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Geochemistry of volcanic rocks in the Bajawa geothermal field, central Flores, Indonesia

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Hirofumi MURAOKA, Asnawir NASUTION, Minoru URAI, Masaaki TAKAHASHI and Isao TAKASHIMA (2002) Geochemistry of volcanic rocks in the Bajawa geothermal field, central Flores, Indonesia. *Bull. Geol. Surv. Japan,* vol. 53 (2/3), p. 147-159, 10 figs., 1 table.

Abstract: Multi-components of 46 volcanic rocks were analyzed from the Bajawa geothermal field, central Flores, Indonesia. Twenty six samples were taken from the Bajawa rift zone volcanic rocks including numerous cinder cones called the Bajawa Cinder Cone Complex. The results show that tholeiitic basalt to dacite are rather common in the field, but the Bajawa rift zone volcanic rocks are calc-alkaline andesite and extremely homogeneous throughout the samples in major and minor components. The plot of the Bajawa rift zone volcanic rocks to pseudoternary diagrams reveals that their cluster is constrained by the phase boundaries and equilibrated at about 3 kbar or 10 km depth. This depth corresponds with the bottom of the oceanic crust in this region, and the rift type magmatism might have caused such a shallow depth magma generation. The homogeneity of the Bajawa rift zone magma is ascribed to its short path from the magma source region to the surface and its non-stop rising as a dike swarm.

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 an 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 the western half of the Ngada District. 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 (the ESSEI Project; Muraoka and Uchida, 2002). Numerous cinder cones are distributed along the NNW-SSE trending zone in the study area, and major geothermal manifestations are closely associated with those volcanoes (Figs. 2 and 3). Muraoka *et al.* (2002a) described tectonic, volcanic and stratigraphic geology of the study area in this volume where those cinder cones were collectively called the Bajawa Cinder Cone Complex. Their potentials as a geothermal heat source were recently demonstrated by the phreato-magmatic eruption that occurred at the Inie Lika volcano, Flores Island, from January 11 to 16, 2001 as reported by Muraoka *et al.*, (2002b) in this volume. These numerous cinder cones are, however, one of the results of volcano-tectonic processes in the zone that can be more comprehensively represented as the Bajawa rift zone (Muraoka *et al.*, 2002a).

This paper describes results of geochemical analyses of volcanic rocks in the study area, particularly focusing on the characterization of the Bajawa rift zone magmatism.

2. Outline of the Bajawa rift zone volcanism

Figure 2 shows a JERS-1 SAR imagery acquired on February 3, 1996 five years before the eruption (Urai *et al.*, 2002). The Inie Lika volcano is situated immediately north of Bajawa, a capital city of Ngada District, Nusa Tenggara Timur Province and

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Keywords: rift zone, dike swarm, cinder cone, geothermal field, calc-alkaline andesite, multi-component analysis, Inie Lika Volcano, Bajawa, Flores, Indonesia

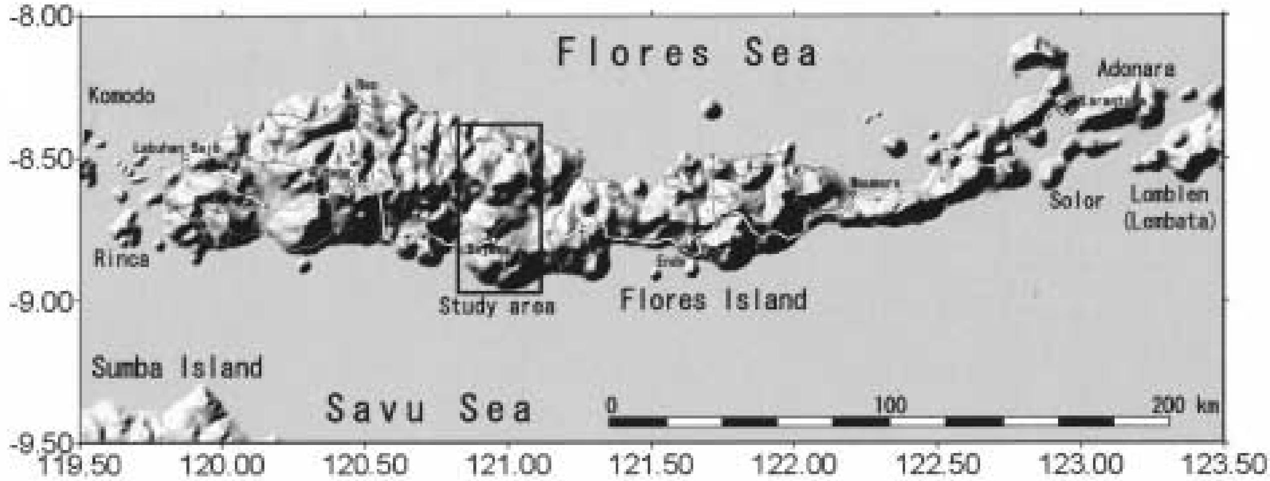

Fig. 1 Shaded relief map of Flores Island and the study area. The source DEM data are GTOPO30 released from USGS EROS Data Center and were shaded by Masao Komazawa. The rectangle in central Flores shows the study area.

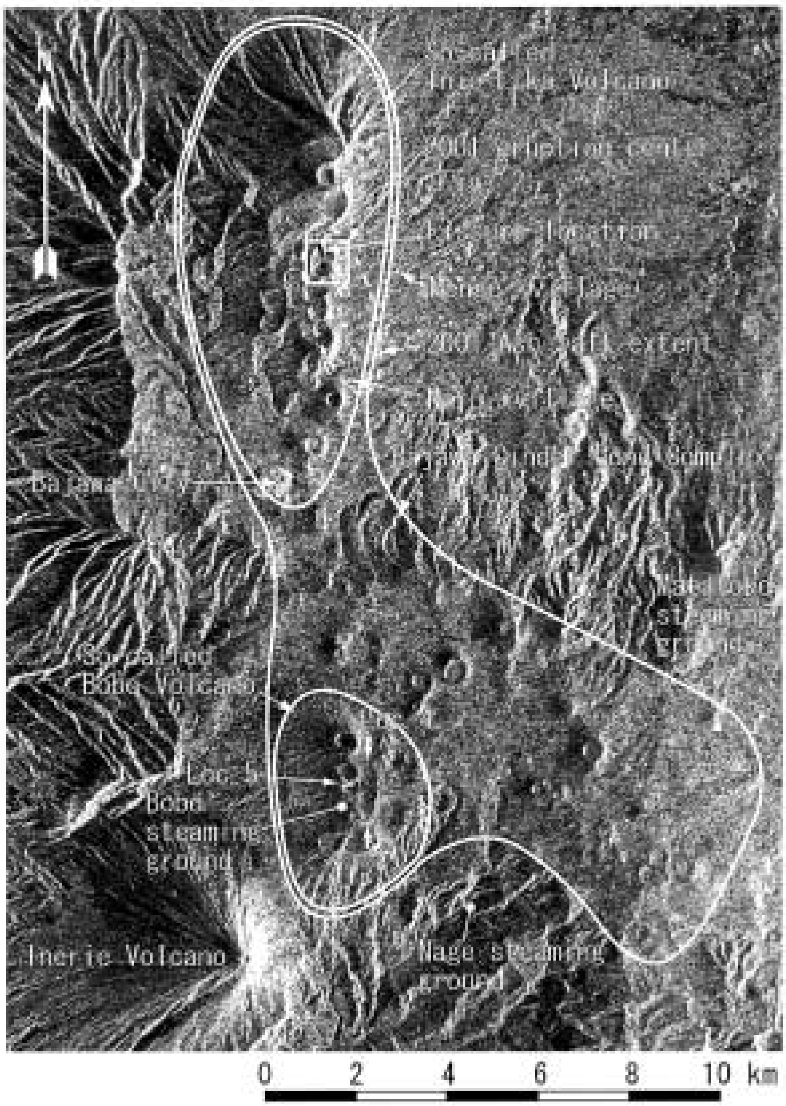

Fig. 2 JERS-1 SAR image (Urai *et al.*, 2002; Copyright METI/NASDA) showing the Bajawa Cinder Cone Complex. The extent of the 2001 ash fall of the Inie Lika volcano is also shown (broken line; Muraoka *et al.*, 2002b).

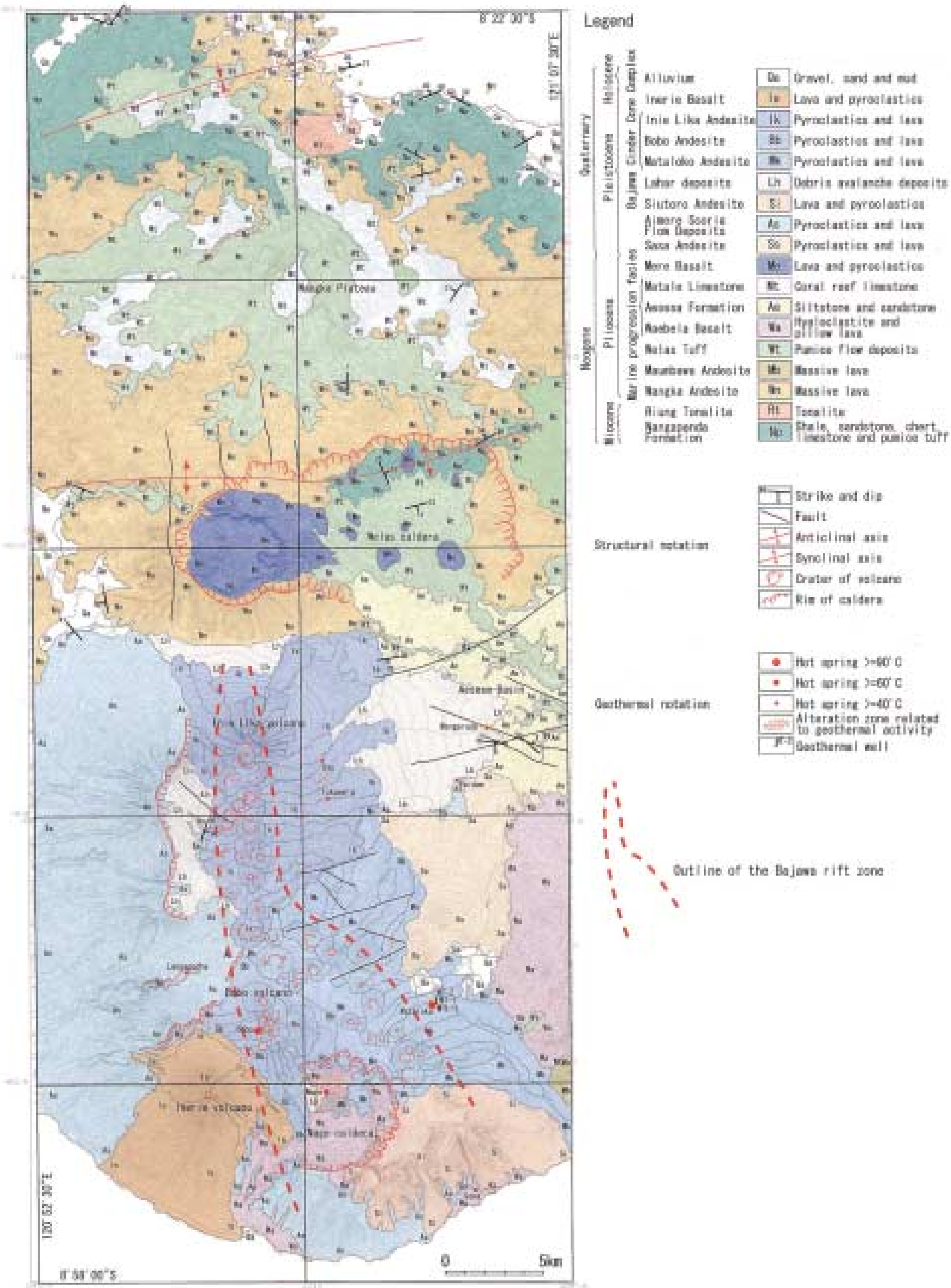

Fig. 3 Geological map of the study area (Muraoka *et al.*, 2002a).

composed of about 25 cinder cones over 10 km in the north-south direction (Fig. 2). To the south, there is the Bobo volcano that is also composed of about 10 cinder cones. Both Inie Lika and Wolo Bobo volcanoes are traditionally distinguished because of the isolation of the major volcanic edifices. However, Fig. 2 shows that small cinder cones are also aligned between them and all the elements form an almost continuous alignment over 20 km. To the southeast, at least two rows of NW-SE trending cinder cone alignments are also found as other branches contain about 25 cinder cones. When we trace all the cinder cone alignments, there seems to be a connected dike complex at a depth so that it is worth clarifying the chemical compositions of these volcanic rocks. Their lithology and eruption mode of cinder cones are similar to each other. Although the precise age seems slightly younger toward the north as shown by the historic eruption records in the northern Inie Lika volcano in 1905 and 2001 (Muraoka *et al.*, 2002b), their cones occupy almost the same stratigraphic horizon. Therefore, regardless of the isolation of volcanic edifices, they seem cognate in their origin and are called the Bajawa Cinder Cone Complex. The age of the Bajawa Cinder Cone Complex is estimated to be younger than 160 Ka by Takashima *et al.* (2002) by the thermoluminescence dating method.

In the genetical point of view, the appearance of the Bajawa rift zone is related to the north-south left-lateral shear stress accommodated between the northerly moving Australian accretion block in the east and the relatively fixed Sundaland block in the west. The Bajawa rift zone was initiated by the formation of the NNW-SSE elongated volcano in the range from 0.8 to 0.2 Ma. The Aimere Scoria Flow Deposits are a representative unit that formed the elongated volcano. The Aimere Scoria Flow Deposits are considerably dissected and their ages range from Matuyama Epoch to immediately before the activity of the Bajawa Cinder Cone Complex, suggesting a relatively long time range of products roughly from 0.8 to 0.2 Ma. It was followed by the collapse of the eastern flanks from its crest, as shown by the N-S trending 10 km wall at the west of the Inie Lika volcano in Fig. 2. The collapsed area produced the Bajawa Cinder Cone Complex. Figure 3 shows a geological map of the study area from Muraoka *et al.* (2002a) where the Bajawa Cinder Cone Complex is classified into three units, the Inie Lika Andesite (Ik), Bobo Andesite (Bb) and Mataloko Andesite (Mk) by their source cone alignments, but they occupy almost the same stratigraphic horizon. Details of geology are given in Muraoka *et al.* (2002a).

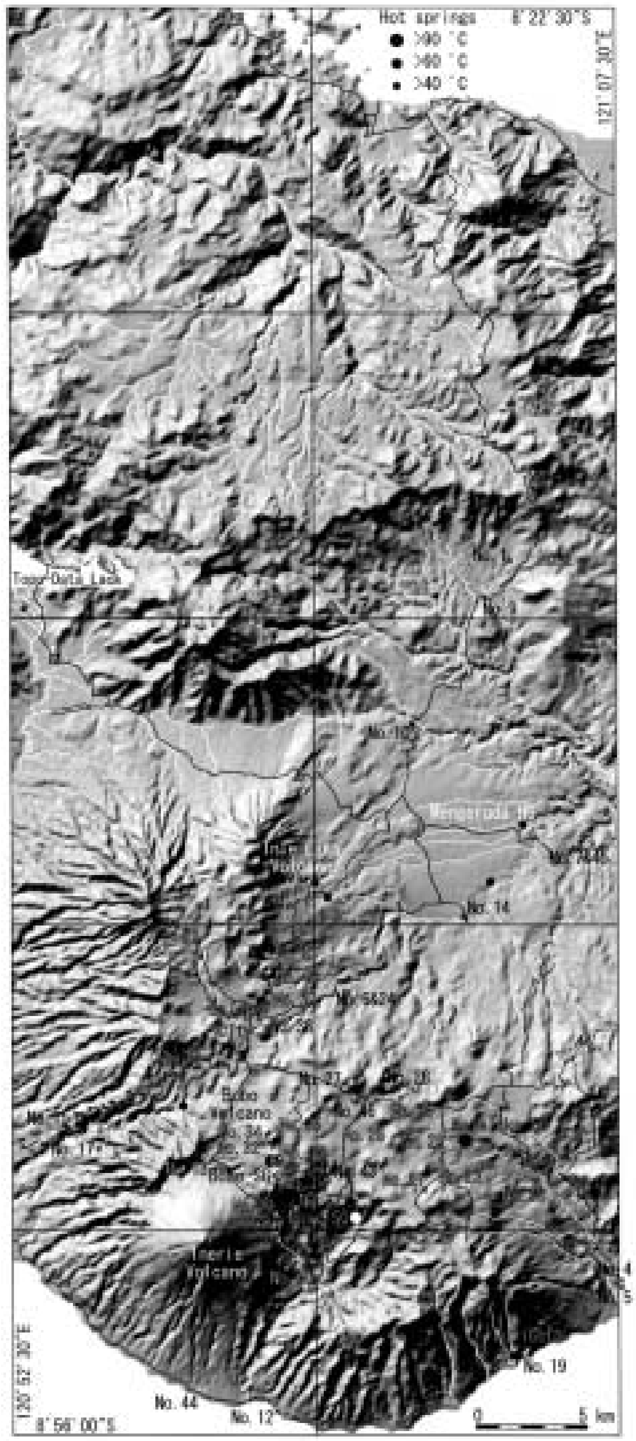

Fig. 4 Sampling locality map shown by the shaded-relief digital topographic map, central Flores, Indonesia. Numbers of sampling localities correspond to the sample numbers of Table 1. Black lines show main roads and white lines show main rivers. High temperature hot springs are also shown. Keiji Tanaka, Hirofumi Muraoka and Masao Komazawa have digitized the data from the topographic maps at a scale 1: 25,000 in this project.

Table 1 Results of multi-component chemical analyses of volcanic rocks in the Bajawa geothermal field, central Flores, Indonesia. The Fe_2O_3 values were calculated by subtracting FeO wt%/0.9 from the originally analyzed total iron values. In the analytical method column, abbreviations are as follows: LOI: Loss of ignition, A: ICP-AES method, W: Wet method, F: Weight loss in furnace, M: ICP-MS method, I: IR detector, T: Titration method and G: Gasometric analyzer.

				Component	SiO_2 (%)	TiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	FeO (%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	Cr_2O_3 (%)	P_2O_5 (%)	$+H_2O$ (%)	$-H_2O$ (%)	TOTAL (%)	LOI (%)	CO_2 (inorg)	C (%)	S (%)
				Method	A	A	A	A	T	A	A	A	A	A	A	A	W	W		F	G	I	I
				Detectability	0.01 (%)	0.01 (%)	0.01 (%)	0.01 (%)	0.01 (%)	0.01 (%)	0.01 (%)	0.01 (%)	0.01 (%)	0.01 (%)	0.01 (%)	0.01 (%)	0.01 (%)	0.01 (%)	(%)	0.01 (%)	0.20 (inorg)	0.01 (%)	0.01 (%)
Unit	Lithology	Locality	No.	Sample no.																			
Ep*	pumice in fall	Mangulewa	46	980715-02	62.37	1.15	12.51	2.31	0.81	0.08	1.79	3.12	1.06	0.41	< 0.01	0.08	5.50	7.22	98.41	12.75	< 0.2	0.06	0.07
	pumice in fall	Mengeruda	45	980725-04	60.67	0.52	16.02	2.48	3.09	0.13	2.13	6.54	2.79	1.02	< 0.01	0.08	3.88	0.55	98.71	3.75	< 0.2	0.06	0.01
Ie	lava	Waebela	44	980727-02	53.22	0.86	19.72	3.09	5.00	0.14	3.11	8.51	3.00	0.76	< 0.01	0.11	0.06	0.08	98.66	< 0.01	< 0.2	0.01	< 0.01
	scoria in fall	Lasamaza	43	980724-01	50.82	1.01	17.82	6.19	3.82	0.20	4.45	8.56	2.09	0.63	< 0.01	0.11	3.31	1.36	98.37	4.46	0.3	0.06	0.01
	pumice in fall	W of Bajawa	42	980718-01	45.04	0.81	20.58	4.74	3.94	0.15	3.81	5.47	1.49	0.31	< 0.01	0.10	5.58	5.87	97.89	11.79	< 0.2	0.08	< 0.01
Ik	lava	Wolo Ruru	41	980726-05	58.84	0.76	16.36	2.70	4.03	0.12	3.41	6.59	3.16	1.66	< 0.01	0.12	1.04	0.09	98.91	0.66	< 0.2	0.04	< 0.01
	volcanic breccia	Wolo Leboleke	40	980726-04	58.17	0.71	16.97	2.89	3.88	0.12	3.30	6.81	3.18	1.50	< 0.01	0.12	0.89	0.11	98.32	0.66	< 0.2	0.02	< 0.01
	volcanic breccia	Wolo Ngedukelu	39	980721-05	57.91	0.71	16.83	2.56	4.03	0.12	3.34	7.05	3.20	1.53	< 0.01	0.13	0.92	0.15	98.48	0.61	< 0.2	0.01	< 0.01
	volcanic breccia	Wolo Pipipodo	38	980721-04	54.97	0.82	16.83	3.09	4.80	0.13	4.32	8.18	3.00	1.31	< 0.01	0.16	0.91	0.18	98.48	0.80	< 0.2	0.01	0.01
Bb	lava	Bobo-8	37	980721-01	59.76	0.70	16.21	2.25	3.96	0.11	3.38	6.49	3.09	1.85	< 0.01	0.10	0.46	0.08	98.42	0.34	< 0.2	0.01	< 0.01
	volcanic breccia	Bobo-4	36	980720-03	59.61	0.85	16.15	2.64	3.69	0.11	3.55	6.41	2.95	1.83	< 0.01	0.10	0.40	0.14	98.31	0.45	< 0.2	0.01	0.01
	volcanic breccia	Bobo-1	35	980717-01	58.72	0.71	16.21	3.42	3.18	0.12	3.57	6.79	2.54	2.03	< 0.01	0.12	1.17	0.19	98.78	1.01	< 0.2	0.01	0.01
	volcanic breccia	Bobo-2	34	980720-01	58.20	0.69	16.60	2.65	3.81	0.12	3.87	6.66	2.92	1.59	< 0.01	0.11	0.65	0.06	98.23	0.75	< 0.2	0.02	0.01
	volcanic breccia	Bobo-5	33	980720-04	57.94	0.74	16.43	2.34	4.59	0.13	3.92	7.09	2.87	1.47	< 0.01	0.11	0.39	0.11	98.10	0.35	< 0.2	0.05	0.01
	volcanic breccia	Bobo-3	32	980720-02	57.84	0.73	16.49	2.70	4.26	0.13	4.00	7.11	2.80	1.46	< 0.01	0.11	0.56	0.03	98.61	0.78	< 0.2	< 0.01	< 0.01
	volcanic breccia	Bobo-6	31	980720-05	57.25	0.75	16.68	2.21	4.92	0.13	4.34	7.46	2.80	1.45	< 0.01	0.12	0.26	0.03	98.65	0.03	< 0.2	0.01	< 0.01
	scoria in flow	Nage	30	980716-06	56.26	0.75	16.14	3.74	3.46	0.14	3.26	7.15	3.06	1.30	< 0.01	0.11	1.00	0.32	97.33	1.93	< 0.2	0.09	0.23
	lava	Bobo-7	29	980721-02	56.24	0.76	16.75	2.84	4.83	0.15	4.05	7.40	2.74	1.39	< 0.01	0.11	0.37	0.42	98.13	0.70	< 0.2	0.05	< 0.01
Mh	volcanic breccia	Wolo Leya	28	980717-02	58.70	0.77	16.34	2.84	4.07	0.12	3.45	6.52	2.93	1.56	< 0.01	0.12	0.46	0.34	98.32	0.62	< 0.2	0.02	0.02
	lava	Wolo Lele	27	980724-06	58.27	0.78	16.45	2.65	4.13	0.13	3.40	6.51	3.18	1.56	< 0.01	0.13	0.81	0.17	98.47	0.87	< 0.2	0.01	< 0.01
	lava	Wolo Sage	26	980724-04	56.95	0.76	16.85	2.60	4.65	0.13	3.95	7.44	2.84	1.44	< 0.01	0.17	0.98	0.06	98.84	0.74	< 0.2	0.01	< 0.01
	volcanic breccia	Wolo Nawa	25	980724-05	56.89	0.76	16.74	2.19	4.97	0.13	3.90	7.30	2.85	1.43	< 0.01	0.13	1.21	0.10	98.42	0.87	< 0.2	0.02	< 0.01
	lava	Ogi	24	980717-04	56.58	0.81	16.71	3.39	4.06	0.13	4.09	7.76	2.97	1.29	< 0.01	0.14	0.04	0.06	98.07	< 0.01	< 0.2	0.01	< 0.01
	volcanic breccia	Wolo Bina	23	980724-03	56.23	0.82	16.65	3.36	4.43	0.13	3.55	7.73	2.75	1.32	< 0.01	0.17	1.05	0.18	98.37	1.03	< 0.2	0.04	< 0.01
	lava	Wolo Belu	22	980715-01	55.83	0.72	17.46	3.38	4.06	0.13	3.87	7.26	2.61	0.94	< 0.01	0.13	1.33	0.79	98.41	1.96	< 0.2	0.01	< 0.01
	volcanic breccia	Wolo Bela	21	980724-02	54.99	0.84	17.91	5.03	2.74	0.13	3.66	6.79	2.77	1.17	< 0.01	0.12	1.83	0.71	98.69	2.36	< 0.2	0.03	0.01
	lava	Laja	20	980726-01	53.53	1.01	16.30	4.78	3.87	0.14	4.72	8.55	2.90	1.44	< 0.01	0.20	0.71	0.14	98.29	0.71	< 0.2	0.05	< 0.01
Si	lava	Soka	19	980722-05	59.55	0.82	17.03	2.98	3.74	0.17	2.19	6.53	3.65	1.19	< 0.01	0.16	0.80	0.08	98.77	0.59	< 0.2	0.01	< 0.01
As	scoria in flow	Soka	18	980722-03	59.00	0.68	16.24	2.31	4.20	0.12	3.59	6.98	3.00	1.30	< 0.01	0.12	1.00	0.10	97.93	1.09	< 0.2	0.01	< 0.01
	scoria in flow	Way to Aimere	17	980718-04	57.23	0.78	16.63	2.82	4.17	0.13	3.30	7.19	3.16	1.10	< 0.01	0.17	0.94	0.34	98.16	1.26	< 0.2	0.02	0.01
	scoria in flow	Soka	16	980722-04	56.55	0.82	16.46	3.21	4.42	0.14	3.22	6.96	2.61	1.30	< 0.01	0.12	1.72	0.29	98.27	1.81	< 0.2	0.03	0.01
	scoria in flow	Way to Aimere	15	980718-03	54.06	0.82	17.14	4.20	4.00	0.14	4.29	8.42	3.16	0.95	< 0.01	0.13	0.66	0.19	98.19	0.55	< 0.2	0.02	0.01
	scoria in flow	Mengeruda	14	980725-06	49.53	0.79	22.18	7.80	0.33	0.86	1.16	0.98	0.32	0.91	< 0.01	0.06	9.65	5.02	99.84	13.93	< 0.2	0.09	0.05
We	lava	Bela	13	980721-03	50.00	1.02	18.40	3.33	6.54	0.25	4.26	10.77	2.22	0.39	< 0.01	0.10	0.39	0.63	98.30	0.74	< 0.2	0.04	0.01
	lava	Waebela	12	980727-01	49.27	0.89	19.45	3.46	5.42	0.15	4.46	11.84	2.42	0.37	< 0.01	0.10	0.47	0.39	98.40	0.53	< 0.2	0.02	0.01
Wt	lithic in flow	Laja	11	980726-03	61.07	1.29	13.75	5.03	2.97	0.16	1.67	3.80	3.12	1.96	< 0.01	0.26	1.82	0.67	98.57	2.47	< 0.2	0.04	< 0.01
	pumice in flow	Wae Nanggo	10	980723-02	59.07	0.64	13.78	6.11	1.07	0.11	1.64	3.32	1.76	1.07	< 0.01	0.09	4.79	5.22	98.66	9.66	< 0.2	0.09	0.01
	pumice in flow	Wae Nangawelu	9	980723-06	56.69	1.07	14.04	5.75	3.20	0.15	1.60	4.93	1.72	0.58	< 0.01	0.16	5.46	3.35	99.04	8.38	0.3	0.13	0.02
	pumice tuff	Laja	8	980726-02	54.55	1.23	14.96	6.74	0.57	0.15	2.42	3.96	2.68	1.41	< 0.01	0.21	5.66	1.96	98.52	7.75	< 0.2	0.25	0.01
	pumice in flow	Mengeruda	7	980725-05	54.25	1.17	14.89	8.25	1.40	0.10	2.47	5.30	1.89	0.33	< 0.01	0.10	3.80	6.27	99.97	9.14	< 0.2	0.02	< 0.01
	scoria in flow	Ogi	6	980717-03	51.02	0.87	17.97	6.78	1.52	0.12	2.06	7.10	1.86	0.52	< 0.01	0.14	3.31	5.29	98.56	8.59	< 0.2	0.08	0.01
	pumice in fall	Maumbawa	5	980722-02	46.16	0.55	12.24	3.58	3.61	0.17	3.72	15.60	1.40	0.24	< 0.01	0.07	2.25	1.20	90.79	11.34	6.7	2.27	0.04
Mb	lava	Maumbawa	4	980722-01	56.35	1.02	17.37	3.33	4.73	0.12	2.64	7.94	3.02	0.55	< 0.01	0.18	0.48	0.76	98.49	1.02	< 0.2	0.01	0.01
Wn	lava	Mulu	3	980723-04	70.94	0.38	13.18	1.47	1.16	0.08	0.76	2.70	3.30	1.98	< 0.01	0.07	2.11	0.58	98.69	2.66	< 0.2	0.02	< 0.01
	lava	Ndekonderu	2	980723-03	62.07	0.65	14.65	5.28	0.42	0.15	0.91	5.63	3.06	0.40	< 0.01	0.18	1.26	1.67	96.73	4.71	1.1	0.37	< 0.01
	lava	Weles	1	980723-05	51.67	0.86	17.90	2.54	8.30	0.15	4.06	10.17	2.36	0.73	< 0.01	0.14	0.91	0.50	98.32	0.85	< 0.2	0.04	0.01

Table 1 (Continued) Results of multi-component chemical analyses of volcanic rocks in the Bajawa geothermal field, central Flores, Indonesia. The Fe_2O_3 values were calculated by subtracting FeO wt%/0.9 from the originally analyzed total iron values. In the analytical method column, abbreviations are as follows: LOI: Loss of ignition, A: ICP-AES method, W: Wet method, F: Weight loss in furnace, M: ICP-MS method, I: IR detector, T: Titration method and G: Gasometric analyzer.

	Rb (ppm)	Ba (ppm)	Th (ppm)	U (ppm)	Nb (ppm)	La (ppm)	Ce (ppm)	Pr (ppm)	Sr (ppm)	Nd (ppm)	Sm (ppm)	Zr (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Y (ppm)	Ho (ppm)	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)
	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
	1 (ppm)	10 (ppm)	1 (ppm)	0.5 (ppm)	1 (ppm)	0.5 (ppm)	0.5 (ppm)	0.1 (ppm)	1 (ppm)	0.5 (ppm)	0.1 (ppm)	1 (ppm)	0.1 (ppm)	0.1 (ppm)	0.1 (ppm)	0.1 (ppm)	0.5 (ppm)	0.1 (ppm)	0.1 (ppm)	0.1 (ppm)	0.1 (ppm)	0.1 (ppm)
No.																						
46	26	730	8	0.5	6	7.5	13.5	1.7	230	6.0	1.3	138	0.6	1.6	0.3	1.5	7.0	0.3	1.0	0.1	0.6	0.1
45	42	225	3	0.5	6	8.0	15.5	2.1	242	8.0	2.2	64	0.7	2.0	0.3	2.6	14.0	0.5	1.6	0.2	1.4	0.3
44	30	175	3	0.5	6	9.0	19.0	2.3	308	10.0	3.1	80	0.7	2.5	0.5	2.5	14.5	0.6	2.1	0.3	1.8	0.1
43	34	340	6	1.5	8	12.0	32.5	3.7	406	13.5	3.5	105	0.8	3.9	0.6	3.6	16.5	0.7	2.1	0.3	1.5	0.3
42	22	370	14	1.0	12	16.0	45.5	4.6	296	17.0	3.3	177	1.1	3.9	0.6	4.1	19.0	0.7	2.9	0.4	2.0	0.3
41	74	390	11	2.5	8	22.5	43.5	5.1	324	18.5	3.6	138	1.0	3.4	0.6	3.7	18.5	0.7	2.2	0.3	1.5	0.4
40	66	350	8	2.0	8	18.5	35.0	4.1	338	16.0	3.4	117	1.1	3.8	0.6	3.1	17.5	0.7	1.9	0.3	1.7	0.3
39	62	340	9	2.0	8	18.0	36.5	4.3	334	18.0	3.8	120	1.2	3.2	0.5	3.2	17.5	0.7	2.0	0.3	1.9	0.3
38	52	355	8	1.5	10	24.0	42.5	5.1	442	23.0	3.7	105	1.2	4.8	0.7	4.0	19.0	0.7	2.2	0.3	2.2	0.3
37	92	395	11	2.5	8	20.5	41.5	5.1	272	19.0	4.0	144	0.7	3.8	0.6	3.2	19.0	0.8	2.4	0.4	2.0	0.4
36	90	390	10	2.0	10	19.5	37.0	4.6	278	18.5	3.4	141	0.7	3.8	0.6	3.3	17.5	0.6	1.9	0.4	2.1	0.3
35	88	340	10	2.0	9	18.5	38.0	4.6	268	17.0	4.1	129	0.6	3.8	0.6	3.4	19.0	0.7	1.6	0.4	1.9	0.3
34	72	355	8	2.0	8	16.5	33.5	3.8	290	16.0	4.1	123	0.9	3.5	0.4	3.0	16.0	0.6	2.2	0.3	1.6	0.3
33	66	330	8	2.0	8	17.0	35.0	3.8	286	14.5	3.5	120	0.8	3.1	0.5	3.3	17.0	0.6	2.2	0.2	1.9	0.3
32	72	325	9	2.0	9	17.5	35.0	4.0	286	16.0	3.0	120	0.7	3.4	0.6	4.1	17.5	0.6	2.2	0.4	1.9	0.3
31	64	315	8	2.0	8	18.0	36.5	3.8	288	16.5	3.3	111	0.6	3.6	0.6	3.0	17.0	0.7	1.9	0.4	1.6	0.2
30	84	345	10	2.5	9	17.5	36.0	3.8	296	16.0	4.1	120	0.7	3.7	0.7	3.6	19.5	0.6	2.0	0.3	2.2	0.3
29	60	315	8	2.0	8	15.5	31.5	3.9	270	16.0	3.3	108	0.6	3.3	0.5	3.3	18.5	0.7	2.0	0.3	1.8	0.3
28	68	320	8	1.5	4	14.0	27.5	3.7	282	14.5	3.2	126	0.7	3.0	0.5	3.5	19.0	0.6	2.1	0.3	2.2	0.4
27	70	380	10	2.0	8	22.0	41.0	5.2	310	21.5	4.2	129	1.2	4.2	0.6	4.6	22.0	0.9	2.3	0.4	2.5	0.4
26	60	305	6	1.5	8	18.0	36.0	4.4	320	16.5	2.8	114	0.8	3.6	0.6	3.5	16.0	0.7	1.9	0.3	1.5	0.3
25	62	310	6	1.5	10	18.5	36.5	3.9	314	16.5	3.6	114	1.2	3.9	0.5	2.8	17.5	0.6	2.0	0.3	1.8	0.3
24	54	335	7	1.5	9	19.0	38.0	4.3	340	19.0	4.2	108	1.0	3.6	0.6	3.4	16.0	0.7	2.2	0.4	1.7	0.3
23	54	295	6	1.5	6	14.5	31.0	3.6	344	15.5	3.3	102	0.9	4.0	0.6	3.6	17.5	0.7	2.0	0.4	2.4	0.3
22	32	185	5	0.5	6	10.5	21.0	2.8	330	12.0	2.6	81	1.2	2.9	0.7	3.2	16.0	0.7	2.0	0.4	1.8	0.3
21	52	350	8	2.0	8	22.0	38.0	5.3	322	23.5	4.9	129	1.3	4.7	0.7	3.7	23.0	0.9	2.4	0.4	2.0	0.4
20	56	365	10	2.0	8	24.5	49.0	5.7	546	22.5	4.2	105	1.1	4.1	0.5	3.3	18.0	0.6	2.4	0.3	2.0	0.3
19	38	245	4	1.0	6	12.0	23.5	3.2	276	13.5	2.8	117	1.1	3.9	0.6	3.8	22.0	0.8	2.5	0.4	2.0	0.4
18	66	280	7	2.0	6	11.5	26.0	3.3	262	13.0	3.8	117	0.9	3.8	0.6	3.4	18.0	0.7	2.4	0.3	1.9	0.4
17	42	535	8	1.5	6	16.5	31.0	4.2	360	16.5	4.3	111	0.9	4.7	0.8	3.8	22.5	0.9	2.4	0.4	2.2	0.3
16	48	220	5	1.5	6	10.5	20.0	2.7	288	10.5	2.9	90	0.8	3.2	0.5	3.0	16.5	0.7	2.0	0.3	1.7	0.3
15	38	280	5	0.5	6	12.5	26.0	3.5	362	14.5	3.0	87	1.1	3.6	0.6	3.3	18.0	0.7	2.6	0.4	1.8	0.2
14	78	500	5	1.5	6	10.5	26.5	2.2	82	8.5	2.1	96	0.3	2.0	0.3	1.7	8.5	0.4	1.2	0.1	1.1	0.2
13	22	115	2	< 0.5	4	4.5	10.5	1.3	228	6.0	2.6	51	0.7	3.4	0.5	3.2	18.0	0.7	2.6	0.3	2.0	0.4
12	10	105	1	< 0.5	2	5.0	10.0	1.5	318	7.5	1.8	45	0.9	2.4	0.4	2.3	12.5	0.5	1.7	0.2	1.3	0.2
11	74	450	3	0.5	2	11.5	27.5	3.9	320	18.5	5.3	132	1.8	7.1	1.0	6.8	38.0	1.5	4.5	0.5	3.8	0.5
10	34	185	1	0.5	2	8.5	19.5	3.3	154	15.5	4.6	129	1.3	6.3	1.1	7.2	39.5	1.4	4.5	0.8	3.8	0.8
9	22	195	1	< 0.5	2	6.5	16.0	2.3	200	11.5	3.6	99	1.2	4.8	0.8	5.5	27.0	1.1	3.5	0.8	2.9	0.5
8	60	190	1	< 0.5	4	7.5	18.0	2.8	204	14.0	3.0	93	1.2	5.0	0.8	5.2	29.5	1.1	3.2	0.5	2.8	0.6
7	16	220	1	< 0.5	2	6.0	12.5	1.9	282	10.0	2.8	78	0.9	3.5	0.7	3.7	21.5	0.9	2.7	0.4	2.0	0.4
6	42	290	5	0.5	8	14.0	30.0	3.3	438	13.0	2.5	69	1.2	2.8	0.4	2.4	11.5	0.5	1.8	0.3	1.1	0.2
5	14	75	< 1	< 0.5	4	2.0	4.5	0.8	230	4.0	1.7	33	0.5	1.7	0.3	2.2	11.5	0.4	1.9	0.2	1.4	0.3
4	16	125	1	< 0.5	2	5.0	12.0	2.0	228	9.5	3.4	72	1.1	3.7	0.7	4.4	24.0	0.8	2.8	0.4	2.6	0.4
3	166	500	14	3.0	2	20.0	37.0	4.5	138	20.0	5.0	189	0.9	5.1	0.9	5.4	30.0	1.2	3.2	0.6	3.5	0.7
2	8	260	4	0.5	4	14.5	32.0	4.1	224	17.0	4.3	117	1.2	4.3	0.8	5.5	30.5	1.2	3.5	0.5	4.0	0.7
1	24	170	3	0.5	2	9.0	19.5	2.4	268	10.5	2.8	78	1.0	3.7	0.6	2.4	19.5	0.8	2.1	0.3	2.0	0.3

3. Analytical methods

Volcanic rock samples taken from 46 localities in the study area have been analyzed (Table 1). Their localities are given in Fig. 4. The SiO_2, TiO_2, Al_2O_3, Fe_2O_3 as total irons, MnO, MgO, CaO, Na_2O, K_2O, Cr_2O_3 and P_2O_5 were analyzed by the Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES) method. The Rb, Ba, Th, U, Nb, La, Ce, Pr, Sr, Nd, Sm, Zr, Eu, Gd, Tb, Dy, Y, Ho, Er, Tm, Yb and Lu were analyzed by the Inductively Coupled Plasma - Mass Spectrometry (ICP- MS) method. Ignition loss (L.O.I.) was measured after heating to a temperature of 1,000 ℃ in a furnace. The H_2O (+) and H_2O (-) were analyzed by the apparatus (LECO-RMC 100) that could detect the thermal conductivity of materials drawn from the fusion chamber. The C and S were analyzed by the Infra Red Analyzer (LECO-IR DETECTOR). Inorganic CO_2 was analyzed by the gasometric detector (LECO-GASOMETRIC). The FeO was analyzed by the titration method. These analyses were done in the Chemex Labs Ltd., Canada. The results of analyses are given in Table 1 where the analytical method and its detectability for each component are described.

4. Results

4.1 Homogeneity of the Bajawa rift zone magmatism

In Table 1, samples are stratigraphically arranged from the older to younger units in ascending order. The serial numbers of samples correspond to those of the sampling location map (Fig. 4). Abbreviation of each geological unit corresponds to that of Fig. 3, except for "Ep*" that is thin pumice fall deposits probably derived from the Ebulobo volcano in the east of the study area. Sample No.5 is shown as evidence of scoria falls in the coral reef environment by the high calcium and carbon dioxide contents but is omitted in the following petrological diagrams. Likewise sample No.14 is extremely hydrated due to geothermal alteration near the Paidae hot spring so this sample is also omitted in the following discussion. As a result, there remain 44 volcanic rock samples for the following discussion. Four samples were taken from the Aimere Scoria Flow Deposits and 22 samples were taken from the Bajawa Cinder Cone Complex (the Mataloko Andesite, Bobo Andesite and Inie Lika Andesite) so that 26 samples represent the Bajawa rift zone volcanism. Porous samples are abundant and more or less hydrated. For this reason, anhydrous basis recalculation was made including minor elements before the plot on the following diagrams.

Figure 5 shows the SiO_2-(Na_2O+K_2O) diagram. All 44 samples plotted on the field of the non-alkaline series. It is noteworthy that the chemical features of the Aimere Scoria Flow Deposits (0.8-0.2 Ma) are almost the same as the Bajawa Cinder Cone Complex in spite of the difference of their ages. This proposes a concept that the Bajawa rift zone

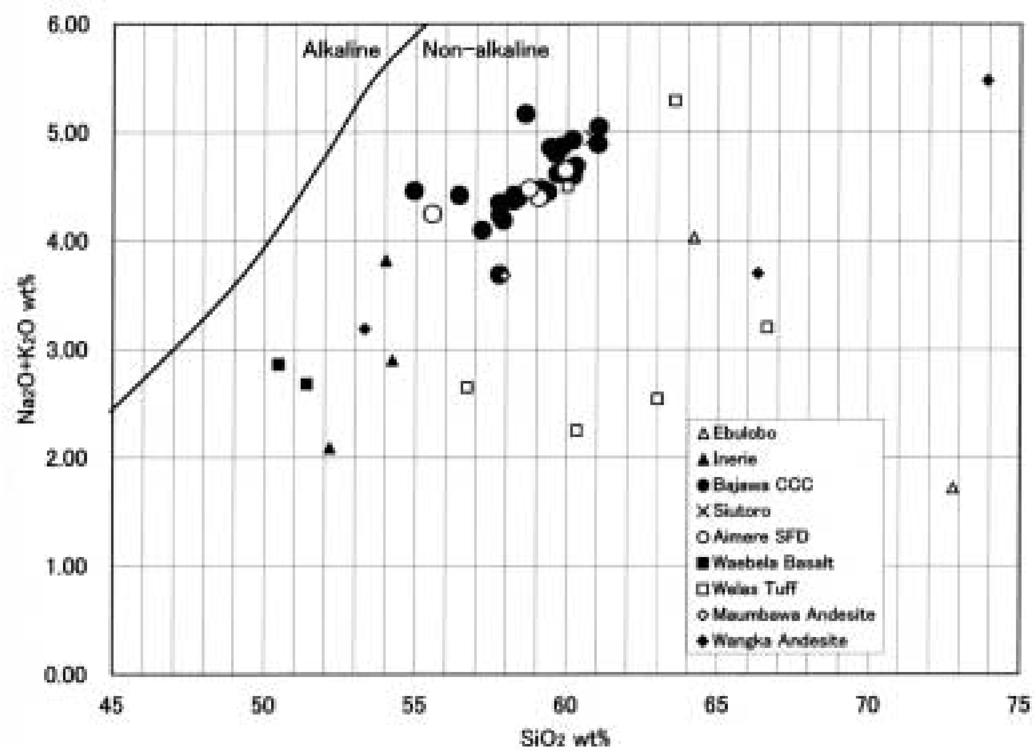

Fig. 5 The SiO_2-(Na_2O+K_2O) diagram of 44 volcanic rock samples in the Bajawa geothermal field. The thick curve shows the boundary of the alkaline and non-alkaline series by Kuno (1960).

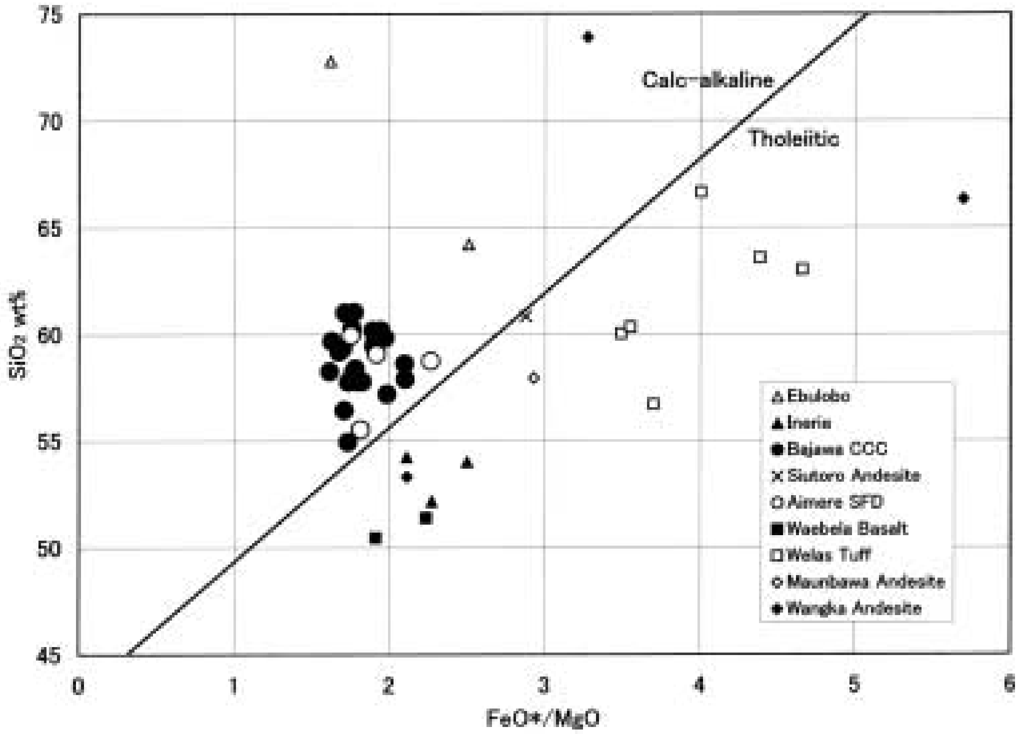

Fig. 6 The SiO_2-FeO*/MgO diagram of 44 volcanic rock samples in the Bajawa geothermal field. The thick line shows the boundary of the tholeiitic and calc-alkaline series by Miyashiro (1974).

volcanism was composed not only of the activity of the Bajawa Cinder Cone Complex but also the pre-existing elongated volcano. Therefore, the Aimere Scoria Flow Deposits and the Bajawa Cinder Cone Complex are called the Bajawa rift zone volcanic rocks hereinafter. The Bajawa rift zone volcanic rocks are quite homogeneous compared to their spatial extent, while other units are heterogeneous on the diagram.

Figure 6 shows the SiO_2-FeO*/MgO diagram. Most units are scattered and rather dominant in the tholeiitic field. However, the Bajawa rift zone volcanic rocks again form a confined cluster in the calc-alkaline field. Empirically and theoretically, calc-alkaline magma tends to rise to a shallower depth due to its buoyancy and play a major role for the geothermal heat sources in continental crust regions (Muraoka, 1997). Actually, most geothermal manifestations in the study area are closely associated with the Bajawa rift zone (Fig. 4) and indicate that the Bajawa rift zone is the major geothermal heat sources in the study area. Figure 7 shows the N-type MORB-normalized diagram where element concentrations of N-type MORB was quoted from Sun and McDonough (1989). All rocks show a typical island-arc pattern with a strong enrichment of incompatible elements (left side of the diagram) and dips of high field strength elements (e.g., Nb and Ti). The homogeneity of the Bajawa rift zone volcanic rocks (red color) is again prominent. They occupy 60 % of analyzed samples, nevertheless, their extent is confined to a narrower zone compared to other units. When we subdivide all the volcanic rocks into the Bajawa rift zone volcanic rocks, the units older and units younger than these rocks, the MORB-normalized patterns show that the incompatible elements become enriched and compatible elements become depleted with age. This may be explained by the decreasing degree of partial fusion with the change from an enriched mantle to a depleted mantle since the collision of the Australia continent. It is at least clear that the Bajawa rift zone volcanic rocks are quite homogeneous not only in major elements but also minor elements, suggesting their cognate origin. Their magma has probably been produced by partial fusion under a constant physical condition during the past 0.8 million years.

4.2 A possible shallow source of the Bajawa rift zone magmatism

In the last two decades, pseudoternary phase diagrams have been often used on the mid-ocean ridge basalt and some researchers have expanded the diagrams to the silicic region (Baker and Eggler, 1983, 1987). We try to apply these methods to the Bajawa rift zone volcanic rocks. Only 26 samples of the Bajawa rift zone volcanic rocks are treated because volcanic rocks of other units have an wide variety in composition.

Figure 8 shows the Pl-Ol-SiOr pseudoternary diagram of 26 samples of the Bajawa rift zone volcanic

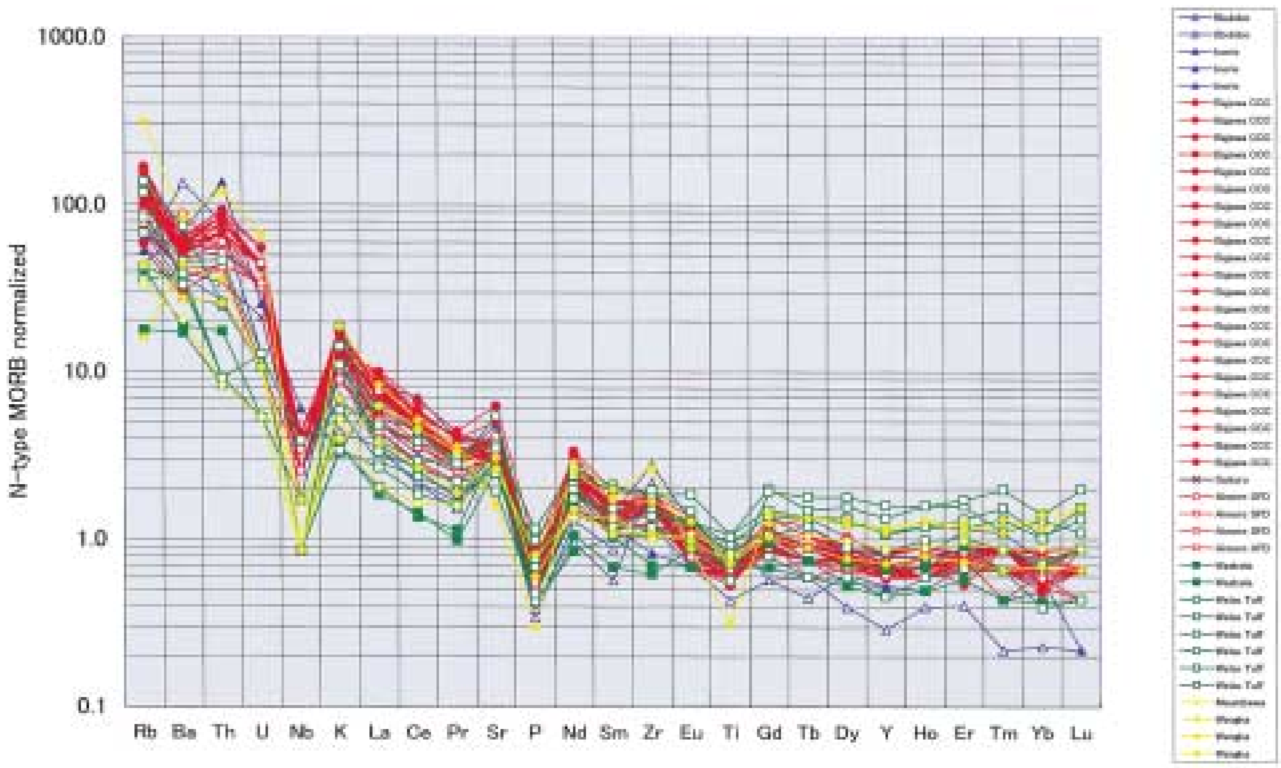

Fig. 7 The N-type MORB normalized diagram of 44 volcanic rock samples in the Bajawa geothermal field.

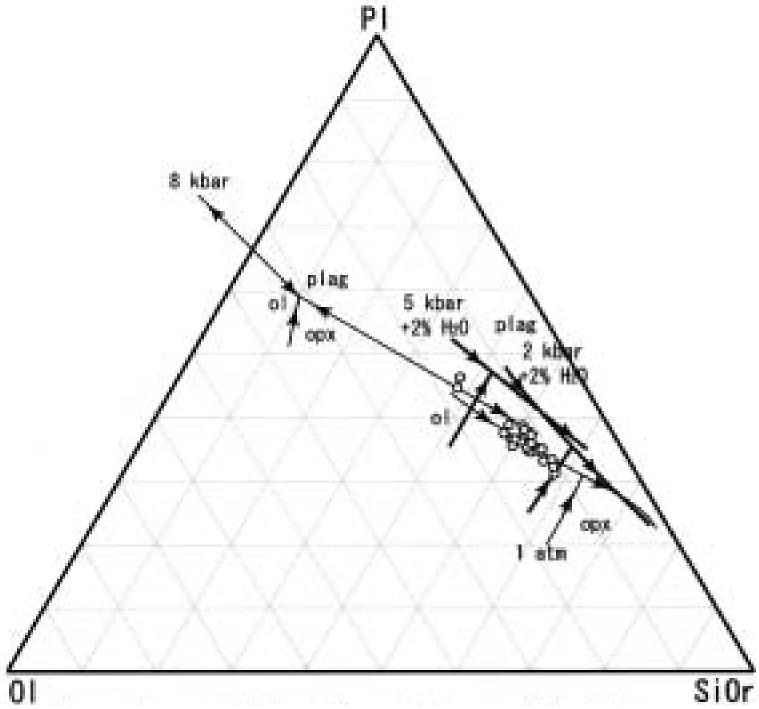

Fig. 8 The Pl-Ol-SiOr pseudoternary diagram of 26 Bajawa rift zone volcanic rock samples. Phase relations were determined by Baker and Eggler (1987).

rocks (Baker and Eggler, 1987) where Pl is plagioclase, Ol is olivine, and SiOr is quartz + orthoclase components. The calculation method of a molecular ratio of each end member followed Baker and Eggler (1983). Phase boundaries at 1 atm, 2 kbar, 5 kbar and 8 kbar were shown in the figure, but phase relations at 2 kbar and 5 kbar were determined under a hydrous condition with a 2 % H_2O addition. We cannot simply compare the pressure effect. In Fig. 8, a cluster of 26 samples is close to the phase boundary of 1 atm but is also close to 8 kbar. This diagram does not identify the pressure condition. The only information from this diagram is that the cluster is parallel with phase boundaries (pl+ol or pl+opx) at various pressure conditions. Therefore the Bajawa rift zone volcanic rocks are likely equilibrated at some pressure.

Figure 9 shows the Di-Ol-SiOr pseudoternary diagram of 26 Bajawa rift zone volcanic rock samples where Di is a diopside component. On this diagram, the cluster seems to be situated between 5 kbar and 2 kbar, particularly two samples at the dioxide poor end seem to trace a phase boundary between the olivine and orthopyroxene fields. The another information on this diagram is that if the magma represented by the cluster is driven from a higher pressure condition at 4 or 3 kbar to 2 kbar, the magma settles in the olivine-initial field even in silicic compositions. This may explain the reason why olivine phenocrysts are common in the Bajawa rift zone volcanic rocks even in andesite compositions.

Figure 10 shows the Pl-Di-SiOr pseudo-ternary diagram of 26 Bajawa rift zone volcanic rock samples. This diagram seems to identify the pressure condition, that is, the equilibrium pressure is confined between 5 and 2 kbar. The extent of silica poor side is rather close to 2 kbar. However, we realize that the pressure may not be exactly 2 kbar from Fig. 9. Therefore, 3 kbar may be adopted as the equilibrium pressure on the Bajawa rift zone magma.

The estimated pressure of 3 kbar is only about 10 km in depth. The depth may normally be ascribed to the depth of a magma chamber. However, if there exists a magma chamber at a 10 km depth, fractional crystallization inevitably occurs resulting in the heterogeneity of the magma. The homogeneity should be maintained only when the dike swarm rapidly rises from the magma source region. A subsurface dike swarm estimated from linear alignments of the Bajawa Cinder Cone Complex also suggests rift-type magmatism along a tectonic line that is incompatible with the magma chamber. The homogeneity of magma, a possible dike swarm and the presence of the rift zone are all features indicating that a depth of 10 km is rather ascribed to the magma source region. One may doubt the depth for a magma source region of the Bajawa rift zone volcanic rocks. If we consider common-type subduction magmatism, at least a 90 km depth will be required as a magma source region at a volcanic front. However, although the Bajawa rift zone is a small-scale rift in the contraction tectonic field, this zone is situated in the N-S trending left-lateral shear stress region constrained by the plate interactions (Muraoka *et al.*, 2002a). In the mid-ocean ridges, recent topics are the shallow-depth magmatism such as near the surface (Grove and Bryan, 1983) or from 4500 to 250 m (Singh *et al.*, 1998). If rift type magmatism is adopted, the 10 km depth is not surprisingly shallow as a magma source region.

Another constraint is that the thickness of continental crust is estimated to be only 5 km in the Flores Island area (Curray *et al.*, 1977). When we assume the thickness of the underlying oceanic crust is 7 km from the earth's average, a total crust thickness for Flores Island is only 12 km. It is possible that the calc-alkaline andesitic magma of the Bajawa rift zone volcanic rocks has been derived from mantle peridotite, because we have enough depth for the magma source region. However, generally calc-alkaline magma is difficult to be directly generated from the mantle peridotite as calc-alkaline magma in oceanic regions is a rare occurrence. In other words, when we consider that the magma has been derived from the bottom of the oceanic crust, the depth is limited to 12 km due to the immature continental crust.

We consider that the shear stress concentration has generated the left-lateral en echelon fractures and formed a rift zone. The rifting activity might have produced abundant tholeiite basalt magma from the upper mantle such as the Waebela Basalt, a considerable part of which might have been accommodated at the Moho discontinuity. Their heat might have caused partial fusion of the oceanic crust bottom that could be the source of the calc-alkaline magma in the Bajawa rift zone. The homogeneity of the Bajawa rift zone volcanic rocks is thus ascribed to its short pass from the magma source region at a 10 km depth to the surface and its non-stop rising as a dike swarm.

5. Conclusions

(1) Geochemical analyses of volcanic rocks in the Bajawa geothermal field show that the tholeiitic basalt to dacite are rather common in the field, but the Bajawa rift zone volcanic rocks are calc-alkaline andesite. The Bajawa rift zone plays a major role for geothermal heat sources in the study area, because of this feature.

(2) The Bajawa rift zone volcanic rocks indicate that

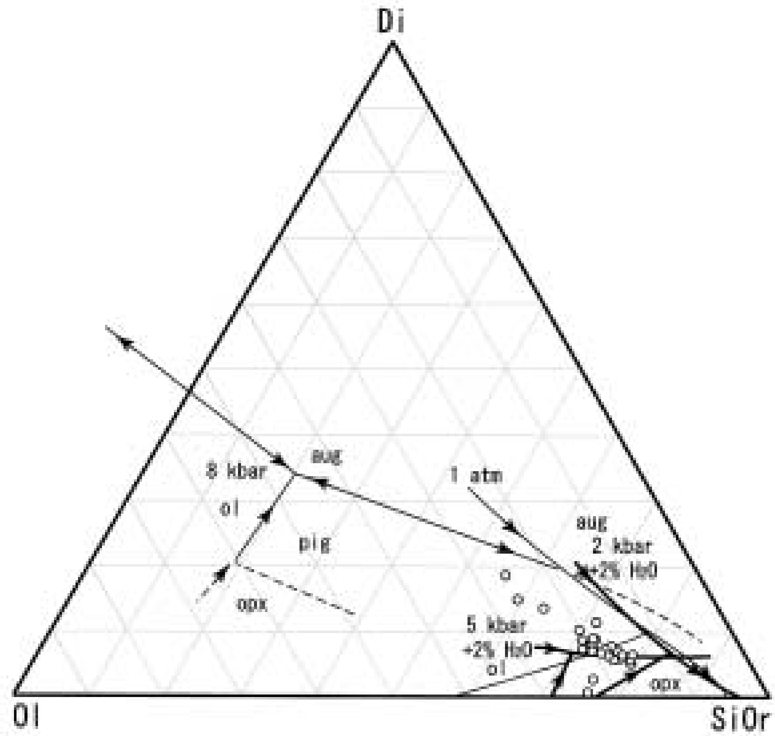

Fig. 9 The Di-Ol-SiOr pseudo-ternary diagram of 26 Bajawa rift zone volcanic rock samples. Phase relations were determined by Baker and Eggler (1987).

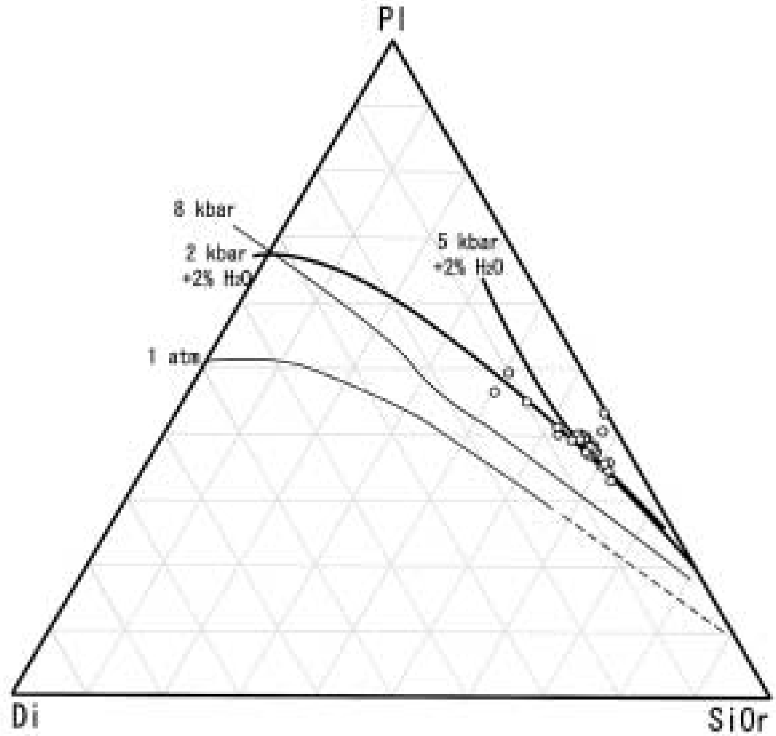

Fig. 10 The Pl-Di-SiOr pseudo-ternary diagram of 26 Bajawa rift zone volcanic rock samples. Phase relations were determined by Baker and Eggler (1983).

they are extremely homogeneous in major as well as minor components compared to their spatial extent. This supports that they originated as cognate magma in the rift type magma generation process along the Bajawa rift zone.

(3) A plot of their molecular components to the pseudoternary phase diagrams displays that the elongated extent of the cluster seems to be equilibrated on phase boundaries of the diagrams, suggesting that their magma source region is 3 kbar or 10 km in depth. The homogeneity of the Bajawa rift zone volcanic rocks is ascribed to the short path from the magma source region to the surface and its non-stop rising as a dike swarm.

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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火山岩類の地球化学的研究

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要　　旨

インドネシア・フローレス島中部バジャワ地熱地域から46個の火山岩類の多成分分析を行った．このうち26個はバジャワシンダーコーン群と呼ばれる多数のシンダーコーンを含め，バジャワリフトゾーン火山岩類から採取した．分析の結果，この地域にはどちらかといえば玄武岩からデイサイトにわたるソレイアイトが多いが，バジャワリフトゾーン火山岩類は カルクアルカリ安山岩であり，26個の試料を通じて，主成分も微量成分もきわめて均質であることがわかった．バジャワリフトゾーン火山岩類を擬似三成分系図にプロットすると，その分布は相境界に規制されており，約3 kbarあるいは10 kmの深度で平衡していたことを示す．この深さはこの地域の海洋性地殻の底に近いことから，リフト型マグマ活動がこのような浅部でのマグマ生成を可能にしたものと考えられる．バジャワリフトゾーン火山岩類のマグマの均質性はマグマ発生域から地表までの短い距離と，途中で停止することのない岩脈群としての上昇に起因している．