eastern Indonesia. An on-line global relief image ETOPO2 (Global 2-min gridded data) was used as a base map from the National Geophysical Data Center (NGDC), NOAA. Red lines show the estimated boundaries of tectonic blocks with different motions based on the current GPS data.

the Pacific, Eurasian and Indian-Australian Plates (Fig. 2). It is not a simple triple junction and many microplates are involved in the interactions, making it one of the most complicated tectonic regions on the earth. For this reason, numerous studies of tectonics have been done in this region but many of the topics still remain controversial (Hall and Wilson, 2000). Comprehensive reviews of these works are beyond the scope of this paper. We shall thematically review a few topics in relation with the study area: (1) Why does the Banda arc form an unusual curvature? (2) Why does the inner Lesser Sunda arc form en echelon islands? and (3) What is the described geological history of Flores Island?

2.1 Why does the Banda arc form an unusual curvature?

Although numerous studies of tectonics have been done in this region, only a few papers have treated this topic. A classical work by Hamilton (1979) has drawn a spoon-shaped Wadati-Benioff zone along the Banda arc that dips inward from the south, east and north. However, as McCaffrey (1988) has pointed out geometrically that the subduction of the Australian Plate is simultaneously impossible to be beneath both the Timor and Seram Troughs because of their opposite polarities. He proposed that the Bird's Head of New Guinea is decoupled from the Australian Plate and moves west or southwest respective to Australia. Milsom (2001) has recently reviewed the hypocenter locations along the Banda arc and concluded that the Wadati-Benioff zone is separated at a depth above 150 km by the Tarera-Aiduna Fault as shown in Fig. 2, but is continued at a depth below 150 km. Therefore, paradoxical subduction geometry is partly explained by the shallow-depth decoupling of the subducted slab in the Banda arc.

It gives rise to another question whether the curvature of the Banda arc is derived from a primary shape or tectonic bending. Generally, curvatures of island arcs are tectonically and secondarily attained. Available evidence supporting this idea is a paleomagnetic study that Miocene pillow lava at Kelang Island near Seram Island indicates a large counter-clockwise rotation up to 74±4° (Haile, 1979) since its K-Ar age 7.6±1.4 Ma or later (Beckinsale and Nakapadungrat, 1979). Further paleomagnetic studies are necessary, but based on the work the curvature of the Banda arc has likely been attained through a tectonic process since the late Miocene or Pliocene age. Another major finding of the work is that it provides an incipient or nearly incipient age of the collision of the northern tip of the New Guinea-Australia continent.

The driving force of the bending of the Banda arc can be explained by the combination of the north-moving Australia continent and the west-extruding northern part of the New Guinea continent respective to Sundaland (Fig. 2). The observation of the

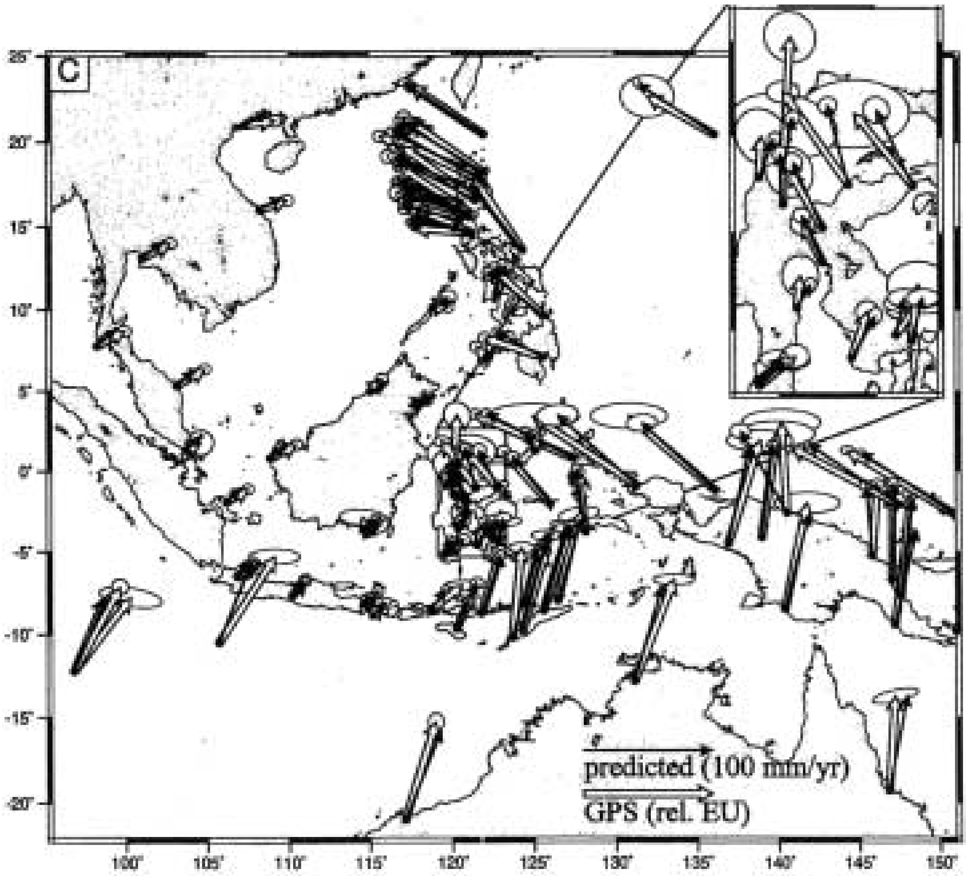


Fig. 3 GPS observation velocity (open vectors) and predicted velocity field from GPS-seismicity combined model (solid vectors) respective to the determined Australia-Eurasia pole of rotation by Kreemer *et al.* (2000).

Global Positioning System (GPS) has currently brought us quantitative insight into the active plate motions in the Southeast Asia Region (Wilson *et al* ., 1998; Kreemer *et al.*, 2000). These works make it possible to calculate relative convergence rates among the tectonic blocks. Based on Wilson *et al.* (1998), the Indian-Australian Plate is moving north at 75 mm/y respective to Sundaland, while Flores (Ende) is moving north at 50 mm/y. As a result, relative convergence rate along the Timor Trough south of Ende is calculated to be 25 mm/y. Likewise, shortening between Flores and Seram is calculated to be 10 mm/y. Whether this shortening is due to the back-arc thrusting (Silver *et al.* 1983) or shortening of the entire upper plate (McCaffrey, 1988), it must be clear that Flores Island is subject to the north-south contraction tectonics.

Figure 3 shows a map of the relative motions by Kreemer *et al.* (2000), where the open vector shows relative motions measured by GPS respective to the Australia-Eurasia pole of rotation. Based on the data, a region of Fig. 2 can be subdivided into four tectonic blocks, which are bounded by red color lines, in terms of motions: (1) A block of Sundaland and its eastern margins are apparently coherent in motions so that the motions are here assumed to be fixed to other blocks as a reference, (2) A block of Indian-Australian Plate and its northern accretions are moving north or NNE, (3) A block of Pacific-Caroline-Philippine Sea Plate and its western accretions are moving WNW or northwest and (4) An internal block including Flores, Banda Sea and Sulawesi Island plays a role of a strain absorber where the strains given from the surrounding blocks are almost absorbed within the block by the internal deformations. In other words, most deformations are concentrated in the Flores-Banda-Sulawesi block. In the Flores-Banda-Sulawesi block, the northern part is subject to the motion of the Pacific block and the southern part is subject to the motion of the Indian-Australian block. As a result, the block is rotating counter-clockwise even now. This suggests that the counter-clockwise bending of the Banda arc is still ongoing.

2.2 Why does the inner Lesser Sunda arc form en echelon islands?

Landsat MSS imagery in Fig. 4 shows a part of the inner Lesser Sunda Islands from Flores to Alor Islands. This part of the arc distinctively forms en echelon-shaped volcanic islands and becomes obscured to the east and west. Each element of en

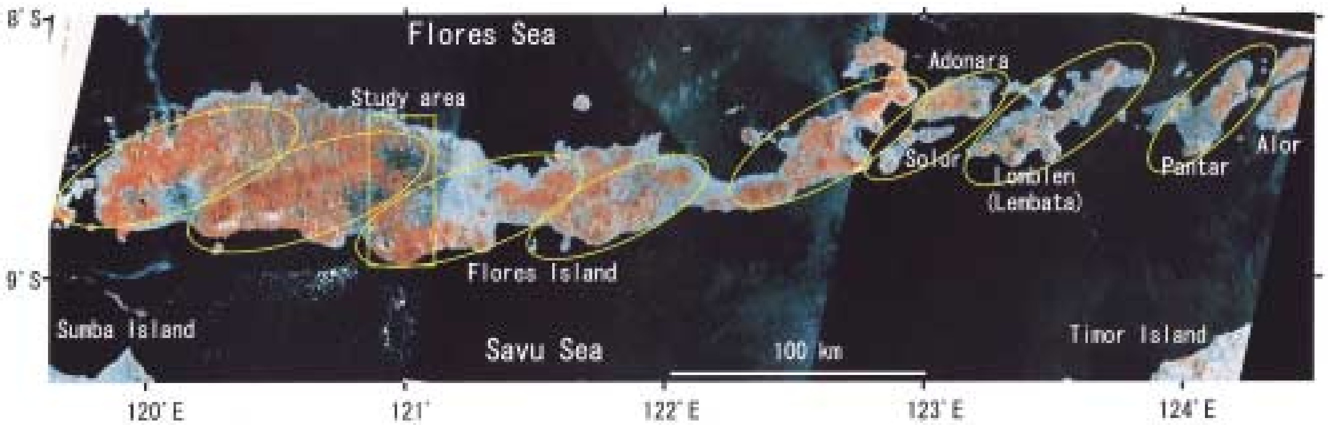


Fig. 4 Mosaic of three scenes of Landsat MSS imagery on the inner Lesser Sunda Islands. Note the en echelon shaped topographic structure in this sector of the Lesser Sunda Islands. Each element of en echelon structure consists of a culmination of the anticline and clustered young volcanoes.

echelon forms topographically an elongated dome that is composed both of a culmination of an anticline and cluster of young volcanoes. Island itself sometimes coincides with an element of the en echelon structure such as Lomblen and Pantar Islands.

Generally, en echelon volcanic islands are common in the oblique subduction zone like Kuril and Aleutian arcs, where the direction of the subduction tends to be perpendicular to the anticline axes of each echelon element. However, the direction of the subduction is NNE for the inner Lesser Sunda Islands and an array of en echelon elements is opposite to this direction. This is an enigma that requires another explanation for the formation process.

Again, GPS measurements provide a clue to this problem. Based on Fig. 3, the outer Lesser Sunda Islands including Timor Island seem almost accreted to the Indian-Australian Plate in terms of motions, where the estimated Savu Fault (Rutherford *et al.*, 2001) is a possible block boundary rather than the Timor Trough (Kreemer *et al.*, 2001) as shown in Fig. 2. As a result, the en echelon sector from Flores to Alor Islands is a place for the shear strain absorber between the Sundaland block and Indian-Australian block, where the western tip is rather fixed relative to the Sundaland block but the eastern tip is subject to the north moving Indian-Australian block. A force of this left lateral shear stress in the north-south direction or anticlockwise moment might have caused the array of en echelon islands in a limited part of the inner Lesser Sunda sector.

2.3 What is the described geological history of Flores Island?

Many geological studies have been done on the offshore geology in the Lesser Sunda-Banda sector. Hamilton (1979) and Bowin *et al.* (1980) suggested that the leading edge of the Australia continent started to enter the Timor Trough around 3 Ma. Silver *et al.* (1983) have described the significance of back arc thrust of the Lesser Sunda arc such as Flores Thrust and Wetar Thrust and also drawn attention to a series of the NNE or NE trending left-lateral faults from Flores to Wetar Islands.

Compared to offshore geology, relatively few studies have been done on the onshore geology on Flores Island. A geological map with a scale of 1: 250,000 has been published from the Geological Research and Development Centre, Indonesia (Koesoemadinata *et al.*, 1994). Probably, one of the few radiometric age measurements from the Flores Island has been the fission track age on zircon of andesite taken from the Kiro Formation east of Ende by Nishimura *et al.* (1980). This age shows 19 ± 2 Ma for the Kiro Formation.

The seismic refraction data (Curray *et al.*, 1977) suggest that the continental crust of Flores Island on the order of 5 or 10 km in thickness is built on the oceanic crust. The inner volcanic arc of the Lesser Sunda-Banda arc appears to have been formed in the Early Miocene on the oceanic crust, probably after a clockwise rotation about 50 degrees of Borneo, southwestern arm of Sulawesi and the Celebes Sea during 24 − 17 Ma (Nishimura and Suparka, 1997). The age of the Kiro Formation (Nishimura *et al.*, 1980) is almost consistent with this idea. However, the Kiro Formation and intercalated Miocene strata have mostly deposited in a marine environment, and the Miocene immature volcanic arc could have been mainly below sea level. During this age, the oceanic lithosphere might have been subducted along the Timor Trough. Many researchers believe that the collision of the Australian continent has started since 3 Ma along the Timor Trough (Hamilton, 1979; Bowin *et al.*, 1980; Nishimura and Suparka, 1997). However, as has already been mentioned, a paleomagnetic study by Haile (1979) and Beckinsale and Nakapadungrat

(1979) provides the possible incipient age to be 7.6 ±1.4 Ma or later on the collision of the northern tip of New Guinea-Australia continent. This means that there is an allowance on the incipience age of collision of the Australia continent from 7.6 Ma or later to 3 Ma, depending on the given location and local shape of the leading edge of the Australia continent. The incipience of the collision has likely caused many changes such as the bending of the Banda arc, accretion of the outer arc, uplift of the arc and continental crust-forming volcanism like calc-alkaline magmatism.

3. Physiographical setting

A digital topographic map and JERS-1 SAR imagery (Urai *et al.*, 1998, 1999, 2002) of the study area are shown in Figs. 5 and 6, respectively. The SAR (synthetic aperture radar) has an advantage of easily acquiring fine imagery even in tropical monsoon regions due to the penetration of microwaves through the cloud cover but has a disadvantage of showing an elevation-derived distortion on imagery such as the lay-over and fore-shortening. Therefore, the comparison of both Figs. 5 and 6 is better for physiographical and geological interpretations. All the locality numbers (Loc.1-32) in the following text are shown in Fig. 5, except three localities on Lomblen Island. Volcanoes are concentrated along two lines: a southern coast at a volcanic front and a north-central part. This setting apparently resembles the double volcanic belts in the Northeast Japan arc, but macroscopically, the clusters of volcanoes along the double lines are ascribed to neighboring two elements of the en echelon structure as has already been mentioned (Fig. 4). Double volcanic belts are obscured on Flores Island, probably due to the en echelon structure and steeply dipping subduction regime.

3.1 Aesesa Basin

The Aesesa River, whose branches are called by various names in the study area, is relatively a long river that drains precipitated water from a ridge of the southern volcanic front to the northeastern coast. Many branches at the upper reaches of the Aesesa River form an elliptic basin about 20 km (E-W) by 15 km (N-S) that contains the Mengeruda hot spring as seen in Fig. 6. Here we name it the Aesesa Basin. The lacustrine Aesesa Formation deposited in this basin during the Pliocene to Early Pleistocene age. This basin originated as an area sandwiched between two volcanic terrains along the southern coast and north-central part. The Aesesa Formation and its Pliocene lake indicate that the two volcanic terrains have been present since at least the late Pliocene age. Figure 7a shows a photograph of the flat topography formed by the Aesesa Formation with a southwest view looking from Loc. 1 (Fig. 5) to Inie Lika volcano.

3.2 Welas caldera

Volcanoes in the north-central part seem relatively dissected and old. They are represented by a caldera that is here named Welas caldera as shown in Fig. 6. The caldera collapse area is 15 km (E-W) by 8 km (N-S). The rim of this caldera is open to the southeast to the Aesesa Basin. As described below, the distribution of the Welas Tuff and Aesesa Formation indicates that the southeastern rim of the caldera has been open since the late Pliocene age. Post-caldera cones are typically developed in the western half of the caldera. We have tried to find hot springs in this caldera, and recently we have found only one hot spring in this caldera at Loc. 2 (Fig. 5). However, the temperature is about 30 ℃ probably due to the old age of the caldera. Figure 7b shows a photograph of the inside of the Welas caldera looking from Loc. 3 (Fig. 5) west of the caldera. A flat plateau as high as 1000 m developed in the surroundings of the Mere post-caldera cone in the western half of the caldera. This plateau is composed of plateau lava of the Mere post-caldera cone.

3.3 Wangka Plateau

North of the Welas caldera, an extensive hill about 20 km (E-W) by 10 km (N-S) is recognized on the SAR imagery in Fig. 6 and is clearer on the digital topographic map in Fig. 5. The surface of the hill has a 900 m elevation at the northern rim of the Welas caldera and a 750 m elevation at its northern edge. Here this hill is named Wangka Plateau. The hill is mainly composed of Wangka Andesite and Welas Tuff, but a thin veneer of the Plio-Pleistocene Matale Limestone overlies them in some places, indicating a continuing uplift during the past 2.5 million years.

3.4 Nage caldera

Nage caldera is not easy to detect from the SAR imagery in Fig. 6 but is clearer as a circular basin with a 7 km diameter on the digital topographic map in Fig. 5. This caldera is situated at the southern crest of an elongated volcano related to the Bajawa rift zone described below.

3.5 Bajawa rift zone

Numerous cinder cones are recognized in the southern part of the study area on the SAR imagery (Fig. 6), and they are distributed almost 20 km from north to south. They are named the Bajawa Cinder Cone Complex as described below. In the surroundings of the Bajawa Cinder Cone

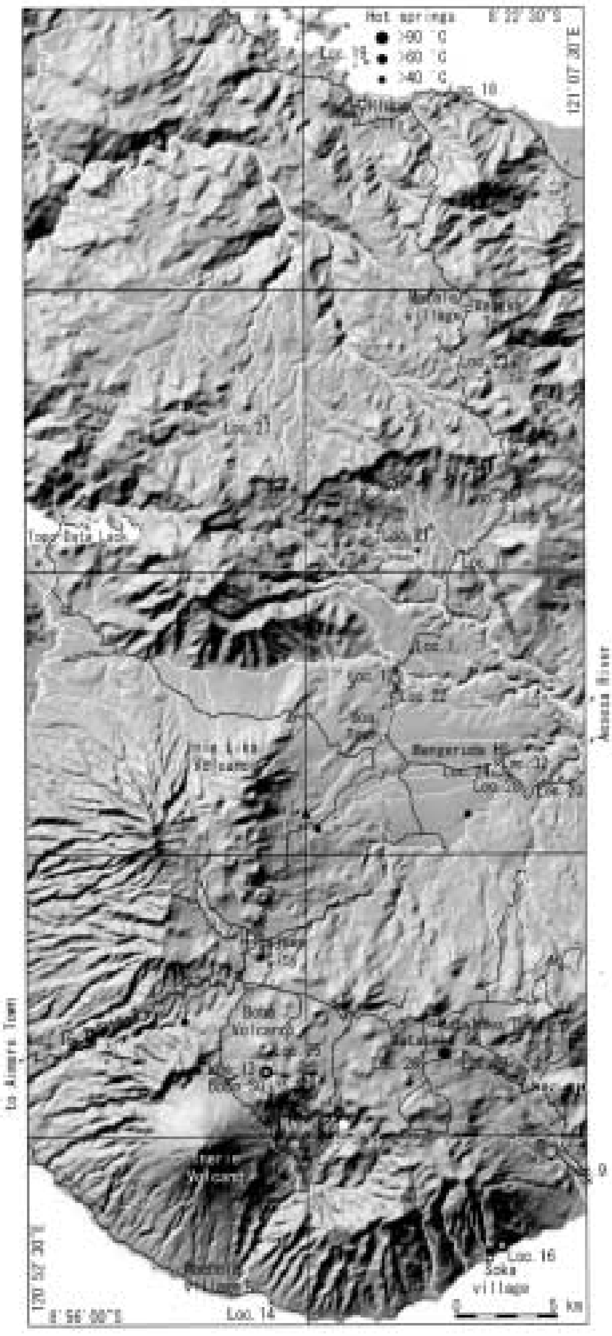


Fig. 5 Study area of the Geological Survey of Japan in the "Research Cooperation Project on the Exploration of Small-scale Geothermal Resources in the Eastern Part of Indonesia" shown by a shaded-relief digital topographic map, central Flores, Indonesia. Keiji Tanaka, Hirofumi Muraoka and Masao Komazawa have digitized the data from the topographic maps at a scale 1: 25,000 in this project. Black lines show main roads and white lines show main rivers. High temperature springs and locality numbers are also shown.

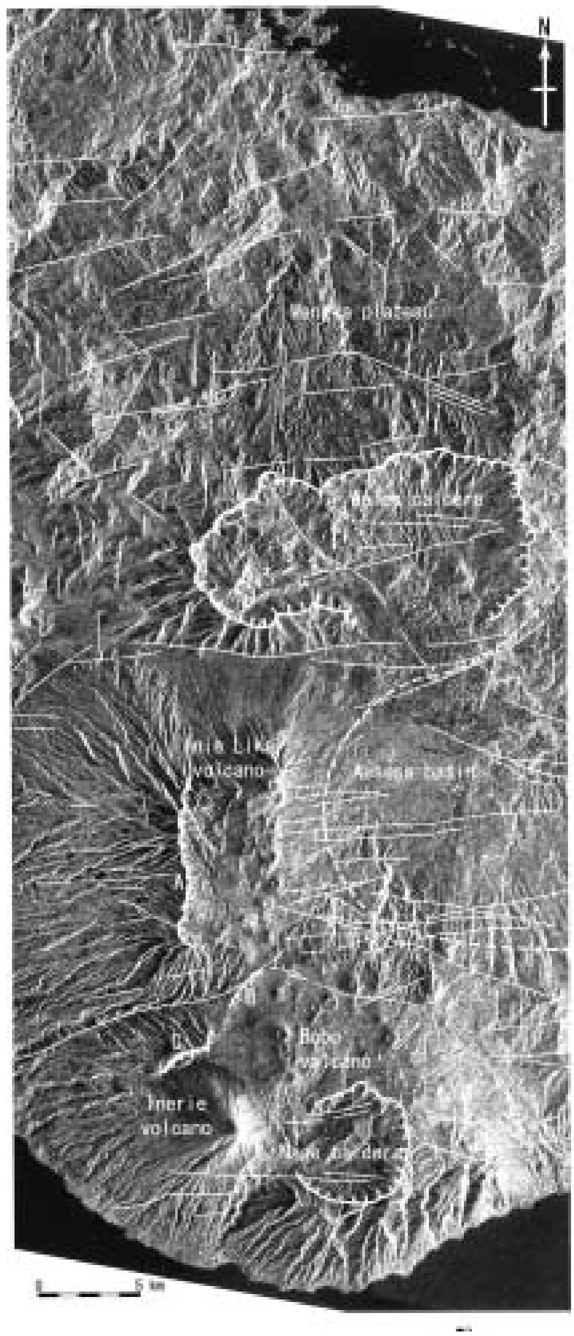


Fig. 6 JERS-1 SAR imagery of the study area acquired on February 3, 1996 (Urai *et al.*, 1998, 1999, 2002; Copyright METI/NASDA). Extracted lineaments, calderas, walls of the rift zone and other features are shown.

a) b)

Fig. 7 Photographs of the Aesesa Basin and Welas caldera. a) Flat topography at a top of the Aesesa Formation in the Aesesa Basin and Inie Lika volcano looking from Loc.1 in Fig. 5. b) Inside of the Welas caldera looking from eastern rim at Loc.3 in Fig. 5.

Complex, a few fragmentary cliffs are recognized on the satellite imagery (Fig. 6) and in the field. They are labeled A, B and C in Fig. 6. Cliffs like C are commonly found in the surroundings of stratovolcanoes such as Inerie and Mt. Fuji. Suzuki (1968) once proposed that such cliffs could be formed in a possible sinking of the stratovolcano edifice by its own weight. One of the conspicuous cliffs is the north-south trending cliff A facing east at the western flank of the Inie Lika volcano (Fig. 6). This is 10 km long, but there is no counter wall east of the Inie Lika volcano. Another example is cliff B at the northwestern flank of the Bobo volcano (in Fig. 6). Those cliffs suggest that there exists a small rift zone along the Bajawa Cinder Complex as discussed by Walker (1999). One may suggest the cliffs are caldera walls because the Aimere Scoria Flow Deposits are widely distributed on its western flanks and the Bajawa Cinder Cone Complex seems to be post-caldera cones. We actually once thought they were caldera walls (Muraoka *et al.*, 1999a, 2000a). In this case, however, we must consider the very elongated caldera 20 km long from north to south. Volcanic rift zones recently reviewed by Walker (1999) are a more adoptable category for this area in respect with the elongated extent, discrete linear walls and alignments of numerous monogenetic cinder cones. Therefore, here we shall name Bajawa rift zone to the Bajawa Cinder Cone Complex and related discrete walls.

3.6 Young volcanoes and Bajawa Cinder Cone Complex

Two active volcanoes are known in the study area; Inerie volcano at the south and Inie Lika volcano at the middle. The Inerie volcano is a stratovolcano and fumarolic activity at its summit crater has often been observed throughout historic time. The Inie Lika volcano is a clustered volcano (Fig. 7a) and has a record of a historic phreatic eruption in 1905 (Neumann van Padang, 1951). It is noted that a phreato-magmatic eruption of the Inie Lika volcano has recently occurred from January 11 to January 16, 2001, after 95 years of quiescence (Muraoka *et al.*, 2002b). The Bobo volcano is also a young clustered volcano that is very similar to the Inie Lika volcano, although this volcano has no records of historic eruptions (Fig. 8a). Inie Lika and Bobo volcanoes are composed of numerous cinder cones (Fig. 8a) that almost form a north-south trending single alignment. Two alignments of cinder cones with NW-SE trends are also recognized southeast of Bajawa (Fig. 8b). These alignments of cinder cones suggest dike-shaped magma chambers beneath them, and regardless of their isolation of volcanic edifices, they seem cognate in origin. Therefore, we collectively name them Bajawa Cinder Cone Complex.

4. Chronology of volcanic rocks

The K-Ar age measurements for ten volcanic rock samples were carried out from the study area. These results are shown on Table 1. The K-Ar age measurements for three volcanic rock samples from Lomblen Island were preliminarily reported by Muraoka (1989), but their original data have not yet been published. These results are also shown on Table 1. The sampling locations of Flores and Lomblen Islands are shown in Fig. 5 and Fig. 9, respectively.

Most younger volcanic units of the study area seem too young to be dated by the K-Ar method so the thermoluminescence (TL) age dating method was

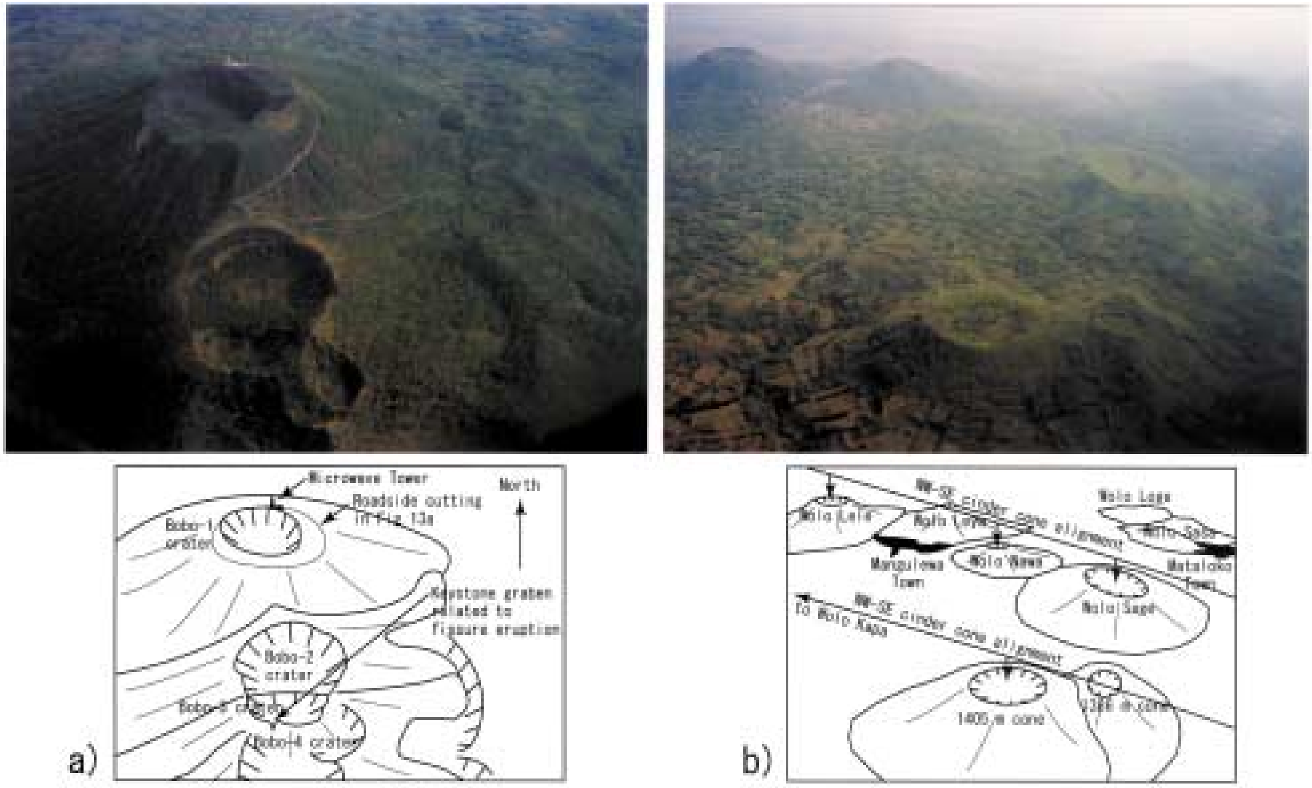


Fig. 8 Photographs of the Bajawa Cinder Cone Complex taken from a low altitude airplane. a) Northern cinder cones of Bobo volcano. b) NW trending cinder cones west of the Mataloko area.

Table 1 Results of K-Ar age measurements of the volcanic rocks in the Bajawa geothermal field of Flores Island and Lomblen Island. The sampling localities (Loc.4-16) are given in Figs. 5 and 9.

Location no.	Sample no.	Rock type (Unit)	Analysis	Potassium (wt %)	Rad 40Ar (10^{-5} cm^3/g)	Air cont. (%)	Age ± 1σ (Ma)
Lomblen Island (Muraoka, 1989)							
Loc.4	871010-05	Andesite lava	Whole rock	2.82	0.025	21.30	2.24±0.18
Loc.5	871009-04	Essential of dacitic welded tuff	Whole rock	1.84	0.015	5.85	2.20±0.50
Loc.6	871010-02	Andesite lava	Whole rock	3.82	0.026	11.50	1.72±0.28
Flores Island (Muraoka et al., 2002, this work)							
Loc.7	980723-03	Andesite lava (Wn)	Whole rock	0.30	4.81±0.33	93.65	4.13±0.50
Loc.8	980723-04	Andesite lava (Wn)	Whole rock	1.47±0.04	16.92±0.74	89.64	2.96±0.16
Loc.9	980722-01	Basalt lava (Mb)	Whole rock	0.42±0.04	5.49±0.27	90.76	3.37±0.38
Loc.10	980726-03	Andesite lithic of pumice tuff	Whole rock	1.06±0.03	11.25±0.40	87.61	2.73±0.13
Loc.11	980723-06	Pumice of pumice tuff (Wt)	Whole rock	0.42±0.04	4.12±0.26	90.75	2.52±0.30
Loc.12	980723-02	Pumice of pumice tuff (Wt)	Whole rock	1.37±0.04	8.81±0.51	92.47	1.66±0.11
Loc.13	980721-03	Basalt lava (Wa)	Whole rock	0.30±0.03	2.79±0.25	92.25	2.40±0.32
Loc.14	980727-01	Basalt pillow lava (Wa)	Whole rock	0.26±0.04	1.62±0.43	91.72	1.61±0.49
Loc.15	980718-04	Scoria of scoria tuff (As)	Whole rock	0.77±0.05	−0.91±1.39	100.22	<0.15
Loc.16	980722-04	Scoria of scoria tuff (As)	Whole rock	0.89±0.05	−0.95±0.36	100.85	<0.15
λ_e=0.581x10^{-10}yr^{-1}; λ_β=4.962x10^{-10}yr^{-1}; ^{40}K/K=1.167x10^{-4}mol/mol.							

employed by Takashima *et al.* (1999, 2002). Therefore, ten samples for K-Ar age measurements were selected from relatively older volcanic units. Dacitic or andesitic lava (980723-03 and 980723-04) clearly forms pre-caldera volcanoes at the western rim of the Welas caldera, and their older ages of 4.13 Ma and 2.96 Ma are reasonable. They are commonly sheared on the outcrop. A sample of basaltic lava (980722-01) taken on the way to Maumbawa also shows a similar age of 3.37 Ma and indicates that the active volcanism occurred in the Pliocene age. Ages of caldera-forming tuff of the Welas caldera are obtained to be 2.52 Ma (980723-06) and 1.66 Ma (980723-02). When we consider that both samples are pumice being easily devitrified, the older age of 2.5 Ma may be rather reliable. This age is nearly the same as that of the caldera-forming tuff of the Watuipet caldera on Lomblen Island (871009-04 in Table 1 and Fig. 9; Muraoka, 1989) and suggests that the widespread caldera-forming-scale magmatism

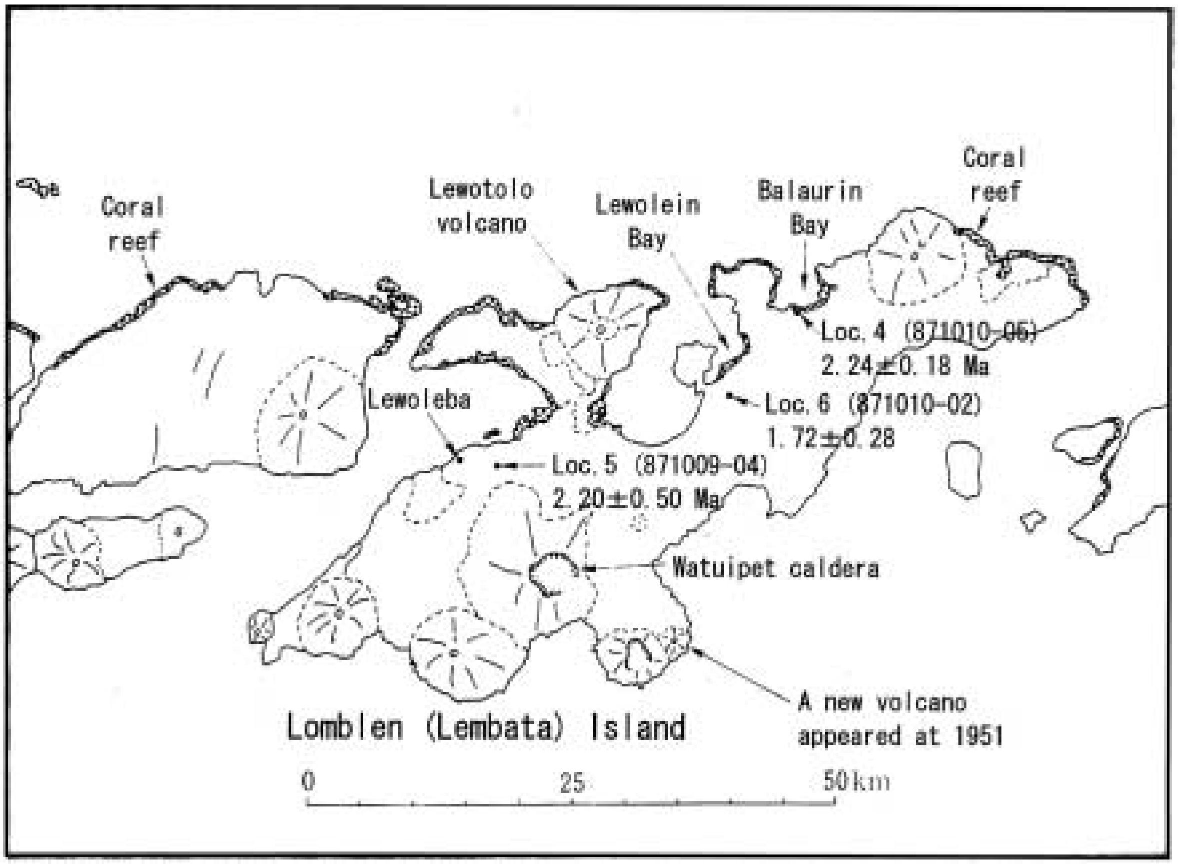


Fig. 9 Locality map of the K-Ar age measurement samples taken on Lomblen Island.

occurred in the inner arc of the Lesser Sunda arc around 2.5 Ma. This age also indicates the incipient time of the Pliocene Aesesa Lake because the Welas Tuff composes the lowermost part of the lacustrine deposits named the Aesesa Formation. An exposure of green-altered tuff was found at Wae Nagu, southeast of Mataloko. Two possibilities for this unit were considered in the field: the stratum is correlated to the Miocene Nangapanda Formation or the Welas Tuff was deposited in a marine environment. To analyze these possibilities, a relatively fresh lithic fragment was taken from the green-altered tuff for a K-Ar age measurement. The K-Ar age of the lithic fragment of the green-altered tuff (980726-03) shows 2.73 Ma and supports the latter possibility. Samples of basalt lava (980721-03 and 980727-01) were taken from the southwestern part and their ages of 2.40 Ma and 1.61 Ma are close to that of the Welas Tuff, the incipient age of Aesesa Lake. Submarine occurrence of this unit such as pillow lava and hyaloclastite indicates that the marine transgression occurred in higher altitude areas at that time. Although we have not obtained direct stratigraphic evidence, this unit named the Waebela Basalt may overlie the Welas Tuff and may be one of the contemporaneous heterotopic facies with the Matale Limestone in the north and Aesesa Formation in the middle of the study area. Samples of scoria from scoria tuffs (980718-04 and 980722-04) were taken on the way to Aimere and Soka, distant from each other. Both ages show less than 0.15 Ma and are ascribed to one unit of tuff named the Aimere Scoria Flow Deposits.

5. Stratigraphy

5.1 Outline of stratigraphy

A geological map and geological cross sections are shown on Plate 1. This section will give explanations to these geological maps. The oldest unit exposed in the study area is the Miocene Series that consists of the Nangapanda Formation (Np) and Riung Tonalite (Rt). The Pliocene Series consists of the Wangka Andesite (Wn), Maumbawa Basalt (Mb), Welas Tuff (Wt), Waebela Basalt (Wa), Aesesa Formation (Ae), Matale Limestone (Mt) and Mere Basalt (Me) in ascending order. The Quaternary System consists of the Sasa Andesite (Ss), Aimere Scoria Flow Deposits (As), Siutoro Andesite (Si), Lahar deposits (Lh), Mataloko Andesite (Mk), Bobo Andesite (Bb), Inie Lika Andesite (Ik), Inerie Basalt (Ie) and Alluvium (Qa) in ascending order.

5.2 Nangapanda Formation (Np)

The name, Nangapanda Formation, was originally given by Koesoemadinata *et al.* (1994). The type

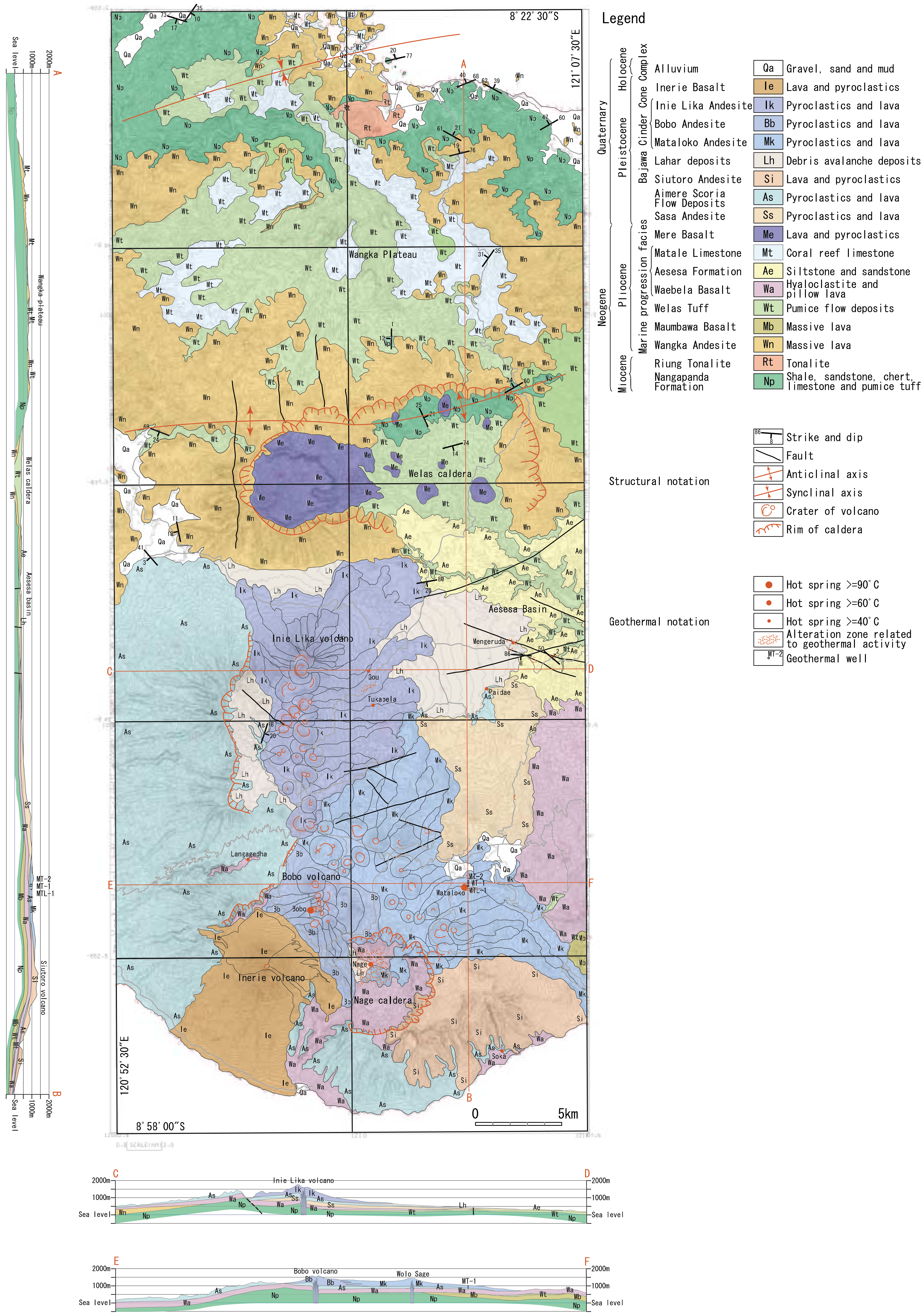


Plate 1 Geological map and geological cross sections of the Bajawa geothermal field, central Flores, Indonesia.

locality of this unit is Nangapanda Town, 50 km east of Bajawa City on the way to Ende City. This unit is distributed in the northern part of the study area. Along a pair of syncline and anticline axes, this unit is roughly exposed in a S-shaped area, but it is obscured in the Welas caldera collapse area. At the northern rim of the Welas caldera, this unit forms a crest of the anticline axis (Fig. 10a, Loc.17 in Fig. 5). Its northern wing is widely distributed to the north. The northern wing of this unit is steeply dipping at the northern coast (Fig. 10b, Loc.18 in Fig. 5) and gently dipping at Palau Kalong Island close to the syncline axis (Fig. 10c, Loc.19 in Fig. 5). The total thickness of this unit cannot be estimated because its lower limit is not exposed, but it is at least 1,000 m in its exposed part. Stratigraphically this unit is intruded by the Riung Tonalite and uncomformably overlain by the Wangka Andesite. The lower part of this unit is predominant with pelagic sediments such as shale, siltstone and chert, and the upper part is prevalent with neritic sediments such as sandstone, pumice tuff and limestone. They are entirely derived from a submarine environment and their volcanic facies are more or less suffered by green alteration, containing chlorite.

5.3 Riung Tonalite (Rt)

Koesoemadinata *et al.* (1994) have drawn this unit as one of the intrusive bodies of Quartz Diorite on their map, but they have not given any local name. The name, Riung Tonalite, is newly given in this paper. The type locality of this unit is southwest of Riung City. The Riung Tonalite has an exposure of 4.5 km (E-W) by 2.5 km (N-S) southwest of Riung City and evidently intrudes the Nangapanda Formation. The stratigraphic relation of this unit to the Wangka Andesite is not evident, but the Wangka Andesite probably overlies this unit. This unit is partly altered, resulting in iron ore mineralization.

5.4 Wangka Andesite (Wn)

The Wangka Andesite is newly named in this paper and the type locality is the south of Wangka Town. This unit is widely distributed in the rims of the Welas caldera and its surrounding areas. Physiographically, the maximum thickness of this unit is estimated to be 500 m. This unit unconformably overlies the Miocene strata with a hiatus, and a paleogeographic change from the marine to subaerial conditions occurred during the time of this hiatus.

The Wangka Andesite consists of lava flows and/or lava domes of andesite, dacite and rhyolite compositions, and silicic lava often contains biotite. This unit commonly shows sheared occurrence with zeolite and chlorite veins. Shear planes are developed in the north-south direction (Fig. 10d, Loc.8 in Fig. 5). Two K-Ar ages, 4.13 Ma and 2.96 Ma, were obtained.

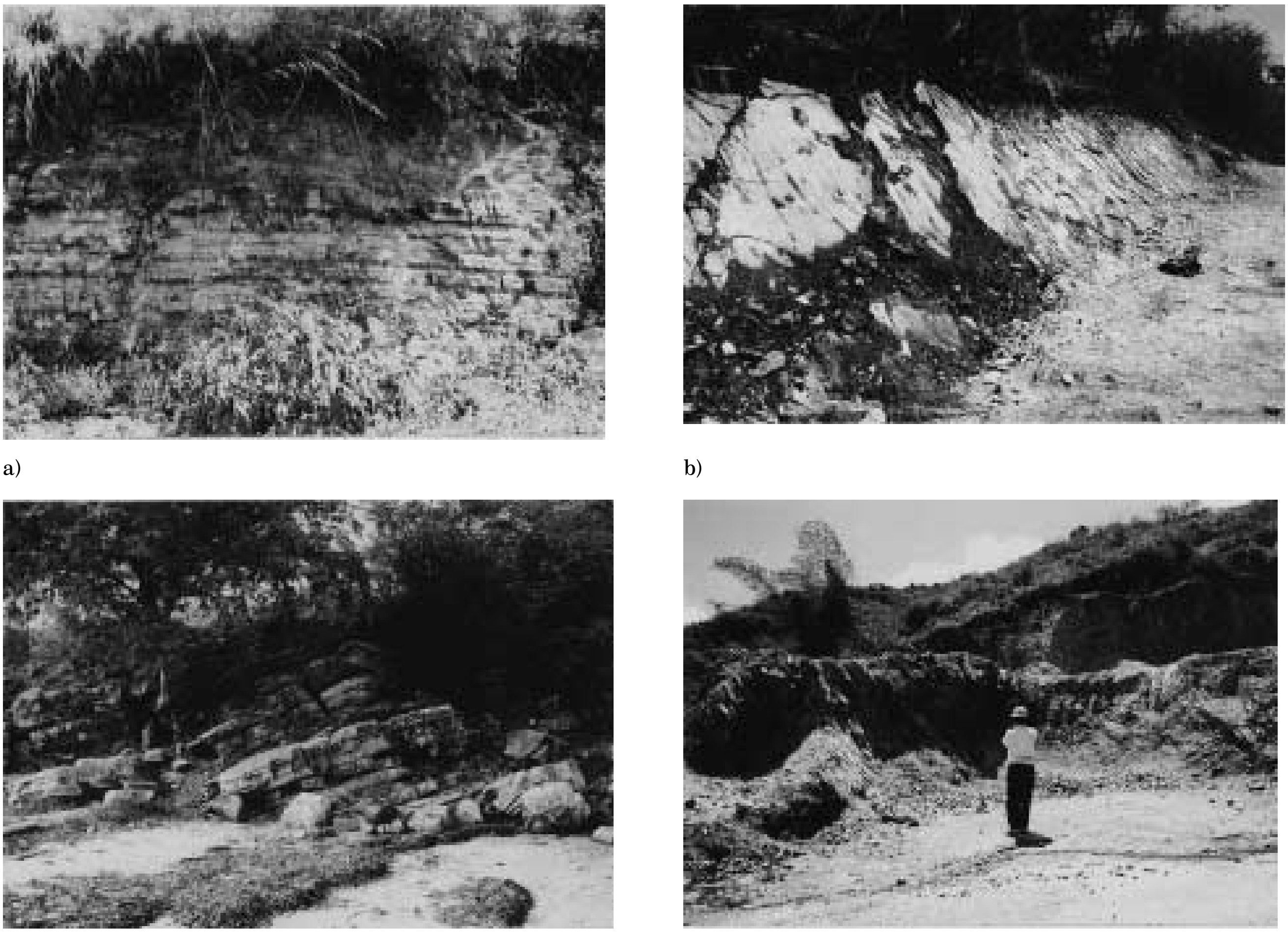
5.5 Maumbawa Basalt (Mb)

The Maumbawa Basalt is newly named in this paper, and the type locality is a quarry on the way from Mataloko to Maumbawa immediately outside of the study area. The distribution is limited to the southeastern part of the study area. The lower limit is not exposed but physiographically the thicker part of this unit may be at least 200 m. There is no evidence on its relation to the Miocene strata, but this unit unconformably overlies the Miocene strata with a time hiatus and paleogeographic change from the marine to subaerial environment occurred during the time of this hiatus. This unit is stratigraphically correlated to the Wangka Andesite. This unit consists of massive lava flows and commonly shows sheared occurrence with zeolite and chlorite veins. A K-Ar age, 3.37 Ma, was obtained.

5.6 Welas Tuff (Wt)

The name, Welas Tuff, is newly given in this paper and the type locality is along the river named Wae Nangawelu at the southeastern rim of the Welas caldera. The Welas Tuff is exposed not only in the surroundings of the Welas caldera (Fig. 11a, Loc.20 in Fig. 5) but also in the inside of the caldera (Fig. 11b, Loc.21 in Fig. 5). The Welas Tuff is a voluminous ash flow tuff related to the collapse of the Welas caldera, and its extent is quite wide covering the almost entire study area except for the area that is highly eroded or concealed by younger volcanic rocks. The maximum thickness of this unit is approximately 100 m in the surroundings of the Welas caldera but it may exceed 300 m in the inside of the caldera. The Welas Tuff unconformably overlies the Nangapanda Formation, Riung Tonalite, Wangka Andesite and Maumbawa Basalt.

The Welas Tuff contains not only abundant essential pumice but also abundant accidental lithic fragments (Fig. 11a). Pumice and lithic range from boulder to lapilli sizes. The matrix consists of sandy-size glass shards and crystals. The tuff has andesitic and tholeiitic compositions. This unit was deposited in a lacustrine environment inside of the caldera and in the Aesesa Basin, while it was probably deposited in a shallow marine environment north of the northern caldera rim and south of the Mataloko-Bobo ridge. In a lacustrine environment, this unit often contains lenses of siltstone bed. In a marine environment, this unit was often altered into green colored tuff (Fig. 11c, Loc.10 in Fig. 5). At the quarry in the type location of the Maumbawa Basalt,



a) b) c) d)

Fig. 10 Photographs of the Nangapanda Formation and Wangka Andesite. a) Outcrop of shale and siltstone of the Nangapanda Formation at the crest of the anticline at the northern rim of the Welas caldera (Loc. 17 in Fig. 5). b) Outcrop of tilting sandstone and clastic limestone of the Nangapanda Formation at the northern coast (Loc.18 in Fig. 5). c) Outcrop of siliceous shale and chert of the Nangapanda Formation at the Pulau Kalong Island, north of Riung (Loc. 19 in Fig. 5). d) Outcrop of the sheared Wangka Andesite in the northern rim of the Welas caldera (Loc.8 in Fig. 5).

thin scoria fall layer that covers the Maumbawa Basalt consists of a mixture of scoria fall and coral reef limestone. This scoria fall layer is considered as Plinian eruption products of the Welas Tuff at the coastal environment. The Welas Tuff consists of at least two cooling units. Three K-Ar ages, 2.73 Ma for a lithic fragment and 2.52 Ma and 1.66 Ma for pumice samples, were obtained. A reasonable age for this unit may be 2.5 Ma. Geochemically, the Welas Tuff is tholeiitic andesite in composition that is similar to tholleiitic dacite composition of 2.20 Ma tuff from the Watuipet caldera, Lomblen Island (Muraoka, 1989). This means that the caldera-forming scale shallow-depth magmatism widely occurred around 2.5−2.2 million years ago in the Lesser Sunda arc, but the magma chambers were still immature and tholeiitic in composition. Probably, the high degree of partial fusion of the tholeiitic ocean crust caused less differentiated magma chambers.

5.7 Waebela Basalt (Wa)

The Waebela Basalt is newly named in this paper, and the type locality is the Waebela Village on the southern coast. This unit is exposed northwest and east of the Inerie volcano and east of Mataloko. The maximum thickness is estimated to be 250 m. This unit may overlie the Welas Tuff and is the contemporaneous heterotopic facies with the Matale Limestone in the north and Aesesa Formation in the middle of the study area. During the deposition of these units, marine transgression probably occurred. This unit consists of massive lava flows and their clinkers. Near the southern coast such as at Waebela, this unit occurs as a submarine lava flow composed of massive lava flow, hyaloclastite and pillow lava with pillow robe (Fig. 11d, Loc.14 in Fig. 5). Occurrence of hyaloclastite can also be observed near the Langagedha hot spring along the upper reach of the river Wae Bua north of the Inerie volcano. Two K-Ar ages, 2.40 Ma and 1.61

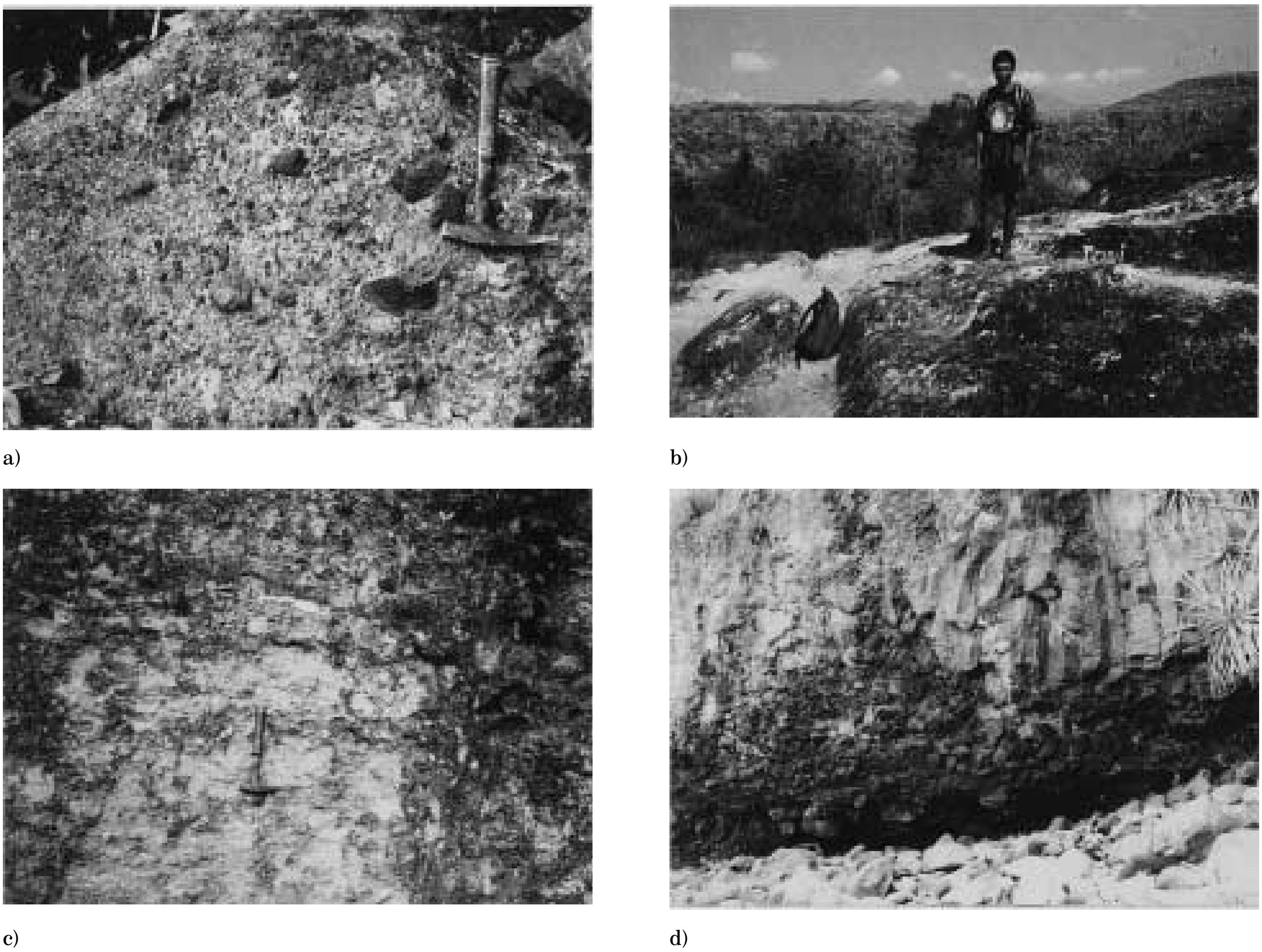


Fig. 11 Photographs of lithology of the Welas Tuff and the Waebela Basalt. a) Outcrop of the typical Welas Tuff in the Aesesa Basin (Loc.20 in Fig. 5). b) Outcrop of the intracaldera Welas Tuff in the Welas caldera (Loc.21 in Fig. 5). c) Outcrop of the green-altered Welas Tuff in a marine environment east of the Mataloko steaming ground (Loc.10 in Fig. 5). d) Outcrop of the hyaloclastite and overlying massive lava with pillow-like rinds of the Waebela Basalt east of Waebela Village (Loc.14 in Fig. 5).

Ma, were obtained. These ages are slightly younger than those of the Welas Tuff.

5.8 Aesesa Formation (Ae)

The Aesesa Formation is newly named in this paper, and the type locality is high altitude areas along the river named Wae Nangawelu at the southeastern rim of the Welas caldera. The Aesesa Formation is lacustrine sediments deposited in the Aesesa Basin. The maximum thickness of the Aesesa Formation may be 100 m. The Aesesa Formation conformably overlies the Welas Tuff and is the contemporaneous heterotopic facies with the Matale Limestone in the north and Waebela Basalt in the south of the study area. This unit consists of thin-laminated siltstone, sandstone, scoria fall deposits and pumice fall deposits (Fig. 12a, Loc.22 in Fig. 5). Frequent intercalation of layers of pyroclastic deposits indicates that the volcanism has actively occurred during the sedimentation of this unit.

The incipient time of deposition of the Aesesa Formation is estimated to 2.5 Ma based on the age of the Welas Tuff. The age at the end of deposition is not evident, but is probably middle Pleistocene because the large-scale uplift of the northern extent of this unit towards the Welas caldera requires a long time to complete the uplift after the end of deposition.

5.9 Matale Limestone (Mt)

The name, Matale Limestone, is newly given in this paper, and the type locality is Matale Village near Wangka Town. Koesoemadinata *et al.* (1994) have already drawn a small distribution of limestone as the Late Miocene-Pliocene Waihekang Formation on their map, but it is very limited and substantial parts of this unit are included into the Miocene Nangapanda Formation on their map. To avoid the complication, a local name is newly given in this paper. This unit and its affinity of terrace limestone are widespread over the Lesser Sunda Islands, particularly in north-facing marine terraces of islands not only in the inner volcanic arc but also in the outer non-volcanic arc such as Sumba Island (Pirazzoli *et al.*, 1993). The Matale Limestone is basically distributed in the Wangka Plateau and its north in the study area. This unit commonly occurs as a thin veneer with its maximum thickness up to 50 m and conformably overlies the Welas Tuff. This relation is well observed near Matale Village (Fig. 12b, Loc.23 in Fig. 5). The Matale Limestone is the contemporaneous heterotopic facies with the Aesesa Formation in the middle and Waebela Basalt in the south of the study area.

The incipient time of deposition of the Matale Limestone is estimated to 2.5 Ma based on the age of the Welas Tuff. The age at the conclusion of deposition is not evident, but is probably the middle Pleistocene because a large-scale uplift of the southern extent of this unit towards the Welas caldera requires a long time to complete the uplift after the conclusion of deposition. Pirazzoli *et al.* (1993) described that those coral reefs on marine terraces around Sumba Island indicate continuous uplifting during the past 2.5 million years. This is well consistent with the chronostratigraphic situation of the Matale Limestone in the present study.

5.10 Mere Basalt (Me)

The name, Mere Basalt, is newly given in this paper, and the type locality is a river named Wae Muu that is the drainage along the southern moat of the Wolo Mere cone. This unit forms several post-caldera cones in the Welas caldera. Physiographically the maximum thickness of the Wolo Mere cone is estimated to be 1000 m. This unit overlies the Welas Tuff. A direct relation to the Aesesa Formation cannot be observed but logically this unit may also be contemporaneous heterotopic facies with the Aesesa Formation. The Wolo Mere cone is physiographically the most prominent, but it is less accessible. We have observed only a part of the Wolo Mere cone. The Wolo Mere cone is composed of basalt lava that characteristically contains abundant plagioclase megacrysts 1 to 2 cm in diameter.

5.11 Sasa Andesite (Ss)

The Sasa Andesite is newly named in this paper, and the type locality is the Wolo Sasa cone immediately north of Mataloko Town. Wolo Sasa on the topographic map "Mataloko" with a scale of 1: 25,000 is actually called Wolo Loge while a nameless cone immediately north of Mataloko town on the map is actually called Wolo Sasa by local residents. We shall follow the local residents usage in this paper. The Sasa Andesite is widely distributed north of the Mataloko area, including three source cones with their summit heights 1264 m (Wolo Sasa), 1019 m (Wolo Loge) and 982 m (unknown name or nameless) from west to east, respectively. Those three cones have some resemblance with those of the Bajawa Cinder Cone Complex such as the Mataloko Andesite, Bobo Andesite and Inie Lika Andesite, but are more dissected (Fig. 5). These cinder cones are reversely magnetized in magnetic polarity by our measurements and older than 0.73 Ma (Mankinen and Dalrymple, 1979). The maximum thickness of this unit is estimated to be 300 m. This unit overlies the Waebela Basalt and Aesesa Formation. Lithology is almost the same as the Mataloko Andesite, Bobo Andesite and Inie Lika Andesite described later.

5.12 Aimere Scoria Flow Deposits (As)

The Aimere Scoria Flow Deposits are newly named in this paper, and the type locality is along the way from Bajawa City to Aimere Town at western outside of the study area. The Aimere Scoria Flow Deposits are widely distributed in the surroundings of the Bajawa Cinder Cone Complex, particularly in the western flank of the north-south trending 10 km cliff. However, a small exposure is found immediately east of the cliff and east of the Bajawa Cinder Cone complex. A relatively wide exposure is also found at the southern coast of the study area. The maximum thickness is estimated to be 300 m. This unit overlies the Aesesa Formation, Waebela Basalt and Sasa Andesite. Two K-Ar ages, both less than 0.15 Ma, were obtained. However, considering the dissected topographic pattern of this unit, occurrence of reversely magnetized lava at the lower member and a large gap between age and those of the Waebela Basalt, the lower part of this unit may be older than 0.15 Ma. Probably this unit has a wide range in age as much as 0.8-0.2 Ma. This unit is mainly composed of scoria tuff but is sometimes intercalated with andesitic lava flows. Each tuff unit is only a few meters in thickness (Fig. 12c, Loc.15 in Fig. 5). Some units contain boulder-size scoria but other units are composed of very fine ash (Fig 12c). This tuff was deposited in a subaerial environment. Scoria is not very porous but is more porous compared to pyroclastic materials of the Bajawa Cinder Cone Complex such as the Mataloko Andesite, Bobo Andesite and Inie Lika Andesite described later. This tuff is mainly composed of essential materials and rare in accidental lithic fragments. This tuff is andesitic and calc-alkaline in composition.

5.13 Siutoro Andesite (Si)

The Siutoro Andesite is newly named in this paper, and the type locality is the Soka Village on the southern coast in the study area. The Siutoro

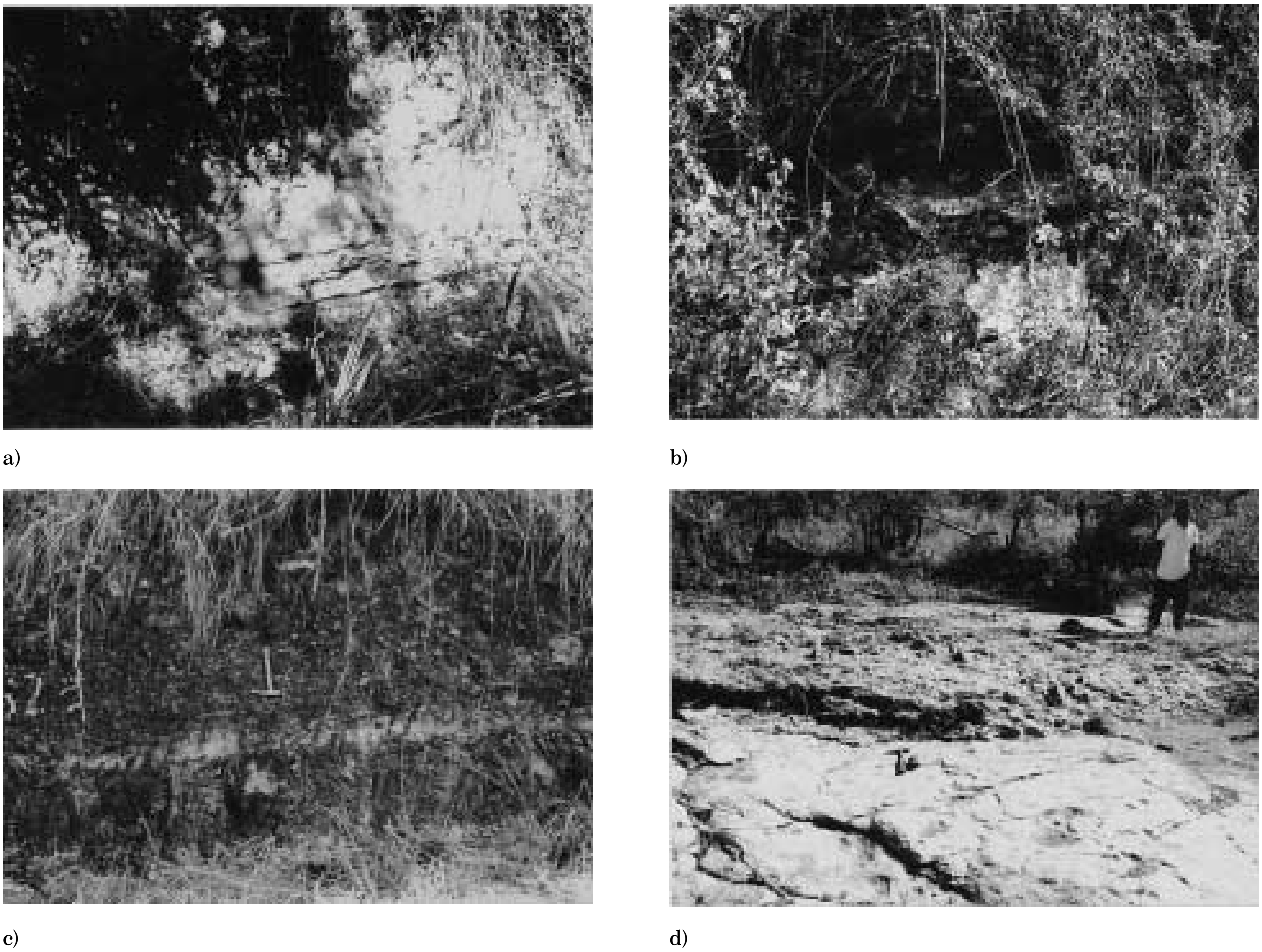


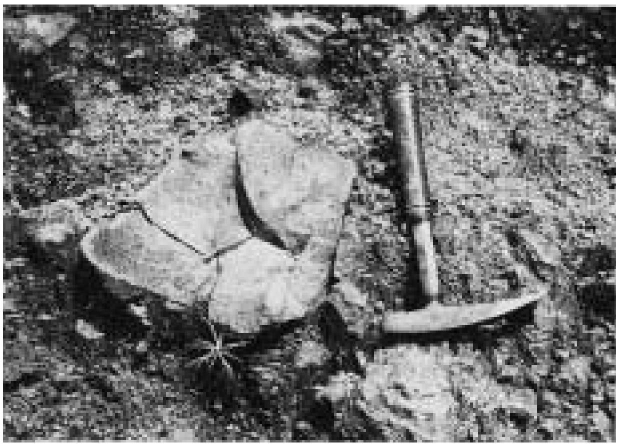
Fig. 12 Photographs of lithology of the Plio-Pleistocene units. a) Outcrop of lacustrine siltstone beds of the Aesesa Formation north of Soa (Loc.22 in Fig. 5). b) Outcrop of the conformity boundary of the Welas Tuff and overlying Matale Limestone near Wangka (Loc.23 in Fig. 5). c) Outcrop of the Aimere Scoria Flow Deposits on the way from Bajawa City to Aimere Town (Loc.15 in Fig. 5). d) Outcrop of the unconformity boundary of the Aesesa Formation and overlying the Lahar Deposits near the Mengeruda hot spring (Loc.24 in Fig. 5).

Andesite forms an early Pleistocene volcano at Wolo Siutoro and Wolo Batulaba. The maximum thickness is estimated to be 400 m. This volcano is relatively dissected but this unit overlies the Aimere Scoria Flow Deposits. In addition, one of the lava flows is normally magnetized in paleomagnetic polarity, probably being younger than 0.73 Ma (Mankinen and Dalrymple, 1979). This unit mainly consists of andesite lava domes and andesite lava flows with minor amounts of pyroclastic materials.

5.14 Lahar Deposits (Lh)

The Lahar Deposits are newly named in this paper, and the type locality is 4 km south of Soa Town. The Lahar Deposits are distributed in places associated with various volcanic edifices such as the Inie Lika and Bobo volcanoes. Their stratigraphic horizons may vary but they are collectively and conventionally treated as one unit in this paper. This unit consists of boulder-size gravel and unsorted fine matrix that were derived from related volcanic edifices. At the lower stream of the Nage steaming ground, the riverbed of Wae Bana is composed of the Lahar Deposits. They are slightly silicified or argillized and hosting a river stream at 48.5 ℃ and ca. 1000 tons per hour. At the Mengeruda hot spring, the riverbed of Wae Bana is composed of the Lahar Deposits. They are slightly silicified or argillized and hosting a river stream at 41.3 ℃ and ca. 1620 tons per hour. A WNW-trending fault is found near the hot spring that may be controlled by this fault as described later. However, at the same time, the Lahar Deposits unconformably overlies the Aesesa Formation near the Mengeruda hot spring where the Aesesa Formation and Lahar Deposits are both silicified (Fig. 12d, Loc.24 in Fig. 5). This suggests that a hydrothermal aquifer is also controlled by a stratigraphic boundary.

a)



b)

c)

Fig. 13 Photographs of lithology of the Bajawa Cinder Cone Complex. a) Outcrop of the Bobo Andesite near the summit of Wolo Bobo (Loc.25 in Fig. 5). b) Enlarged part of the outcrop of a). c) Outcrop of the Mataloko Andesite at a quarry of Wolo Sage (Loc.26 in Fig. 5).

5.15 Mataloko Andesite (Mk)

The Mataloko Andesite is newly named in this paper and the type locality is the quarry at the west flank of the Wolo Sage cinder cone. The Mataloko Andesite forms northwest-southeast alignments of cinder cones. At least 25 summit craters are recognized (Plate 1). They consist of at least parallel two alignments: one is Wolo Lele, Wolo Nawa, Wolo Sage, Wolo Bina and Wolo Bela and the other is Wolo Kapa and several nameless cones in its southeastern extension (Fig. 8b). Wolo Leya and Wolo Belu are situated further east and their alignment is not clear. These cinder cones seem less dissected compared to those of the Sasa Andesite. The maximum thickness of this unit is physiographically estimated to be 500 m. This unit overlies the Sasa Andesite, Aimere Scoria Flow Deposits and most parts of the Lahar Deposits. This unit is conventionally distinguished from the Bobo Andesite and Inie Lika Andesite by the spatial clustering of cinder cones. However, there is no other specific reason to distinguish them and all three units are stratigraphically and geochemically ascribed to a cognate origin. Therefore, in the genetical sense, they are collectively named the Bajawa Cinder Cone Complex.

Lithology is basically not different among the Mataloko Andesite, Bobo Andesite and Inie Lika Andesite so the description on lithology is given here as the Bajawa Cinder Cone Complex. Each cone is mainly composed of ballistic pyroclastic falls with subordinate lava flows. Pyroclastic materials consist of poorly bedded layers that range in thickness from a few tens centimeters to a several meters (Fig. 13a, Loc.25 in Fig. 5). Pyroclastic materials of each layer are poorly sorted by size (Fig. 13b, Loc.25 in Fig. 5), but generally show weak normal grading (Fig. 13a). However, reverse grading is also not rare in highly tilted layers (Fig. 13c, Loc.26 in Fig. 5), probably due to the secondary downslope movement. It is noted that all the fragments are not very porous and seem to be lava breccia rather than scoria. The term "scoria cone" is, therefore, inadequate to represent these cone volcanoes so that we call them cinder cones. Larger fragments are sometimes a few meters in diameter and have chilled rims and radial cracks (Fig. 13b). Smaller fragments are also not very porous and ash finer than 1 mm diameter is not prevalent in the volume ratio. Therefore, qualitatively speaking, these pyroclastic materials can be categorized into Strombolian eruption products in terms of the classification scheme of the fragmentation degree versus dispersal degree by Walker (1973). Lava flows are also important effusive components from these cinder cones. They are easily recognized away from the limit of ballistic distance of cinder cones because the thick pyroclastic materials do not overlie the areas. This unit is andesitic and calc-alkaline in composition.

5.16 Bobo Andesite (Bb)

The Bobo Andesite is newly named in this paper, and the type locality is the roadside cutting the east flank near the summit of the Wolo Bobo cinder cone (Fig. 13a; Loc.25 in Fig. 5). The Bobo Andesite forms a north-south alignment of cinder cones in the Wolo Bobo cone and several nameless cinder cones in its southern extension. At least 10 summit craters are recognized (Plate 1). Those cinder cones seem less dissected compared to those of the Sasa Andesite. The maximum thickness of this unit is physiographically estimated to be 600 m. This unit overlies the Sasa Andesite, Aimere Scoria Flow Deposits and most parts of the Lahar Deposits. This unit is conventionally distinguished from the Mataloko Andesite and Inie Lika Andesite by the spatial clustering of cinder cones. However, there is no other specific reason to distinguish them and all three units are stratigraphically and geochemically ascribed to a cognate origin. Therefore, in the genetical sense, they are collectively named the Bajawa Cinder Cone Complex.

Lithology is basically not different among the Mataloko Andesite, Bobo Andesite and Inie Lika Andesite so the description on lithology is given in the section of the Mataloko Andesite as the Bajawa Cinder Cone Complex.

5.17 Inie Lika Andesite (Ik)

Neumann van Padang (1951) described the Inie Lika volcano as an active volcano and recorded a phreatic eruption in 1905. Recently, another phreatomagmatic eruption occurred during January 11-16, 2001 (Muraoka *et al.*, 2002b). The Inie Lika Andesite is named in this paper after Neumann van Padang (1951). The Inie Lika Andesite forms a north-south alignment of cinder cones at the Inie Lika volcano area. At least 25 summit craters are recognized (Plate 1). These cinder cones seem less dissected compared to those of the Sasa Andesite. The maximum thickness of this unit is physiographically estimated to be 600 m. This unit overlies the Sasa Andesite, Aimere Scoria Flow Deposits and most parts of the Lahar Deposits. This unit is conventionally distinguished from the Mataloko Andesite and Bobo Andesite by the spatial clustering of cinder cones. However, there is no other specific reason to distinguish them and all three units are stratigraphically and geochemically ascribed to a cognate origin. Therefore, in the genetical sense, they are collectively named the Bajawa Cinder Cone Complex. Neumann van Padang (1951) described the Inie Lika volcano as a stratovolcano, however, based on the recognition of the Bajawa Cinder Cone Complex, the Inie Lika volcano is considered to be a cinder cone complex with a small spacing of each cinder cone.

Lithology is basically not different among the Mataloko Andesite, Bobo Andesite and Inie Lika Andesite so the description on lithology is given in the section of the Mataloko Andesite as the Bajawa Cinder Cone Complex.

5.18 Inerie Basalt (Ie)

Neumann van Padang (1951) described Ineri volcano as an active volcano and recorded that a column of smoke sometimes occurred in the summit crater such as in June 1911. However, the name "Ineri" is not currently used. The Inerie Basalt is newly named in this paper, and the type locality is along the coastal road from Aimere to Waebela. The Inerie Basalt forms the volcanic edifice of the Inerie stratovolcano. The maximum thickness of this unit is physiographically estimated to be 1500 m. The entire stratigraphic relation of this unit to the Bobo Andesite is not clear. Wood (1980) showed that 50 per cent of the cinder cones were formed during eruptions that lasted less than 30 days and 95 per cent of them had eruptions that lasted less than one year. On the other hand, a stratovolcano like Inerie has a life span of tens or hundreds of thousands of years. Considering this point, probably the upper part of the Inerie Basalt is intercalated with the Bobo Andesite. However, the life span of the Inerie volcano will continue. Therefore, this paper conventionally treats the Inerie Basalt as stratigraphically younger than Bobo Andesite. This unit is basaltic and tholeiitic in composition and composed of lava flows, pyroclastic flows, scoria fall deposits and lahar deposits.

5.19 Alluvium (Qa)

Alluvium is distributed at the northern coast, southern coast, Mataloko and west of Welas caldera. This unit is composed of mud, sand and gravel.

6. Structure

As seen in the A-B (north-south) cross section in Plate 1, the north-south transection of Flores Island in the study area displays the presence of two broad anticlines corresponding to the two volcanic terrains in the north-central and southern coastal areas. This indicates that the element of the Lesser Sunda islands' en echelon structure is actually composed of two factors: the anticline of volcanic basement units and overlying clustered volcanoes. If the Aesesa Formation and Matale Limestone are assumed to have been deposited as horizontal strata, they have been involved in the folding movements, indicating that the uplift of anticline axes was continued during the past 2.5 million years.

Figure 14 summarizes the structural elements observed in the field survey. There are not enough observed points, but most of observed fractures are almost vertical and north-south trending shear fractures in the study area as shown in Figs. 10d (Loc.8 in Fig. 5) and 15a (Loc.27 in Fig. 5). It is consistent with the review of tectonics described above. Trends of fractures are close to the north-south direction but have the NNW-SSE preferred direction in a strict sense. Folding axes are also consistent with this observation. If cinder cone alignments are considered as an indicator of subsurface dike swarms as schematically illustrated in the C-D and E-F cross sections on Plate 1, their trends also represent the NNW-SSE preferred direction. In addition, their NNW-SSE trends are composed of the patterns of en echelon-shaped alignments that confirm the left-lateral shear as described above. The maximum horizontal compressive stress axis in the study area is thus estimated to be the NNW-SSE direction at present as well as during the past 2.5 million years. A 300 m long fissure that appeared at the 2001 eruption has the direction of N16°W (Muraoka *et al.*, 2002b), and this direction may be adopted as a representative maximum horizontal compressive stress axis in the study area.

However, an important exception is a pair of numerous WNW-ESE and ENE-WSW trending lineaments as seen in Fig. 6. One lineament is actually observed as a fault on an outcrop near the Mengeruda hot spring as shown in Fig. 15b (Loc.28 in Fig. 5). The dip is almost vertical (86°N) and strike is N70°W. The fault bounds the Lahar Deposits to the north and Aesesa Formation to the south so that the northern block is down thrown 5 m or more in vertical separation. This fault is apparently a reverse fault in the displacement sense, but is probably a strike-slip type fault with a larger lateral separation. A pair of WNW-ESE and ENE-WSW trending lineaments is also recognized on the JERS-1 OPS (optical sensor) imagery (Fig. 16). Although the quality of the imagery is not good due to the weather condition, numerous WNW-ESE and ENE-WSW trending lineaments are well recognized and seem a conjugate set of strike-slip faults where the angle of shear are relatively small at the surface.

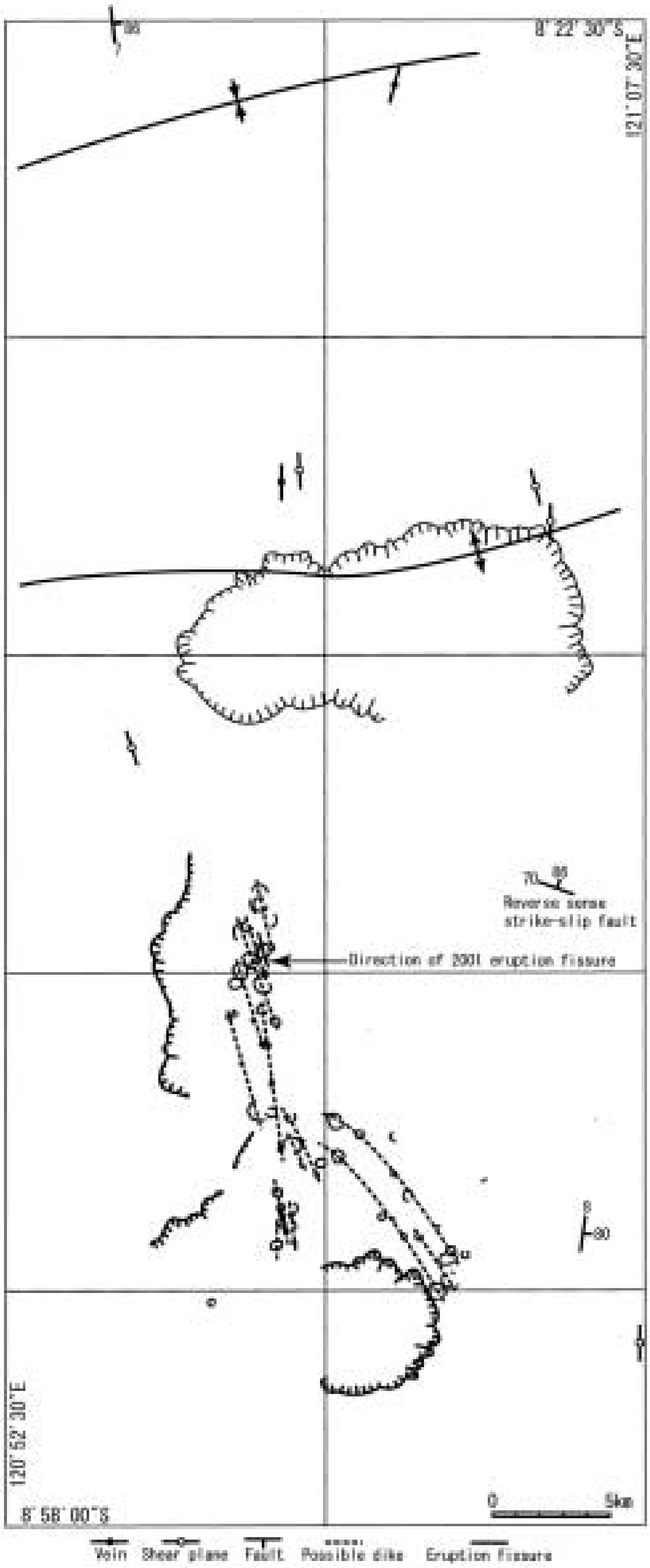
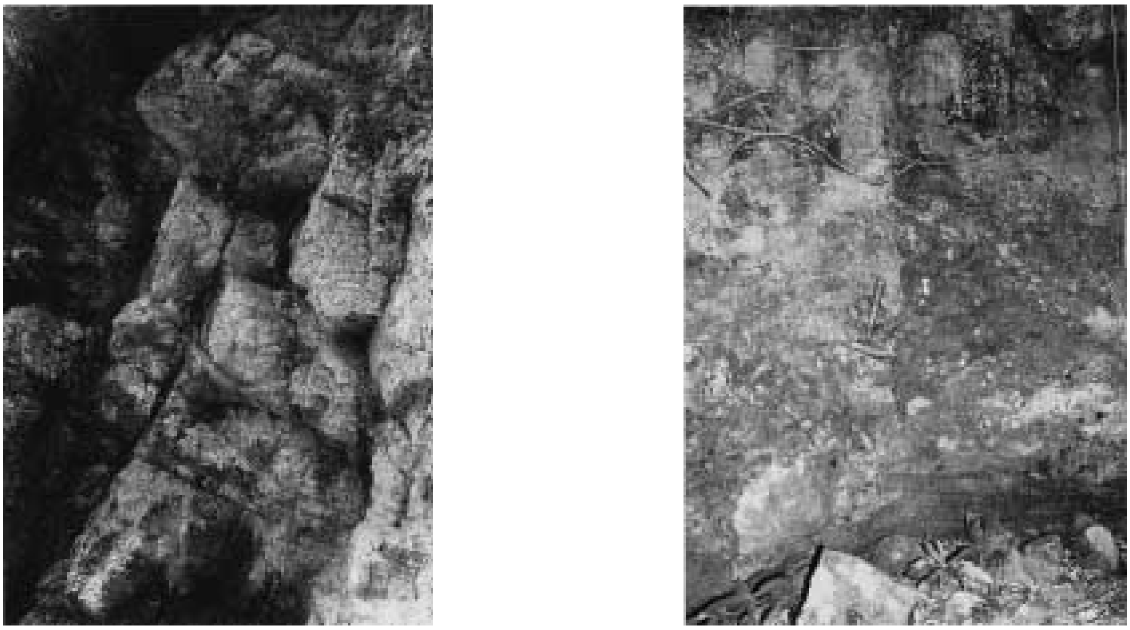


Fig. 14 Structural elements observed in the study area.



a) b)

Fig. 15 Photographs of fractures in the study area. a) 3 cm thick chalcedony vein (N-S, 72°W) in the Wangka Andesite on the Wangka Plateau (Loc.27 in Fig. 5). b) Strike-slip fault (N70°W, 86°N) bounding the Lahar Deposits to the north (left) and Aesesa Formation to the south (right) near the Mengeruda hot spring (Loc.28 in Fig. 5).

Fig. 16 Enlarged JERS-1 OPS (optical sensor) imagery of the Aesesa Basin acquired on July 9, 1998 on the west and October 13, 1994 on the east (Urai *et al.*, 1998, 1999, 2002; Copyright METI/NASDA) with numerous strike-slip faults (arrows).

These faults indicate the E-W contraction tectonics that are incompatible with the N-S contraction tectonics represented by major N-S trending shear fractures described above. However, a clue to this incompatibility may be that the spatial distribution of the pair of WNW-ESE and ENE-WSW trending strike-slip type faults are confined to the vicinity of the Bajawa rift zone. They are considered as a local and surface compressive stress regime compensating the appearance of the Bajawa rift zone as discussed later.

7. Geothermal Manifestations

Atmospheric temperature often exceeds 30 ℃ in the study area. Therefore, only the hot springs higher than 40 ℃ are reliable geothermal manifestations in the study area and displayed on the Plate 1. It is clear that they are closely associated with the Bajawa Cinder Cone Complex. Even if the Inerie volcano is young in the age, empirically and theoretically, tholeiitic stratovolcano seldom bears any geothermal manifestations, probably due to its magma chambers being too deep (Muraoka, 1997). Therefore, it can be said the Bajawa Cinder Cone Complex is only a prospective geothermal heat source in the study area. The distribution of geothermal manifestations supports this idea.

We shall describe the main geothermal manifestations. There are many hot springs in the study area, but prospective geothermal areas may be four areas, Mataloko, Nage, Wolo Bobo and Mengeruda. Here we describe the geological settings of the four areas.

The Mataloko area is situated at the southern foot of a small cinder cone called Wolo Belu. Steaming ground is about 150 m in diameter, but an acid alteration zone, 300 m by 1000 m, extends along the rivers named Wae Belli and Wae Luja. Figure 17a (Loc.29 in Fig.5) shows a fossil fumarole found at the lowermost margin of the alteration zone that is 700 m away from the steaming ground. One of the candidates for heat source volcanoes is the Wolo Belu volcano. However, a northwest-southeast alignment of cone volcanoes including Wolo Lele, Wolo Nawa, Wolo Sage, Wolo Bina and Wolo Bela may be more promising in terms of the volume of the magma chamber. Fault control on the discharge of the Mataloko steaming ground is highly probable, and some papers of this special volume may emphasize the presence of the Wae Luja Fault, but the river Wae Luja is apparently interpreted as a boundary of lava flows (Plate 1).

The Nage area is situated at the bottom of the Nage caldera. The steaming ground, 200 m by 500 m, is elongated along a river named Wae Bana (Fig. 17b, Loc.30 in Fig. 5). The alteration zone of 2 km diameter reaches the surrounding wall of the Nage caldera. Alteration zone covers the Nio Village, 650 m high and Bea Village, 900 m high in altitude. The heat source volcano is ascribed to the Bobo volcano. The caldera type of the Nage caldera is not clear, but it is noted that Nage caldera is characterized by a high gravity anomaly (Komazawa *et al.*, 2002), even if the caldera floor as subsided by more than 300 m. When we think the combination of the Bajawa rift zone and high gravity anomaly of Nage caldera, one possibility is the Kilauea-type pit caldera collapsed at the southern end of the crest of the N-S elongated volcano, which is composed of the Aimere Scoria Flow Deposits.

The Bobo area is situated at the western flank of one of the Bobo cinder cones. The steaming ground is only 100 m in diameter and some sort of volcanic fumarole (Fig. 17c, Loc.31 in Fig. 5). The alteration zone is only 300 m in diameter and forms a spoon-shaped landslide open to the western foot. The steaming ground is situated at 1400 m in altitude on the steep flank of a cinder cone and not realistic for a geothermal power plant to be developed there. However, it is noted that the heat source is clearly the Bobo volcano.

There is no steaming ground in the Mengeruda area but it is noticed for its high discharge rate capacity of 1620 tons per hour of hot spring water of 48.5 ℃. Figure 17d (Loc.32 in Fig. 5) shows the outflow of voluminous hot spring waters to a river. The alteration zone is 800 m in diameter. However, silicified alteration zones are also sporadically found to the east along WNW-ESE trending faults (Plate 1 and Fig. 15b). The heat source may be the Inie Lika volcano. Figure 15b shows exposure of a fault near Mengeruda at Loc. 28. The fault bounds the Lahar Deposits to the north and Aesesa Formation to the south, so that the northern block is down thrown more than 5 m in vertical separation. The dip is almost vertical and strike is N70°W. This is important to understand the discharge of the Mengeruda hot spring as well as the elongation of the alteration zones. Many similar faults are also recognized on the JERS-1 SAR and OPS images (Figs. 6 and 16). Their dominant trends are WNW-ESE and ENE-WSW. The fault that may control the Mengeruda hot spring discharge is thus found in the field so that this area is clearly understood as on under the fault control. However, as described above, the Mengeruda hot spring is also close to the stratigraphic boundary between the Aesesa Formation and Lahar Deposits. A hydrothermal aquifer is likely derived from the WNW-trending fault but is mainly derived from the fault trace within the Aesesa Formation and Lahar Deposits tend to play a role of cap rocks even in the part that was cut by the fault.

a)

b)

c)

d)

Fig. 17 Photographs of geothermal manifestations in the study area. a) Fossil fumarole at the eastern margin of the Mataloko steaming ground (Loc.29). b) Nage steaming ground (Loc.30 in Fig. 5). c) Bobo steaming ground (Loc.31 in Fig. 5). d) Mengeruda hot spring (Loc.32 in Fig. 5).

8. Discussion and Conclusions

8.1 Tectonic evolution

Generally, the subduction of the Australia continent might not be a necessary key to the Pliocene volcanism in the study area because the subduction of oceanic plates can cause island arc volcanism. However, the widespread Pliocene volcanism is distinctive from the Miocene volcanism by such points as the relatively long time hiatus from the middle Miocene (ca. 16.2−10.2 Ma) Nangapanda Formation to the Wangka Andesite (ca. 4−3 Ma), appearance of subaerial environment due to uplifting, appearance of part of the calc-alkaline rock series and voluminous products for arc crust building scale. The Pliocene volcanism temporally occurred in close relation to the tectonic regime of the possible bending of the Banda arc that was clearly subject to the collision of the New Guinea and Australia continents. Therefore, the incipient time of the underplating of the Australia continent along the Timor Trough is evaluated by the ages of the Wangka Andesite and Maumbawa Basalt that are 4 to 3 Ma. If the subduction of the Australia continent was a trigger to the Pliocene volcanism, approximately 300 km of the plate leading edge must have already underplated from the Timor Trough to the 90 or 100 km depth of the Wadati-Benioff zone beneath the volcanic front until 4 Ma. Extrapolating the present velocity 75 mm/year of the Australia continent to the past, it takes about 4 million years to consume 300 km of the plate. As a result, it is estimated that the Australia continent started to enter the Timor Trough in the Flores sector 8 million years ago. This estimate of 8 Ma is quite different from commonly adopted age of 3 Ma for the event (Hamilton, 1979; Bowin *et al.*, 1980; Nishimura and Suparka, 1997). This estimate is, however, consistent with 7.6 Ma, possibly an incipient time of the bending of the Banda arc induced by the paleomagnetic study (Haile, 1979; Beckinsale and Nakapadungrat, 1979).

Appearance of the Bajawa rift zone is a remarkable event that requires consideration on the specific tectonic settings in the study area. Figure 18a shows a simplified and schematic model of the tectonic regime of the Lesser Sunda-Banda arc that is shaded in the figure. Although further chronological and paleomagnetic studies are required, the unusual curvature of the Banda arc might have been formed by the lateral bending since 8 Ma. Current GPS data show that the bending is still ongoing (Fig. 3) because the driving force of the bending is explained even by the present-day plate motions: the north moving Indian-Australian Plate in the south and northwest moving Pacific Plate in the north respective to the coherent Sundaland and its eastern accretions as a fixed reference. As a result, the Flores to Alor sector of the Lesser Sunda Islands is subject to a north-south trending left-lateral shear stress where its eastern tip is moving north with the Australian accretions and its western tip is fixed to the Sundaland (Fig. 18a). It is not clear whether this shear stress is homogeneously distributed or heterogeneously concentrated to narrow zones. As described above, the Flores to Alor sector of the Lesser Sunda Islands is characterized by en echelon-shaped volcanic islands. The pattern of the en echelon array has an opposite polarity to the NNE-trending oblique subduction and is only explained by the presence of the left-lateral shear stress or counterclockwise moment. This suggests a broad distribution of the shear stress in the sector. The Bajawa rift zone might have, however, been formed as one of the shear stress liberation zones. Gravity data (Komazawa *et al.*, 2002) show that the cinder cone alignments themselves coincide with a high gravity anomaly crest indicating a subsurface and vertically-extending dike complex. But immediately east of the crest, there exists a low gravity anomaly with a steep gradient zone indicating that a vertical displacement occurred along the dike complex. Probably a left-lateral displacement might have occurred too. One of the possibilities to localize the Bajawa rift zone to the present position may be that the Bajawa area is a southern extension of the left-lateral and large-scale Walanae Fault in the southern Sulawesi Island (Fig. 2).

Volcanic vent alignments, eruptive fissures and elongation of volcanic edifices are usually known to be parallel with the trajectory of the motion of the plate on which they are situated, which is the orientation of the horizontal maximum principal stress (Nakamura *et al.*, 1977). However, there is a considerable discrepancy between the direction of the plate motion and alignments of cinder cones in the study area. The motion of the Indian-Australian Plate is in NNE-trends, while the preferred directions of cinder cone alignments are in NNW-trends. This is also ascribed to the counterclockwise moment due to the left-lateral shear stress with the same polarity as the en echelon pattern. Directions of shear fractures and folding axes in the study area also confirm the NNW-trending maximum horizontal compressive stress axis that is different from the direction of the Indian-Australian Plate's motion.

Another factor we should consider is the effect of the tight lateral bending of the Banda arc. Figure 18b shows a schematic illustration on the effect of the tight bending. Contraction and extension fields will appear in the tight bending. When we assume the bending of not only the island arc but also the back-arc marginal sea, the island arc may be considered as an outer extension field. This effect prefers the across-arc fracturing. We cannot evaluate this effect to the directions of fractures in the study area. However, another point on fracturing by this effect is it should prefer that the fracturing will propagate from the outer arc to the inner arc, and the outer arc has wider rooms for space fillers such

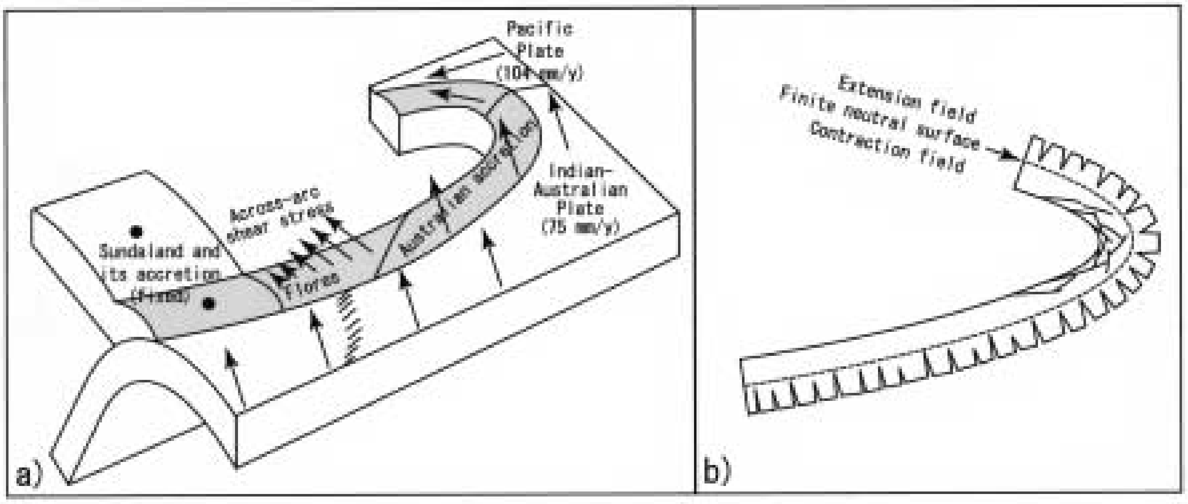


Fig. 18 Schematic model of the tectonic regime of the Lesser Sunda-Banda arc. a) Schematic model of the derivation of the shear stress in the Flores sector. b) Schematic model of the effect of lateral bending in the Banda arc.

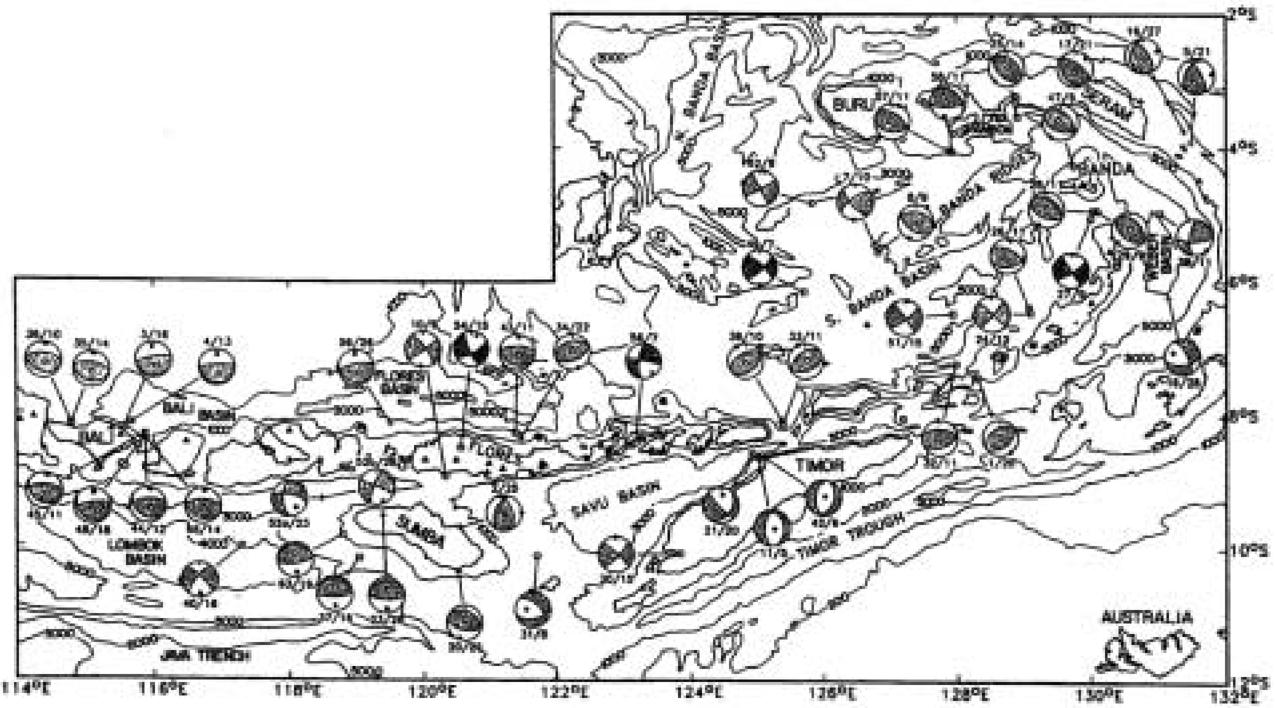


Fig. 19 Fault plane solutions for shallow earthquakes (McCaffrey, 1988). Labels beside focal spheres indicate the event number and depth in kilometers. Compressional quadrants of the lower hemisphere projection are stippled, and the dots and circles represent the P and T axes respectively.

as fractures, intrusions and volcanoes. The Bajawa rift zone has exactly these features. Southern cones of the Bajawa Cinder Cone Complex have no historic eruption records, while the northern part of the Inie Lika volcano has historic eruption records in 1905 and 2001. Therefore, there is a possibility that the activity propagated from south to north along the rift zone. In addition, the Bajawa rift zone and Bajawa Cinder Cone Complex are wider to the south and narrower to the north.

Discussions described above are well consistent with the focal mechanism of 63 earthquakes in the Lesser Sunda-Banda arcs by McCaffrey (1988) as shown in Fig. 19. Most dominant events are thrustic fault type, but strike-slip fault type is concentrated in the Banda-Weber Basins and Sumbawa-Alor sector. The latter area almost coincides with the en echelon volcanic island sector in this paper. This seems to reflect the north-south shear stress because the strike-slip type faults are more efficient in liberating the north-south shear stress than the thrustic faults. Shallow earthquakes in the Sumbawa-Alor sector's upper plate are six strike-slip (10, 30, 40, 52, 54 and 56 in Fig. 19) and four normal fault types (11, 21, 31 and 42 in Fig. 19). All four normal fault types are situated in outer than the volcanic front. The maximum compressive stresses of the six strike-slip fault types and intermediate compressive stresses of the four normal fault types indicate that the NNW trends are consistent with the results of this paper.

8.2 Volcano-stratigraphic evolution

Whether neritic or pelagic, the Nangapanda Formation was deposited in a marine environment during the Middle Miocene (ca.16.2−10.2 Ma). After relatively a long time hiatus, volcanism of the Wangka Andesite and Maumbawa Basalt widely occurred in a subaerial environment during 4−3 Ma. Probably, Lesser Sunda Islands might have first appeared above sea level at this stage because subaerial Miocene strata have seldom been reported from this region. Afterward, a small marine transgression occurred. This marine transgression was smaller than that of the Miocene but was the largest since the Pliocene. At 2.5 Ma in the peak stage of the marine transgression, the Welas caldera collapsed and produced the voluminous Welas Tuff.

Figure 20 shows eustatic changes of sea levels during the Tertiary (Vail and Hardenbol, 1979). Estimate of eustatic changes of sea levels in geologic time is still progressing. If the marine transgression peak at 4 Ma illustrated on Fig. 20 could be modified to 3 Ma, this figure is well consistent with the paleogeographic history from the Middle Miocene to Pliocene in the study area. The marine transgression at 2.5 Ma has also been reported from northeast Japan (Muraoka and Takakura, 1988; Muraoka and Hase, 1990), and their synchronization is ascribed to the global sea level change rather

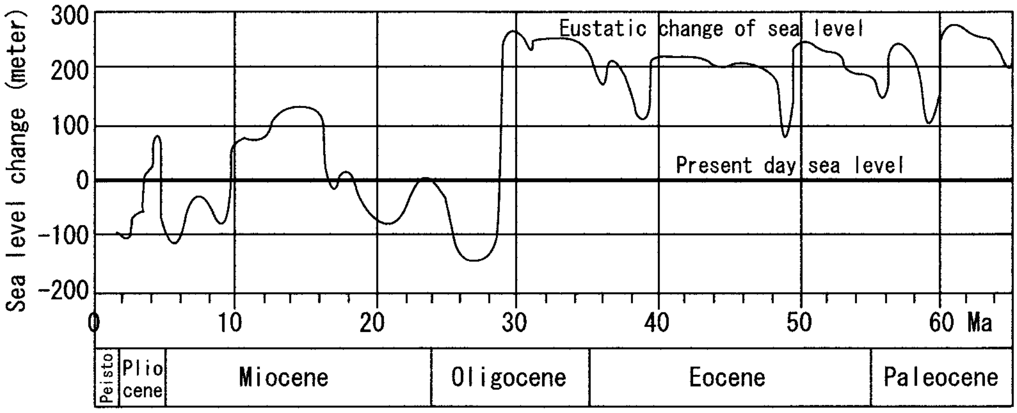


Fig. 20 Eustatic change of sea levels since the Tertiary (Vail and Hardenbol, 1979).

than local tectonics. Some researchers have insisted that an extreme sea level lowstand of −80 m may have occurred at 2.5−2.3 Ma (Raymo *et al.*, 1989), and there still remains a possibility that a peak of the high sea level occurred at 2.5 Ma.

The Welas Tuff was deposited in a marine environment south of the present Bobo-Mataloko ridge and north of the northern rim of the Welas caldera, as speculated from the Fig. 21. The tuff was also deposited in a lacustrine environment called the Aesesa Basin between the two ridges (Figs. 21b and 21c). Successively after the Welas Tuff, three units, the Waebela Basalt, Aesesa Formation and Matale Limestone, were deposited in a marine environment south of the Bobo-Mataloko ridge, lacustrine environment at the Aesesa Basin and marine environment north of the northern rim of Welas caldera, respectively. These three units are the contemporaneous heterotopic facies in a broad sense.

Figures 21a, 21b and 21c show the shaded relief digital topographic maps in order to evaluate paleogeographic conditions at 2.5 Ma assuming the

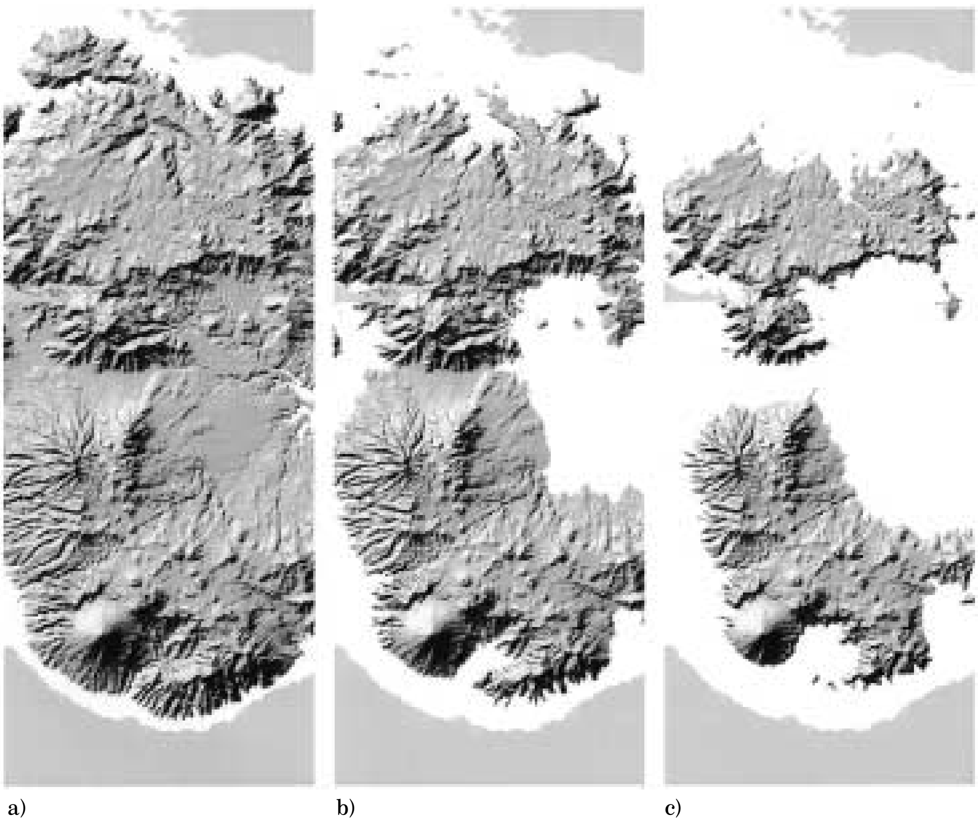


Fig. 21 Paleogeographic conditions of the Bajawa geothermal field at the marine transgression stage inferred from the shaded relief digital topographic map. a) Assumed shoreline to be 250 m above sea level. b) Assumed shoreline to be 500 m above sea level. c) Assumed shoreline to be 750 m above sea level.

shoreline to be +250 m, +500 m and +750 m. The units younger than the Mere Basalt were not yet present at that time. Presently the highest distribution of the Matale Limestone is 900 m and hyaloclastite of the Waebela Basalt is 900 m above sea level. It is easily found that their present levels are very difficult to be explained solely by the sea level change. Considerable parts of the uplift was ascribed to a tectonic process such as the anticline forming activity. Of course, their inland distribution of the marine deposits clearly indicates that the marine transgression more or less occurred. Eustatic change of sea level can, however, explain only a hundred meters of sea level rise at the maximum since the Miocene (Fig. 20). In other words, the Matale Limestone and the Waebela Basalt at 900 m above sea level suggest that, if 100 m of sea level rise is assumed, 800 m uplift was derived from the anticline-forming tectonics near the anticline axes. This means that the average uplifting rate is 0.32 mm/year during the past 2.5 million years.

8.3 Evolution of the Bajawa rift zone

The appearance of the Bajawa rift zone is due to the special tectonic regime of the study area as discussed above. We shall here discuss the evolving process of the Bajawa rift zone. Figure 22 shows a schematic model of the Bajawa Cinder Cone Complex and its subsurface radial dike complex, modified from Muraoka *et al.* (2000c). At the time of Muraoka *et al.* (2000c), we have emphasized a radial dike complex inferred from the surface alignments of the cinder cones. We still believe that the configuration of the subsurface dikes may not be actually very different from this figure. However, genetically speaking, the radial dike complex requires a central volcano and central source of magmatic local stress. At the center of the radial dikes in the study area, we do not any large central volcano so that our present genetical idea has been shifted to a concept of a rift zone. Walker (1999) made statements on volcanic rift zones as follows: the rifts in volcanic settings are dilational ground cracks. Those that emit lava are eruptive fissures: the sites of fissure eruptions. Groups of fissures combine to delineate rift zones. Dikes or other sheet-like intrusions are the subsurface equivalents of eruptive fissures. Swarms of these minor intrusions may contain tens to hundreds of members. This statement well describes the zone of the Bajawa Cinder Cone Complex.

Figures 23a and 23b show a schematic model on the evolving process of magma in the Bajawa rift zone. Figure 23a speculates the magma source region to supply the volcanic products in the Bajawa rift zone. Thickness of the continental crust of Flores Island is estimated to be 5 km (Curray *et al.*, 1977). If we assume the thickness of the underlying oceanic crust to be 7 km from the earth's average, the Moho discontinuity is estimated only at a depth of 12 km. It seems difficult to generate calc-alkaline andesite magma related to the Bajawa rift zone from mantle peridotite so that the magma source region is ascribed to the bottom of the oceanic crust. Geochemical data of volcanic rocks from the Bajawa rift zone are consistent with this idea (Muraoka *et al.*, 2002a). Probably, abundant tholeiitic magma supplied from the rift zone in the upper mantle has been accumulating at the bottom of the oceanic crust, and it might have caused the partial

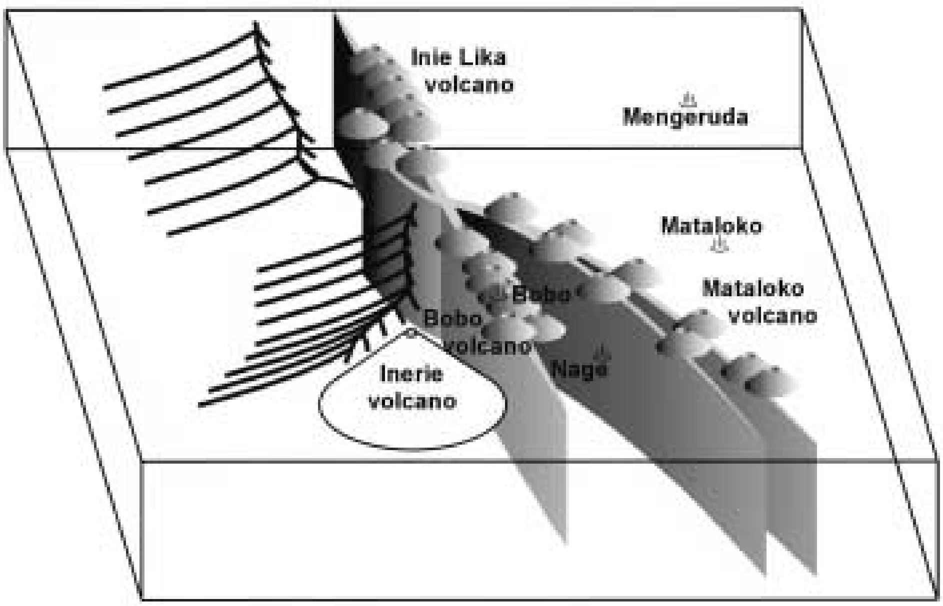


Fig. 22 Schematic model of the Bajawa Cinder Cone Complex and its subsurface radial dikes (modified from Muraoka *et al.*, 2000).

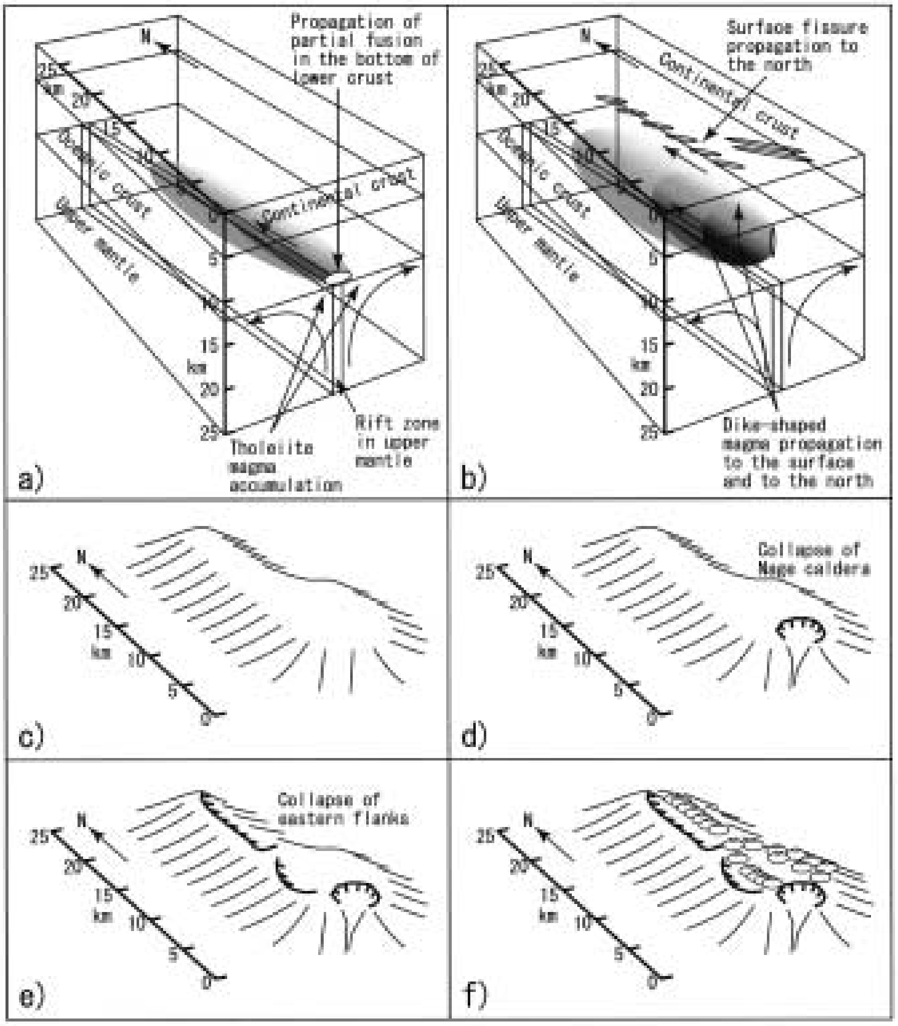


Fig. 23 Schematic model of the evolving process of the Bajawa rift zone. a) A model of the magma source region. b) A model of the dike propagation and surface fissures. c) Stage of elongated volcano. d) Stage of collapse of Nage caldera. e) Stage of collapse. f) Present stage.

fusion of the oceanic crust to form a calc-alkaline magma pocket. This event might have occurred from the south to north with time as described above. Figure 23b shows the shallower and contemporaneous events to Fig. 23a. Dikes of calc-alkaline andesitic magma might have risen from the magma pocket, and they might have also propagated from the south to north with time. This has formed fissures at the surface from the south to north. These fissures are probably en echelon-shaped because of the left-lateral shear stress of the rift zone.

Figures 23c, 23d, 23e and 23f show the evolving process of the surface events in the Bajawa rift zone. As shown in Fig. 23c, the first event was the appearance of the elongated volcano. In many rift zones, numerous dike intrusions are known to form the elongated volcanic edifices by elastic deformation and volcanic ejecta deposits as represented by the Ko'olau volcano, Hawaii (Annen *et al.*, 2001). Wide flanks formed by the Aimere Scoria Flow Deposits indicate the presence of such a NNW-SSE elongated volcano in this area. The ages of the Aimere Scoria Flow Deposits are not yet determined, but some lava is reversely magnetized and their ages have probably a wide range roughly from 0.8 Ma to 0.2 Ma. In addition, the Aimere Scoria Flow Deposits are composed of numerous thin tuff layers, not like caldera-forming tuffs. All these facts suggest that there was a long-standing volcano in the Bajawa rift zone. Figure 23d shows the next event, the collapse of the Nage caldera. The type of this caldera is not clear, but it is characterized by a high gravity anomaly, and therefore, the Kilauea-type pit caldera is possibly related to the rift zone. Figure 23e shows the collapse of eastern flanks of the elongated volcano. Topographic features of this event are still preserved such as the north-south trending 10 km wall. This event might have occurred due to the apical tension associated with elastic doming of the elongated volcano by the frequent dike invasion to shallow depths (Annen *et al.*, 2001). Figure 23f shows the final stage that was the eruption of the Bajawa Cinder Cone Complex. This process may still be ongoing as seen by the 2001 eruption (Muraoka *et al.*, 2002b). Probably, each cone formation corresponds to each dike intrusion (Wood, 1980). Subsurface dikes shown in Fig. 22 may be composed of numerous dikes in a strict sense where a left-lateral pattern of en echelon array may be common in the direction of dikes.

A conjugate set of strike-slip type fault that is widely developed east of the Inie Lika volcano (Fig. 16) suggests E-W contraction tectonics. This is a paradoxical to regional tectonics in the study area that is under NNW-SSE contraction tectonics as described above. Those strike-slip type faults are particularly dominant east of the Inie Lika volcano and ascribed to the local contraction tectonics caused by the numerous dike intrusions in the Bajawa rift zone. Evidence for this is given by the satellite imagery (Fig. 6), that is, the ENE trending faults tend to show the southern block down thrown and WNW trending faults tend to show the northern block down thrown. This means that the maximum compressive stress axis of those strike-slip faults slightly plunges to the west, indicating the subsurface dike complex in the west as a stress source. High gravity anomalies along the cinder cone alignments (Komazawa *et al.*, 2002) also strongly support the presence of the subsurface dike complex as a vertically-extending high-density body.

8.4 Evaluation of geothermal systems

The Bajawa Cinder Cone Complex such as the Mataloko Andesite, Bobo Andesite and Inie Lika Andesite are relatively young, and relatively silicic and calc-alkaline in composition. All of them are geochemically very homogeneous (Muraoka *et al.*, 2002a). This fact strongly suggests that they share the same rift zone magma system. Their spatial alignments support the presence of a shallow-depth and dike-shaped magma complex. Calc-alkaline magma is known to be important for geothermal heat sources in a continental crust region even in a thinner crust because the buoyancy of the calc-alkaline magma tends to form shallow intrusions compared to tholeiitic magma (Muraoka, 1997). Actually, the Inerie volcano is a typically tholeiitic stratovolcano and very young, but the geothermal activity is rarely associated with this volcano except for the summit fumarole. Therefore, the dike complex of the Bajawa Cinder Cone Complex could be the most important heat sources in the study area. All the steaming grounds and high temperature hot springs are, in fact, observed in close association to the cinder cone complex.

A conjugate set of strike-slip type fault that is widely developed east of the Inie Lika volcano (Fig. 16) may be important as a pathway for a hydrothermal aquifer. However, at this moment, only one fault was identified in the field near the Mengeruda hot spring (Fig. 15b). In Mengeruda, it is important that the site of the hot spring discharge is spatially close not only to the fault, but also to the stratigraphical boundary between the Aesesa Formation and overlying Lahar Deposits. It is suspected that hot aquifer laterally flowed from the Inie Lika volcano through the relatively deeper part in or beneath the lacustrine sediments along the fault. Where the Lahar Deposits are thick, the hot aquifer discharge is capped by the unit. Therefore, the only site to discharge was the marginal area where the Lahar Deposits are thinning out. This process can explain the discharge of the Mengeruda hot spring.

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インドネシア，フローレス島中部，バジャワ地熱地域のテクトニクス，火山および層序に関する地質学的研究

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要　旨

遠隔離島小規模地熱の探査に関する研究協力（ESSEI プロジェクト）の一環として，インドネシア，フローレス島中部のバジャワ地熱地域とその周辺地域において，1998 年以来，広域地質の研究が実施されてきた．この地域では 4 Ma 以降，中央部と南海岸部において火山活動が起こった．この両地域はフローレス島からアロール島にかけて特徴的なエシェロン状火山島構造の要素を構成している．これら両地域では，過去 250 万年の間に，約 800 m の隆起が起こった．中央部においては約 2.5 Ma にウェラスカルデラが形成され，その後カルデラ火山活動の後は，ほとんど，火山活動が終息している．南海岸部では，4 Ma 以降，現在に至るまで，火山活動が続いている．とくに顕著な出来事はバジャワリフトゾーンの出現であり，これは東側の北進するオーストラリア付加体ブロックと西側の相対的に静止したスンダランドブロックとの間に生じた南北方向の左横ずれ剪断応力に関係づけられる．バジャワリフトゾーンはおそらく 0.8－0.2 Ma 頃の，NNW-SSE 方向に伸びた火山体の形成によって始まった．次いで，この稜線付近より，東側の火山体の崩落が起こった．その後，この崩落域はバジャワシンダーコーン群を生成し，これは NNW-SSE 方向のリフトゾーンに沿って 20 km にわたって配列する 60 個以上のシンダーコーンから成る．調査地域の大部分の火山岩類は玄武岩質，ソレイアイト岩系であるが，このバジャワリフトゾーンの噴出岩は南北に伸びた火山体とバジャワシンダーコーン群とを含めて，安山岩質，カルクアルカリ岩系であり，かつ組成的に非常に均質な特徴をもつ．このことは，バジャワシンダーコーン群の多数のコーン配列の地下で岩脈群マグマが相互に連結していることを示唆する．調査地域の 3 つの蒸気湧出域といくつかの高温温泉湧出域は，熱源としてのバジャワリフトゾーンマグマ系に密接に伴って分布している．