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THE GEOLOGY AND GEOCHEMISTRY OF MATALOKO -NAGE-BOBO GEOTHERMAL AREAS, CENTRAL FLORES, INDONESIA

Asnawir Nasution[1], Isao Takashima[2], Hirofumi Muraoka[3], Hiroshi Takahashi[4], Koji Matsuda[5], Hideo Akasako[5], Masao Futagoishi[6], Dedy Kusnadi[1], Fredy Nanlohi[1]
[1]Volcanological Survey of Indonesia, Jl.Diponegoro 57, Bandung, Indonesia
[2]Research Institute of Materials and Resources Mining College, Akita University, Akita, Japan
[3]Geothermal Research Department, Geological Survey of Japan 1-1-3 Higashi, Tsukuba, Ibaraki, Japan
[4]MMRC, 6-23, Takanawa 4 chome, Minato-ku, Tokyo, 108-0074, Japan
[5]West-Jec Denki Bldg., Annex 5F, 2-1-82, Watanabe-dori, Chuo-ku, Fukuoka, Japan
[6]NEDO, 28th Floor, Sunshine 60 Building, 1-1, Higashi-Ikibukuro 3-chome, Toshima-ku, Tokyo, Japan

Key words: Geothermal, geology, geochemistry, Flores, Indonesia

ABSTRACT

The preliminary interpretation of geological and geochemical data from the Mataloko-Nage-Bobo areas indicates the presence of a geothermal prospect. The geothermal manifestations are situated in andesitic to basaltic volcanic terrain between 500-1400 m above sea level. K/Ar and ^{14}C ages of the volcanics range from 2.4 - 0.01 Ma, consistent with a high temperature geothermal heat source at depth. The prospect is divided into three areas with different characteristics. The SE-NW trending alteration zone of Mataloko (900 m asl) is mainly characterized by strong argilitization, consisting of kaolinite, alpha-cristobalite, alunite and pyrite that are probably associated with a fault structure of Wai Luja. The extension of hydrothermal alteration to deeper levels is suggested by low resistivity soundings (<10 Ω-m) and strongly affected by sulfuric acid dissolution. The hot, sulphate water assumed to be caused by H_2S oxidation in near-surface yields gas geothermometer temperatures of ~ 283°C. The low values for $\delta^{34}S(SO_4)$ and chloride suggest that the gases are not derived from a magma reservoir, but rather from a deep aquifer (reservoir). The NE-SW trending alteration zones of Nage (520 m asl) are characterized by silicification-argilitization (pyrophyllite, quartz, and gypsum), with an average alteration age less than 0.2 Ma. The sulphate-chloride hot water has high boron, fluorine, arsenic and bromium contents, probably due to volcanic gases mixing with shallow ground water. The relatively high values for $\delta^{34}S$ (SO_4) are due to an increasing SO_4 concentration, probably indicating a contribution of magmatic SO_2 to the hot spring aquifer. The N-S trend of young volcanic cones (1400 m asl) in the Bobo area have mainly alunite, kaolinite and cristobalite clay alteration. The presence of volcanic gases in fumaroles, especially SO_2, suggests high temperature gases and a young heat source. Gas geothermometry indicates an underground temperature of 287°C.

1. INTRODUCTION

A new five-year international cooperation program on geothermal research between Japan and Indonesia was signed in March 1998 by three institutions: NEDO (New Energy Development Organization, Japan) the GSJ (Geological Survey of Japan), and VSI (Volcanological Survey of Indonesia). One of the first objectives of the program has been an assessment of the Bajawa geothermal area (Mataloko, Nage and Bobo), located in Flores, in the Ngada regency of Nusa Tenggara (Figs. 1 & 2; between 120°55'-121° 05' E latitude 08°41.5'- 08°43.8' longitude). The region has good accessibility and a high rainfall (1750-2250 mm/year).

Past reports, particularly about the tectonics, regional geology, and hot water occurrences, as well as an early interpretation of the geothermal area have been carried out by Katili (1973), Hamilton (1979) Koesoemadinata et al. (1981), Silver and More (1981), Nasution and Aswin (1996), and Muraoka et al. (1998, 1999).

This paper will give a preliminary interpretation of new exploration data (geology and geochemistry) and an understanding of the water rock interaction from the Mataloko, Nage and Bobo geothermal prospects.

2. TECTONIC SETTING

The Indonesian Island arcs result from the interaction of the Eurasian, Indian-Australian, Pacific plates and possibly also the Philippine plate to the north of Sulawesi (Katili, 1973; Hamilton, 1979, Silver and More. 1981). These island arcs mostly display microcontinental arc volcanism associated with an oceanic trench subduction zone (Fig.1). The Sunda arc, where the Flores Island is situated, represents a part of collision zone between the Indian-Australian to the south and the Eurasian plate to the north, generating an east-west trending volcanic chain: e.g. Lewotobi, Egon, Kelimutu, Iya, Ebulobo, Ine-Rie, Ine-Lika and Anak Ranakah volcanoes.

The Bajawa thermal features are situated between three active volcanoes, Ine-rie, Ine-lika and Ebulobo. They are associated with structural and fracture systems passing through the volcanic complex (e.g. Wolo Pure, Sasa, Rhea, Bela, Hoge and Belu, Bobo, and Bajawa volcanic cones). The volcanic cones probably indicate a heat source that supports the Bajawa geothermal prospect.

3. GEOLOGIC SETTING

The geology of the prospect area comprises young Quaternary volcanic products (Qvc) of andesitic-basaltic composition, eg. Wolo Bobo, Manulalu and Belu (Fig. 2). A carbon age of 0.01

Ma from Bobo airfall deposits indicates very young volcanic activity, and perhaps a shallow crystalline magma beneath the Bajawa thermal areas.

The Mataloko andesites (Qma) and the Bajawa andesites (Qba-b) are characterized by high relief, a relatively high erosion rate, and high altitude (500-1000m asl). They are composed of fresh to weathered lavas and thick pyroclastics (Fig.2). K/Ar dates of lavas and pyroclastics give ages of 0.15, 0.12 and <0.1 Ma (Muraoka et.al, 1999). The Bajawa pyroclastics are inferred to be caldera and post-caldera forming eruption products.

The Waebela basalt (Qvwb) is intercalated, weathered and has columnar jointing, and is characterized by coarse relief, plateau volcanics and a high erosion stage. One such basalt outcrops at Wolo Paga (2.4 Ma) to the North of Ine Rie, probably as a somma of Ine Rie active volcano. The massive lava of Waebela basalt (1.6 Ma) located to the south coast (Fig. 2), is a hyaloclastic and submarine pillow lava with pillow robe. Other Waebela lavas (1.1 Ma) are probably associated with the pre-caldera formation of Bajawa.

The Tertiary weathered Maumbawa basalt (Tvmb) and The Tertiary Welas tuff (Tvw) are characterized by a high erosion stage. They have ages of 3.37 and 2.73 Ma (Fig.2), indicating Pliocene volcanism in the southern part of the prospect. The Welas tuff is characterized by compacted material, unwelded altered greenish pumice and poorly sorted lithics. These rocks were presumably derived from the Welas caldera (the northern volcanics) and deposited in a southern shallow marine environment. The age of lithic fragments (2.73 Ma) corresponds to the age of Welas pre-caldera lava, 4.14 and 2.9 Ma (Muraoka et.al., 1999). They form a Tertiary volcanic basement which is unconformable overlain by Quaternary volcanic products.

The geological structures associated with the southeast-northwest trending fault systems occupying regional structures of Central Flores (Fig.2) are probably influenced by the tectonic driving from the south. Generally the thermal discharges in the Bajawa prospect are associated with structure or fracture systems oriented in NW-SE, SW-NE, N-S directions and influence or replace original rock minerals to form alteration or clay minerals.

The SE-NW Wailuja normal fault is a major control structure for channeling thermal fluids of the Mataloko geothermal area. This is demonstrated by a trend of hot springs and alteration zones, characterized by strong argilitization (kaolinite, alpha-cristobalite, alunite and pyrite). The resistivity surveying (by Head-On method) shows that the fault dips at >70^o to the north (Andan et.al., 1997), and suggests that fluid discharges rise to higher elevations on the northern part of the Wailuja fault.

The SE-NW Boba normal Fault is characterized by old topographic lineations, escarpments and triangular facets in some places. The southern hanging wall is part of Bajawa and Mataloko old volcanics, while the northern foot wall is covered by younger products. There are no indications of thermal discharges along the fault, suggesting that thick volcanic products cover the area.

The NE-SW trending alteration zones of Nage (520 m asl) are characterized by silicification-argilitization (pyrophyllite, quartz, and gypsum). They are probably affected by strong sulfuric acid leaching along the NE-SW Nage fault. In addition, an average alteration age (Thermoluminecence dating) for Nage of less than 0.2 Ma suggests an early thermal history for the geothermal area.

The N-S structural pattern of Bobo is represented by volcanic lineaments that are probably strongly affected by a combination of normal and strike slip fault systems. The large number of geothermal features and clay alteration (alunite, kaolinite and cristobalite) along fault suggests that fracture trend dominates permeability within the Bajawa geothermal area.

4. WATER CHEMISTRY

Chemical analyses of thermal discharges is listed in Table 1. Generally, the Bobo springs are characterized by high sulphate, low chloride, sodium, and calcium contents, indicating a sulphate-type water (Fig.3a). The high sulphate suggests that the volcanic gases, particularly H_2S, oxidize near the surface, influencing the shallow ground water composition. The water chemistry suggests immature water beneath Bajawa (Fig.3b), and strong mixing with shallow ground water. The low B/Cl ratios (Fig.3c) are consistent with the system being hosted by andesitic rocks.

The chemical concentrations of Mataloko and Nage hot springs are different. The former has low chloride, boron, fluorine, arsenic and bromium contents, indicating a neutral pH water flowing through volcanic terrain and interacting with shallow ground water. The latter is a sulphate-chloride water with high chloride, boron, fluorine, arsenic and bromine concentrations, presumably a result of volcanic gases mixing with brine water and then influencing shallow ground water.

4.1 Isotopic composition of fluid

Oxygen-18 and deuterium (D) contents are an indicator of fluid origin and the degree of water-rock interaction at high temperature (Craig, 1963). Isotopic compositions of ground water and thermal discharges are shown in Table 1.

The ground or surface cold waters of the Mataloko, Nage and Bobo areas are close to the meteoric water line $\delta D = 8.58 \delta ^{18}O + 19.8$ for this area. These waters are derived from meteoric water (Fig.4). The values of $\delta D (H_2O)$ and $\delta ^{18}O (H_2O)$ for Mataloko hot spring water are higher than those for cold surface water and are also close to the meteoric water line (Fig.4), indicating a meteoric origin with a shift due to steam loss. At Nage hot springs however, the shift is toward higher values, indicating a partial mixing of magmatic water into the hot water aquifer.

The $\delta ^{34}S(SO_4)$ values and the Cl concentrations (Fig.5) of the Mataloko hot springs are relatively low (- 1.6 to 2.5 $^o/_{oo}$) and extremely low (<3 mg/l) respectively. These water smell of H_2S, independent of SO_4 concentration. The low values for $\delta ^{34}S(SO_4)$ and chloride suggest that the gases are not derived from magmatic sources, but from a deeper aquifer (reservoir). The geothermal brine in the deeper reservoir is considered to be chloride rich and pH neutral, as brine is in many geothermal systems (e.g. Hatchobaru, Japan; Ulumbu and

Salak, Indonesia). The up-flow of the brine water to the shallower aquifer will be prevented by a sealing zone above the reservoir. Judging from hot spring temperature (near the boiling point), the reservoir is considered to have a high potential for geothermal development.

Nage hot springs are acid with high Cl concentrations (Table 1), classified as sulphate type water (Fig. 3a). The SO_4/Cl ratios at Nage of about 1 are very close to those of acid crater lake water from Kelimutu, Ende (Fig. 6, Pasternack and Varekamp, 1994). These values indicate that magmatic gases might contribute to the Nage geothermal system. The values of $\delta^{34}S$ (SO_4) for Nage hot spring are relatively high, 9.9 to 11.1 ^{o}/oo (Fig.5) and increase with increasing SO_4 concentration, indicating a contribution of magmatic SO_2 to the hot spring aquifer. In addition, geothermometry based on the saturation index of anhydrite (calculated using "Solveq", Reed and Spycher, 1984); suggests that the shallow aquifer is heated to 210^{o}C.

4.2 Isotope Hydrology

Meteoric water from a recharge area will penetrate into the geothermal reservoir, acquiring heat and dissolved salts. Árnason (1976) used stable isotope data from meteoric and geothermal water to locate recharge areas. He contended that geothermal water and recharging meteoric water have similar δD values, since rock contains little exchangeable hydrogen to cause a δD shift. Consequently, the unchanged δD value defines the recharge areas of a geothermal system.

Isotopic compositions of ground meteoric water (Table 2) are influenced by latitude, altitude, distance from the sea and season (wet or dry). In Bajawa, they are most strongly affected by altitude and topography. In the survey area, the isotope data for surface water is represented by the regression function: $\delta D = 8.58\ \delta^{18}O + 19.8$.

The altitude effect on δD (H_2O) and $\delta^{18}O$ (H_2O) is shown in Figs. 7, 8 and 9 respectively. δD and $\delta^{18}O$ values of hot and cold surface water in the Bajawa area decrease at the rate of 98 $^o/_{oo}$ and 0.14 $^o/_{oo}$ respectively, per 100 m ascending altitude. The distribution of δD in cold surface water is estimated as shown in Fig. 8. It is likely that, the origin of geothermal fluids is meteoric water precipitated at an altitude greater than 1400 m where potential recharge occurs. The circular faults and lineament structures assist penetration of meteoric water into the ground.

In addition, gas concentrations from Mataloko and Bobo fumaroles are shown on Table 3. They show high CO_2/H_2S and H_2S/SO_2 ratios, consistent with high temperature fluids travelling rapidly from the source before condensing in the upper part of the system or shallow ground water. Based on gas geothermometry (D'Amore and Panichi, 1980), both areas indicate high underground temperatures: ~ 283^{o}C at Mataloko, while the Bobo fumarole (which contains a small amount of SO_2) shows ~ 287^{o}C.

5. DISCUSSION

The preliminary geological and geochemical data suggest that shallow alteration is affected by low temperature gases from steam condensate, especially H_2S which is oxidized close to the surface. These gases dissolve primary minerals, forming clay minerals (e.g. montmorillonite, kaolinite, illite, and alunite) and indicate that fluid pH gradually decreases from montmorillonite through kaolinite to alunite. The argilitization zone of Mataloko and the silicification-argilitization zone of Nage have alteration ages of less than 0.2 Ma, probably correlated with the formation of young forming structures.

The geothermal heat source of Mataloko is presumably associated with the Wolo Belu and inactive young volcanic cones (Qvc). However, the Mataloko andesites (Qma) are probably a heat contributor to the geothermal system as well. Mataloko geothermal brine is derived from meteoric water. It has low values of δ^{34} (SO_4) and chloride, indicating that the fluids are of non-magmatic origin. Instead, the fluids are thought to be from a deeper neutral pH chloride water which has a temperature resources of ± 283 °C. Therefore, the Mataloko reservoir is considered to have a high potential for geothermal development.

The water from Nage is derived from meteoric water as well. Chemically, it has high chloride, boron, fluoride, arsenic and bromide concentrations. The values of $\delta^{34}S$ (SO_4) are relatively large (9.9 to 11.1 ^{o}/oo) and increase due to increasing SO_4 concentration, indicating a magmatic contribution of SO_2 or a partial mixing of magmatic water into the hot water aquifer.

6. CONCLUSIONS

The data presented herein suggest that the Mataloko area is a significant geothermal prospect. Crystallization of Mataloko andesitic-to-basaltic magma supplies a conductive latent heat source that penetrates passing the system and heats the deep meteoric water. The up-flows of sulphate type water at the surface, indicate a high sub-surface fluid temperature (283-287°C). Acid geothermal fluid strata produce argilitic and silicified rocks.

The Mataloko geothermal water has low values of δ^{34} (SO_4) and chloride, indicating that it is derived from a deeper reservoir of neutral pH chloride water with temperature ~ 283 °C. The Nage hot springs are sulphate-chloride type, deriving from meteoric water. Their recharge area is located north of Nage and Bobo at altitude above 1200 m. The high values for $\delta^{34}S$ (SO_4) indicate a partial mixing of magmatic water into the hot water aquifer. Therefore, the Mataloko reservoir is of considerably higher potential and better than Nage for development of a small scale geothermal power source to support rural electrification and industrial growth of the district. Geothermal brine in a deeper reservoir of Nage may be strongly acid, indicating a significant magmatic contribution which is probably associated with the Ine Rie active volcano.

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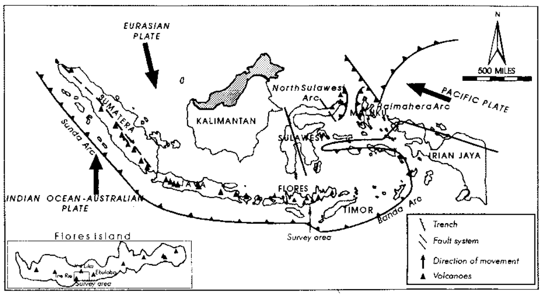

Fig. 1 Plate boundaries of Indonesia (from Katili, 1973)

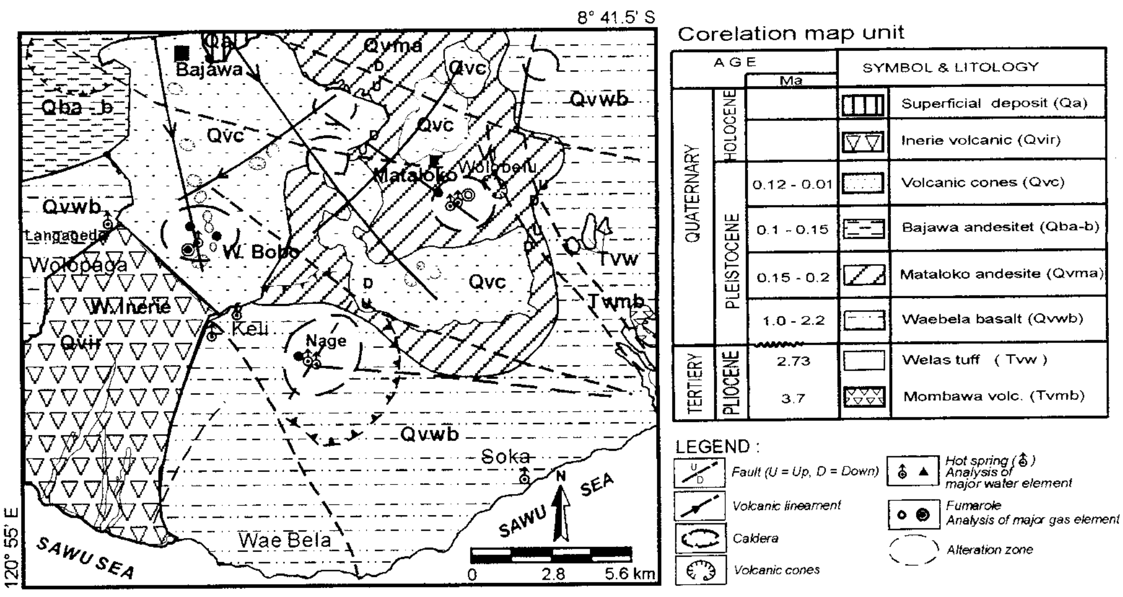

Fig. 2 Geothermal geological map of Mataloko, Wolo Bobo and Nage area

Table 1

CHEMICAL ANALYSES OF HOT SPRING WATER

Location	Parameters	Mataloko-1	Mataloko-2	Mataloko3	Nage-1	Nage-2	Keli-1	Keli-2	Bena	Soka	Langagede
pH		2,4	3,6	2,7	2,1	2,1	6,7	3,0	6,6	5,2	7,4
E.C.	μS/cm	248	49,4	130	515	454	207	163	148	88,3	109
Turb.	mg/l	51,9	221	160	3,02	0,881	0,524	0,646	0,153	0,075	0,316
TSM	mg/l	1930	520	941	1460	1380	2040	1240	1300	733	841
Na	mg/l	27	15,6	17	142	128	120	62,7	64,9	37,3	145
K	mg/l	4,912	4,62	9,54	39,8	38,1	69,1	26,7	22,7	9,9	48,7
Li	mg/l	0,0213	0,042	0,0203	0,343	0,329	0,0416	0,0283	0,0318	0,0069	0,0893
Ca	mg/l	59,3	31,3	25	90,5	82,7	232	127	174	130	56,8
Mg	mg/l	30,3	13,3	16,9	30,5	27,8	81,6	47,6	70,8	14,7	15,6
Al	mg/l	45	2,48	1,99	31,6	29,9	n.d	3,94	n.d	0,158	-
T - Fe	mg/l	35,9	1,44	7,56	12,5	15,6	0,0268	0,0788	0,0092	0,0102	-
Cl	mg/l	2,91	2,89	1,46	461	399	110	40,4	42,3	8,69	35,6
SO_4	mg/l	928	210	344	792	740	962	680	499	413	136
HCO_3	mg/l	n.d	n.d	0	n.d	n.d	84,8	n.d	286	14,6	404
CO_3	mg/l	n.d	n.d	0	n.d	n.d	n.d	n.d	n.d	n.d	n.d
F	mg/l	0,271	0,129	0,131	7,53	6,02	0,86	0,74	0,923	0,86	0,156
B	mg/l	0,0913	0,0247	0	8,85	7,85	1,26	0,518	0,676	0,0978	0,86
As	mg/l	0,00242	n.d	0,0022	1,77	1,95	0,144	0,0156	0,0137	0,499	0,208
T - SiO_2	mg/l	295	179	352	118	111	219	154	118	55,7	165
NH_4	mg/l	7,39	0,532	2,23	0,12	0,162	0,0352	n.d	n.d	n.d	n.d
Br	mg/l	n.d	n.d	0	1,46	1,3	0,234	0,148	0,136	0,049	0,115
$\delta D(H_2O)$	0/00	-14	-34	-28	-36	-36	-41	-38	-36	-28	-41
$\delta^{18}O(H_2O)$	0/00	1,5	-5,7	-3	-6,3	-6,3	-7,1	-6,9	-6,5	-5,6	-7,2
$\delta^{34}S(SO_4)$	0/00	-2,5	-2,1	-1,6	11,6	9,9	11,1	4,8	9,8	9,3	0

Table 2

CHEMICAL COMPOSITION OF SURFACE WATER

Location	Parameters	Bajawa	Mukufoka	WaeRhea	Liba	Mataloko1	Mataloko3	Wae Putih	Keli	Bena	Soka
pH		7	7,1	7	7,3	7,2	7	2,5	7,5	7,3	7,2
Description	river/stream	rain wat.	coldspring	coldspring	cold sp	stream	coldspring	cold spring	stream	cold sp	stream
Elevation	m.asl	1220	1260	1390	1100	1000	1150	1050	810	770	110
Flow Rate	L/min.	-	270	6	>1000	20	40	6	50	3	5
Air Tmp	oC	21,1	18,1	21,4	21,8	21,7	23,8	24	24,3	21,7	27,3
Water Tmp.	oC	20	19,2	19,8	24,2	22,1	25,3	22,4	26	26,6	27,6
E.C.	mS/m	3,18	18,2	9,47	23	19,9	22,9	183	39,4	60	20,6
dD(H2O)	0/00	-5,2	-38,5	-38,8	-39,6	-30	-37,4	-34,3	-35,8	-33,2	-21,5
d18O(H2O)	0/00	-3,3	-7	-7,2	-7,1	-5,6	-6,7	-6,5	-6,6	-6,3	-5

Table 3

Gas Composition

Location	Gas Composition (% v/v)								
	CO_2	H_2S	NH_3	HCl	SO_2	N_2	O_2 + Ar	H_2	CH_4
Mataloko	5,2	0,06	0,00021	0,06	0,01	0,03	0,00781	0,000294	0,000915
Wolobobo	8,14	1,5718	0,00002	0,05	0,1	0,09	0,014	0,000012	-

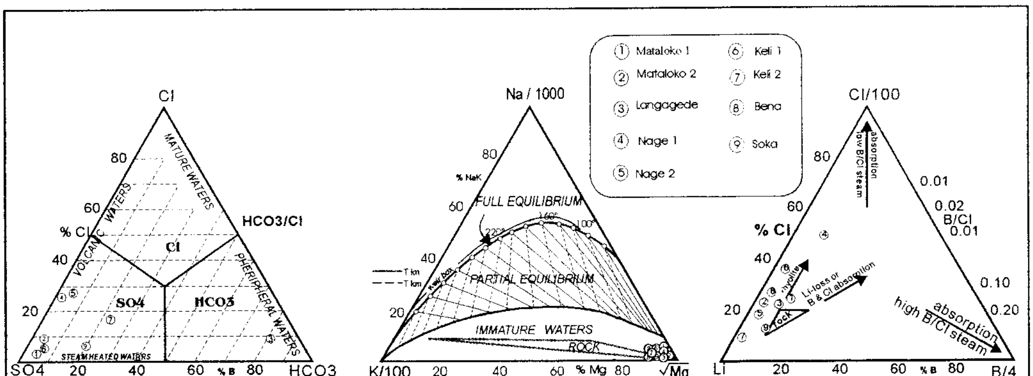

Fig. 3a Diagram Cl, SO4, HCO3 (Giggenbach, 1988) of Bajawa area

Fig. 3b Diagram Na, K & Mg (Giggenbach, 1988) of Bajawa area

fig. 3c Diagram Cl, Li and B, (Giggenbach, 1988) of Bajawa area

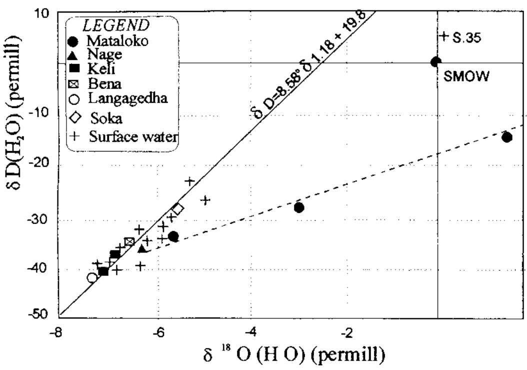

Fig. 4 Relationship between δD and δ^{18}O (Hot and surface water)

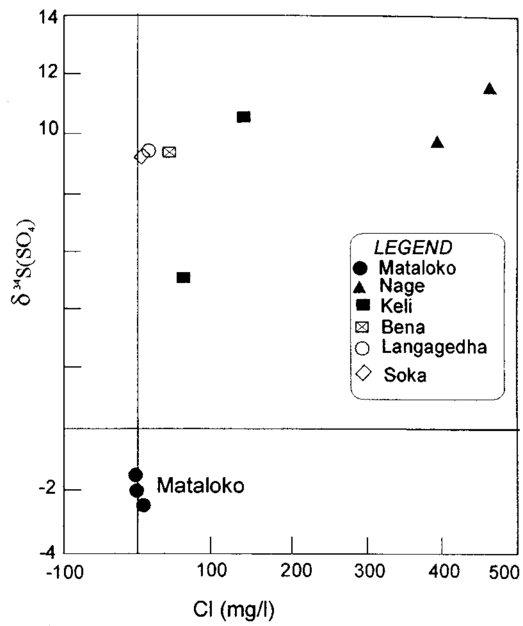

Fig.5 Relationship between Cl and δ^{34}S(SO)

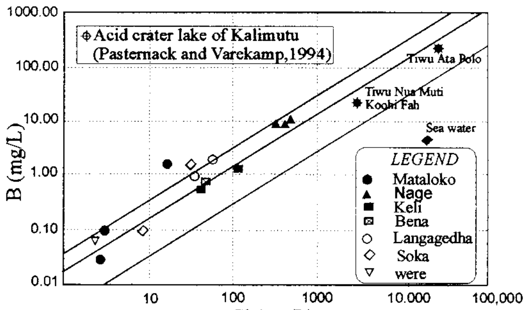

Fig. 6 B versus Cl diagram on hot spring water

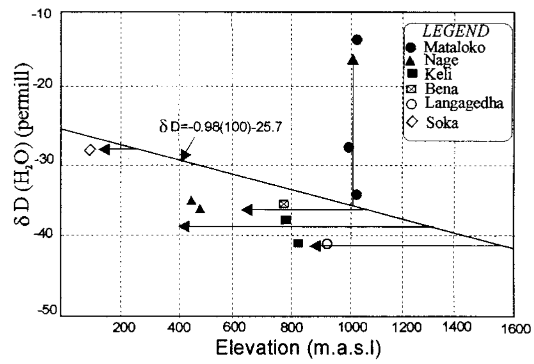

Fig. 7 δ D versus Elevation Diagram on Hot Spring Water

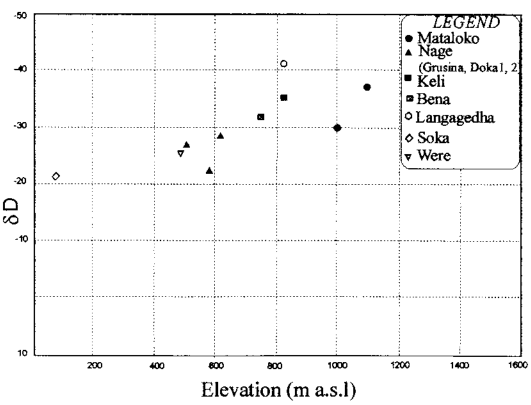

Fig.8 Relationship between δD and elevation (surface water)

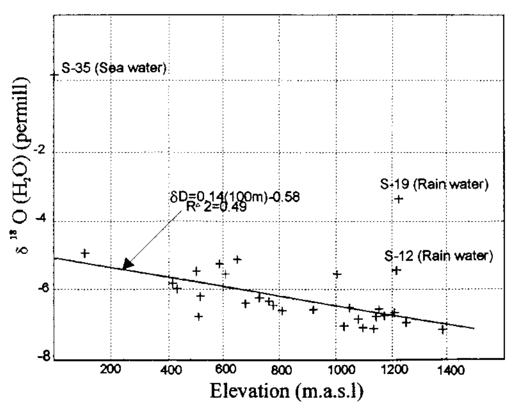

Fig. 9 Relationship between δ^{18}O and elevation (Surface water) (From NEDO,1998)