Bulletin of the Geological Survery of Japan, vol. 53 (2/3), p. 183-199, 2002

Geochemical characteristics of hot spring water in Bajawa area, central Flores, Indonesia

Masaaki TAKAHASHI[1], Minoru URAI[2], Kasumi YASUKAWA[3], Hirofumi MURAOKA[3], Koji MATSUDA[4], Hideo AKASAKO[4], Takehiro KOSEKI[5], Koichi HISATANI[6], Dedi KUSNADI[7], Bangbang SULAEMAN[7] and Asnawir NASUTION[8]

Masaaki TAKAHASHI, Minoru URAI, Kasumi YASUKAWA, Hirofumi MURAOKA, Koji MATSUDA, Hideo AKASAKO, Takehiro KOSEKI, Koichi HISATANI, Dedi KUSNADI, Bangbang SULAEMAN and Asnawir NASUTION (2002) Geochemical characteristics of hot spring water in Bajawa area, central Flores, Indonesia. *Bull. Geol. Surv. Japan,* vol. 53 (2/3), p. 183-199, 7 figs., 2 tables.

Abstract: Water and gas samples taken from hot and cold springs, streams, rainfall and fumaroles were analyzed geochemically to assess the geothermal resources of the Bajawa area, central Flores Island, eastern part of the Nusa Tenggara Islands, eastern Indonesia. Five prospective manifestation areas, Mataloko, Nage-Keli Tiworiwu-Wolo Bobo, Soka, Mengeruda, Gou-Tukapela, are near three active volcanoes, Inerie, Inie Lika and Ebulobo and more than 30 monogenetic volcanoes. One hot spring, Mbay, is near the northeastern seashore. Temperatures of the hot springs were >90 ℃ at the Mataloko, >75 ℃ at the Nage, >70 ℃ at the Keli Tiworiwu, >60 ℃ at the Mbay and 40 to 45 ℃ at the other areas. Geochemical characteristics of most hot water were acid sulfate type, except for Nage hot water, which is acid sulfate-chloride type. Origin of dissolved sulfate and chloride of acid hot springs was relatively low temperature volcanic gases containing hydrogen sulfide gases and interstitial water in acid alternation zone. However, dissolved sulfate and chloride of Nage hot springs may be from high temperature volcanic gases, which contain hydrogen chloride and sulfur dioxide, and interstitial water in the acid alternation zone and volcanic ash.

1. Introduction

In the modern Indonesian State, the group of island east of Bali is called Nusa Tenggara, the "Southeastern Islands", or the Lesser Sunda Islands. The Indonesian government is supporting the construction of small-scale geothermal power stations on these islands: Sembalun (5MW) on the Lombok Island and Ulumbu (3MW) on the Flores Island, through the Rural Electrification Program. Two Japanese national research organizations, the Geological Survey of Japan (GSJ) and New Energy and Industrial Technology Development Organization (NEDO) started an international cooperation program between Indonesia and Japan, named the Research Cooperation Project on Exploration of Small-Scale Geothermal Resources in the Eastern Part of Indonesia (ESSEI) in fiscal 1997. Participating organizations were the Directorate General of Geology and Mineral Resources of the Mines and Energy of the Republic of Indonesia (DGGMR), NEDO and GSJ. The Volcanological Survey of Indonesia (VSI) and Indonesian State Electricity Company (PLN) also participated in this project under the coordination of DGGMR (Muraoka and Uchida, 1999). In 1997, three GSJ researchers carried out a reconnaissance survey at five prospective geothermal fields for the ESSEI project in the eastern part of Nusa Tenggara Islands, islands of Flores, Lembata and Alor, in co-

[1] Research Center for Deep Geological Environments, GSJ
[2] Institute of Geoscience, GSJ
[3] Institute for Geo-Resources and Environment, GSJ
[4] West Japan Engineering Consultants, Inc., Watanabe-dori 2-1-82, Chuo, Fukuoka, 810-0004 Japan
[5] Mitsubishi Materials Natural Resources Development Corp., Nihonbashi Hamacho 3-21-1, Chuo, Tokyo, 103-0007 Japan
[6] New Energy and Industrial Technology Development Organization, Sunshine 60, 30F, Higashi-Ikebukuro 3-1-1, Toshima, Tokyo, 170-6030 Japan (present address: Metal Mining Agency of Japan, Tokiwa Bldg., 1-24-14 Toranomon, Minato, Tokyo, 105-0001 Japan
[7] Directorate of Mineral Resources Inventory, Jl. Soekarno-Hatta 444, Bandung, 40254 Indonesia
[8] Directorate of Volcanology and Geological Hazard Mitigation, Jl. Diponegoro No.57, Bandung, 40122 Indonesia

Keywords: geochemistry, isotope, hot spring, Bajawa, Flores, Indonesia

operation with VSI researchers (e.g. Takahashi *et al.,* 1998a, Fig.1(b)). In this study, we investigated geochemical characteristics of hot spring water in the Bajawa area, central Flores, which was selected for the project based on the 1997 reconnaissance survey, to assess geothermal resources in the area.

2. Geological background

The Nusa Tenggara Islands span a distance of 1,300 kilometers and lie 8 to 10 degrees south of the equator (Fig. 1(a)). They connect the Greater Sunda Islands in the west to the scattered islands of Banda and Maluku, and the large island of Irian Jaya to the east forming a central link in the 5,600 kilometer Indonesian archipelago. The Nusa Tenggara Islands form two distinct arcs. The long northern arc, containing Lombok, Sumbawa, Komodo, Flores, Lembata, Alor and other islands., is volcanic in origin. The islands of the shorter southern arc: Sumba, Savu, Rote, Timor and other islands, are formed of raised coral reef limestone and pelagic sedimentary rocks (e.g. Hamilton, 1979; McCaffrey, 1988). Most of these volcanic islands have the potential to provide geothermal energy (e.g. PERTAMINA, 1994). The Flores Island is in the eastern part of the Nusa Tenggara Islands and a long, narrow island 350 km long (east to west) and 20-70 km wide (north to south) (Fig. 1(b)). Bajawa City is the central part of the island and provincial capital of the Ngada prefecture. In the Bajawa area, there are two volcanic alignments (Fig. 1(c)). The southern coast side volcanic alignment is a volcanic front. Three large-scale active volcanoes, Inerie (2160 m), Inie Lika (1800 m) and Ebulobo (2150 m) form an isosceles triangle in the alignment (Fig. 1(c)). Inie Lika and Ebulobo volcanoes have records of historical eruption and have fumaroles at their summits (Simkin and Siebert, 1994). More than 30 monogenetic volcanoes also are distributed within the triangle (Fig. 1(c)). Muraoka *et al.* (1999) classified those monogenetic volcanoes into four groups, Bajawa, Mataloko, Wolo Bobo and Inie Lika. There is only one fumarolic area on the outside western crater

Fig. 1 (a) Map of Indonesia.

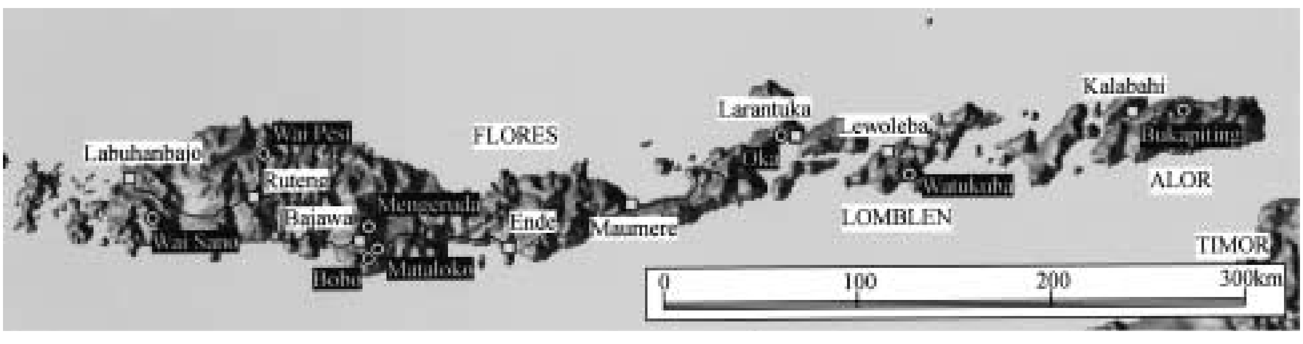

Fig. 1 (b) Map of eastern part of the Nusa Tenggara Islands (Flores to Alor).
Square; provincial capitals in the islands of Flores, Lembata and Alor; Circle with small solid circle; sampling points of hot spring water taken in 1997; Solid line: Flores highway between Labuhanbajo and Larantuka.

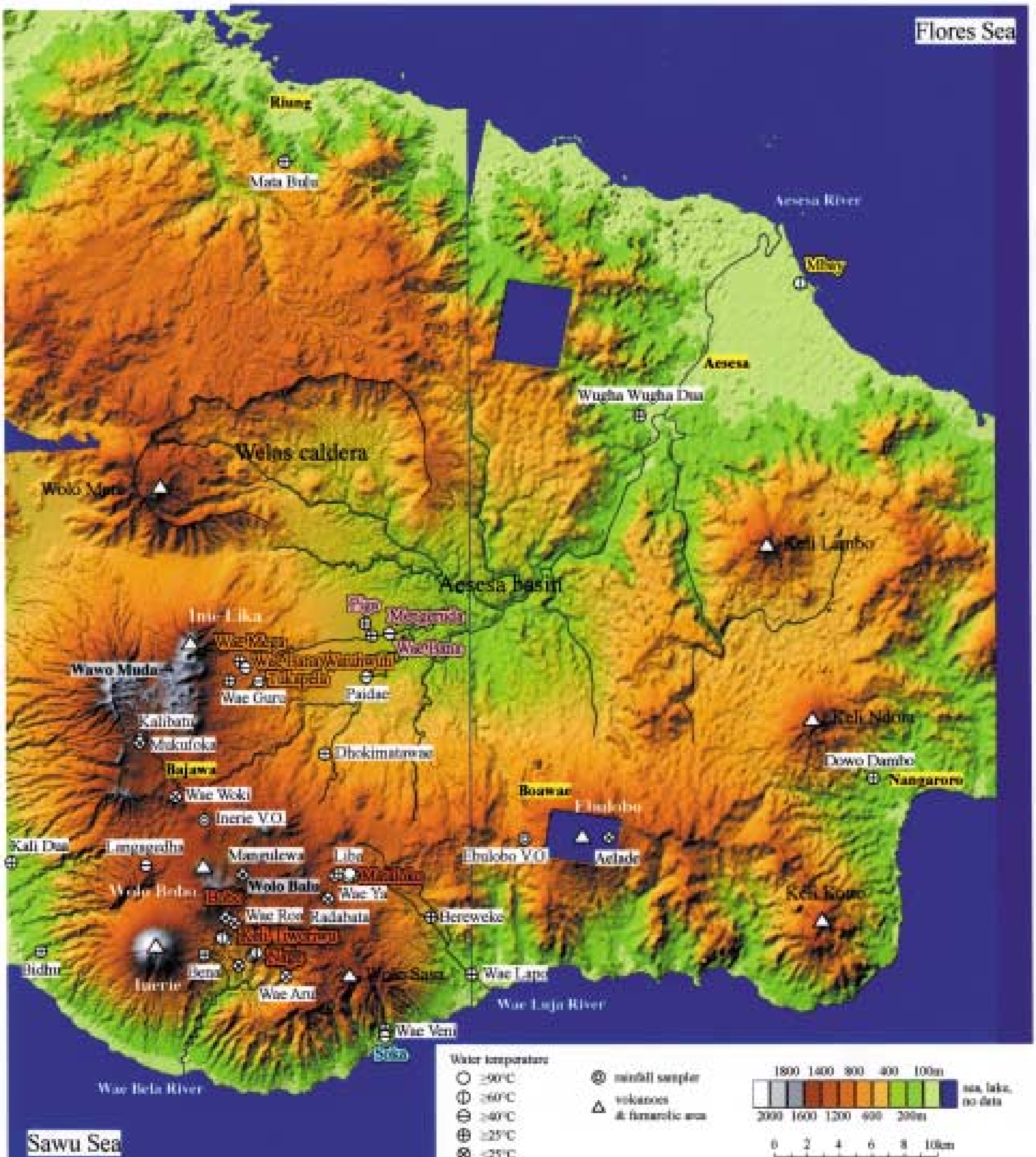

Fig. 1 (c) Locality map of sampling points for hot and cold spring water, and stream water sampled in 1997 - 1999. Colors for prospective manifestation areas; Mataloko (maroon), Nage-Keli Tiworiwu-Bobo (red), Soka (sky blue), Mengeruda (pink), Gou-Tukapela (orange) and Mbay (yellow) areas Name with yellow background; sub-provincial capital in Ngada prefecture. Name with bold white letters; active volcano and major rivers.

rim of Wolo Bobo volcano (1,400 m above sea level) and is 100 m in diameter. Temperature of the fumarolic gas was at the boiling point. The alternation zone is 300 m in diameter and forms a landslide open at the western foot. The Wawo Muda volcano, one of Line Lika monogenetic volcanoes, started to erupt on January 11, 2001, after about one hundred years of dormancy (Fig. 1(c)). The average height of the southern coast side volcanic row (plateau) is 1000-1500 m. On the other hand, the northern side volcanic alignment is a back-arc volcanic row and contains the cocoon-shaped Welas caldera 15 km (east to west) by 8 km (north to south) and post-caldera cone called Mt. Wolo Mere (1550 m). The average height of the northern side volcanic row (plateau) is 500-1000 m. This setting is similar to double volcanic belts in the northeast Japan arc (Muraoka *et al.*, 1999).

Hot springs in the Bajawa area are clustered into six groups, (1) Mataloko, (2) Nage-Keli Tiworiwu-Wolo Bobo, (3) Soka, (4) Mengeruda, (5) Gou-Tukapela and (6) Mbay (Fig. 1(c)). The first five hot spring areas are in the southern coast side volcanic alignment, but only the Mbay hot spring area is near the northeastern coast and far from the two volcanic alignments. Locality and characteristics of the hot springs in each area were summarized as follows;

(1) The Mataloko area is 11 km southeast of Bajawa City and 1000 m above sea level near the southern foot of the Wolo Balu volcano, one of the Mataloko monogenetic volcanoes (Fig. 1(c)). Thermal water higher than 90 ℃ is discharged from the steaming ground having a diameter of 150 m. However, flow rates of these hot springs are very small. The acid alternation zone is 300 m by 1000 m along the Wae Luja River.

(2) The Nage area is 11 km south-southeast of Bajawa City and 520 m above sea level, at the bottom of a small basin. The steaming field is 200 m by 500 m along the Wae Bana River, and hot water higher than 75 ℃ gushes out from three or more springs. The total flow rate of these hot springs is more than 30 tons/min. The acid alternation zone is 500 m by 1500 m near the surrounding wall of the basin. The Keli Tiworiwu area is 2.1 km northwest of the Nage area and 850 m above sea level, at the southern end of the Wolo Bobo monogenetic volcanoes. Thermal water higher than 70 ℃ flows out from two or more springs. The flow rates of these hot springs are 2-3 tons/min. In the Bobo area, 1.3 km north of the Keli Tiworiwu area and 1.8 km southeast of the fumarolic area of the Wolo Bobo monogenetic volcanoes. Low temperature fumarolic gases about 25 ℃ ooze out from the bottom of a ravine.

(3) The Soka area is 10 km south of the Mataloko area and 90 m above sea level near the southern coast. Thermal water higher than 45 ℃ is discharged from a pond. The flow rate of the spring was about 3-4 tons/min. Muraoka *et al.* (1999) categorized the closest volcanoes to the Soka hot spring into the Bajawa monogenetic volcanoes, which is the oldest monogenetic volcanoes in the Bajawa area.

(4) The Mengeruda area is 15 km northeast of Bajawa City and 310 m above sea level. Thermal water about 40 ℃ gushes out from three springs, Mengeruda, Wae Bana and Piga. The total flow rate of those hot springs was more than 30-40 tons/min. Muraoka *et al.* (1999) noted Mengeruda hot springs were located at the eastern end of the Lahar deposits of the Inie Lika monogenetic volcanoes. Thermal water may flow laterally about 11-13 km from the volcanoes to the Mengeruda area.

(5) The Gou-Tukapela area is 7.5-8.0 km north-northeast of Bajawa City and 800 m above sea level. Thermal water higher than 45 ℃ flows out from three or more springs. The total flow rate of those hot springs was large. This area was on the eastern flank of the Inie Lika monogenetic volcanoes.

(6) The Mbay area is 50 km northeast of Bajawa city and about sea level. Thermal water higher than 60 ℃ flows out from the coastal swamp area. Total flow rate of this hot spring may be more than 2-3 ton/min.

3. Sampling and analytical methods

Water and gas samples were collected from hot and cold springs, streams, rainfall and fumaroles in 1997-1999 (Tables 1 and 2). Rainfall samplers (e.g. Scholl *et al.*, 1995) were set at the Inerie and Ebulobo volcano observatories and collected rainfall for year July 1998-July 1999. Water samples from hot and cold springs and streams were filtrated immediately with 0.20-μm cellulose acetate membrane filters to avoid sample oxidation by microbial activities. Temperature, pH, electro-conductivity and redox potential were also measured. Flow rates of springs and streams were measured by the modified velocity-area method (e.g. Sato and Takahashi, 1996).

Chemical and isotopic analyses of water and gas samples were conducted by the following methods.

Bicarbonate: Methyl-red alkalinity method

Free carbon dioxide: Phenol-phthalein acidity method

Total iron: Ferro Ver method

Hydrogen Sulfide: Methylene blue method

Aluminum: Aluminon method

Other cations (lithium, sodium, ammonium, potassium, magnesium and calcium) and anions (fluoride, chloride, bromide, nitrite, nitrate, phosphate and sulfate): The Yokogawa Ion Chromatography IC-7000 model was used for measuring concentrations of cations and anions. The eluent for cation analyses was an 18 mM methanesulfonic acid solution. For anion analyses, the eluent was a 3.0 mM sodium carbonate solution and the scavenger was a 15 mM sulfuric acid solution.

Sulfur isotopic ratios ($^{34}S/^{32}S$) of dissolved sulfate of hot spring water: Dissolved sulfate was precipitated as barium sulfate. Direct conversion

Table 1 The results of chemical and isotopic analysis on hot and cold spring water, stream water, condensed water and rainfall sampled in 1997 - 1999.

sample name	date & sample number	flow rate (l/min)	Temp (°C)	pH	EC* (μS/cm)	ORP** (mV)	Na^+ (mg/l)	K^+ (mg/l)	Mg^{2+} (mg/l)	Ca^{2+} (mg/l)	Li^+ (mg/l)	NH_4^+ (mg/l)	Fe (mg/l)	Al (mg/l)	Cl^- (mg/l)	SO_4^{2-} (mg/l)	HCO_3^- (mg/l)
Mataloko area																	
Mataloko-upper	98071601	0.	88.3	2.45	2500.	176.	27.0	5.86	28.6	61.0		4.36	46.0	34.7	8.21	807.	0.00
Mataloko-upper	99090701	0.	87.2	3.1	873.	-54.											0.00
Mataloko-lower-1	97070901		92.0	3.74	490.		17.1	5.10	8.70	17.7	0.03	2.10			3.70	135.	0.00
Mataloko-lower-2	97070902		94.6	3.0	1550.		43.7	3.10	32.1	107.		8.72			2.60	741.	0.00
Mataloko-lower-2	98071701	0.	84.9	2.76	1190.	-12.	18.3	8.61	17.0	29.3		1.04	5.60	3.99	4.31	303.	0.00
Stream of Mataloko	98071602	L	26.2	7.06	240.	25.	11.2	3.08	9.02	24.1			0.02		3.35	6.14	101.
Wae Ya (spring)	98071702	LL	24.2	6.5	230.	207.	10.0	2.72	9.08	24.3		0.65	0.01		3.03	4.35	100.
Liba	98071703	S	34.8	6.66	430.	127.	16.4	5.32	22.6	42.2		0.43	0.08		3.12	13.8	203.
Nage area																	
Nage-1	98071501	10.	79.4	2.09	53000.	63.	145.	36.6	30.2	78.6	0.30	2.39	13.4	24.7	472.	795.	0.00
Nage-1	99090601	10.	80.0	2.0	4740.	19.	139.	35.0	29.1	74.1	0.29				443.	761.	0.00
Nage-2	98071502	10.	73.2	2.16	48000.	22.	137.	35.0	27.9	72.4	0.29	2.98	15.8	22.5	400.	757.	0.00
Nage-2	99090602	10.	73.4	2.0	4240.	58.	131.	33.0	27.5	70.4	0.27				387.	720.	0.00
Nage-3	98071503	10.	72.0	2.17	47000.	11.	125.	31.8	27.3	71.0	0.26	2.73	14.0	25.5	387.	731.	0.00
Nage (cold spring)	98072802	0.001	23.5	6.81	250.	175.	12.4	2.98	8.81	24.8			0.03		3.27	76.3	35.2
Wae Ara	98072803	0.06	23.3	6.93	270.	148.	16.2	2.46	7.73	23.8			0.10		4.37	91.1	24.7
Keli Tiworiwu-Wolo Bobo area																	
Keli Tiworiwu-1	98071801	0.9	52.8	3.59	1480.	-118.	74.0	30.5	50.4	136.	0.02	0.41	0.04	2.67	53.3	637.	0.00
Keli Tiworiwu-2	98071802	0.9	72.1	5.97	2100.	-256.	128.	67.7	78.5	221.		0.25	0.00	0.36	115.	1070.	43.8
Bobo (Wai Putih)	97071001		21.0	2.73	1700.		28.9	4.20	30.4	80.3					3.30	695.	0.00
Bobo (Wae Putih)	98072302	0.	21.6	2.75	1420.	-60.	21.5	4.42	19.7	51.1		0.39	3.15		4.95	512.	0.00
Wolo Bobo-1	99090801																
Wolo Bobo-2	99090802																
Bana(Wae Wonu)	98071504	M	36.2	6.49	1540.	52.	66.9	21.7	65.8	107.	0.02	0.18	0.00		43.7	574.	154.
Stream of Keli Tiworiwu	98071803	S	25.4	6.81	410.	137.	15.5	2.91	14.6	41.5		0.03	0.03		3.67	131.	47.6
Soka area																	
Soka (Wae Panu)	98072201	3.6	45.7	5.35	850.	-182.	38.8	8.08	14.0	134.			0.02		10.0	407.	11.0
Mengeruda area																	
Mengeruda	97071001		41.1	2.97	1740.		50.6	16.5	32.9	100.	0.03				104.	678.	0.00
Mengeruda	98072001	24.	41.6	2.89	1780.	422.	52.8	16.7	34.2	103.		0.21	17.8		108.	711.	0.00
Mengeruda	99090604	24.	40.9	2.8	1695.	403.	47.9	15.6	31.3	93.2					98.6	647.	0.00
Wae Bana	98072002	5.	37.2	2.85	1790.	436.	43.7	15.0	33.6	106.		0.23	15.2		96.4	679.	0.00
Piga	99090603	10-20?	39.1	2.6	1820.	410.	41.7	14.6	32.5	103.					96.5	678.	0.00
Gou-Tukapela area																	
Gou (Wae Maga)	98072003	L	35.2	3.59	1100.	-106.	30.4	6.93	23.7	118.		0.19	0.92		30.5	550.	0.00
Gou (Wae Bana Watuhwati)	98072004	S	40.5	2.47	2900.	-28.	48.7	13.2	38.6	139.		0.42	6.80		135.	985.	0.00
Tukapela (Boba-Soa)	98072101	S	47.7	1.93	7300.	70.	74.6	30.8	51.5	174.		0.93	24.5		403.	2070.	0.00
Other hot springs in Bajawa area																	
Paidao (Wae Wutu)	98072102	0.12	43.4	6.87	460.	2.	28.1	7.11	16.8	43.4		0.53	0.00		4.61	24.9	192.
Dhokimatawae	98072402	0.86	35.4	6.81	340.	152.	19.3	4.03	13.6	32.9		0.49	0.02		3.69	8.84	155.

* EC: Electro-Conductivity

** ORP: Redox potential

Table 1 continued.

sample name	date & sample number	F^- (mg/l)	Br^- (mg/l)	NO_3^- (mg/l)	PO_4^{3-} (mg/l)	H_2S (mg/l)	$\delta^{34}S$ (‰)	δD (‰)	$\delta^{18}O$ (‰)	chemical characteristics	
Mataloko area											
Mataloko-upper	98071601	0.43				0.02	-1.3	-10.4	2.0	acid	$Ca\cdot Mg\text{-}SO_4$
Mataloko-upper	99090701							-18.8	0.0		
Mataloko-lower-1	97070901	0.07		0.42				-15.5	-0.4		$Ca\cdot Na\cdot Mg\text{-}SO_4$
Mataloko-lower-2	97070902	0.29		0.15				-13.3	-0.4	acid	$Ca\cdot Mg\text{-}SO_4$
Mataloko-lower-2	98071701	0.16		0.17		1.45	-0.9	-22.7	-1.7	acid	$Ca\cdot Mg\cdot Na\text{-}SO_4$
Stream of Mataloko	98071602	0.24					0.8	-42.5	-6.3		$Ca\cdot Mg\text{-}HCO_3$
Wae Ya (spring)	98071702	0.38		3.76			-0.2	-41.4	-6.2		$Ca\cdot Mg\text{-}HCO_3$
Liba	98071703	0.25					-1.3	-43.0	-6.5		$Ca\cdot Mg\text{-}HCO_3$
Nage area											
Nage-1	98071501	4.81	1.43	0.12		1.55	13.2	-39.1	-6.0	acid	$Na\cdot Ca\text{-}SO_4\cdot Cl$
Nage-1	99090601	4.78	1.35	0.03				-33.0	-5.9	acid	$Na\cdot Ca\text{-}SO_4\cdot Cl$
Nage-2	98071502	3.77	1.26	0.11		1.25	10.6	-37.4	-5.5	acid	$Na\cdot Ca\text{-}SO_4\cdot Cl$
Nage-2	99090602	3.97	1.21	0.07				-34.4	-5.9	acid	$Na\cdot Ca\text{-}SO_4\cdot Cl$
Nage-3	98071503	4.00	1.18	0.11		2.00	10.8	-39.6	-5.9	acid	$Na\cdot Ca\text{-}SO_4\cdot Cl$
Nage (cold spring)	98072802	0.40		0.76			-3.8	-40.6	-6.5		$Ca\cdot Mg\cdot Na\text{-}SO_4\cdot HCO_3$
Wae Aru	98072803	0.15		0.23			-4.2	-29.2	-4.7		$Ca\cdot Na\cdot Mg\text{-}SO_4$
Keli Tiworiwu-Wolo Bobo area											
Keli Tiworiwu-1	98071801	0.71	0.13	0.12		19.0	5.0	-35.3	-6.4		$Ca\cdot Mg\cdot Na\text{-}SO_4$
Keli Tiworiwu-2	98071802	1.01	0.28	0.11		28.5	10.9	-33.0	-6.0		$Ca\cdot Mg\cdot Na\text{-}SO_4$
Bobo (Wai Putih)	97071001	1.15		0.67				-37.6	-6.3	acid	$Ca\cdot Mg\text{-}SO_4$
Bobo (Wae Putih)	98072302	0.47				11.5	-3.4	-38.0	-6.2		$Ca\cdot Mg\text{-}SO_4$
Wolo Bobo-1	99090801							-43.9	-7.7		
Wolo Bobo-2	99090802							-44.6	-7.7		
Bena (Wae Wewu)	98071504	0.00	0.10	3.93			14.0	-39.1	-5.6		$Mg\cdot Ca\cdot Na\text{-}SO_4$
Stream of Keli Tiworiwu	98071803	0.18		6.05			4.3	-37.0	-6.1		$Ca\cdot Mg\text{-}SO_4$
Soka area											
Soka (Wae Panas)	98072201	0.92				4.70	9.7	-31.1	-5.7		$Ca\text{-}SO_4$
Mengeruda area											
Mengeruda	97071001	0.46	0.00	0.02				-39.5	-6.5	acid	$Ca\cdot Mg\cdot Na\text{-}SO_4$
Mengeruda	98072001	0.42	0.18	0.10			13.8	-37.9	-6.0	acid	$Ca\cdot Mg\cdot Na\text{-}SO_4$
Mengeruda	99090604	0.42	0.13	0.02				-35.2	-6.4	acid	$Ca\cdot Mg\cdot Na\text{-}SO_4$
Wae Bana	98072002	0.54	0.16	0.04			13.7	-37.0	-5.9	acid	$Ca\cdot Mg\text{-}SO_4$
Piga	99090603	0.55	0.11	0.03				-35.9	-6.4	acid	$Ca\cdot Mg\text{-}SO_4$
Gou-Takapela area											
Gou (Wae Mega)	98072003	0.65	0.05	0.04		6.10	10.1	-36.2	-6.5		$Ca\cdot Mg\text{-}SO_4$
Gou (Wae Bana Watubwuti)	98072004	3.97	0.21	0.05		12.3	13.9	-33.4	-6.6	acid	$Ca\cdot Mg\text{-}SO_4$
Takapela (Boba-Soa)	98072101	10.8	0.63	0.10		3.35	16.8	-37.4	-6.5	acid	$Ca\cdot Mg\text{-}SO_4\cdot Cl$
Other hot springs in Bajawa area											
Paidae (Wae Wata)	98072102	2.02		1.02			8.1	-38.3	-6.3		$Ca\cdot Mg\cdot Na\text{-}HCO_3$
Dhokimatawae	98072402	0.22		0.78			3.0	-38.8	-6.1		$Ca\cdot Mg\cdot Na\text{-}HCO_3$

Table 1 continued.

sample name	date & sample number	flow rate (l/min)	Temp (°C)	pH	EC* (μS/cm)	ORP** (mV)	Na^+ (mg/l)	K^+ (mg/l)	Mg^{2+} (mg/l)	Ca^{2+} (mg/l)	Li^+ (mg/l)	NH_4^+ (mg/l)	Fe (mg/l)	Al (mg/l)	Cl^- (mg/l)	SO_4^{2-} (mg/l)	HCO_3^- (mg/l)
Other hot springs in Bajawa area																	
Langagedha	99083001	1.	57.0	6.9	1130.	218.	167.	49.2	14.5	22.9	0.10				30.7	120.	328.
Mbay	99090402	2-3?	76.4	7.1	18200.	137.	3610.	102.	154.	487.					6390.	760.	108.
Cold springs, streams and rainfalls in Bajawa area																	
Wae Veni	98072202	0.01	27.8	7.06	196.	120.	12.8	2.24	5.28	20.0		0.41	0.01		9.00	19.0	59.8
Wae Roa	98072301	13.	22.8	7.35	230.	113.	10.4	3.29	8.64	25.5			0.02		3.39	23.0	87.9
Wae Guru	98072401	0.07	25.3	6.01	600.	192.	20.3	4.94	20.7	73.1		0.89	0.00		4.04	191.	94.0
Makufeka	98072501	0.27	19.4	6.7	180.	149.	8.98	2.48	7.16	19.8		0.12	0.03		3.08	10.3	67.8
Makufeka	99083102	0.27	19.1	6.7	175.	228.	7.70	3.37	6.92	13.9					2.63	9.33	71.5
Wae Waki	98072502	0.006	22.1	6.66	260.	152.	10.7	1.69	10.4	29.8		0.24	0.01		4.10	1.61	118.
Wae Lapo	98072701	0.9	28.1	7.16	270.	189.	14.8	1.50	9.60	28.7			0.00		7.15	5.94	123.
Borowuku	98072702	5.	27.0	6.95	240.	184.	12.2	2.59	9.00	25.4			0.00		4.17	6.60	106.
Radabata (Wae Ba)	98072801	0.003	20.8	7.3	290.	182.	13.1	16.3	9.48	29.4		0.04	0.00		3.15	3.50	138.
Kalibatu	99083101	0.42	16.0	7.6	101.	224.	5.93	2.25	3.12	8.09		0.99			2.23	7.70	36.4
Mangulewa (Wae Roa)	99083103	10.	23.2	6.9	282.	228.	10.9	3.51	9.05	26.5					2.78	53.2	75.7
Aulade (Boawae)	99090101	0.27	23.9	6.7	184.	227.	11.3	2.52	5.23	14.9					4.13	8.98	65.9
Dowo Dambo (Nangaroro)	99090102		30.2	7.1	428.	218.	25.5	2.44	16.5	39.0					7.48	8.46	206.
Mata Bulu (Riung)	99090201	0.18	29.8	7.1	583.	214.	13.7	1.95	13.3	34.8					8.13	13.1	151.
Kali Dua (Aimere)	99090301	0.24	27.2	7.3	330.	208.	21.1	3.34	13.3	27.0					5.32	7.14	157.
Bidha (Enam Dena)	99090302		28.5	7.9	337.	184.	18.4	3.60	10.6	28.8					10.9	58.7	81.8
Wagha Wagha Dua (Aesesa)	99090401		29.2	7.1	756.	208.	34.8	2.49	21.4	54.3					21.3	122.	150.
Inerie VO rainfall	98.7-99.9																
Ebulobo VO rainfall	98.7-99.9																
Western part of Flores island																	
Wai Sano Lake Water	970707*1		26.8	2.61	2980.												
Wai Sano 1	97070701		41.1	5.71	6760.		1050.	89.0	45.3	236.	2.27	1.82			2150.	63.4	189.
Wai Sano 2 (Bobok)	97070702		83.9	6.07	51100.		9540.	1260.	165.	1990.	22.7				20000.	300.	67.1
Wai Sano 3	970707*2		43.3	3.22	12700.												
Wai Sano 4	970707*3		45.0	3.18	12520.												
Wai Pesi 1	97070801		76.8	6.84	16300.		2320.	113.	46.5	961.	0.29				5460.	260.	36.6
Wai Pesi 2	97070802		89.0	6.75	17400.		2470.	120.	43.1	1050.	0.31				5920.	232.	20.3
Eastern part of Flores island																	
Oka-Larantuka	97071101		57.4	6.83	10780.		1980.	179.	174.	132.	0.35				3360.	399.	260.
Lembata island																	
Karangora fumarole	970713*1		98.6														
Karangora (Waiwejak)	97071301		37.4	7.98	370.		18.0	2.80	13.0	36.3					12.1	16.7	134.
Alor island																	
Alor 1 (Bukapiting)	97071501		b.p.	7.91	9260.		1570.	76.1	29.9	247.	0.94	4.15			2770.	256.	52.9
Alor 2 (Bukapiting)	97071502		b.p.	7.5	9390.		1570.	77.6	27.9	256.	0.94	3.20			2760.	256.	61.0
Alor 3 (Bukapiting)	97071503		b.p.	7.91	9560.		1620.	78.9	27.1	267.	1.00				2870.	254.	48.8

* EC: Electro-Conductivity

** ORP: Redox potential

Table 1 continued.

sample name	date & sample number	F	Br^-	NO_3^-	PO_4^{3-}	H_2S	$\delta^{34}S$	δD	$\delta^{18}O$	chemical characteristics	
		(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(‰)	(‰)	(‰)		
Other hot springs in Bajawa area											
Langagedha	99083001	0.13	0.11	0.29				-40.0	-7.3		$Na\text{-}HCO_3\cdot SO_4$
Mbay	99090402	1.85	21.3	4.11				-20.6	-4.0		Na-Cl
Cold springs, streams and rainfalls in Bajawa area											
Wae Veni	98072202	0.12		1.40			5.6	-24.9	-4.6		$Ca\cdot Na\cdot Mg\text{-}HCO_3\cdot SO_4$
Wae Roa	98072301	0.46		3.58			7.0	-43.3	-6.8		$Ca\cdot Mg\text{-}HCO_3\cdot SO_4$
Wae Gura	98072401	0.39		0.81			6.6	-39.2	-6.3		$Ca\cdot Mg\text{-}SO_4\cdot HCO_3$
Makafoka	98072501	0.38		2.55			4.7	-40.9	-6.6		$Ca\cdot Mg\text{-}HCO_3$
Makafoka	99083102	0.38		2.96	0.06			-37.5	-7.1		$Ca\cdot Mg\cdot Na\text{-}HCO_3$
Wae Woki	98072502	0.22		2.81			8.4	-39.7	-6.2		$Ca\cdot Mg\text{-}HCO_3$
Wae Lapo	98072701	0.25		2.58			5.9	-27.0	-4.5		$Ca\cdot Mg\cdot Na\text{-}HCO_3$
Berewoka	98072702	0.15		2.08			5.8	-33.9	-5.6		$Ca\cdot Mg\cdot Na\text{-}HCO_3$
Radabata (Wae Ba)	98072801	0.21					7.4	-36.0	-6.4		$Ca\cdot Mg\text{-}HCO_3$
Kalibatu	99083101	0.43		0.33				-37.1	-7.0		$Ca\cdot Na\cdot Mg\text{-}HCO_3\cdot SO_4$
Mangulewa (Wae Roa)	99083103	0.63		2.06	0.09			-40.4	-7.2		$Ca\cdot Mg\text{-}SO_4\cdot HCO_3$
Aelado (Boawae)	99090101	0.24		4.96				-37.9	-6.8		$Ca\cdot Na\cdot Mg\text{-}HCO_3$
Dowo Dambo (Nangaroro)	99090102	0.16		1.68				-30.0	-5.7		$Ca\cdot Mg\cdot Na\text{-}HCO_3$
Mata Bulu (Riung)	99090201	0.23		1.24				-32.1	-6.4		$Ca\cdot Mg\text{-}HCO_3$
Kali Dua (Aimere)	99090301	0.51		2.40				-27.3	-5.9		$Ca\cdot Mg\cdot Na\text{-}HCO_3$
Bidhu (Enam Desa)	99090302	0.48	0.02	2.10	0.47			-34.7	-6.8		$Ca\cdot Mg\cdot Na\text{-}SO_4\cdot HCO_3$
Wugha Wugha Dua (Aesesa)	99090401	0.42	0.05	0.57				-28.8	-5.9		$Ca\cdot Mg\cdot Na\text{-}SO_4\cdot HCO_3$
Inerie VO rainfall	98.7-99.9							-44.7	-7.9		
Ebulobo VO rainfall	98.7-99.9							-38.9	-7.1		
Western part of Flores island											
Wai Sano Lake Water	970707*1									acid	
Wai Sano 1	97070701	0.62	6.39	0.38				-28.0	-4.8		Na-Cl
Wai Sano 2 (Bobok)	97070702	6.34	59.2	1.63				-30.5	4.4/4.3		Na-Cl
Wai Sano 3	970707*2										
Wai Sano 4	970707*3										
Wai Pesi 1	97070801	2.09	18.2	0.62				-21.9	-4.4		Na·Ca-Cl
Wai Pesi 2	97070802	2.34	19.7	0.32				-23.8	-4.6		Na·Ca-Cl
Eastern part of Flores island											
Oka-Larantuka	97071101	1.06	11.3	0.42				-33.8	-5.2		Na-Cl
Lembata island											
Karangora fumarole	970713*1										
Karangora (Waiwejak)	97071301	1.08		24.7				-32.1	-5.7		$Ca\cdot Mg\cdot Na\text{-}HCO_3$
Alor island											
Alor 1 (Bukapiting)	97071501	1.25	9.27	0.32				-29.1	-4.1		Na-Cl
Alor 2 (Bukapiting)	97071502	1.40	9.25	0.23				-28.2	-3.9		Na-Cl
Alor 3 (Bukapiting)	97071503	1.56	9.66	0.26				-26.2	-4.2		Na-Cl

Table 2 The results of chemical and isotopic analysis on fumarolic gas from the Wolo Bobo fumarolic area and bubble gas from the Mataloko hot spring.

sample	date & sample number	Tempetature (C)	water (%)	acid gas (%)	R gas (%)	CO2 (% in acidic gas)	H2S (% in acidic gas)
Wolo Bobo	99090801	95.6	95.84	4.06	0.10	99.065	0.935
Wolo Bobo	99090802	95.6	97.00	2.94	0.06		
Mataloko	99090901	84.4		94.15	5.85	99.661	0.339

sample	date & sample number	H_2 (% in R gas)	N_2 (% in R gas)	CH_4 (% in R gas)	He (% in R gas)	Ar (% in R gas)	O_2 (% in R gas)
Wolo Bobo	99090801	0.036	98.7	0.511	0.072	0.401	0.187
Mataloko	99090901	13.2	80.1	5.67	0.034	0.819	1.60

sample	date & sample number	$\delta^{13}C$ (‰)	$\delta^{34}S$ (‰)	$^3He/^4He$ ($\times 10^{-6}$)	$^4He/^{20}Ne$
Wolo Bobo	99090801	-4.6	-3.0	5.02±0.06	8.0
Mataloko	99090901	-2.8	-0.1	6.52±0.08	17.

method of barium sulfate to sulfur dioxide by vanadium pentoxide (Ueda *et al.*, 1991) was employed. The Finnigan-MAT Mass Spectrometer DELTA-E model was used for analyzing sulfur isotopic ratios of sulfur dioxide.

Hydrogen and oxygen isotopic ratios (D/H and $^{18}O/^{16}O$) of water samples: For the measurement of hydrogen isotopic ratios of water, the automatic H_2-H_2O equilibration method with Pt catalyst was employed, whereas the automatic CO_2-H_2O equilibration method was used for the measurement of oxygen isotopic ratios of water samples (Takahashi *et al.*, in preparation). The Finnigan-MAT Mass Spectrometer Delta-S model was used for analyzing hydrogen and oxygen isotopic ratios of H_2 and CO_2, respectively.

Fumarolic gas and condensed water from the Wolo Bobo fumarolic area and bubble gas from the Mataloko hot spring were taken by the two-mouth syringe method. Residual gases (H_2, N_2, O_2, CH_4, He, Ar) were separated from acidic gases (CO_2, H_2S (+SO_2), HCl gases) by an addition of 5-10 ml of 8 N KOH solution into the syringe. Gas/water ratios and acidic gas/residual gas ratios were calculated from their volumes (Ozawa, 1966).

CO_2 gas compositions: The Shimadzu Total Organic Carbon Analyzer TOC-5000A model.

Total sulfur (H_2S+SO_2): The Perkin Elmer ICP Optima 3000XL model.

HCl: The Yokogawa Ion Chromatography IC-7000 model.

Residual gas compositions: Gas chromatography by the Shimadzu GC-9AM and GC-14B models on a 5 m molecular sieve 5A column with TDC and FID detectors, respectively. The O_2 carrier gas was used for the measurement of H_2, N_2, He and Ar gas compositions, whereas the Ar carrier gas was used for O_2 gas compositions. The He carrier gas was used for the measurement of CH_4 gas compositions.

4. Results and discussions

Chemical compositions of water samples

The piper diagram of hot and cold springs, and stream water in Bajawa area was made in order to know their geochemical characteristics (Fig. 2).

Most cold spring and stream water and neutral-pH hot water of the Bajawa area were classified into carbonate hardness type (type I) and noncarbonate hardness type (type II). Most acidic hot springs of this area were plotted on the upper right-side axis of noncarbonate in the diagram. It has been clarified that most artesian type of subsurface water in Japan were distributed in type I and hot/mineral spring water except for the seawater origin in type II on the diagram (e.g. GSJ, 1978, p.520-522). Thus, most water in the Bajawa area originate from an artesian type of subsurface water and/or hot/mineral spring water except for those of seawater origin.

Water samples from Nage and Mbay are a noncarbonate alkali type (type III). Water samples from Wai Sano (western Flores, Fig. 1(b)), Wai Pesi (central Flores, Fig. 1(b)), Bukapiting (Alor, Fig. 1(b)) are also a type III. Only Nage hot water is an acid sulfate-chloride type, whereas other hot spring water is a neutral sodium-chloride type. Wai Pesi and Bukapiting hot water were from Neogene marine layers (e.g. Takahashi *et al.*, 1998a). Wai Sano hot water is from a small geyser near the crater lake of the Wai Sano Volcano (Takahashi *et al.*, 1998a).

Water sample from Langagedha was the only one sample distributed in carbonate alkali type (type IV), which shows the existence of stagnant groundwater (e.g. GSJ, 1978, p. 520-522).

The relation between dissolved chloride and sulfate of water samples

Geochemical characteristics of most hot water from Mataloko, Keli, Soka, Mengeruda and Gou-

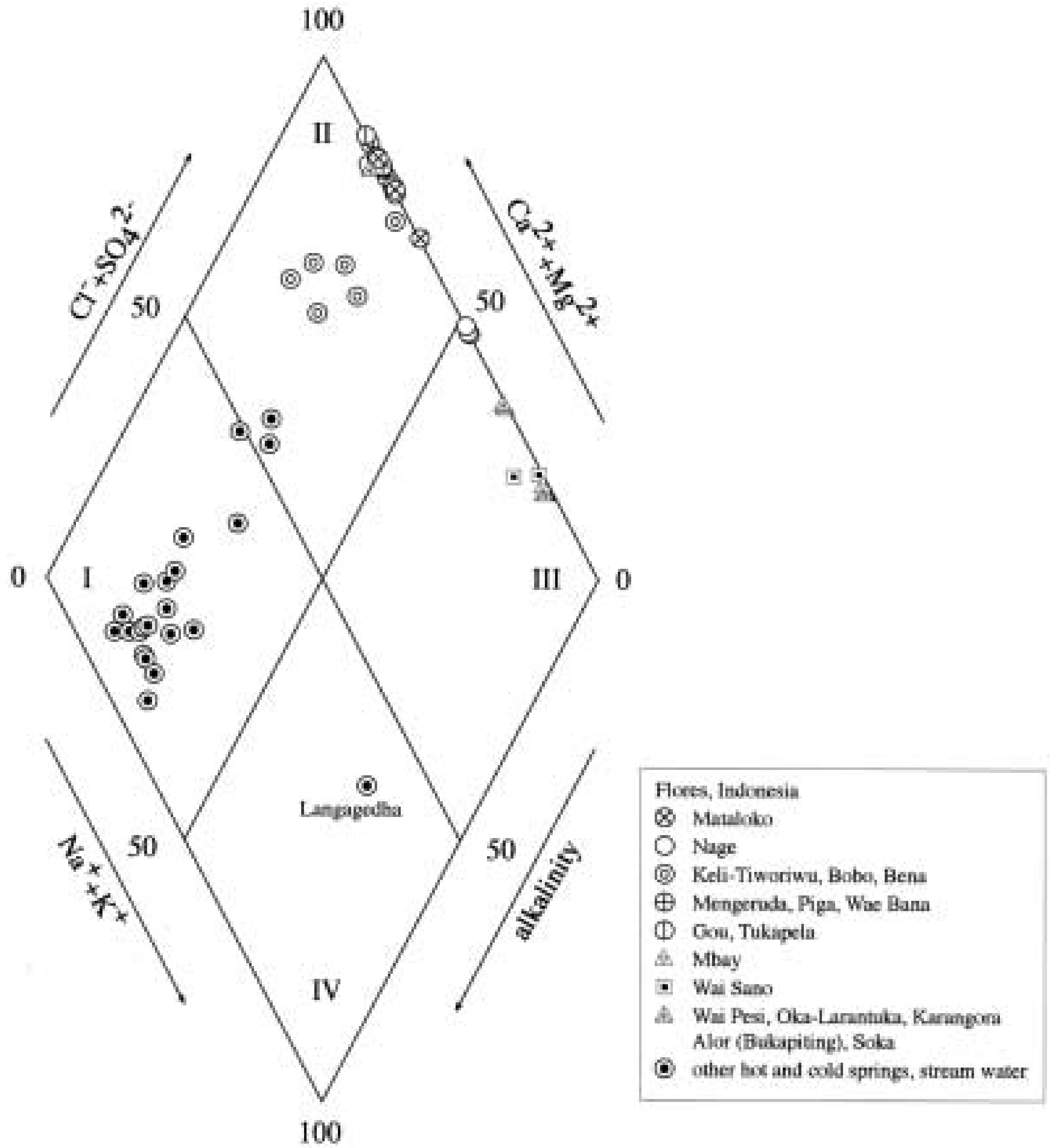

Fig. 2 The piper diagram of thermal and cold springs, and stream water in the Bajawa area.
The piper diagram is the rhombus diagram (GSJ, 1987, p. 520-522). Each point on the diagram shows anion (Cl^-+SO_4^{2-} or alkalinity) and cation (Na^++K^+ or Ca^{2+}+Mg^{2+}) concentrations in percent-equivalents per liter. Alkalinity show weak acid concentrations, which are composed mainly of carbonate and bicarbonate ions.

Tukapela areas were an acid sulfate type ($SO_4/Cl > 4$ in equivalent ratio), except for Nage hot water, which was classified into an acid sulfate-chloride type ($1 < SO_4/Cl < 4$ in equivalent ratio; Fig. 3). Acid sulfate type hot water in the Bajawa area was plotted on the diagram among type "F/G" and type "H" source water, and meteoric water (stream water; Fig. 3). Noda and Takahashi (1992) described that dissolved sulfate contained in the type "F/G" source water originated from the oxidation of hydrogen sulfide in relatively low temperature volcanic gases. Noda and Takahashi (1992) described also that dissolved sulfate and chloride in the type "H" source water was from those in the interstitial water in the acid alternation zone. Thus, most acid hot water in the Bajawa area was likely formed by mixing relatively low temperature volcanic gases containing hydrogen sulfide gas, and interstitial water in the acid alternation zone.

Only Nage hot water, which is an acid sulfate-chloride type, was plotted among hot water types "A", "H" and "V". Noda and Takahashi (1992) described that dissolved sulfate contained in the type "A" source water originated from a self reduction-oxidation reaction of sulfur dioxide and dissolved chloride in the water originated from hydrogen chloride. Both sulfur dioxide and hydrogen chloride gases are contained in high temperature volcanic

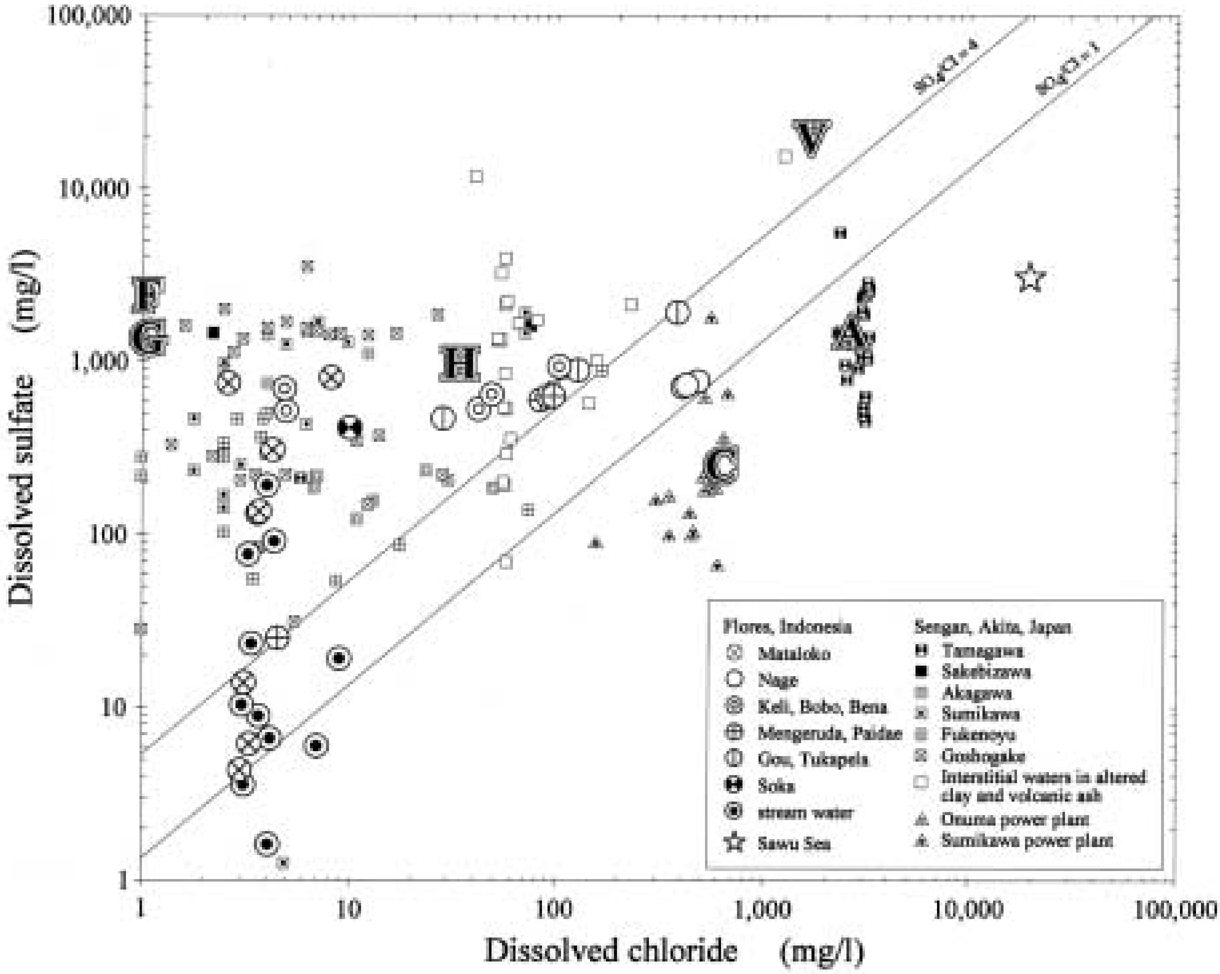

Fig. 3 The relation between dissolved chloride and sulfate of thermal spring water in the Bajawa area, and in the Sengan area, northeastern Japan.

Large letters, A, C, F, G and H were from the classification scheme of Noda and Takahashi (1992) and the letter of V from Takahashi *et al.* (1998b). Geochemical characteristics of hot water of the most geothermal power plants in Japan are concordant with type "C" source water, which is a neutral sodium chloride type. Geochemical characteristics of type "A", "F/G" and "H" source water and "V"-letter noted water are shown in the text.

Under the line noted $SO_4/Cl=1$, the dissolved chloride of water is higher than 50 percent-equivalents per liter (%-eq/l), which is called chloride type water. Above the line noted $SO_4/Cl=4$, the dissolved sulfate of water is more than 80 %-eq/l, which is called sulfate type water. Between these two lines, the dissolved sulfate of water is 50-80 %-eq/l, which is called sulfate-chloride type water (e.g. GSJ, 1978, p. 540-550).

gas. Takahashi *et al.* (1998b) found that chemical compositions of the interstitial water, which was centrifuged from altered clay in the acid alternation zone and volcanic ash of the 1998 phreatic eruption of Akita-Yakeyama volcano, in northeast Japan, were plotted in the diagram near the "V"-letter-noted water and the type "H" source water. Thus, Nage hot water was likely formed by mixing relatively high temperature volcanic gases containing sulfur dioxide and hydrogen chloride gases, and interstitial water in the acid alternation zone or volcanic ash.

The relation between dissolved sulfate and its sulfur isotopic ratio of water samples

The relation between dissolved sulfate and its sulfur isotopic ratio of hot and cold springs, and stream water in the Bajawa area was plotted in a V on the diagram (Fig. 4). The relation of volcanic hot water, seawater and hot water from greentuff regions and granitic provinces in Japan was also distributed in a V in the diagram. In the Bajawa area, Mataloko hot water was plotted on the left side of the V and have -1.8 to +0.8 ‰ sulfur isotopic ratios. Nage and Keli Tiworiwu hot water was distributed on both sides of the V and have -4.2 to +13.2 ‰ sulfur isotopic ratios. Several sulfur isotopic studies (e.g. Hoefs, 1980; Sakai and Matsuhisa, 1996) show volcanic hot water originated from the oxidation of hydrogen sulfide in volcanic gases is rich in ^{32}S (and

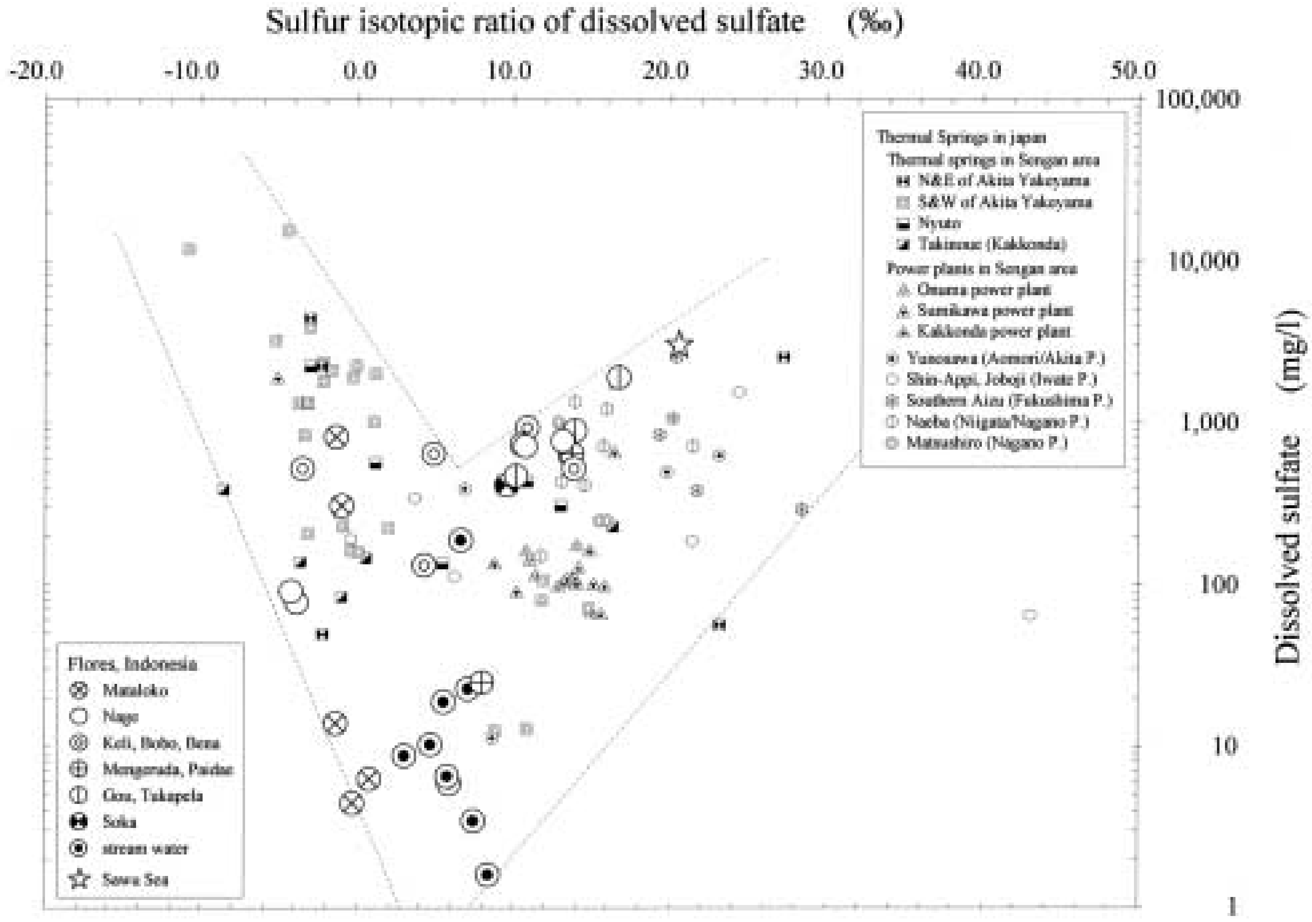

Fig. 4 The relation between dissolved sulfate and its sulfur isotopic ratio of thermal and cold spring water, and stream water in the Bajawa area, and several types of volcanic thermal water in Japan.
Standard deviation for the measurement of sulfur isotopic ratio of dissolved sulfate is ±0.2 ‰.

lie left of the V in the diagram). The NEDO (1991) noted hot springs around Akita Komagatake volcano, southern part of the Sengan area, were plotted on both sides of the V in the diagram (Nyuto and Kakkonda areas). These areas were classified into Rank A volcanic geothermal resources where at least one hot spring is >90 ℃ (e.g. Yamaguchi *et al* , 1992). Thus, these areas hot water were affected from volcanic activities and originated from the oxidation of hydrogen sulfide and/or sulfur dioxide in volcanic gases.

On the other hand, the hot water of Mengeruda, Gou and Soka, however, was plotted only on the right side of the V and have +9.7 to +16.8 ‰ sulfur isotopic ratios. Several sulfur isotopic studies (e.g. Hoefs, 1980; Sakai and Matsuhisa, 1996) also describe that (i) geothermal fluids from power plants, (ii) volcanic hot water originated from a self reduction-oxidation reaction of sulfur dioxide in high temperature volcanic gases, (iii) hot spring water from Rank B volcanic geothermal resources where no hot springs are >90 ℃ (e.g. Yamaguchi *et al*, 1992), (iv) seawater and (v) hot water from greentuff regions and granitic provinces, are rich in ^{34}S (and lie right side of the V in the diagram). Meteoric water and stream/river water are at the bottom of the V and have +4.7 to +8.4 ‰ sulfur isotopic ratios. Plotted region of hot water from Mengeruda, Gou and Soka was close to hot water of Naeba, Yunosawa and Matsushiro, which was classified into Rank B volcanic geothermal resources. Thus, the Mengeruda, Gou and Soka geothermal resources may not be as prospective as Mataloko, Nage and Keli geothermal resources.

The relation between hydrogen and oxygen isotopic ratios of water samples

The relation between hydrogen and oxygen isotopic ratios of hot and cold spring water sampled in 1997 - 1999 is shown in Fig. 5. Mataloko hot water was distributed along a line, which has an inclination ($\delta D/\delta^{18}O$) of 4.3 in the diagram, indicating evaporation at 130 ℃ (e.g. Horita *et al.*, 1995). On the other hand, Wai Sano hot water was plotted

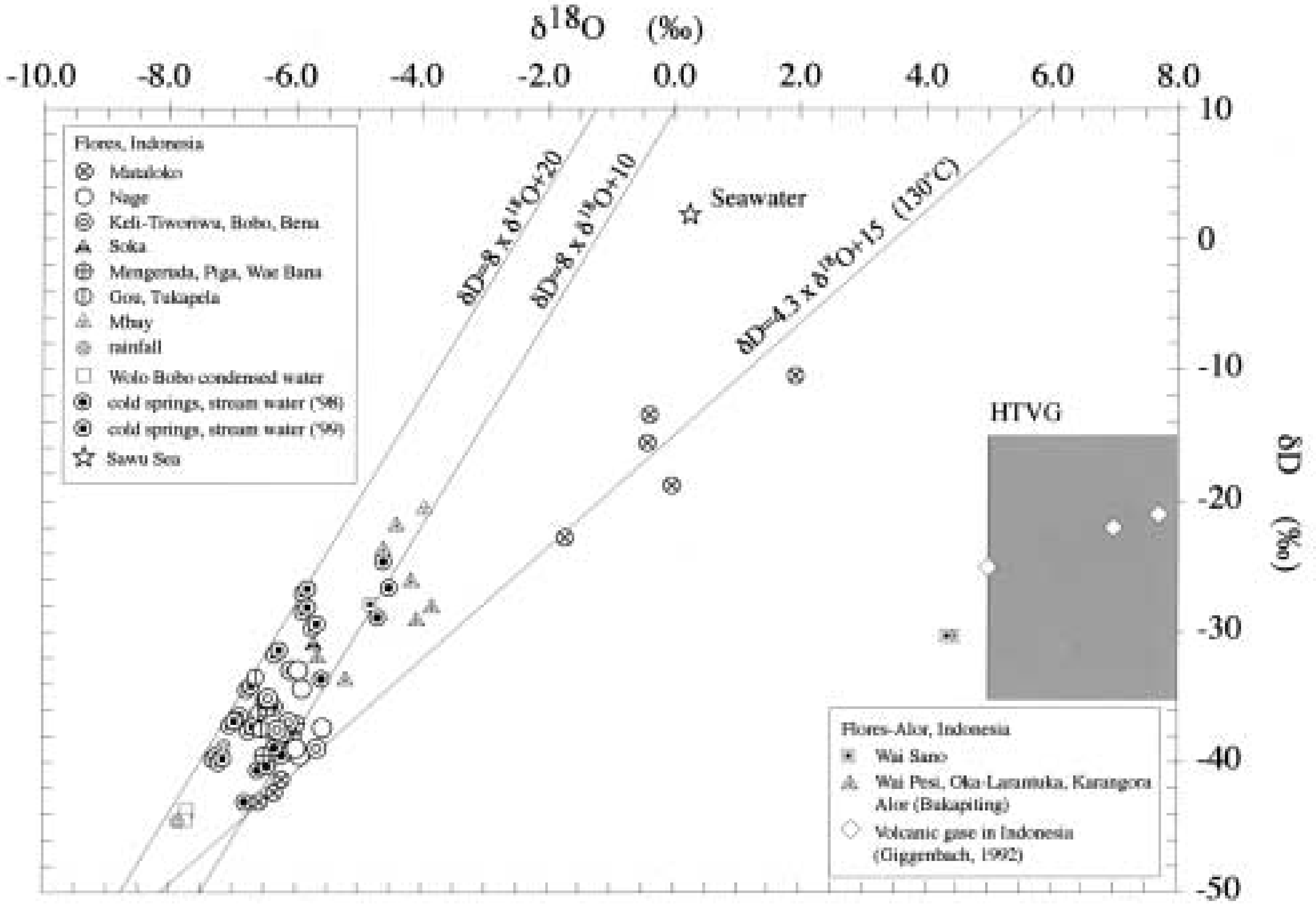

Fig. 5 The relation between hydrogen and oxygen isotopic ratio of thermal and cold spring water in the Bajawa area. Standard deviations for the measurement of hydrogen and oxygen isotopic ratio of water are ±0.5-1.0 ‰ and ±0.1 ‰, respectively.
HTVG: High temperature volcanic gases from island arc andesitic volcanoes (e.g. Kusakabe and Matsubaya, 1986).

near the area of high temperature volcanic gases from island arc andesitic volcanoes (Kusakabe and Matsubaya, 1986) and volcanic gases from three Indonesian volcanoes (Giggenbach, 1992). Other all water samples were plotted near the meteoric water line, which has an inclination of 8 and an intercept for Y axis (d-value) of 10-20 (see Takahashi *et al.*, this issue). Mbay and Wai Pesi hot water was plotted near the mixing line of local meteoric water and seawater. The mixing trend was so similar to those of Ghyben-Herzberg's lens (e.g. Takahashi *et al.*, 1991), oil and gas field brine (Kato and Kajiwara, 1986; Nakai et al., 1974) and Shimogamo hot spring (Mizutani and Hamasuna, 1972). Geochemistry of those hot water were classified into type III, which originate from seawater (Fig. 2). Thus, Mbay and Wai Pasi hot water originates from saline water of Ghyben-Herzberg's lens or oil field brine (fossil seawater).

Chemical compositions of gases from fumaroles and hot springs

The relation between He/Ar ratios and N_2/Ar ratios of fumarolic gas obtained from the Wolo Bobo fumarolic area and bubble gas from the Mataloko hot spring are shown in Fig. 6. The mixing line between magmatic gas in northeast Japan (Kiyosu, 1985) and dissolved air in the groundwater is also shown. The ratios of gases sampled from the Bajawa area were so close to the mixing line and well gases taken from Mori and Yanaizu-Nishiyama geothermal power plants (e.g. Takahashi, 1994). On the other hand, He/Ar ratios of gases obtained from several volcanoes between Lembata Island and Banda islands (Poorter *et al.*, 1991) are much different from those of Flores.

Schematic diagram of geothermal systems in Bajawa area

Geothermal systems in the Bajawa area is shown in Fig. 7.

Geochemical characteristics of Mataloko, Keli Tiworiwu-Bobo, Soka, Mengeruda and Gou-Tukapela hot water were an acid sulfate type. The chemical and isotopic compositions indicated that these hot springs were formed by the oxidation of relatively

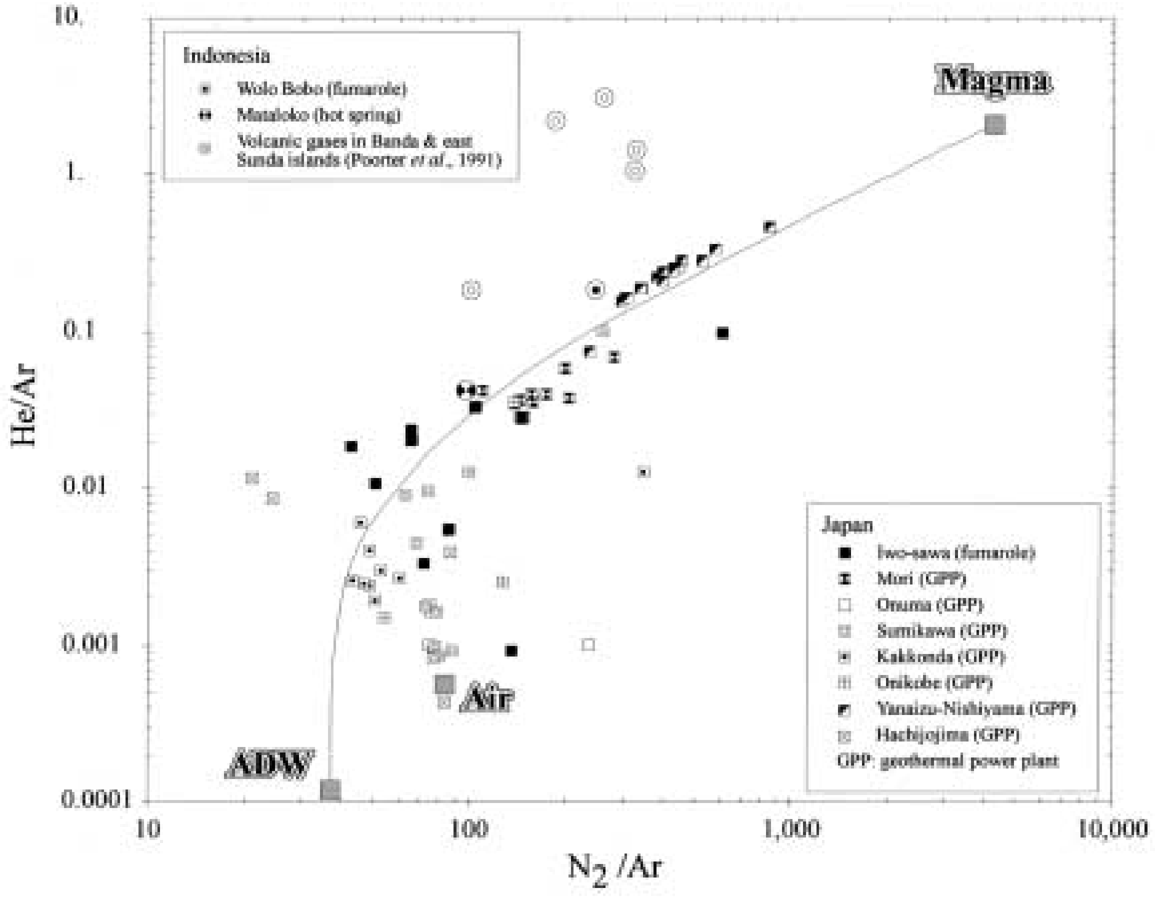

Fig. 6 The relation between He/Ar ratios and N_2/Ar ratios of fumarolic gas obtained from Wolo Bobo and Mataloko areas.
ADW; dissolved air in groundwater, Magma; magmatic gas in northeast Japan (Kiyosu, 1985).

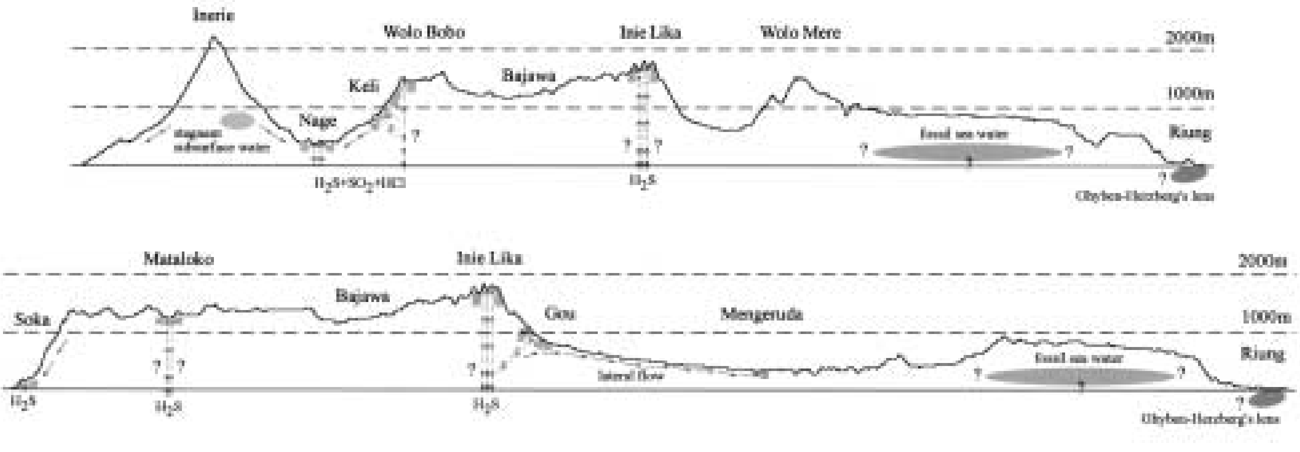

Fig. 7 Schematic diagram of geothermal systems in the Bajawa area.
Upper cross section is between Inerie volcano and Riung via Wolo Bobo, Inie Lika and Wolo Mere volcanoes, which shows the western section of the Bajawa area. Lower cross section is between Soka and Riung via Mataloko, Gou-Tukapera and Mengeruda hot springs, which shows the eastern section of the Bajawa area.
Solid line: subsurface water flow, Broken line: volcanic gas and/or heat flow, Dashed line: water contained in the acid altered zone.

low temperature volcanic gases containing hydrogen sulfide gases and mixed with interstitial water in the acid alternation zone and meteoric water.

Geochemical characteristics of Nage hot water are a sulfate-chloride type. Nage spring may be formed by mixing of high temperature volcanic gases, which contain hydrogen chloride and sulfur dioxide, and interstitial water in the acid alternation zone, and meteoric water.

Mbay hot spring originated from saline water of the Ghyben-Herzberg's lens or oil field brine (fossil seawater).

Conclusions

Water and gas samples were analyzed to understand the geochemical characteristics of geothermal resources in the Bajawa area, central Flores, eastern part of Nusa Tenggara Islands, Indonesia. Six prospective manifestation areas are in the area. Mataloko, Nage-Keli Tiworiwu-Wolo Bobo, Mengeruda, Gou-Tukapela areas are in the southern-coast-side volcanic alignment, whereas the Mbay area is near the northeastern coast. Temperatures of hot springs were > 90 ℃ at the Mataloko, >75 ℃ at the Nage, >70 ℃ at the Keli Tiworiwu, >60 ℃ at the Mbay and 40-45 ℃ at the other areas.

Geochemical characteristics of most hot water was an acid sulfate type except for Nage hot water, an acid sulfate-chloride type. The origin of dissolved sulfate and chloride of acid hot springs was relatively low temperature volcanic gases containing hydrogen sulfide gases and interstitial water in the acid alternation zone. However, the origin of dissolved sulfate and chloride of Nage hot springs may be from high temperature volcanic gases, which contain hydrogen chloride and sulfur dioxide, and interstitial water in the acid alternation zone and volcanic ash.

Chemical and sulfur isotopic characteristics of dissolved sulfate show that Mataloko, Nage and Keli Tiworiwu hot water were similar to Rank A volcanic geothermal resources areas in Japan, whereas hot water of Mengeruda, Gou and Soka was related to Rank B volcanic geothermal resources areas in Japan. The Mengeruda, Gou and Soka geothermal resources may not be as prospective as the Mataloko, Nage and Keli Tiworiwu geothermal resources.

References

Giggenbach, W. F. (1992) Isotopic shifts in water from geothermal and volcanic systems along convergent plate boundaries and their origin. *Earth and Planetary Science Letters,* **113**, 495-510.

GSJ: Geological Survey of Japan (1978) *Analytical Methods of Geological Materials.* Vol.2, no.51, p.269-619.

Hamilton, W. (1979) Tectonics of the Indonesia region. *U. S. Geol. Surv. Prof. Pap.,* **1078**, 345p.

Hoefs, J. (1980) *Stable Isotope Geochemistry. Second, completely revised and updated edition.* Springer-Verlag, Berlin-Heidelberg-New York-London-Paris-Tokyo, 208p.

Horita, J., Cole, D.R. and Wesolowski, D.J. (1995) The activity-composition relationship of oxygen and hydrogen isotopes in aqueous salt solutions: III. Vopor-liquid water equilibration of NaCl solutions to 350C. *Geochimica et Cosmochimica Acta,* **29**, 1139-1151.

Kato, S. and Kajiwara,Y. (1986) Isotopic composition of hydrogen and oxygen in water associated with oil and gas from Niigata basin, Japan. *Journal of the Japanese Association for Petroleum Technology,* **51**, 113-122 (in Japanese with English abstract).

Kiyosu, Y. (1985) Variations in N_2/Ar and He/Ar ratios of gases from some volcanic areas in northeastern Japan. *Geochemical Journal,* **19**, 275-282.

Kusakabe, M. and Matsubaya, O. (1986) Volatiles in magmas, volcanic gases, and thermal water. *Bulletin of the Volcanological Society of Japan,* **30**, S267-S283.

McCaffery, R. (1988) Active tectonics of the eastern Sunda and Banda arcs. *Journal of Geophysical Research,* **B, 15**, 15163-15182.

Mizutani, Y. and Hamasuna, T. (1972) Origin of the Shimogamo geothermal brine, Izu. *Bulletin of the Volcanological Society of Japan,* **17**, 123-134 (in Japanese with English abstract).

Muraoka, H., Nasution, A., Urai, M., Takahashi, M. and Takashima, I. (1999) Regional geothermal geology of the Ngada district, central Flores, Indonesia. *1998 Interim Report of Geological Survey of Japan, Research Cooperation Project on the Exploration of Small-scale Geothermal Resources in the Eastern Part of Indonesia (ESSEI),* 17-46.

Muraoka, H. and Uchida, T. (1999) Overview of 1998 investigations of the "Research Cooperation Project on the Exploration of small-scale Geothermal Resources in the Eastern Part of Indonesia" by the Geological Survey of Japan. *1998 Interim Report of Geological Survey of Japan, Research Cooperation Project on the Exploration of Small-scale Geothermal Resources in the Eastern Part of Indonesia (ESSEI),* 1-8.

Nakai, N., Yoshida, Y. and Ando, N. (1974) Isotopic studies on oil and Natural gas fields in Japan. *Chikyukagaku,* **8**, 87-98 (in Japanese with English abstract).

NEDO: New Energy and Industrial Technology Development Organization (1991) *Report of the third Nation-wide geothermal resources exploration project, Akita-Komagatake district, FY1990,* 119p (in Japanese).

Noda, T. and Takahashi, M. (1992) Geochemical classification of source water relating to geothermal system. *Chikyukagaku,* **26**, 52-63 (in Japanese with English abstract).

Ozawa, T. (1966) Chemical analysis of volcanic gases containing water vapor, hydrogen chloride, sulfur dioxide, hydrogen sulfide, carbon dioxide, etc. *Nippon Kagaku Zasshi,* **87**, 848-853 (in Japanese).

PERTAMINA (The Indonesian State Oil Company) (1994) *Indonesia Geothermal Reserves and Resources.* 45p.

Poorter, R. P. E., Varekamp, J. C., Poreda, R. J., van Bergen, M. J. and Kreulen, R. (1991) Chemical and isotopic compositions of volcanic gases from the east Sunda and Banda arcs, Indonesia. *Geochimica et Cosmochimica Acta,* **55**, 3795-3807.

Sakai, H. and Matsuhisa, Y. (1996) *Stable Isotope Geochemistry.* University of Tokyo Press, 403p.

Sato, T. and Takahashi, M. (1996) Anomalous groundwater discharge after the 1995 Kobe earthquake in Awaji Island -Part II: Change in discharge rate-. *Chishitu News,* no.506, 24-28 (in Japanese).

Scholl, M. A., Ingebritsen, S.E., Janik, C.J. and Kauahikaua J. P. (1995): An isotope hydrology study of the Kilauea Volcano area, Hawaii. *U. S. Geol. Surv. Water Resources Investigation Report,* **95-4113**, 44p.

Simkin, T. and Siebert, L. (1994) Volcanoes of the world, 2nd ed. -A regional directory, gazetteer and chronology of volcanism during the last 1000years-. *Smithsonian Institution Global Volcanism Program,* Geoscience Press, Inc., Tuscan, Arizona, 349p.

Takahashi, M., Abe, K., Noda, T., Kazahaya, K., Ando, N., Endo, H. and Soya, T. (1991) Remarkable temperature rising of groundwater observed in Izu Oshima Island. *Bulletin of the Volcanological Society of Japan,* **36**, 403-418 (in Japanese with English abstract).

Takahashi, M. (1994) Influence of Quaternary volcanic activity on the formation of geothermal reservoir fluids. *The Memoirs of the Geological Society of Japan,* No.43, 156-168 (in Japanese with English abstract).

Takahashi, M., Muraoka, H., Urai, M. and Nasution, A. (1998a) Preliminary study of geothermal resources areas in the eastern Nusa Tenggara, Indonesia. *Chishitu News,* no.521, 54-64 (in Japanese).

Takahashi, M., Tsukamoto, H., Itoh, J., Yasuhara, M., Kawanabe, Y. and Endo, H. (1998b) Changes in geochemical characteristics of thermal water observed at Sumikawa and Akagawa Spas, after the 1997.5.11 Sumikawa Landslide, Akita Prefecture. *Journal of Japan Landslide Society,* **35**, 62-68 (in Japanese with English abstract).

Takahashi, M., Urai, M., Yasukawa, K., Muraoka, H., Matsuda, K., Akasako, H., Koseki, T., Hisatani, K., Kusnadi, D., Sulaeman, B., Sriwana, T. and Nasution, A. (2002) Hydrogen and oxygen isotopic compositions of subsurface water at Bajawa area, central Flores, Indonesia. *Bull. Geol. Surv. Japan,* **53**, 201-209.

Takahashi, M., Kazahaya, K. and Yasuhara, M. (in preparation) Handling of the Hokko beads® in H_2-H_2O equilibration method for D/H measurement of water.

Ueda, A., Kubota, Y., Katoh, H., Hatakeyama, K. and Matsubaya, O. (1991) Geochemical characteristics of the Sumikawa geothermal system, northeast Japan. *Geochemical Journal,* **25**, 223-244.

Yamaguchi, Y., Sumi, K. and Tanaka, K. (1992) *Geothermal resources map of Japan. Geological Atlas of Japan,* Asakura, Tokyo.

Received September 14, 2001
Accepted February 21, 2002

インドネシア，フローレス島中部バジャワ地域の温泉の地球化学的性質

高橋正明・浦井　稔・安川香澄・村岡洋文・松田鉱二・赤迫秀雄・小関武宏・久谷公一・
Dedi KUSNADI・Bangbang SULAEMAN・Asnawir NASUTION

要　　旨

インドネシア東部，ヌサ・テンガラ諸島東部，フローレス島中部のバジャワ地域の地熱性状を評価するため，温泉，湧水，河川水，降水を採取し，地化学的な分析を行った．

マタロコ，ナゲ-ケリ　ティオリブ-ボボ，ソカ，メンゲルーダ及びゴウ-トゥカペラの5有望地熱兆候地帯は，イネリ，イネリカ及びエブロボ火山と30以上の単成火山群の近傍にあり，ンバイ地域は北東部海岸地帯にある．温泉の温度は，マタロコで90℃以上，ナゲで75℃以上，ケリ　ティオリブで70℃以上，ンバイで60℃以上，その他の地域で40-45℃である．大部分の温泉は酸性硫酸塩型，ナゲ温泉水のみは酸性硫酸塩-塩化物塩型の性質を示す．

ナゲ以外の酸性温泉の温泉水中の溶存硫酸塩と塩化物塩の起源は，硫化水素を含む相対的に低温の火山ガスの酸化と，酸性変質帯の間隙水との混合である．ナゲ温泉水の溶存硫酸塩と塩化物塩の起源のみは，塩化水素や二酸化硫黄を含む高温火山ガスと酸性変質帯の間隙水である可能性がある．