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Geothermal prospects of Flores Island in Indonesia viewed from their volcanism and hot water geochemistry

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Asnawir NASUTION, Hirofumi MURAOKA, Mawardi RANI, Isao TAKASHIMA, Masaaki TAKAHASHI, Hideo AKASAKO, Koji MATSUDA and Muhammad BADRUDIN (2002) Geothermal prospects of Flores Island in Indonesia viewed from their volcanism and hot water geochemistry. *Bull. Geol. Surv. Japan,* vol. 53 (2/3), p. 87-97, 9 figs., 3 tables.

Abstract: Lavas of the Flores volcanic arc have a range of compositions from basalt to dacite but mostly andesite, containing pigeonite and olivine in island arc tholeiitic series and amphibole and biotite in calc-alkaline series. Chemically, the rocks show a wide variety of SiO_2 (51 - 67 wt.%), Al_2O_3 (14 - 20 wt.%) and low TiO_2 (<1 wt.%), together with relatively high Rb, Sr and Ba. These K group elements represent an increase of SiO_2 with increasing depth of the Benioff zone. Strontium isotope ratios of tholeiitic to calc-alkaline lavas are 0.7042 - 0.7045, assumed to be correlated with the depth of the subducted slab across the island. Flores geothermal prospects are situated in young volcanic terrains of andesite and basalt between 500 to 1000 m above sea level (a.s.l.) and associated with post volcanic fractures, faults and caldera structures. Hot water discharges represent a wide variety of chemical water types; sulfate, bicarbonate and chloride waters. Sulfate type is mostly associated with fumaroles and located on high volcanic terrains (700 - 1100 m a.s.l.), indicating the near-surface H_2S oxidation (Ulumbu, Mataloko, Nage and Sokoria). Bicarbonate waters are located at the moderate slope of volcanics (400 - 700 m a.s.l.), shown by Langageda and Sokoria 2. Neutral chloride waters are located at the lower volcanic terrains approximately 5 - 600 m a.s.l., indicating an outflow from geothermal reservoirs with a temperature of 210 to 280 ℃. Geothermal wells that were drilled at the Ulumbu and Mataloko prospects to a depth of 700 - 1800 m and 200 m, respectively have a subsurface temperature of 200 to 240 ℃, indicating that the high sulfate concentration is associated with a vapor-dominated system. The same system probably occurs in the Sokoria field. While the geothermal prospects of high chloride water type are probably associated with hot-water or mixture system (Wai Sano, Wai Pesi, Jopu, Lesugolo and Oka).

1. Introduction

The Indonesian volcanic arcs represent a wide variety of volcanic rocks in compositions. The spatial and temporal variations of magma compositions are known of many island arcs (Gill, 1970). It is also known from the eastern Sunda arc (Whitford *et al.,* 1979). Hatherton and Dickinson (1969) show that the potassium content of volcanic rocks or "K" value is positively correlated with increasing depth to the seismic plane or "h" beneath the arc. Flores forms a part of the eastern Sunda arc and represents a row of active and inactive volcanoes where some of them are associated with calderas. Compositions of these volcanic rocks will give information of the tectonic settings.

Some of active and inactive volcanoes in Flores exhibit fumaroles, solfatara and hot springs. Those geothermal manifestations are found along almost the entire island. Water and gas geochemistry in those areas provides a method to evaluate geothermal potential of the prospects. White *et al.* (1971) have studied characteristics of chemical elements of high temperature and high pressure fluid. Ellis and Mahon (1977) have classified geothermal prospects

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based on water geochemistry and their volcanic activities. These methods will give geothermal information on potential areas to be promoted for geothermal developments.

This paper tries to inform the spatial variation of the volcanic rocks of active volcanoes and hot water geochemistry of geothermal prospects on Flores Island.

2. Tectonic frame work

Tectonically, Indonesian island arcs are the result of the interaction of the Eurasian, Pacific, Philippines and Indian-Australian Plates (Fig. 1). Most of these island arcs display micro-continental arc volcanism associated with an oceanic trench subduction zone (Cas and Wright, 1987). They can be divided into four arcs: the Sunda arc in the west, Banda arc in the east, two small Sangihe-North Sulawesi and Halmahera arcs situated north of the Banda arc.

The Flores volcanoes and geothermal prospects form a part of the eastern Sunda arc. The evolution of the volcanic arcs occurred from pre- to mid-Tertiary associated with the collision of the Australia Continent (Audly-Charles, 1975). This event might have caused active volcanisms and associated geothermal activity and resulted in a complicated differentiation in tectonic settings from west to east along the arc.

3. Volcanic activity

Flores Island has eight active volcanoes, the Anak Ranakah, Inerie, Inelika, Ebulobo, Iya, Kelimutu, Egon, and Lewotobi (Fig. 2). Some of these volcanoes are associated with collapse calderas. The last volcanic eruptions occurred at Anak Ranakah in 1987, Lewotobi in 1992 and Inelika volcanoes in 2001, producing lava dome and pyroclastic products.

Petrographical data of volcanic rocks represent a variety of rock types as reflected by the phenocryst assemblages and rock chemistry. Figure 3 illustrates the distribution of rock types of lavas from each active volcano. In terms of SiO_2 contents, they are from 51 to 67 wt.% and span the range of basalt, basaltic andesite, andesite and dacite, but are predominantly basaltic andesite and andesite where dacite is relatively rare.

The volcanic products show a large variation in compositions even for a single centre of each active volcano. Tholeiitic series contain pigeonite, olivine and plagioclase phenocrysts, while calc-alkaline series contain hydrous minerals, amphibole and biotite, representing higher potassium contents. Rock nomenclature in this figure largely follows the chemical scheme of Le Bas *et al.* (1986; Fig. 3).

4. Chemistry of volcanic rocks

4.1 Major elements

Flores volcanic rocks of eastern Sunda arc are characterized by the wide variation of SiO_2 (51 - 67 wt.%), high contents of Al_2O_3 (14 - 20 wt.%), low contents of TiO_2 (below 1.0 wt.%), and relatively low MgO/FeO ratios. Except for Na_2O and K_2O, all major elements decrease in abundance with increasing SiO_2 in the Harker diagram (Fig. 4).

Representative major elements analyses of basalt, basaltic andesite, andesite and dacite of tholeiitic, calc-alkaline and high calc-alkaline suite are listed

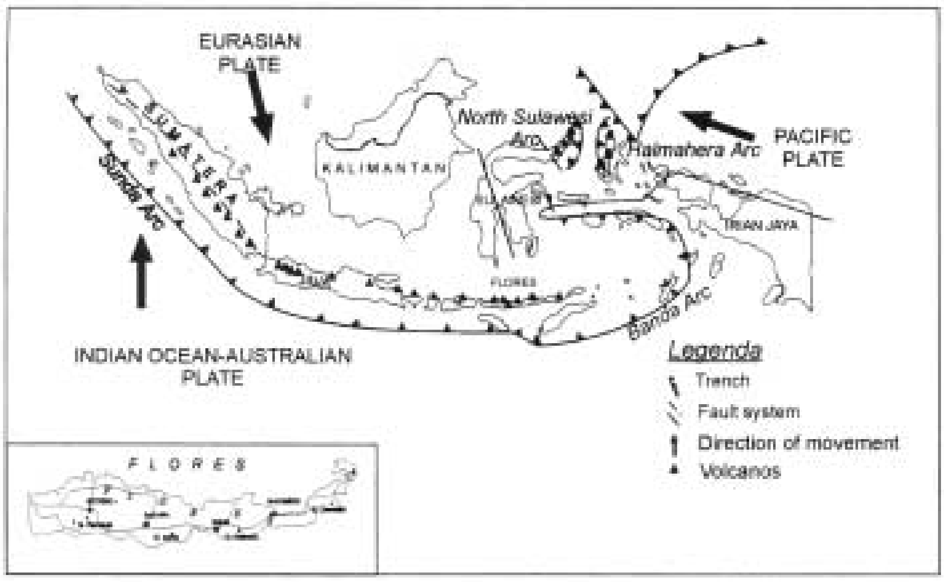

Fig. 1 Plate boundaries in Indonesia (Katili, 1973).

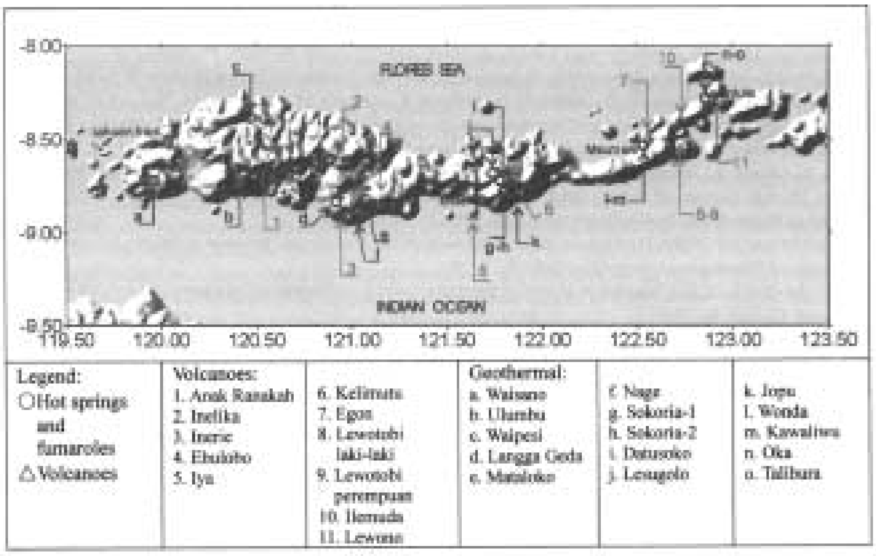

Fig. 2 Distribution of volcanoes and geothermal areas in Flores Island, Indonesia shown on the shaded-relief digital topographic map. The source DEM data are GTOPO30 released from USGS EROS Data Center and were shaded by Masao Komazawa.

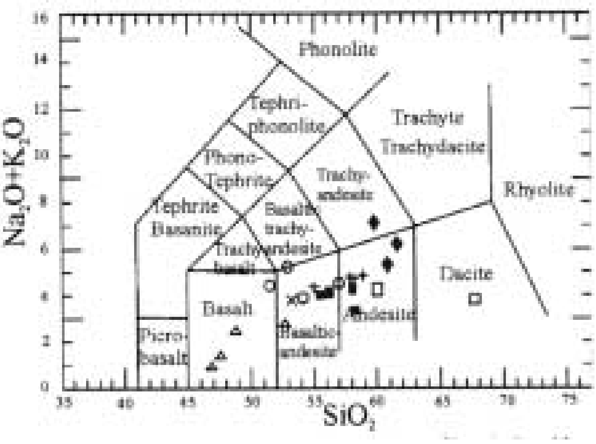

Fig. 3 Total alkali-silica diagram (Le Bas *et al.,* 1986) showing the regions of basalt, basaltic andesite and andesite. ◆ Anak Ranakah; + Inelika; × Inerie; ○ Ebulobo; Δ Iya; ■ Lewotobi Laki-Laki; □ Lewotobi Perempuan.

in Table 1. The elements are mostly calc-alkaline suite (Fig. 5). Tectonically, the variation in concentration of major elements from each suite is presented in Fig. 6. The MnO-TiO_2-P_2O_5 diagram shows that most of the rocks are derived from calc-alkaline basalt and island arc tholeiitic series.

Using the classification scheme of Gill (1981), the K variation has shown that K_2O contents of volcanic rocks range from low K to high K or from tholeiitic to high K calc-alkaline. The high alkali contents characterize the volcanic rocks located away from the trench (Fig. 2). They have lateral variations across the island arc, probably closely related with the depth of the subducted slab.

In relation between the depth of the subduction zone and geochemical association suggested by Jakes and Gill (1970), magma types of Flores volcanic rocks can be evaluated. The tholeiitic associations are found close to the trench over the Benioff zone with a depth ranging from 100 to 150 km. The calc-alkaline to high K calc-alkaline associations reflect increasing contents of K and related compatible elements within the apparently continuous spectrum of the compositions. These associations are more distant from the trench over the Benioff zone depth ranging from 150 to 250 km.

4.2 Trace elements

The trace element concentration of rocks from some volcanoes varies widely (Table 1) and is useful to identify mantle geochemical processes. The concentrations of Large Ion Lithophile (LIL) such as Rb, Ba and Sr show 12 - 60 ppm, 175 - 830 ppm and 244 - 481 ppm, respectively. These K group elements are positively correlated to each other, as shown by Rb vs. K or Sr vs. K. They increase with increasing silica from basalt, basaltic andesite to andesite, probably due to the fractionation of magma (Fig. 7). This is in harmony with the chemical variation across the island arc or LIL elements increase away from the trench.

Compatible element concentrations such as Ni, Sc, Co and V show <8 - 12.9 ppm, 25 - 30 ppm, 24 - 175 ppm and 166 - 209.87 ppm, respectively (Fig. 7). These low concentrations may be caused by fractionation and probably a few primary mantle-derived melts. In addition, the Y concentration falls into a range of 16 - 28 ppm, which are average values for orogenic andesite (Lambert and Holland,

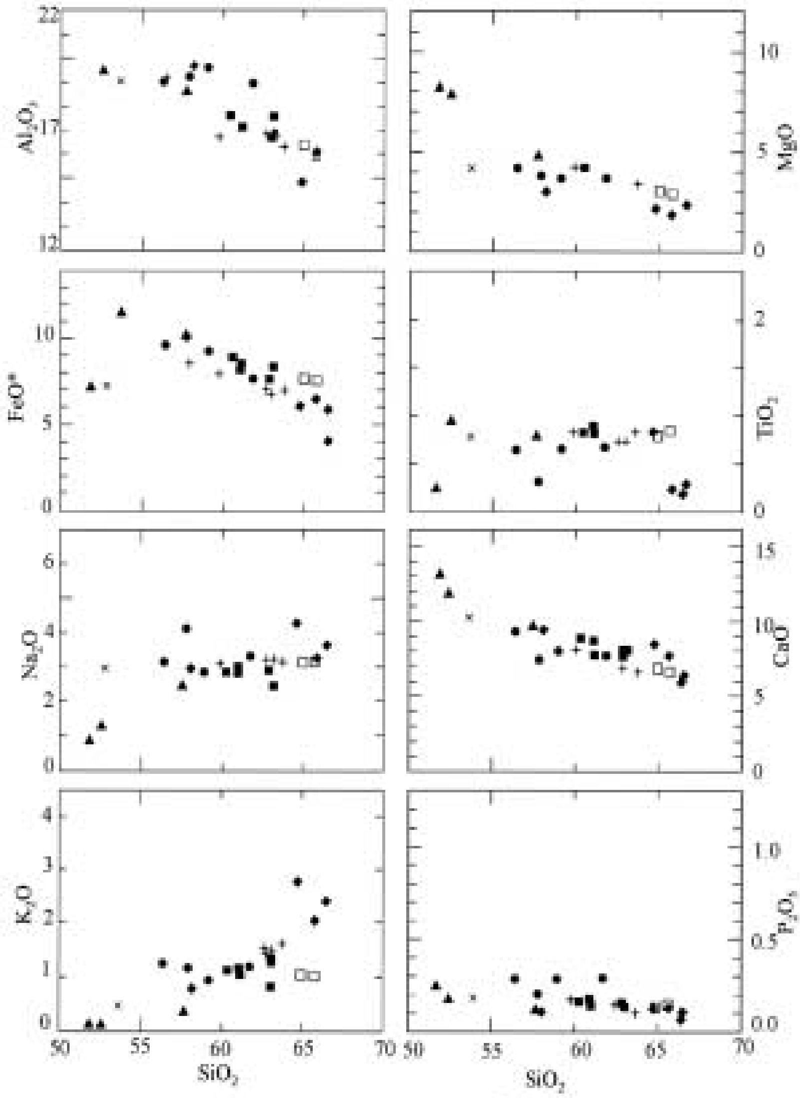

Fig. 4 Harker diagram showing Na_2O and K_2O increase, and the other elements quantity decrease with increasing silica. ◆ Anak Ranakah; + Inelika; × Inerie; ● Ebulobo; ▲ Iya; ■ Lewotobi Laki-Laki; □ Lewotobi Perempuan.

Table 1 Major and trace elements of volcanic rocks from active volcanoes in Flores (Lewotobi and Iya volcanoes).

Analyst		GE	GE	GE	GE	GE	GE	GE	GE	GE	GE
Date		22-04-91	6-06-91	6-06-91	6-06-91	8-06-91	08-06-91	22-04-91	08-06-91	22-04-91	06-06-91
Lab.Code		VSI	VSI	VSI	VSI	VSI	VSI	VSI	VSI	VSI	VSI
Sample Code		LW33 P	LW34 P	G.IYA	LW20	LW32 P	LW30	LW24	LW27	LW31	LW28
Volcano		Lewotobi	Lewotobi	Iya	Lewotobi	Lewotobi	Lewotobi	Lewotobi	Lewotobi	Lewotobi	Lewotobi
SiO_2	%	60.75	60.03	52.73	58.25	67.77	55.47	58.01	56.17	58.03	56.23
Al_2O_3	%	15.94	16.42	18.63	17.61	17.05	17.64	16.73	17.20	16.79	16.81
MnO	%	0.17	0.17	0.17	0.16	0.18	0.17	0.17	0.16	0.16	0.17
MgO	%	2.97	3.06	4.83	3.85	3.63	4.20	4.01	4.04	3.56	3.72
CaO	%	6.75	7.00	9.69	8.14	7.61	8.91	8.02	8.60	7.78	7.82
Na_2O	%	3.14	3.14	2.41	2.86	2.78	2.81	2.94	2.80	2.94	3.00
K_2O	%	1.04	1.08	0.33	0.84	1.02	1.15	1.24	1.20	1.32	1.12
TiO_2	%	0.84	0.78	0.77	0.81	0.82	0.83	0.79	0.82	0.77	0.78
P_2O_5	%	0.15	0.14	0.11	0.14	0.16	0.17	0.17	0.17	0.17	0.15
L.O.I	%	1.49	0.35	<0.35	0.53	0.89	0.26	0.12	<0.05	0.85	0.13
Total	%	99.6	99.80	99.8	101.12	99.74	100.39	100.12	99.93	99.46	98.09
Fe_2O_3t	%	7.85	7.98	10.2	8.46	8.72	9.04	8.02	8.77	7.94	8.29
$H_2O(+)$	%	0.53	0.24	0.03	0.14	0.39	0.16	0.13	0.10	0.31	0.14
Ba	ppm	625.97	640.64	n.a.	835.35	620.87	760.17	836.29	830.76	787.74	742.87
Co	ppm	175.84	122.19	24.99	143.42	95.58	306.31	93.85	185.88	155.72	105.12
Cs	ppm	<2.50	<2.50	n.a.	<2.50	<2.50	<2.50	<2.50	<2.50	<2.50	<2.50
Cu	ppm	13.13	20.21	43.43	22.55	27.05	28.02	28.15	39.93	37.46	28.87
Ga	ppm	16.03	15.95	16.82	17.45	15.90	16.73	17.30	18.75	15.88	17.54
La	ppm	<20.00	<20.00	n.a.	<20.00	<20.00	<20.00	<20.00	<20.00	<20.00	<20.00
Mn	ppm	1349.90	1391.03	n.a.	1282.86	1403.15	1334.11	1240.82	1281.44	1239.38	1323.18
Nb	ppm	4.22	3.35	2.23	3.05	4.15	5.28	4.26	4.24	5.45	4.09
Ni	ppm	<8.00	<8.00	10.90	12.91	11.21	11.20	18.54	10.99	11.84	10.40
P	ppm	<500.00	<500.00	n.a.	<500.00	514.38	531.99	595.92	539.02	524.39	548.84
Pb	ppm	11.59	17.58	8.37	10.49	17.68	15.37	16.97	19.87	21.71	17.00
Rb	ppm	25.70	30.17	12.20	22.21	29.86	31.33	34.40	33.05	36.95	28.81
Sc	ppm	30.88	29.22	n.a.	25.49	28.51	30.79	26.12	28.46	27.09	27.42
Sr	ppm	324.66	324.70	244.30	343.74	381.15	481.81	424.82	461.91	406.13	408.67
Th	ppm	<5.00	<5.00	<5.00	<5.00	<5.00	5.27	<5.00	<5.00	5.59	<5.00
Ti	ppm	5493.01	4787.84	n.a.	4722.33	5252.48	4959.59	4465.64	4739.52	4716.61	4746.27
U	ppm	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00	<5.00
V	ppm	166.23	174.34	n.a.	196.67	176.82	209.87	173.76	192.76	193.43	202.32
W	ppm	622.73	615.40	<10.00	654.83	427.66	1428.23	478.32	937.65	853.32	458.49
Y	ppm	27.16	28.59	17.58	22.91	28.57	26.36	28.04	27.08	27.89	25.42
Zn	ppm	66.08	68.63	67.59	63.63	71.72	68.28	61.69	66.74	65.47	67.68
Zr	ppm	89.68	93.78	43.88	73.38	84.63	86.89	98.18	88.30	102.05	87.73

Table 1 (continued) Major and trace elements of volcanic rocks from active volcanoes in Flores (Inerie, Inelika and Anak Ranakah volcanoes).

Analyst		GE	GE	GE	GE	GE	GE	GE	GE	GE
Date		Dec. 99	21-7-98	21-7-98	26-7-98	26-7-98	Feb-99	Feb-99	Feb-99	Feb- 99
Lab.Code		GSJ	GSJ	GSJ	GSJ	GSJ	VSI	VSI	VSI	VSI
Sample Code		980727 -02	980721 -04	980721 -05	980726 -04	980726 -05	A.R-1	A.R-2	A.R-3	A.R-4
Volcano		Inerie	Inelika	Inelika	Inelika	Inelika	Ranakah	Ranakah	Ranakah	Ranakah
SiO_2	%	53.22	54.97	57.91	58.17	58.84	61.63	61.53	60.86	59.82
Al_2O_3	%	19.72	16.83	16.83	16.97	16.36	15.87	0.21	16.06	14.85
MnO	%	0.14	0.13	0.12	0.12	0.12	0.09	0.10	0.09	0.09
MgO	%	3.11	4.32	3.34	3.30	3.41	2.50	2.40	1.99	2.18
CaO	%	9.51	8.18	7.05	6.91	6.59	6.40	6.14	7.71	8.59
Na_2O	%	3.0	3.0	3.2	3.18	3.16	3.67	3.65	3.22	4.32
K_2O	%	0.76	1.31	1.53	1.50	1.66	2.46	2.46	2.07	2.81
TiO_2	%	0.86	0.82	0.71	0.71	0.79	0.29	0.21	0.23	0.81
P_2O_5	%	0.11	0.16	0.13	0.12	0.12	0.07	0.11	0.13	0.13
Fe_2O_3	%	0.87	0.72	0.70	0.70	0.72	0.61	0.51	0.67	0.61
FeO	%	7.78	7.38	6.34	6.28	6.46	5.49	5.46	5.94	5.49
Cr_2O_3	%	<0.01			<0.01	<0.01	0.19	0.19	0.10	0.10
L.O.I.	%	<0.01	0.8	0.67	0.66	0.99	0.88	0.80	0.14	0.12
Total	%	99.08	98.72	98.53	98.62	99.22	99.08	98.50	98.94	99.70
$H_2O(+)$	%	0.06	0.91	0.92	0.66	1.04	0.19	0.19	0.83	0.10
Ba	ppm	175.0	355	340.0	3350	390.0	n.a	n.a	n.a	n.a
Nb	ppm	6.0	10.0	8.0	8.0	8.0	n.a	n.a	n.a	n.a
Rb	ppm	30.0	52.0	62.0	66.0	74.0	n.a	n.a	n.a	n.a
Sr	ppm	308.0	442	334	336.0	324	n.a	n.a	n.a	n.a
Y	ppm	16.0	22	22	22.0	26.0	n.a	n.a	n.a	n.a
Zr	ppm	60.0	105	120	117	138.0	n.a	n.a	n.a	n.a
$H_2O(-)$	%	0.08	0.16	0.15	0.11	0.09	n.a	n.a	n.a	n.a

Table 1 (continued) Major and trace elements of volcanic rocks from active volcanoes in Flores (Ebulobo and Iya volcanoes).

Analyst	GE	GE	GE	GE	GE	GE	GE
Date							
Lab. ode	VSI	VSI	VSI	VSI	VSI	VSI	VSI
Sample Code	Ebulobo1	Ebulobo2	Ebulobo3	Ebulobo4	Iya 1.a	Iya 1.b	Iya 1.c
Volcano	Ebulobo	Ebulobo	Ebulobo	Ebulobo	Iya	Iya	Iya
SiO_2	54.13	52.95	51.50	56.87	48.78	47.57	46.85
Al_2O_3	19.65	19.27	19.06	19.03	19.75	19.50	23.32
MnO	0.15	0.18	0.17	0.13	0.19	0.14	0.10
MgO	3.62	3.89	4.09	3.65	6.25	7.78	8.22
CaO	8.15	7.49	9.29	7.84	10.42	11.85	12.98
Na_2O	2.90	4.02	3.12	3.29	1.98	1.22	0.81
K_2O	0.96	1.17	1.25	1.19	0.42	0.11	0.06
TiO_2	0.67	0.33	0.61	0.67	0.84	0.93	0.24
P_2O_5	0.28	0.20	0.29	0.71	0.19	0.17	0.11
Fe_2O_3t	0.91	0.91	0.88	0.71	1.07	1.01	0.67
FeO	8.38	9.15	8.85	7.10	10.58	9.99	6.57
$H_2O(+)$	0.22	0.04	0.13	0.09	0.07	0.24	0.04
$H_2O(-)$	0.93	0.81	1.40	0.01			
Total	100.95	100.81	100.64	101.46	99.85	99.88	99.80

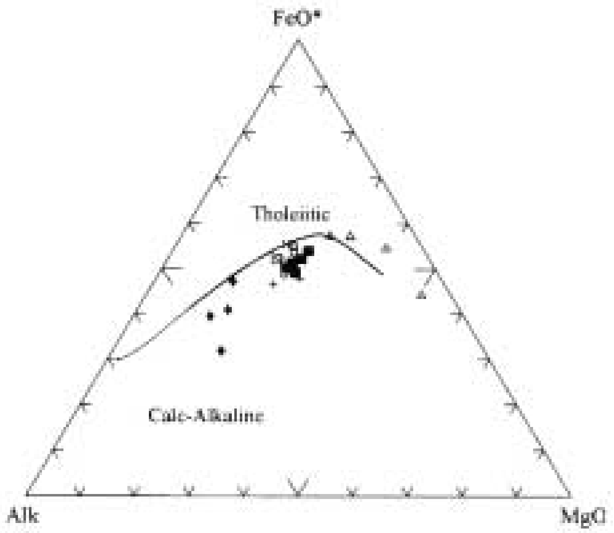

Fig. 5 AFM (Na_2O+K_2O-FeO-MgO) diagram showing that most samples fall into the calc-alkaline suites. A boundary curve is quoted from that of pigeonitic (tholeiitic) rock series and hypersthenic (calc-alkaline) rock series by Kuno (1950). ◆ Anak Ranakah; + Inelika; × Inerie; ○ Ebulobo; Δ Iya; ■ Lewotobi Laki-Laki; □ Lewotobi Perempuan.

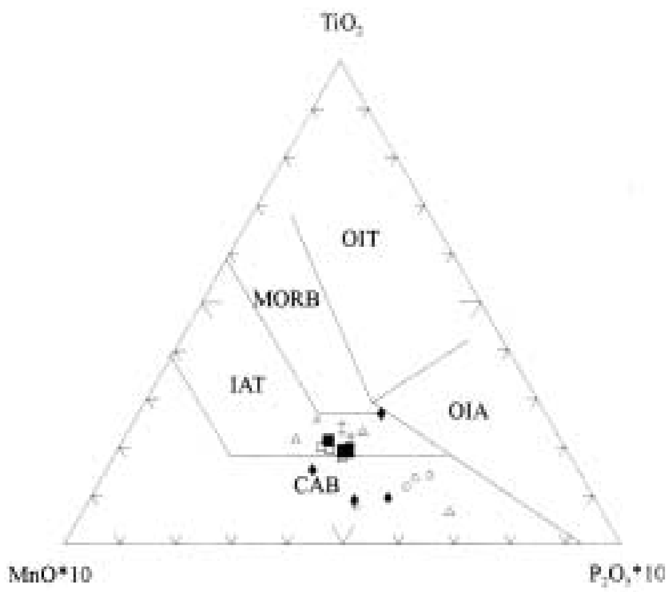

Fig. 6 MnO-TiO_2-P_2O_5 diagram (Mullen, 1983) showing regions of calc-alkaline basalt, island arc tholeiite and others. ◆ Anak Ranakah; + Inelika; × Inerie; ○ Ebulobo; Δ Iya; ■ Lewotobi Laki-Laki; □ Lewotobi Perempuan.

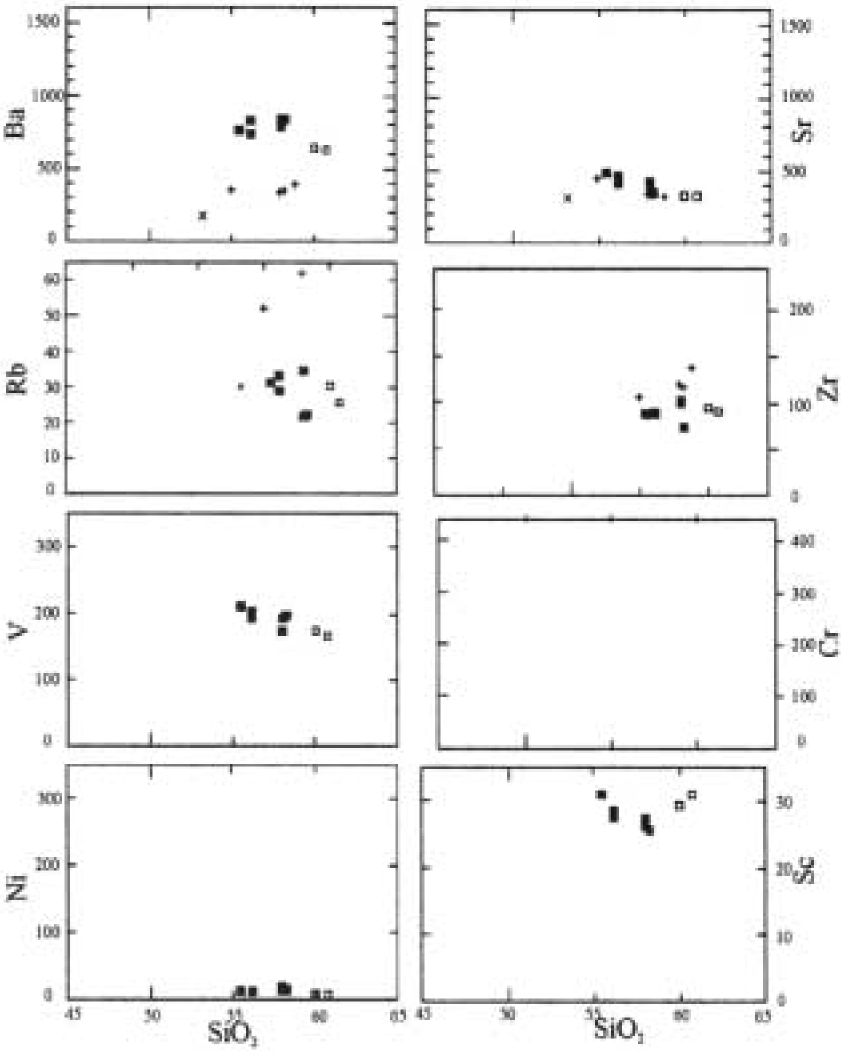

Fig. 7 Harker diagram representing trace elements of basalt, basaltic andesite and andesite of Inelika (+); Inerie (×); Lewotobi Laki-Laki (■) and Lewotobi Perempuan (□).

1974). They have probably formed in the crust with a thickness less than 20 km.

5. Geothermal prospects of Flores

Geothermal prospects are mostly associated with post-volcanic activities and distributed on high-altitude volcanic terrains along the island. They are divided into three segments, the West Flores prospects, Central Flores prospects and East Flores prospects. Major geothermal prospects are Wai Sano, Ulumbu and Wai Pesi (West Flores), Mataloko, Bobo and Langageda (Central Flores), and Sokoria, Lesugolo, Jopu, Detusoko and Oka (East Flores) as shown on Table 2 and Fig. 2.

5.1 West Flores prospects

Wai Sano is a caldera lake, approximately 20 km west from the main Trans-Flores Road. Hot springs are situated in a fossil fumarole field at the southern side of the caldera lake and discharge high temperature and neutral pH water at a low flow rate with thick silica sinter.

Ulumbu is located at the southwestern boundary of the Poco Leok caldera. Hot springs are situated in a fumarolic field on the west slope of the Kokor River (700 m a.s.l.) approximately 11 km south of the main city, Ruteng. The high temperature and low pH water discharges at a relatively low flow rate. High amounts of steam flow from the fumarolic field are clearly seen from far away.

5.2 Central Flores prospects

Geothermal prospects are distributed in a volcanic complex of Wolo Bobo, Wolo Beo and Wolo Belah approximately 1000-1500 m above sea level. They are located ± 2 - 15 km south from the main Trans-Flores Road and easy to access. They are known as the Mataloko and Nage hot springs and fumaroles representing low to high flow rates of acid water (Table 2).

To the north of Bajawa (± 20 km), the hot

Table 2 Chemical analyses of hot springs in Flores. "Fournier" and "Giggenbach" in the table mean Fournier (1981) and Giggenbach (1988), respectively.

No.		1	2	3	4	5	6	7	8
Analitical No.		2369/G/74	2370/G/74	2366/G/74	2354/G/74	2357/G/4	2355/G/74	2363/G 74	E-14/DV/87
Location		Wai Sano	Ulumbu	Wai Pesi	Langageda	Mataloko	Nage (F)	Sokoria 1	Sokoria 2
Temp.	(°C)	92	96	89	58	86	76	95	34
pH		7.10	4.40	7.40	6.90	3.10	2.60	2.90	7.60
Ca	ppm	1945.60	130.00	42.40	49.20	42.20	110.40	28.80	30.86
Mg	ppm	3.20	29.20	9.20	12.90	10.70	21.40	30.80	5.82
Fe	ppm	0.05	0.90	0.20	0.05	9.50	8.50	18.60	0.20
Mn	ppm	0.10	0.20	0.00	0.20	0.10	1.80	0.90	-
K	ppm	1178.90	17.70	17.50	49.00	9.00	95.50	9.00	3.21
Na	ppm	5846.10	72.70	136.90	148.30	13.40	163.20	19.10	12.71
B	ppm	417.50	3.60	2.30	1.70	1.40	7.70	2.60	0.11
CO_3	ppm	312.00	0.00	6.10	0.00	0.00	0.00	0.00	-
HCO_3	ppm	0.00	0.00	119.60	458.10	0.00	0.00	0.00	97.13
SO_4	ppm	81.40	633.70	160.10	125.10	360.10	784.30	1450.50	11.71
Cl	ppm	13290.00	36.00	117.00	57.00	18.00	366.00	30.00	10.79
SiO_2	ppm	35.50	120.00	40.00	114.80	126.80	70.80	176.00	236.28
F	ppm	0.10	0.10	0.10	0.10	0.10	0.10	0.10	-
CO_2		86.40	0.00	0.00	37.50	0.00	0.00	0.00	-
$\sqrt{Mg}$		1.79	5.40	3.03	3.59	3.27	4.63	5.55	2.41
K/100		11.79	0.18	0.18	0.49	0.09	0.96	0.09	0.03
Na/1000		5.85	0.07	0.14	0.15	0.01	0.16	0.02	0.01
Na/K		4.96	4.11	7.82	3.03	1.49	1.71	2.12	3.96
Na/Ca		3.00	0.56	3.23	3.01	3.19	1.48	0.66	0.41
Mg/Ca		0.00	0.22	0.22	0.26	2.55	0.19	1.07	0.19
Temp. SiO_2 max	(°C)	89.40	-	93.93	139.46	-	-	-	177.00
Temp. SiO_2 Con	(°C)	108.89	-	114.41	171.08	-	-	-	219.00
T° Na/K (Fournier)	(°C)	285.67	-	239.13	346.67	-	-	-	-
T° Na-K (Giggenbach)	(°C)	295.18	-	252.65	349.78	-	-	-	-
T° Na-K-Ca-Mg	(°C)	289.44	-	253.59	333.28	-	-	-	255.00

Table 2 (continued) Chemical analyses of hot springs in Flores. "Fournier" and "Giggenbach" in the table mean Fournier (1981) and Giggenbach (1988), respectively.

No.		9	10	11	12	13	14	15	16
Analitical No.		2363/G/74	2358/G/74	2364/G/74	2360/G/74	2362/G/74	2348/G/74	2349/G/74	2350/G/74
Location		Detusoko	Lesugolo	Wolokepo	Jopu	Wonda	Kawaliwu	Oka	Talibura
Temp	(°C)	48	98	64	48	73	49	72	55
pH		7.20	7.30	7.40	6.70	6.90	6.60	6.80	7.40
Ca	Ppm	171.20	53.40	16.40	157.40	105.40	76.00	102.60	67.00
Mg	Ppm	5.40	0.20	9.50	52.20	3.60	57.30	107.30	3.60
Fe	Ppm	0.05	0.00	0.30	0.05	0.05	0.05	0.05	0.20
Mn	Ppm	0.30	0.00	0.00	0.05	0.00	1.42	0.00	0.10
K	Ppm	15.60	22.00	4.50	66.40	30.10	101.70	190.90	5.30
Na	Ppm	231.80	483.00	148.40	598.70	311.60	452.60	1391.10	250.70
B	Ppm	2.10	4.85	2.10	10.20	3.70	2.50	4.80	5.00
CO_3	Ppm	0.00	10.80	0.00	0.00	0.00	0.00	0.00	0.00
HCO_3	ppm	123.80	150.10	300.10	640.50	131.20	285.50	348.90	240.30
SO_4	Ppm	726.70	590.10	125.10	252.70	382.70	244.00	301.60	191.30
Cl	Ppm	39.00	198.00	30.00	825.00	303.00	750.00	1807.50	231.00
SiO_2	Ppm	40.00	101.20	134.00	122.80	46.00	117.20	109.20	74.00
F	Ppm	0.10	0.10	0.10	0.10	0.10	1.30	0.10	0.10
CO_2		11.20	0.00	11.20	163.00	6.70	87.10	96.00	17.40
$\sqrt{Mg}$		2.32	0.45	3.08	7.22	1.90	7.57	10.36	1.90
K/100		0.16	0.22	0.05	0.66	0.30	1.02	1.91	0.05
Na/1000		0.23	0.48	0.15	0.60	0.31	0.45	1.39	0.25
Na/K		14.86	21.95	32.98	9.02	10.35	4.45	7.29	47.30
Na/Ca		1.35	9.04	9.05	3.80	2.96	5.96	13.56	3.74
Mg/Ca		0.03	0.00	0.58	0.33	0.03	0.75	1.05	0.05
Temp. SiO_2 max	(°C)	93.93	133.43	147.11	142.76	99.38	140.47	137.05	119.19
Temp. SiO_2 Con	(°C)	114.41	163.45	180.82	175.27	121.08	172.36	168.02	145.58
T° Na/K (Fournier)	(°C)	185.38	157.87	132.50	226.17	214.18	297.99	245.85	112.39
T° Na-K (Giggenbach)	(°C)	202.54	176.47	152.18	240.67	229.53	306.31	258.84	132.74
T° Na-K-Ca-Mg	(°C)	210.83	187.85	166.07	243.60	234.05	298.24	258.92	148.72

springs are distributed in several areas and closely associated to the Inelika volcanic complex represented by Mengeruda (± 300 m above sea level). They have a very high flow rate and are relatively acidic and low temperature, > 400 1/sec, pH 3 - 4 and 42 - 47 ℃, respectively. The Mengeruda hot springs are known as a recreation area with small cottages and a nice natural warm pool.

5.3 East Flores prospects

Geothermal indications are situated in a large area distributed from Ende to Larantuka (the eastern tip of Flores). Sokoria (± 600 - 1050 m a.s.l.) is a caldera complex associated with an active volcano to the north, known as a Kelimutu volcano (1690 m). The prospects are indicated by fumaroles and hot springs such as Sokoria, Detusoko and Jopu. They have low flow rates (0.5 - 5 1/sec), low pH and high water temperatures as shown on Table 2. The other hot spring discharges are located in relatively low land areas (5 - 600 m a.s.l.), Oka-Larantuka, Waigate, Lesugolo, Jopu and Detusoko (Fig. 2).

6. Water chemistry

Hot waters of Flores are classified into chloride

(Cl), sulfate (SO_4) and bicarbonate (HCO_3) type water.

6.1 Chloride water (Cl)

Wai Sano neutral hot springs represent a high concentration of Na, Cl, K, Ca and boron (B), 5946, 132900, 19456 and 418 ppm, respectively (Table 2). These show chloride type water, providing an indication of outflow water from a reservoir (Fig. 8). A ternary diagram of Na, K and Mg shows that the Wai Sano hot water is located in a "partial equilibrium" (Fig. 9), indicating a relatively small influence of surface water dilution. A high boron concentration is assumed to be the involvement of sedimentary materials in high temperature geothermal water, where boron is easily dissolved in high temperature water (Koga, 1981).

The other chloride water types are at the Wai Pesi, Detusoko, Jopu, Lesugolo, Oka and Kawalewu hot springs (Fig. 2), which are higher in the Na > Ca > Mg cation ratio and higher in the Cl/SO_4 ratio (Table 2). They are interpreted as an outflow water from an immatured and partially equilibrated hydrothermal system that contains juvenile volcanic gases such as CO_2, H_2S and NH_3.

6.2 Bicarbonate water (HCO_3)

The bicarbonate waters are found at Sokoria and Langageda (Bajawa) on moderate topographical terrain (300 - 700 m above sea level). They show an average flow rate and neutral pH water (Table 2) indicating the neutral chloride water contains condensed CO_2 and H_2S in a shallow aquifer (Ellis and Mahon, 1977).

6.3 Sulfate water (SO_4)

Wai Kokor (Ulumbu), Mana-Mataloko, Nage, Sokoria and Detusoko hot springs are sulfate type water (Fig. 7) and are located on high volcanic terrain (Table 3). They represent a high concentration of SO_4, low flow rate and high water temperature (80 - 95 ℃). The Cl/SO_4 ratio is relatively low, assumed to be an upflow of volcanic gasses (especially H_2S) oxidized on the way up to the surface with oxygen at a shallow water level. The hot springs plotted on a Na-K-Mg ternary diagram are located in an "immature water" and are interpreted that shallow meteoric water were much involved in hydrothermal processes near the surface (Fig. 9).

6.4 Subsurface temperature estimation

Chemical geothermometry using SiO_2, Na-K and Na-K-Ca-Mg components can be used for estimating the subsurface reservoir temperatures, especially for neutral pH water. Acid hot springs are better estimated by gas geothermometry. In general, neutral pH water of each Flores hot spring exhibits high Na/K and low Mg/Ca ratios, 4.96 and 0.016, respectively indicating a high reservoir temperature condition. The SiO_2 and Na/K or Na-K-Ca-Mg geothermometers show subsurface temperatures from 108 to 219 ℃ and 275 - 290 ℃ respectively as shown in Table 2. Therefore, high potentials are estimated in Flores in terms of the chemical geothermometry.

Ulumbu, Mana (Mataloko) or Nage and Sokoria are high temperature fumarolic fields showing subsurface temperature estimation from 240, 240 - 283

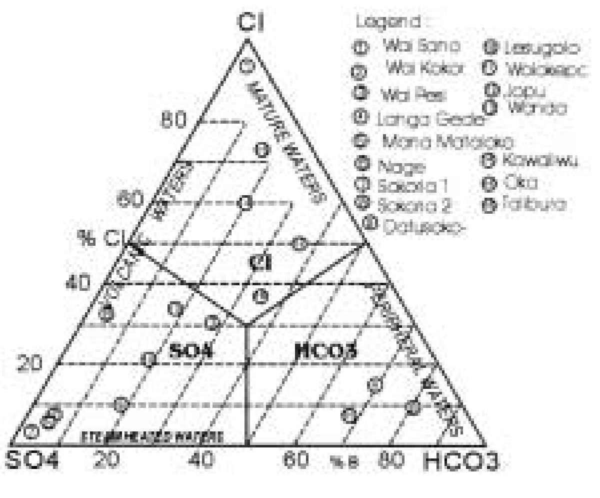

Fig. 8 Cl-SO_4-HCO_3 ternary diagram (Giggenbach, 1988) showing that Flores's hot springs are mostly sulfate and chloride type waters.

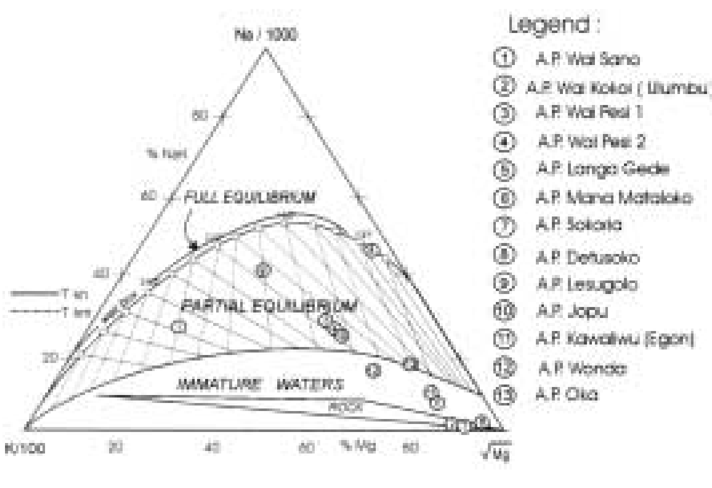

Fig. 9 Na-K-Mg ternary diagram (Giggenbach, 1988) showing Flores's hot springs located in a partial equilibrium indicating a possible subsurface hydrothermal system. A.P. means a hot spring in Indonesian.

Table 3 The distribution of geothermal manifestations from West, Central and East Flores.

Area	Geothermal discharges		Elevation above sea level	Structural relationship
	Hot spring (°C)	Fumarole (°C)	(m)	
West Flores				
Waisano	53-90		600-650	Associated with Waisano caldera's
Ulumbu	76-94	96-98	700-1300	Associated with Pocoleok caldera's at Kokor river
Wai Pesi	90		100-150	Possibly associated with old volcanic dome (?)
Central Flores				
Mataloko	77-90	94-96	900-1020	Associated with inactive volcanic cones dan dome
Nage	71-90		480-500	Kaldera Inirie ?
Langa geda	50-55		600-700	**Flank of Bajawa caldera**
Boho		90-96	1400	Associated with young volcanic cone
East Flores				
Mutubusa 1,2		90-95	1100-1200	Associated with Sokoria caldera
Sokoria 1	87-95		600-1050	Associated with Sokoria caldera
Sokoria 2	43		1000	Associated with Sokoria caldera
Detusoko	60-70		650	Associated with flank of Kelimutu volcano
Lesugolo	60-80		600	
Jopu	45-60		200	Lower flank of Kelimutu volcano
Wonda, Egon			75	Flank of Egon volcano
Kawaliwu			60	Flank of Egon volcano
Oka-Larantuka	72		7-10	South Flank of Ilimandiri volcano
Talibura	56		4	North flank of Ilimandiri volcano

and 260 ℃, respectively (Nasution *et al.,* 2000). Therefore, there is a good correlation between water and gas geothermometry in assuming subsurface Mataloko and Sokoria geothermal fields.

Two drilling areas, Ulumbu and Mataloko have shown good geothermal prospects. Three wells (1800, 900 and 700 m) such as an exploration well, production well and injection well have been drilled in the Ulumbu geothermal field. The production well represents downhole temperatures approximately 230 - 245 ℃ with a vapor dominated system (Johnson, 1995 personal communication). The shallow Mataloko exploration drilling (200 m) has given subsurface temperature information of about 200 ℃ and has a vapor dominated system. These two areas have indicated good geothermal resources. Therefore, the SO_4 type water of Sokoria fumarolic field will probably have a similar system as the Ulumbu and Mataloko fields.

7. Discussion and conclusions

Geochemistry of Flores volcanic rock associations has characteristics of most island arcs. For more details, however, it is better to be volumetrically evaluated for the magmatic processes and genesis. The wide array of SiO_2 - K_2O trend of volcanic rocks of the Flores Island reflects variation in petrogenetic controls in the direction across the Flores volcanic arc. The tholeiitic lavas of Flores have average values of $^{87}Sr/^{86}Sr$ = 0.7042 at the Benioff zone depth between 100 - 150 km. The high K calc-alkaline lavas have average values of $^{87}Sr/^{86}Sr$ = 0.7045 at the Benioff zone depth of 200 - 250 km (Whitford and Jezek, 1982). The source regions of isotopic values are correlated to the depth of the subducted slab, and the isotopic variation reflects the involvement of subducted materials (Whitford and Jezek, 1982). These data are supported by Ben Abraham and Emery (1973) that the depth of Benioff zone under Flores volcanic island is approximately 100 - 250 km.

Volcanologically, geothermal prospects of Flores are located in Quaternary volcanic areas, especially in volcanic caldera types. The hot springs are mostly associated with post-volcanic activities. The high temperature gasses (SO_2, HCl and toxic gasses such as CO) are mostly found in an active volcano and will probably not exist or will be very low concentration in geothermal fields. Therefore, the corrosive and toxic gases will probably be avoided.

In general, the high temperatures of sulfate type water are mostly obtained on a high topographic terrain, as shown by the Sokoria, Mana Mataloko and Ulumbu geothermal fields. They presumably represent the same system that volcanic gas tends to flow up through volcanic rock fractures to the surface (it is represented by an active volcano). In a lower topographic terrain, hot springs are mostly derived from neutral pH chloride water. They apparently tend to flow through low land and high porosity rocks (Wai Sano, Wai Pesi, Detusoko, Lesugolo and Oka).

Drilling of exploration-production wells in the Ulumbu geothermal field have been carried out by PLN (an Indonesian private company) and GENZL (New Zealand private company) and their producing steam capacity is approximately 12 MWe (Johnson, 1996, a personal communication). The shallow drilling in the Mataloko geothermal field gives a low steam capacity of approximately 14 - 15 ton/hour, equivalent to 1.5 MWe. Therefore, young volcanoes contribute for the Flores geothermal heat source. Information on the post-volcanic activities provides useful data for detailed exploration of the geothermal prospects in Flores such as Wai Sano, Sokoria, Detusoko and Lesugolo.

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火山活動および熱水化学組成からみたインドネシア・フローレス島の地熱有望地域

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要　旨

フローレス火山弧の溶岩類は玄武岩からデイサイトの組成範囲をもつが，とくに安山岩に卓越し，ソレイアイト岩系ではピジョン輝石，カンラン石を，カルクアルカリ岩系では角閃石や黒雲母を斑晶として含む．化学的には，広い範囲の SiO_2（51－67 wt.%）および Al_2O_3（14－20 wt.%）含量と低い TiO_2（<1 wt.%）含量を示し，比較的高い Rb，Sr および Ba 含量を示す．これらKグループ元素はベニオフ帯の深度の増大につれて増加する．ソレイアイトからカルクアルカリ溶岩にかけてのストロンチウム同位体比は 0.7042－0.7045 であり，これも島弧を横断して沈み込むスラブの深度に比例していると推定される．フローレス島の地熱有望地域は若い安山岩や玄武岩の火山地域に位置し，標高 500－1000 mにあって，火山活動後の断裂と断層や，カルデラ構造に伴う．湧出熱水は広い化学的タイプを示し，硫酸塩型，塩素型，重炭酸塩型に分けられる．硫酸塩型は主に噴気に伴って，高い火山地域（標高700－1100 m）に位置し，表層における H_2S の酸化を示す（Ulumbu，Mataloko，Nage および Sokoria）．重炭酸塩型熱水は Langageda や Sokoria2 のように火山中腹（標高 400－700 m）に位置する．中性塩素型熱水は低い火山地域（標高 5－600 m）に位置し，温度 210－280 ℃ の地熱貯留層からのアウトフローを示す．地熱井は Ulumbu と Mataloko 地熱有望地域でそれぞれ 700－1800 mと 200 m の深度まで掘削されているが，200 から 240 ℃ の地下温度を示し，その高い硫酸塩濃度が蒸気卓越型に伴うことを示している．同様の型は Sokoria 地域にも期待される．他方，高塩素型の地熱有望地域はおそらく熱水卓越型か混在型を示すのであろう（Wai Sano，Wai Pesi，Jopu，Lesugolo および Oka）．