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Geology, geochemistry and geochronology of the Bajawa area, central Flores, Indonesia: Geologic structure and evolution of the Bajawa depression

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Abstract: The Bajawa area is located in the central part of Flores Island in eastern Indonesia. The area is widely underlain by Pliocene to Pleistocene voluminous volcanic products and includes a depression called the Bajawa depression. It extends 13-16 km east-west and is more than 12 km north-south with well-preserved steep cliffs up to 300-400 m in height at the western margin. Stratigraphy of the study area consists of older volcanic rocks (V1), Bajawa volcanic rocks (Bv), products of cinder cone (C1, C2), Aimere tuff (At) and products of the Inerie volcano (Ie) in ascending order. Evolution of the Bajawa area is divided into four stages: (1) In the Pliocene to Early Pleistocene, the Bajawa area became a site of intense volcanic activity to form a broad volcanic edifice that comprised the older volcanic rocks (V1) ranging from basalt to andesite in the tholeiite series. (2) Bajawa depression occurred on the central highland of the volcanic edifice formed during stage 1. Displacement of subsidence is estimated to have been more than 400 m. (3) The depression was widely filled by Bajawa volcanic rocks (Bv) consisting of andesite lavas and volcaniclastic rocks. Subsequently, andesitic cone volcanism occurred along linear fractures and formed some cinder cones (C1, C2). This volcanism was caused by calc-alkaline magma. (4) A large stratovolcano (Inerie volcano) consisting of tholeiitic andesite (Ie) grew at the southwestern margin of the depression. Based on the lineament on the satellite imagery, alignments of the cinder cones and linear discontinuities of resistivity, it is considered that the formation of the Bajawa depression results from the subsidence of the pre-depression rocks that is segmented by north-south, northwest-southeast and northeast-southwest trending faults. The north-south trending fault in the western part may be interpreted as the bounding fault that defined the western rim of the subsidence.

1. Introduction

Eastern Indonesia is one of the most geologically active and complex regions in the world, because it is at the junction of major plates: the Eurasian, Indian, Australian and Philippine Sea plates (Fig. 1). For example, the Indian plate is moving to the north at about 5 cm/year and Australian plate is moving to the north at 8 cm/year. The Eurasian plate is stationary, with respect to a static hotspot reference frame (Minster and Jordan, 1978; Nishimura and Suparka, 1990). Its geomorphologic feature is characterized by an arc-trench system: island arcs (Sunda arc and Banda arc) and trenches (Java trench and Timor trough). The island arcs, extending about 2,850 km from west to east, are made up of several major islands, e.g. Lombok, Sumbawa, Sumba, Flores, Alor and Timor, and many other small islands. Most islands with the exception of Sumba and Timor are typical volcanic islands having Quaternary active volcanoes.

During the past two decades, geological and seismological studies relevant to the island arcs in eastern Indonesia have been reported by many researchers (e.g., Hamilton, 1979; Silver *et al.*, 1983; McCaffrey, 1988; Hall and Nichols, 1990; Nishimura and Suparka, 1990; Milsom *et al.*, 1992). They revealed major geologic features and the basic tectonic framework of island arc. However, it seems that little attention has been paid regarding the type and timing of vol-

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Keywords: volcanism, depression, chemical analysis, K-Ar dating, Flores, Indonesia, Pliocene, Pleistocene

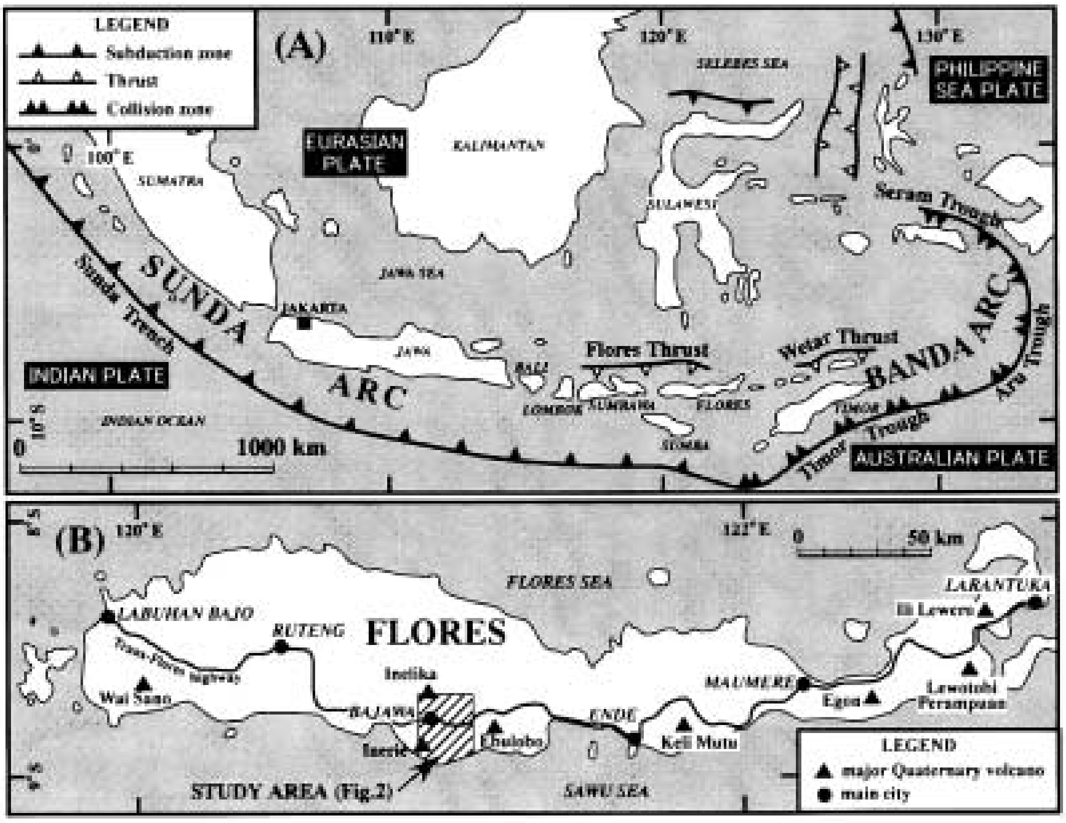

Fig. 1 (A) Major tectonic features in East Indonesia. Location of the trench is after Hamilton (1979), Silver *et al.* (1983), Hall and Nichols (1990) and Milsom *et al.* (1992).
(B) Location map of the study area on Flores Island.

canic eruptions. Recently, geological surveys were carried out from 1998 to 1999 in the Bajawa area and its vicinity, central part 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, under the International Research Cooperation Program of NEDO (New Energy and Industrial Technology Development Organization). In this paper, we report the volcanic stratigraphy in the Bajawa area and characteristics of a depression, and discuss the structural feature and evolution of the depression based on field evidence, geochemical and geochronological data.

2. Outline of the Flores Island

Flores Island, 360 km long (east-west) and varies from 15 to 70 km wide (north-south), is an unstable island arc because of the arc-continent collision at the Timor trough on the south and back-arc thrust (Flores thrust) on the north (Fig. 1). As a result, the Flores Island thrusts northwards to the Eurasian plate. The Flores Island currently has 14 active volcanoes, which are more prevalent in the central to eastern part of the island. The major volcanic activity is extinct in the western half of the island, where only weak geothermal activities occur at Wai Sano and Pocok Leok caldera that are interpreted to be the waning of volcanism, and other Quaternary volcanoes are deeply eroded (Wheller *et al.*, 1987). The extinction of volcanism in the western Flores is possibly ascribed to the presence of the Flores thrust (Silver *et al.*, 1983; Wheller *et al.*, 1987).

The Flores Island is widely underlain by Tertiary volcanic, sedimentary and the Quaternary volcanic rocks. The Flores Island is understood to have originated under submarine volcanism in the Miocene (Monk *et al.*, 1997). In this survey, along the south coast near Nangapanda 50 km east of the study area, we have observed bedded fine to coarse tuff, siltstone and conglomerate that is pale greenish to light bluish gray, which are interpreted as the marine deposits, although they are not exposed in the study area. In addition, limestone appears as an outcrop near the north coast 45 km north of the study area. Consequently it is considered that these marine deposits form the basement rocks of the study area.

3. Structural feature of the Bajawa depression

The geologic structure of the Bajawa area is characterized by a depression, herein named "Bajawa depression", which includes the Bajawa city (about 1,200 m asl) to the west and the Mataloko geothermal

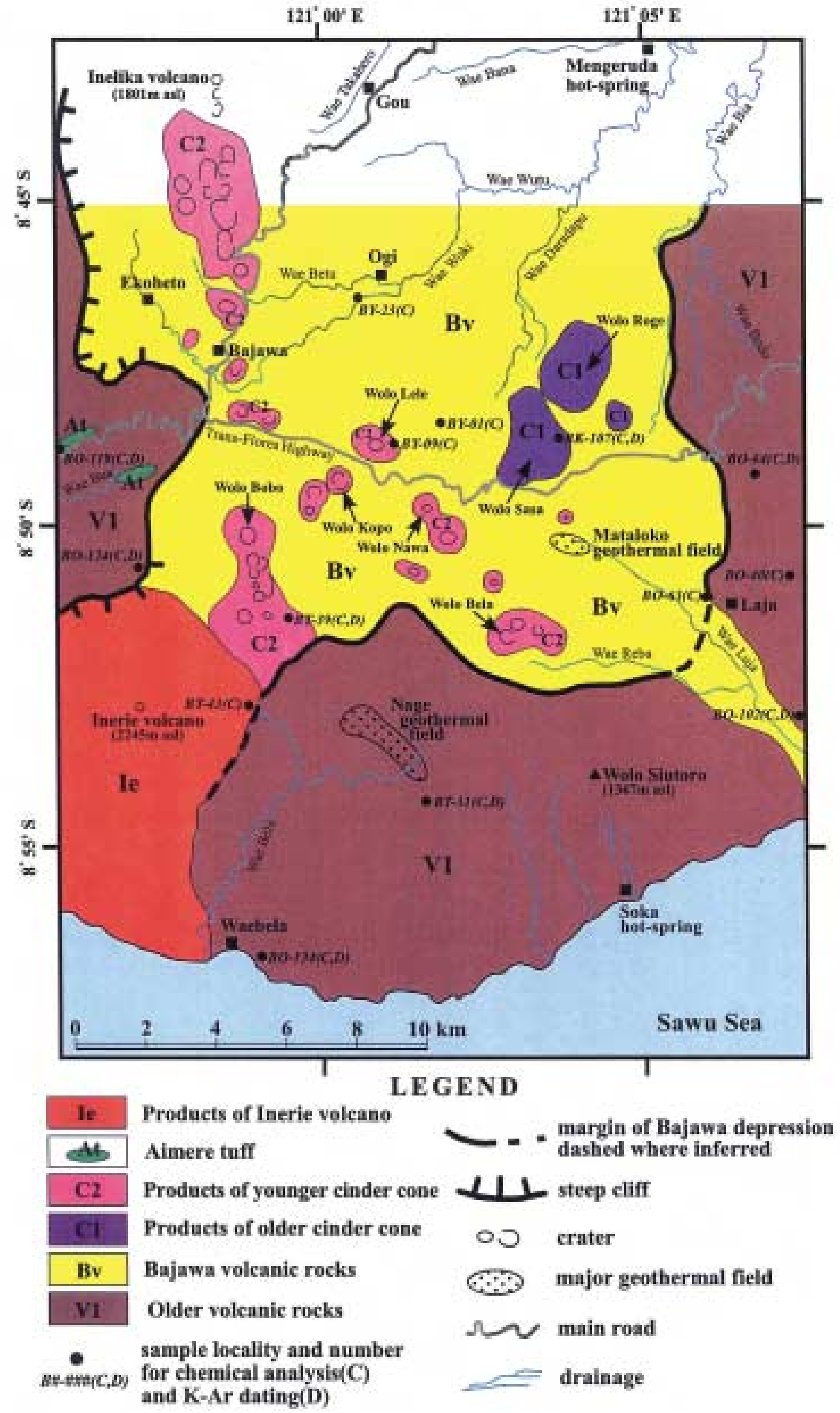

Fig. 2 Geologic map of the Bajawa area characterized by the Bajawa depression. The localities and number of samples for whole-rock chemical analysis and K-Ar dating are also shown. "Wolo" and "Wae" mean mountain and river/creek in Indonesian, respectively.

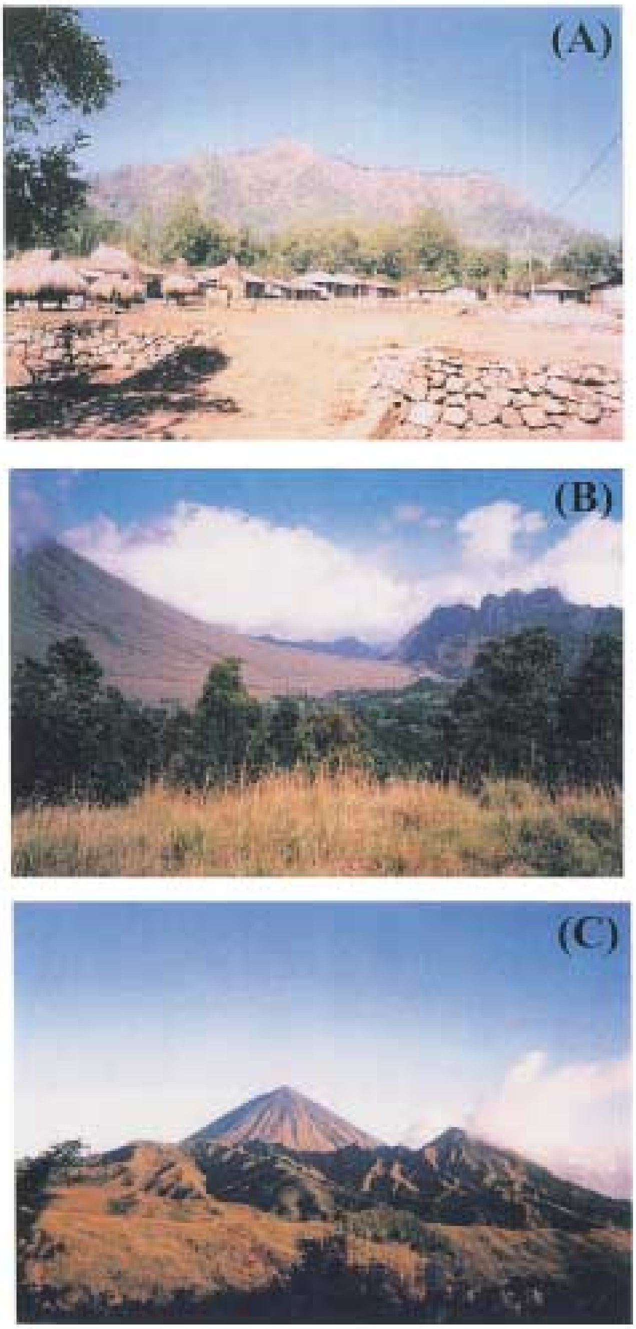

Fig. 3 Typical occurrence of steep cliffs.
(A) North-south trending cliff about 300 m in height at the western margin of the depression, looking west from the Ekoheto village at an area northwest of Bajawa city. This view shows the inside scarp.
(B) A steep cliff (right side) 300-400 m in height on the southwestern margin of the depression. The products of the Inerie volcano (center to left side) abutted directly against this cliff.
(C) A gentle slope of the cliff west of the depression, where the older volcanic rocks (V1) are deeply eroded and show sub-parallel drainage pattern. Inerie volcano is standing behind this cliff.

field (about 1,000 m asl) to the east (Fig. 2). The Bajawa depression extends about 13-16 km east-west and more than 12 km north-south, however the eastern and northern margins are unclear. In the northern part of this depression, there is a elliptic basin (Aesesa basin) filled by lacustrine sediments and ash flow tuff (Welas tuff) showing a K-Ar age of 2.5 Ma (Muraoka *et al.*, 1999). However, we could not clarify the contact relationship between the Bajawa depression and Aesesa basin in this study. The steep cliffs, up to 300-400 m in height, are intermittently preserved only at the western margin of the depression and recognized as inside scarps and outside gentle slopes as shown in Fig. 3. However in the other area, the steep cliff is not exposed. Within the depression, many cinder cones are distributed and notably arranged in the directions of north-south, northwest-southeast and northeast-southwest (Fig. 4). In addition, the major lineament on the satellite imagery trend mainly northwest-southeast and northeast-southwest. It is very interesting that a north-south trending alignment, which extends over 15 km in the western part of the depression, runs roughly parallel to the steep cliffs at the western margin of the depression.

According to the magnetotelluric survey (CSMT/MT) of the Mataloko geothermal field, linear discontinuities of resistivity can be observed to the north-south and northeast-southwest directions on about 0.8 to 1.1 km intervals, which can be delineated from steep boundaries between high and low resistivity zones (Tagomori *et al*, 2002: this volume).

According to the analysis of the satellite imagery (JERS-1/SAR), it is easy to distinguish the distribution area of the intra-depression volcanic rocks from the extra-depression basement rocks except for the northern and eastern parts of the depression because the intra-depression volcanic rocks show such characteristics as low-density, radial drainage pattern, smooth texture and low resistance on the satellite imagery, in contrast to the basement rocks showing a high-density, a sub-parallel drainage pattern, rough texture and high resistance (Fig. 3-C). On the basis of the distribution and morphology of the basement rocks that show a paleo-slope (former slope structure) dipping gently outward from the depression boundary, it is considered that the basement rocks surrounding the Bajawa depression had formed a broad volcanic edifice prior to the formation of the depression.

As for the Bouguer anomaly data, the study area is characterized by two main features; steep gradient zone and gentle gradient zone (Fig. 5). The steep gradient zone is distributed mainly outside of the depression, corresponding to the distribution area of basement rocks where Bouguer anomalies increase from outside of the depression (100-110 mgal) to the

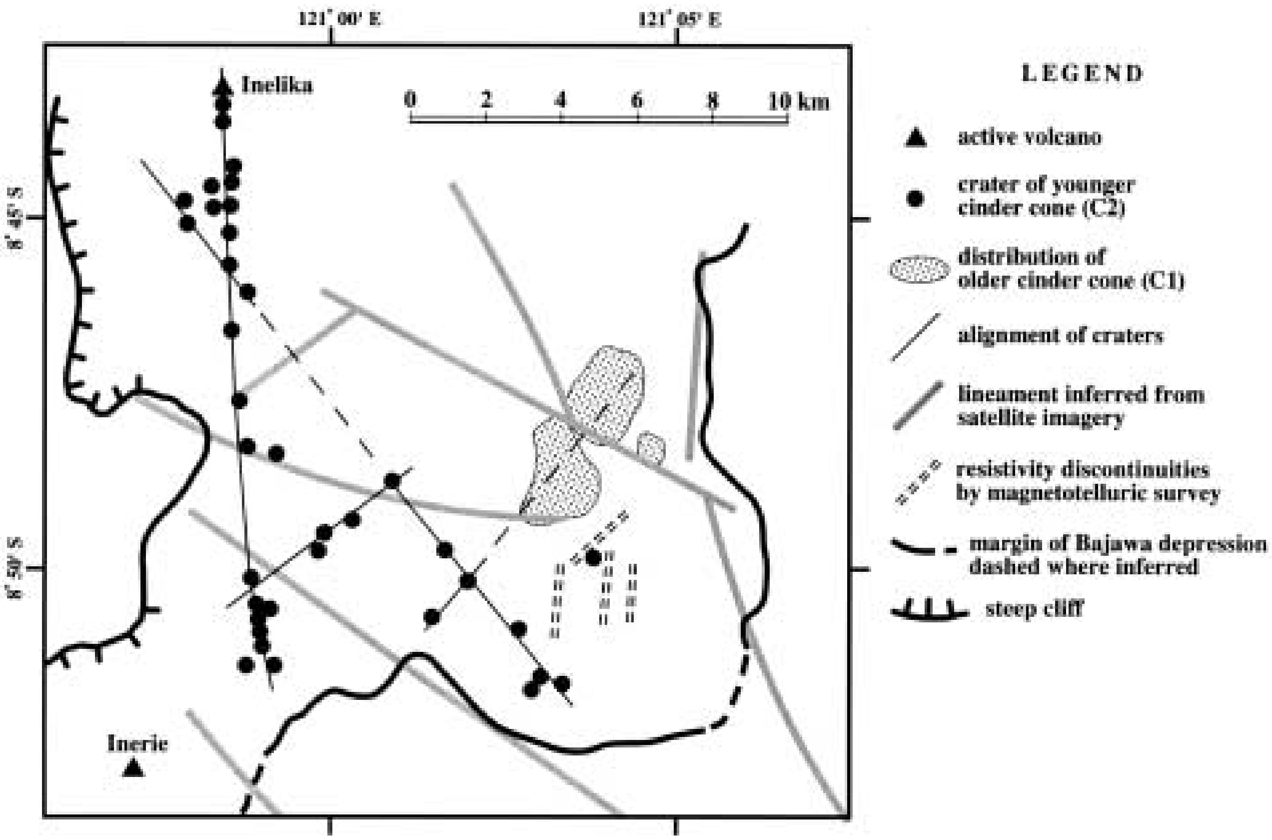

Fig. 4 Structural map of the Bajawa depression. Alignment of craters, lineament and resistivity discontinuities are thought to be reflecting the subsurface faults and associated fractures. Note that the north-south trending alignment of craters is roughly parallel to the steep cliffs at the western margin of the depression.

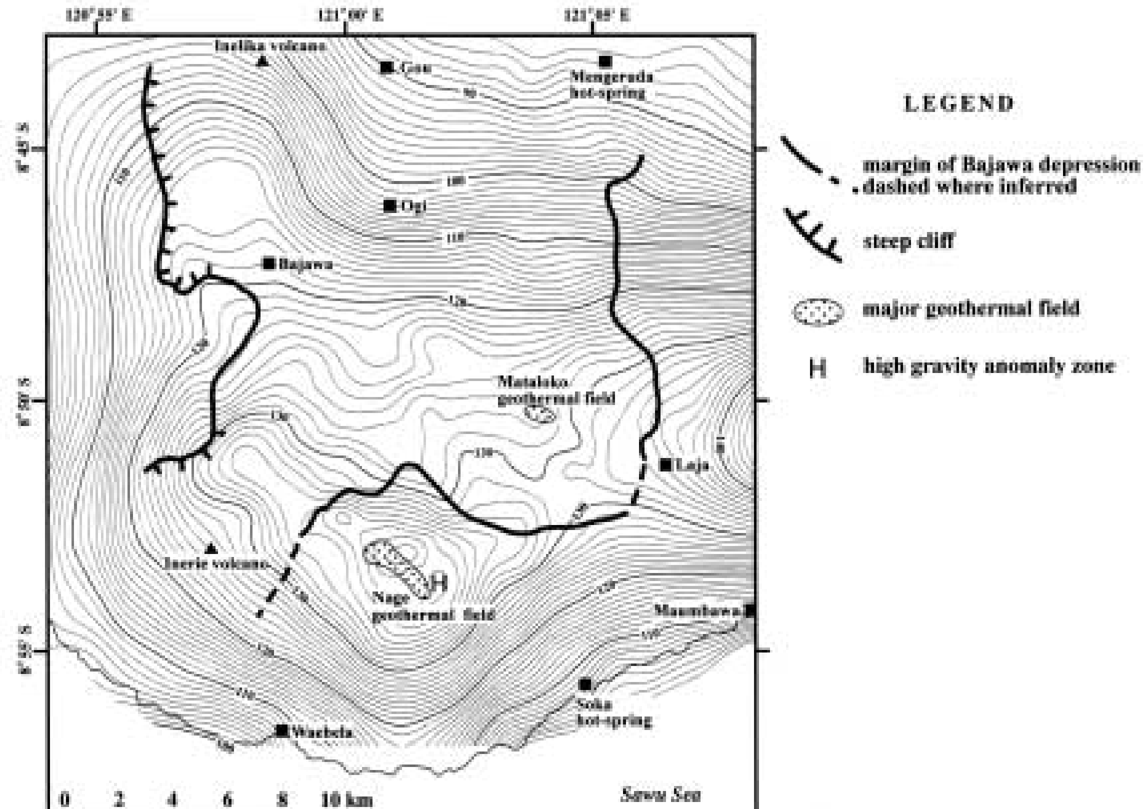

Fig. 5 Bouguer anomaly map in the Bajawa area. Contour interval is 1 milligal. Assumed density is 2.0 g/cm^3.

Table 1 Typical texture and mineral assemblages of the volcanic rocks in the Bajawa area.

Geologic unit	Rock type	Modal composition of total phenocrysts	Phenocryst				Groundmass				Texture
			Pl	Au	Hy	Ol	Pl	Au	Mt	G	
Products of Inerie volcano (Ie)	andesite	30-40 %	◎	△	×	△	○	△	×	◎	porphyritic, hyalo-ophitic, hyalopilitic
Products of cinder cone (C1,C2)	andesite	20-30 %	◎/○	△	△	△/×	○	△	×	◎	porphyritic, hyalo-ophitic, hyalopilitic
Bajawa volcanic rocks (Bv)	andesite	20-30 %	◎/○	△	△	×	○	△/×	×	◎	porphyritic, hyalo-ophitic, hyalopilitic
Older volcanic rocks (V1)	andesite	30-40 %	◎	△	△	×	◎	△	×	×	porphyritic,intersertal, intergranular
	basalt	15-20 %	◎	○	×	△	◎	◎	○	×	porphyritic,intersertal, intergranular

Abundance of phenocryst is presented semi-quantatively. Pl, Plagioclase; Au, Augite; Hy, Hypersthene; Ol, Olivine; Mt, Magnetite; G, Glass
◎, abundant (≧30%); ○, major (30% > ≧10%); △, minor (10% > ≧2%); ×, rare (2% >)

depression boundary (120-130 mgal), especially evident west of the depression. On the other hand, the gentle gradient zone, ranging from 120 to 130 mgal of Bouguer anomalies, roughly coincides with the area inside of the depression except for the northeastern part of the depression.

4. Volcanic stratigraphy

The stratigraphy of the study area consists of older volcanic rocks (V1), Bajawa volcanic rocks (Bv), products of cinder cone (C1, C2), Aimere tuff (At) and products of Inerie volcano (Ie) in ascending order (Fig. 2). Typical texture and mineral assemblages of the volcanic rocks are shown in Table 1.

4.1 Older volcanic rocks (V1)

Older volcanic rocks are distributed on the western and eastern borders and the southern part of the study area. Altitude of the distribution ranges from sea level to 1,400 m asl.

The older volcanic rocks consist mainly of andesite lava, basalt lava, volcaniclastic rocks, and minor lahar deposits. Andesite and basalt lava are generally weakly altered, gray to dark gray lava flows. Although each flow unit of lava can not be recognized on a scale of an outcrop, an individual unit is estimated to be a few meters to a few tens of meters in thickness. Andesite lava is massive or partly foliated porphyritic rock containing phenocrysts of plagioclase, augite and hypersthene within the intersertal or intergranular groundmass lacking glass materials. Modal composition of the total phenocrysts is about 30 to 40 %. In general, the andesite contains alteration minerals such as secondary quartz, smectite and chlorite and is rich in pyroxene phenocrysts 1 to 5 mm long in the southern part of the study area. The andesite dyke ranging from 2 to 5 m wide rarely intrudes andesite lava east of the Inerie volcano, which is interpreted to be the feeder dyke. Although most older volcanic rocks are subaerial volcanic products, it was also observed that the andesite lava showed characteristics of water interaction such as a pillow lobe at Maumbawa harbor in the southeastern part of the study area. Basalt lava is a very hard and massive porhyritic rock containing phenocrysts of plagioclase, augite and olivine within the intersertal or intergranular groundmass lacking glass materials as in the case of andesite lava. The modal composition of the total phenocrysts is about 15 to 20 %. Along the south coast, it shows a distinct columner joint 10 to 20 m in height. In some places, the lahar deposits are intercalated with volcanic rocks and contain abundant andesite clasts ranging from a few cm to a few meters across. The beds of the lahar deposits display massive, poorly sorted and a matrix- or clast-supported framework.

4.2 Bajawa volcanic rocks (Bv)

The Bajawa volcanic rocks are extensively distributed in the central to northern part of the study area and accumulated within the Bajawa depression. It lies uncomformably over the older volcanic rocks (V1).

The Bajawa volcanic rocks consist mainly of andesite lava and minor volcaniclastic rocks, which are interpreted as subaerial volcanic products. The base of the volcanic rocks is not exposed but the thickness is estimated to be at least 160 m at the Mataloko geothermal field according to the drill hole data (MT-2). The andesite lava is generally gray to dark-gray, shows massive lava flow and is partly accompanied with blocky lava due to autobrecciation. The andesite lava is a porphyritic rock containing phenocrysts of plagioclase, augite and hypersthene, and the modal composition of the total phenocrysts is about 20 to 30 %. The groundmass shows a hyalopilitic or hyalo-ophitic texture. Each flow unit of andesite lava is presumably about 10 m or less in thickness where the assemblage of some andesite lava and intercalated volcaniclastic rocks are observed. At the Mataloko geothermal field, the andesite lava and volcaniclastic rocks are strongly altered to form an alteration zone containing minerals such as kaolinite, smectite, quartz, α-cristobali te, alunite, pyrite and sulphur confirmed by the X-ray diffraction analysis.

4.3 Products of cinder cones (C1, C2)

The cinder cones are widely distributed within the Bajawa depression and tend to dominate in the

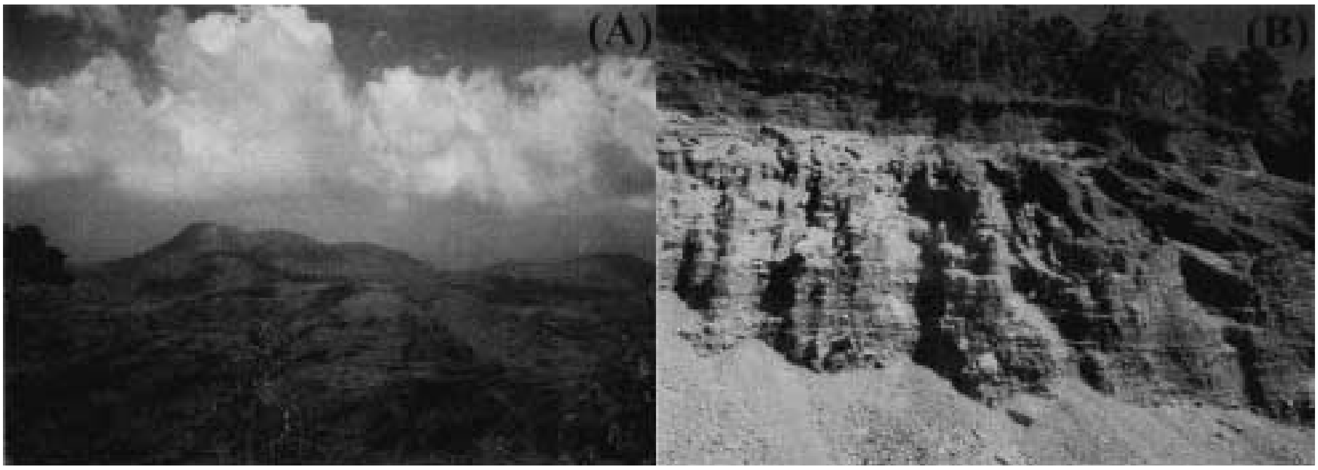

Fig. 6 Typical cinder cone and its products (C1, C2).
(A) Cinder cone cluster comprising Wolo Kopo, Wolo Lele and adjacent cinder cones, looking toward the northeast from Wolo Bobo volcano.
(B) Outcrop of cinder cone north of Bajawa city. This cross-section is parallel to tangential line of the circular rim. The beds of the volcaniclastic deposits crudely display inverse-grading. The outcrop is about 20 m in height.

western part rather than the eastern part of the depression. They were built on the underlying Bajawa volcanic rocks (Bv). Judging from the degree of dissection, the products of cinder cones are divided into two groups: older products (C1) distributed in the northeastern part and younger products (C2) in the southern and western part of the depression.

Many cinder cones usually occur in nested clusters (Fig. 6-A) and the craters are aligned in the directions of north-south, northwest-southeast and northeast-southwest. The cinder cones show relatively well-preserved topography, although partly dissected and have approximately circular or crudely ellipsoidal shape in plane with central bowl-shaped craters. The older cinder cones (C1) such as Wolo Roge and Wolo Sasa are relatively dissected when compared with the younger cinder cones (C2), and do not have clear craters. There are at least 35 craters in the study area. Cone height and basal diameter ranges from 100 to 300 m and 1,000 to 1,500 m, respectively. The volcanic products of cones mostly consist of volcaniclastic deposits but include andesite lava. These units are distinctly bedded and the thickness of the individual units ranges from a few tens of cm to 2 m (Fig. 6-B). The volcaniclastic deposits showing volcanic breccia and tuff breccia facies, contain a large amount of coarse angular to sub-angular fragments of broken country rocks ranging from a few cm to 1m across. The beds are massive and poorly sorted. They appear crudely inverse-graded and clast-supported framework in places, indicating deposition by grain flow.

In general, andesite lava is intercalated with the beds of volcaniclastic deposits and gray to dark gray porphyritic rocks containing phenocrysts of plagioclase, augite, hypersthene and a small amount of olivine within the hyalo-ophitic or hyalopilitic groundmass. The modal composition of the total phenocrysts is about 20 to 30 %. This mineral assemblage differs from that of the underlying older volcanic rocks (V1) and Bajawa volcanic rocks (Bv) lacking olivine phenocryst. Around the Wolo Bobo volcano in the southwestern part of the depression, the andesite lava and volcaniclastic rocks are strongly altered to form an alteration zone and contain hydrothermal alteration minerals such as kaolinite, quartz, α-cristobalite, tridymite, alunite and sulphur according to the X-ray diffraction analysis.

In some places, scoria fall deposits can be observed on the cone surface from the top to the base, which overlie the underlying beds with uniform thickness, forming a mantle carpet. They comprise black to dark gray fine sand to pebble-gravel sized scoriaceous clasts, and the thickness varies from a few cm to 30 cm. Inverse grading is often developed. According to the occurrence, it is considered that they were formed at the final stage of the volcanic activity of the cone.

4.4 Aimere tuff (At)

Outside the Bajawa depression, gray to brownish gray, non-welded ash-flow tuff overlies the older volcanic rocks (V1). The tuff is called "Aimere tuff", which corresponds to the "Aimere scoria flow deposits" by Muraoka *et al.* (1999). It is only exposed on the west side of the depression and absent in other areas. There are outcrops of the Aimere tuff in good condition along the road (Trans-Flores highway) to Aimere from Bajawa city, west of the depression. It is observed that the tuff includes gray to dark gray scoria/pumice clasts 1 cm to a few tens of cm in diameter but is poor in accidental fragments (Fig. 7-A). The thickness of a flow unit is mostly less than 5 m. On the contrary, along the

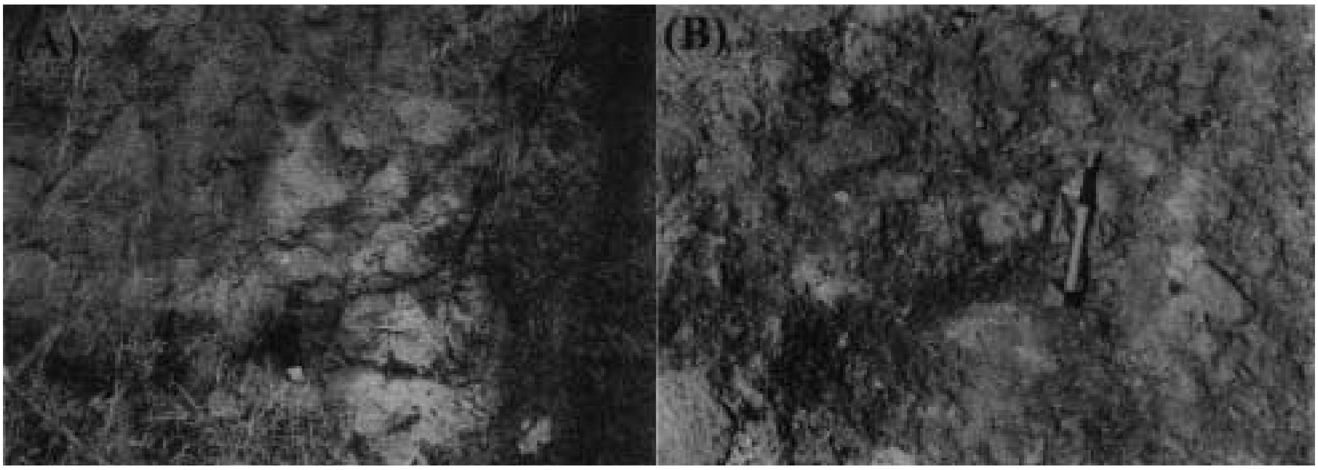

Fig. 7 Typical outcrop of the Aimere tuff (At).
(A) Massive, non-welded tuff containing scoria/pumice clasts along the Trans-Flores highway west of the depression.
(B) Basal part of the Aimere tuff about 50 m thick, where accidental fragments are concentrated, along the Wae Bua river west of the depression.

Wae Bua River south of the road, the tuff shows upward-fining sequences of about 50 m thick and contains many accidental fragments of a few cm to a few tens of cm across the lowermost part (Fig. 7-B).

4.5 Products of Inerie Volcano (Ie)

The products of the Inerie volcano occupy the southwestern part of the study area and lie unconformably on under units (V1, Bv, C1 and C2). The Inerie volcano, the second highest active stratovolcano (2,245 m asl) on the Flores Island (Monk *et al.*, 1997), has about 10 km of basal diameter and circular shape in plane view. The last eruption was in 1988. The products of the Inerie volcano comprise andesite lava and volcaniclastic rocks with lahar deposits. The andesite lava is gray to dark grayish porphyritic rock containing phenocrysts of plagioclase, augite, olivine and a small amount of hypersthene within the hyalo-ophitic or hyalopilitic groundmass. The modal composition of the total phenocrysts is about 30 to 40 %. The lahar deposits are mainly distributed on the southern flank of the volcano, and the thickness of a flow unit ranges from 1 to 5 m with erosional base contact. It contains a large amount of sub-rounded to angular andesite clasts ranging in size from a few cm to 1 m across.

5. Geochemistry

Whole-rock chemical analysis was carried out for 14 volcanic rock samples. Major element analyses were performed by X-ray fluorescence at ALS Chemex Labs in Canada. The chemical variation diagrams and whole rock chemical compositions are shown in Fig. 8 and Table 2, respectively. Sample localities with sample numbers are shown in Fig. 2.

The samples analyzed have a relatively wide variation of SiO_2 content ranging from 50.3 to 64.9 wt.%, and most samples are rich in Al_2O_3 (15-22 wt.%) and poor in TiO_2 (<1.2 wt.%). Such properties of chemical composition are very similar to those of the Quater-

Table 2 Whole rock chemical compositions for 14 volcanic rock samples in the Bajawa area. Sample localities are shown in Fig. 2.

Sample No.	BT-43	BK-107	BT-39	BY-09	BY-01	BO-63	BO-119	BY-23	BO-40	BO-64	BO-102	BO-124	BO-134	BT-31
Geologic unit	Ie	C1	C2	C2	Bv	Bv	Bv	Bv	V1	V1	V1	V1	V1	V1
Rock type	andesite	andesite	andesite	dacite	andesite	andesite	andesite	andesite	andesite	andesite	basalt	basalt	basalt	andesite
East longitude	8°52'41"	8°48'43"	8°51'21"	8°48'45"	8°48'27"	8°51'06"	8°49'03"	8°46'30"	8°50'55"	8°49'25"	8°53'01"	8°50'33"	8°56'48"	8°54'11"
South latitude	120°58'57"	121°03'39"	120°59'17"	121°01'11"	121°01'48"	121°05'57"	120°55'53"	121°00'34"	121°07'23"	121°06'44"	121°07'22"	120°57'21"	120°58'57"	121°01'33"
SiO_2 (wt.%)	54.07	58.12	60.85	64.87	59.30	56.80	56.14	57.25	57.06	58.99	50.27	50.92	51.41	60.09
TiO_2	0.84	0.81	0.71	0.71	0.76	0.82	0.78	0.86	1.20	0.73	0.79	0.98	0.80	0.72
Al_2O_3	20.20	17.05	16.93	15.66	16.91	17.64	18.90	17.60	15.45	15.96	22.16	19.15	18.86	16.40
Fe_2O_3	3.72	3.30	2.69	3.50	4.37	3.00	3.48	4.56	3.85	3.86	3.37	3.33	3.15	4.26
FeO	4.30	4.08	3.52	2.01	2.57	4.77	4.03	3.13	6.02	2.86	5.19	6.28	6.01	2.64
MnO	0.14	0.13	0.11	0.10	0.11	0.13	0.13	0.13	0.19	0.15	0.15	0.32	0.16	0.15
MgO	3.80	3.72	3.15	1.82	3.34	4.29	3.31	4.08	3.35	3.87	2.80	4.17	4.91	2.83
CaO	9.38	7.08	6.43	4.11	6.59	7.67	8.21	7.67	7.44	6.98	11.95	10.85	10.61	6.54
Na_2O	2.88	3.22	3.07	3.26	3.11	3.03	3.27	3.17	3.09	2.80	2.07	2.36	2.33	3.09
K_2O	0.75	1.42	1.72	2.71	1.55	1.11	0.85	1.23	0.54	1.13	0.13	0.42	0.43	1.43
P_2O_5	0.08	0.11	0.10	0.13	0.09	0.11	0.14	0.12	0.21	0.09	0.06	0.09	0.08	0.10
$H_2O(+)$	0.05	0.65	0.42	0.67	0.66	0.67	0.29	0.01	1.11	1.18	0.50	0.57	0.70	0.65
$H_2O(-)$	0.15	0.32	0.16	0.45	0.52	0.15	0.47	0.14	0.37	1.14	0.52	0.52	0.56	0.77
Total	100.36	100.01	99.86	100.00	99.88	100.19	100.00	99.95	99.88	99.74	99.96	99.96	100.01	99.67

Geologic unit: Ie, Products of Inerie volcano; C2, Products of younger cinder cone; C1, Products of older cinder cone;
Bv, Bajawa volcanic rocks; V1, Older volcanic rocks

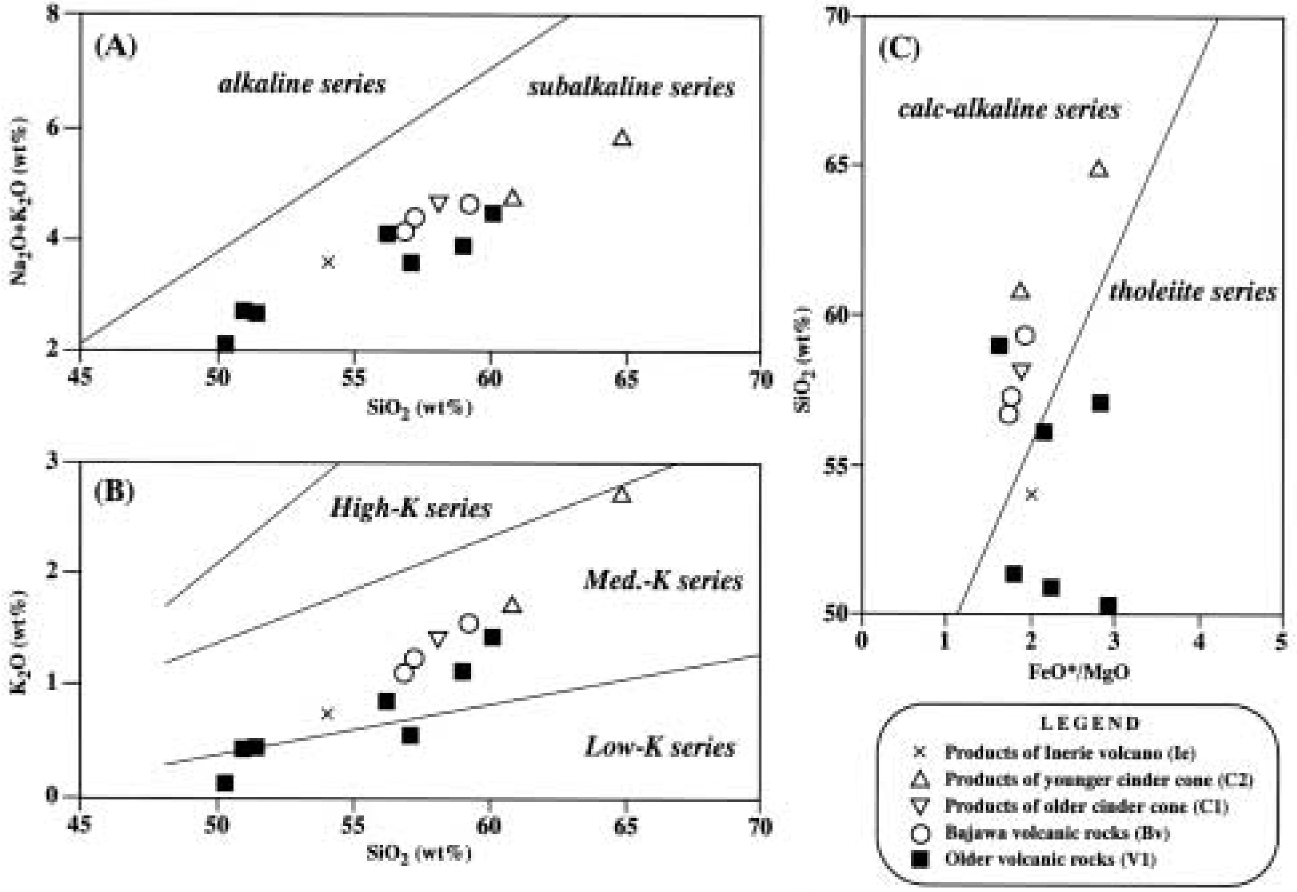

Fig. 8 Chemical variation diagrams for 14 volcanic rock samples in the Bajawa area.
(A) SiO_2 versus (Na_2O+K_2O) diagram. Line shows the boundary between alkaline and subalkaline series (after Kuno, 1966).
(B) SiO_2 versus K_2O diagram. The fields of low-, medium- and high-K are from Gill (1981).
(C) SiO_2 versus FeO*/MgO diagram. Line shows the boundary between calc-alkaline and tholeiite series (after Miyashiro, 1974). Total iron content is expressed as FeO*.

nary volcanic rocks that appeared along the island arc (Sunda and Banda Island Arc) in eastern Indonesia (Wheller *et al.*, 1987).

The volcanic rocks in the study area fall in the subalkaline field of Kuno (1966) on the Na_2O+K_2O versus SiO_2 diagram (Fig. 8-A). Most rocks are mainly plotted in the field of the medium-K series of Gill (1981) on the K_2O versus SiO_2 diagram (Fig. 8-B) although some older volcanic rocks (V1) extend into the field of the low-K series. On the FeO*/MgO versus SiO_2 diagram (Miyashiro, 1974), the volcanic rocks fall into both the calc-alkaline and tholeiite series. However, the FeO*/MgO ratio range is only from 1.7 to 2.9 (Fig. 8-C).

The older volcanic rocks (V1) have a wide range of SiO_2 content from 50.3 to 60.1 wt%, i.e. from basalt to andesite in composition. The Bajawa volcanic rocks (Bv) and products of cinder cone (C1, C2) fall into the calc-alkaline series, whereas most older volcanic rocks (V1) and products of the Inerie volcano (Ie) fall into the tholeiite series. The Bajawa volcanic rocks (Bv) and products of cinder cone (C1, C2) seem to show the same linear relationship between FeO*/MgO and SiO_2 (Fig. 8-A, B, C). The chemistry of products of the Inerie volcano (Ie) is in good accordance with the data analyzed by Wheller *et al.* (1987).

6. Geochronology

Whole-rock K-Ar age determination for eight volcanic rock samples was achieved at the Central Research Institute, Mitsubishi Materials Corporation. The decay constants and atomic ratio in the age calculation were $\lambda\beta=4.962\times10^{-10}$/year, $\lambda e=0.581\times10^{-10}$/year and $^{40}K/K=0.01167$ atom% (Steiger and Jäger, 1977). Error was estimated according to Nagao *et al.* (1984). Dating results are shown in Table 3. Sample localities with the sample numbers are shown in Fig. 2.

The ages of the older volcanic rocks (V1) were estimated to be 0.72 ± 0.04 Ma (sample number: BO-119), 1.03 ± 0.17 Ma (BO-134), 1.09 ± 0.08 Ma (BT-31), 1.63 ± 0.12 Ma (BO-64), 1.82 ± 0.21 Ma (BO-124) and 2.76 ± 0.32 Ma (BO-102). The ages of the products of the cinder cone (C1, C2) are estimated to be 0.51 ± 0.03 Ma and <0.15 Ma, and both ages are significantly younger than the underlying units (V1, Bv).

Table 3 K-Ar ages of the volcanic rocks in the Bajawa area. Sample localities are shown in Fig. 2.

Sample no.	Geologic unit	Rock type	Coordinate	Sample type	Potassium (K wt%)	Rad. ^{40}Ar (10^{-8}cc/g)	Air. Cont. (%)	K-Ar age (Ma)
BT-39	C2	Andesite	8°51'21"S, 120°59'17"E	Whole rock	1.50	-0.36±0.05	101.2	<0.15
BK-107	C1	Andesite	8°48'43"S, 121°03'39"E	Whole rock	0.12	2.36±0.12	91.7	0.51±0.03
BO-119	V1	Andesite	8°49'03"S, 120°55'53"E	Whole rock	0.75	2.08±0.11	78.1	0.72±0.04
BO-134	V1	Basalt	8°56'48"S, 120°58'57"E	Whole rock	0.28	1.12±0.08	98.2	1.03±0.17
BT-31	V1	Andesite	8°54'11"S, 121°01'33"E	Whole rock	1.33	5.61±0.30	91.8	1.09±0.08
BO-64	V1	Andesite	8°49'25"S, 121°06'44"E	Whole rock	0.98	6.20±0.33	89.5	1.63±0.12
BO-124	V1	Basalt	8°50'33"S, 120°57'21"E	Whole rock	0.31	2.15±0.12	93.8	1.82±0.21
BO-102	V1	Basalt	8°53'01"S, 121°07'22"E	Whole rock	0.07	0.75±0.04	93.1	2.76±0.32

Geologic unit: C2, Products of younger cinder cone; C1, Products of older cinder cone; V1, Older volcanic rocks

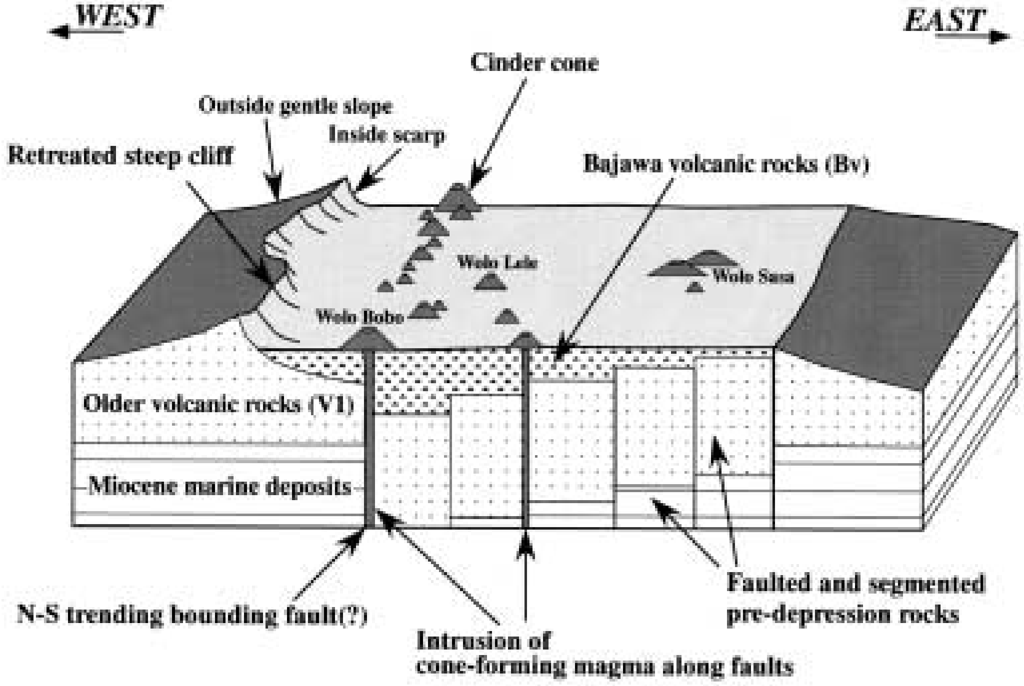

Fig. 9 Schematic diagram showing subsidence geometry related to surface structural features.

7. Discussions

7.1 Subsidence structures of the Bajawa depression

Remnants of the steep cliffs up to 300-400 m in height west of the depression are a good indicator of the formation of the depression. The older volcanic rocks (V1) are widely distributed outside of the depression and interpreted as pre-depression basement rocks. On the other hand, the depression is filled with Bajawa volcanic rocks (Bv) and products of the cinder cone (C1, C2) younger than the old volcanic rocks (V1). These suggest that the depression took place after the formation of the old volcanic rocks (V1). Subsequently the volcanic activity newly occurred within the depression, and the Bajawa volcanic rocks (Bv) and products of the cinder cone (C1, C2) filled this depression.

Schematic diagram (Fig. 9) illustrates the subsidence geometry with a relationship to surface structural features. Within the depression, there are major lineaments inferred from the satellite imagery and alignments of craters of cinder cones trending north-south, northwest-southeast and northeast-southwest (Fig. 4). These structures probably suggest the presence of a subsurface fracture. According to the magnetotelluric survey in the Mataloko geothermal field, linear discontinuities of resistivity extend in the north-south direction (Fig. 4), which can be interpreted as faults. The presence of these fractures and faults suggests the formation of the depression is controlled by the subsidence of pre-depression rocks (the Miocene marine deposits and older volcanic rocks (V1)), which were faulted and segmented into numerous blocks. According to the alignments of the cinder cones, major fractures not only faulted and segmented the pre-depression rocks, but also were the significant lines of weakness which canalized the magma rise during the post-depression volcanic activity.

The steep cliffs are developed only at the western margin of the depression and are not recognized in other areas. Although a possibility was found that cliffs had been removed or concealed by later volcanic activity in other areas, this differential development of steep cliffs may have been indicated that the displacement of subsidence (>400 m) west of the depression was greater than in other areas. However, the Bouguer anomaly not show evidence of differential subsidence.

As for the geometry of the steep cliffs, the observed cliffs show curvilinear or embayment rather than a linear form. This may implies that the steep cliffs are not the original fault (bounding fault). In this case, the bounding fault that delineated the depression is expected to be east of the observed cliffs. Based on the relationship of the location and direction between the steep cliffs and fractures within the depression, a north-south trending fracture inferred from the alignment of the cinder cones at the western margin may be interpreted as the bounding fault that defined the western rim of the subsidence. There is a possibility that the pre-depression rocks of the western part subsided along the north-south trending fracture, and subsequently the fault scarp differently retreated to west in response to landslide and rock falls. This process is similar to the enlargement of caldera walls accompanied by the collapse of the subsidence caldera (Lipman, 1976).

Although in this study it is hard to conclude the subsidence structure of the Bajawa depression mostly due to the lack of direct evidence, it can be stated that the depression is characterized by faulted and segmented pre-depression rocks with greater subsidence to the west. It should be emphasized that the subsidence of pre-depression rocks was controlled by north-south, northwest-southeast and northeast-southwest trending faults probably due to regional tectonic influences.

7.2 Volcanic evolution

On the basis of the field evidence, geochemical and geochronological data on the volcanic rocks and inferred subsurface structures, the evolution of the study area can be proposed as follows.

Stage 1 Initial volcanism

In the Pliocene to Early Pleistocene, the study area became a site of intense volcanic activity to form a broad volcanic edifice consisting of the older volcanic rocks (V1). The fluctuation of K-Ar ages for 6 samples implies that the volcanic activity forming the older volcanic rocks (V1) began in the Pliocene and continued at least 2.0 m.y. The overall volcanic edifice is assumed to have been over 400 km^2 and formed on the basement of Miocene marine deposits. The volcanic edifice is presumed to have consisted of overlapping composite volcanoes made of subaerial volcanic rocks. The magma chamber produced tholeiitic volcanic rocks of a very wide composition from basalt to andesite.

Stage 2 Formation of the Bajawa depression

The Bajawa depression appeared on the central part of the volcanic edifice formed during stage 1. Displacement of the subsidence is estimated to have been more than 400 m based on the well-preserved steep cliffs. As mentioned before, it is considered that the formation of the depression results from the subsidence of the pre-depression rocks that are segmented by north-south, northwest-southeast and northeast-southwest trending faults. The north-south trending fault in the western part of the depression probably bounded the depression geometry during subsidence.

Stage 3 Post-depression volcanisms

After the formation of the Bajawa depression, the depression was filled by the Bajawa volcanic rocks (Bv) consisting of andesite lava and volcaniclastic rocks. Although its sources are not known, according to the wide distribution of volcanic rocks at least 160 m thick, it is inferred that most volcanic rocks should have erupted from multiple sources within the depression. At the southeastern part, andesite lava partly overflowed to outside of the depression. Subsequently, many andesitic cone volcanism occurred within the depression to form numerous cinder cones on the surface. The alignments of craters indicate that the volcanic activity was confined to linear fractures. It is inferred that the volcanic activities forming the Bajawa volcanic rocks (Bv) and products of cinder cone (C1, 2) have originated the same calc-alkaline magma chamber because both volcanic rocks seem to show the same trend on the chemical diagrams (Fig. 8).

The K-Ar ages obtained by this study imply that the older cinder cone (C1) formed around 0.5 Ma and younger cone (C2) occurred at less than 0.15 Ma. However, Muraoka *et al.* (2000) reported that magnetic polarities of andesite lava, corresponded with the older cinder cone (C1), belong to the Matsuyama reverse epoch. Considering this magnetic data, the cone volcanism forming the older cinder cone (C1) probably began before 0.73 Ma. The ages of the Aimere tuff (At) were estimated to be less than 0.15 Ma by Muraoka *et al.* (1999), although its source is unknown.

Stage 4 Formation of Inerie volcano

After the formation of cinder cones, a large andesite stratovolcano (Inerie volcano) grew at the southwestern margin of the depression. However, the magma chamber changed in composition from calc-alkaline to tholeiite series.

8. Conclusions

1. The Bajawa area consists of older volcanic rocks

(V1), Bajawa volcanic rocks (Bv), products of cinder cone (C1, C2), Aimere tuff (At) and products of Inerie volcano (Ie) in ascending order.

2. The Bajawa area includes a depression (Bajawa depression) which extends about 13-16 km east-west and more than 12 km north-south with well-preserved steep cliffs up to 300-400 m in height at the western margin.
3. The formation of the Bajawa depression probably results from the subsidence of pre-depression rocks that are segmented by north-south, north-west-southeast and northeast-southwest trending faults. The north-south trending fault in the western part may be interpreted as the bounding fault that defined the western rim of the subsidence.
4. Evolution of the Bajawa area is characterized by four stages: (1) In the Pliocene to Early Pleistocene, the study area became a site of intense volcanic activity to form a broad volcanic edifice consisting of subaerial volcanic rocks ranging in composition from basalt to andesite. (2) Bajawa depression appeared on the central highland of the broad volcanic edifice formed during stage 1. (3) The depression was widely filled by andesite lava and volcaniclastic rocks. Subsequently, andesitic cone volcanism occurred along linear fractures. (4) A large andesite stratovolcano (Inerie volcano) grew at the southwestern margin of the depression.

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インドネシア共和国フローレス島中央部バジャワ地域の地質，地球化学及び地質年代：バジャワ陥没地の地質構造と変遷

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要　　旨

インドネシア共和国フローレス島中央部には，東西 13-16 km，南北 12 km 以上のバジャワ陥没地が位置する．鮮新世～前期更新世にソレアイト系列の玄武岩～安山岩質複成火山体が形成され，その後火山体中央部において陥没が生じバジャワ陥没地が形成された．その陥没は，北－南，北西－南東，北東－南西方向の断層によって分割された基盤岩ブロックの沈降によって生じたと推定される．陥没地はカルクアルカリ系列の安山岩質の火山活動により安山岩溶岩・火砕岩に埋積され，引き続き断裂沿いに多数の火砕丘が形成された．その後，陥没地南西縁においてソレアイト系列の安山岩質成層火山（イネリエ火山）が成長した．